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Sluttrapport

BIO-garn

Bruk av nedbrytbare garn for å redusere faren for spøkelsesfiske

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SAMMENDRAG
I denne rapporten presenteres resultatene fra ulike forsøk med biologisk nedbrytbare garn. Fiskeforsøk på torsk, sei og blåkveitefiske viser at biogarn har dårligere fangstevne enn tradisjonelle nylongarn. Lavere fangstevne kan gjøre at fiskerne foretrekker tradisjonelle nylongarn frem for biogarn.

Degraderingsforsøk i sjøen viser ca. 26% reduksjon i bruddstyrken i PBSAT-garn etter ca. 25 måneder i sjøen (kaldt vann), mens prøver fra biogarn som ble brukt i en fiskesesong (inntil 3 måneder) viste om lag samme reduksjon i bruddstyrke. Daglig bruk og slitasje av garn fremskynder nedbrytningsprosessen. Kontrollerte labforsøk i 20°C sjøvann viser også ca. 20% degradering etter 12 måneders. Så langt det er ikke blitt registrert fragmentering, dvs. dannelse av mikroplast-partikler.

Miljødirektoratet (2018) har anslått at om lag 13000 garn mistes hvert år. Tapte garn kan fremdeles ha fangstevne og dermed både øke dødeligheten i bestanden og påføre fiskerne et tap i form av tapte fangstmengder. Det anbefales derfor å gjennomføre en bioøkonomisk analyse av garnfisket, og estimere omfanget og betydningen av utilsiktede dødelighet (F) forårsaket av spøkelsesfiske ("ghost fishing"). Vi foreslår også å undersøke videre om bruk av nedbrytbare garn kan bidra til å redusere spøkelsesfiske og plastforurensning i havet, og på den måten bidra til en mer bærekraftig fiskeriforvaltning i Norge.

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Innholdsfortegnelse

1 Innledning og bakgrunn ... 4

2 Aktiviteter og hovedfunn ... 6

2.1 Forsøk i kommersiellfiske (vedlegg 1, 2, 3, 7, 8). ... 6

2.1.1 Effekter av å bruke biologisk nedbrytbare garn i blåkveitefiske. ... 6

2.1.2 Fangstevne av biologisk nedbrytbare PBSAT-garn og konvensjonelle nylon-garn som brukes i det norske torsk- og seifiskeriet. ... 6

2.1.3 Sammenligning av fangstevne mellom nedbrytbare-garn og konvensjonelle nylon-garn. ... 7

2.1.4 Sammenligning av fangstevne mellom nedbrytbare-garn (0.55 og 0.60 mm monofilament) og konvensjonelle nylon-garn (0.55mm monofilament) ... 7

2.1.5 Sammenligning av fangstevne mellom nedbrytbare-garn (0.75 mm monofilament) og konvensjonelle nylon-garn (0.70 mm monofilament) ... 7

2.2 Degraderingsforsøk i havet (vedlegg 4). ... 7

2.2.1 Sammenligning av mekaniske egenskaper av PBSAT- og PA-garn. ... 8

2.3 UV degraderingsforsøk (vedlegg 5 og 6). ... 9

2.3.1 UV-degraderingsforsøk av monofilamenter – Forsøk 1: Utendørstilstand. ... 9

2.3.2 UV-degraderingsforsøk av monofilamenter – Forsøk 2: Høy relativ fuktighet. ... 9

2.4 Degraderingsforsøk av monofilamenter i lab. ... 9

2.4.1 Nedbrytningsstudier med bakterielle anrikningskulturer ... 9

2.4.2 Nedbrytning i naturlig sjøvann ... 10

2.4.3 Nedbrytning i sjøvann med sedimenter ... 10

3 Forslag til videre arbeid ... 11

4 Takk ... 12

BILAG/VEDLEGG

Vedlegg 1: Grimaldo, E., Herrmann, B., Vollstad, J., Su, B., Moe Føre, H., Larsen, R.B. 2018. Fishing efficiency of biodegradable PBSAT gillnets and conventional nylon gillnets used in Norwegian cod (*Gadus morhua*) and saithe (*Pollachius virens*) fisheries. ICES Journal of Marine Science.

Vedlegg 2: Grimaldo, E., Herrmann, B., Tveit, G., Vollstad, J., Schei, M. 2018. Effect of using biodegradable PBSAT gillnets on the catch efficiency and quality of Greenland halibut (*Reinhardtius hippoglossoides*). Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 10:619–629, 2018

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Vedlegg 6: Kubowics, S. 2019. Aging test of monofilament fishing line. SINTEF Rapport. SINTEF Industri. Polymer Kjemi

Vedlegg 7: Jacques N. 2019. Sea trials rapport: Results from sea trials made using biodegradable gillnets on saithe and cod, October-December 2018. SINTEF Ocean

Vedlegg 8: Jacques N. 2019. Sea trials rapport: Results from sea trials made using biodegradable gillnets on cod, January-March 2019. SINTEF Ocean

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1 Innledning og bakgrunn

Denne rapporten oppsummerer bakgrunnen for og hovedfunnene i prosjektet "Development of biodegradable gillnets to reduce the effect of ghost fishing in Norwegian deep-sea gillnet fisheries (BIO-gillnet)". Arbeidet og resultatene i prosjektet er tidligere rapportert og publisert i vedlagte vitenskapelige artikler og rapporter (Vedlegg 1-5). Prosjektet er finansiert gjennom Norges Forskningsråds MARINFORSK-program, Fiskeri- og havbruksnæringens forskningsfond (FHF), og Fiskeridirektoratets tilskuddordning til fiskeriforskning. Prosjektet ble startet i januar 2016 og ble avsluttet i desember 2018. Hovedmålet i prosjektet har vært å utvikle et nedbrytbart garn tilpasset det norske dypvannsfiskeriet etter blåkveite, torsk og sei, og med minst like gode fiskeegenskaper som konvensjonelle nylongarn. Spesifikke delmål har vært å:

- Lage nedbrytbare garn for de norske garnfiskeriene
- Studere fysiske egenskaper (fleksibilitet, forlengelse, bruddstyrke, nedbrytningstid)
- Sammenligne fangstevnen til nedbrytbare garn ift. konvensjonelle nylongarn

Garn er ett av de viktigste fiskeredskapene i Norge, spesielt for kystflåten. Torsk, sei, blåkveite, breiflabb og rognkjeks er de viktigste arter for disse fiskeriene. I 2012 ble torskekvoten fordelt slik: ca. 93.000 tonn til redskapsgruppen som fisker med garn, ca. 76.000 tonn til trål, ca. 58.000 tonn til snurrevad, ca. 40.000 til autoline, og ca. 25.000 tonn til andre[1]. Det estimeres at antall tapte garn per år er ca. 13.900 (tabell 1). Per i dag er Norge og Sør-Korea de landene i verden som har et program for systematisk opprensking av tapte fiskeredskaper fra områdene med høyest fiskeriaktivitet. Fiskeridirektoratet oppgir at det for perioden 1983-2017 er tatt opp totalt 20.450 tapte garn (ca. 572 km total lengde på garnlenkene), og et betydelig antall andre fiskeredskaper. Det er rapportert varierende mengde fangst i redskapene som er hentet opp fra år til år. Noen år er det rapportert flere tonn fisk. I rapporten for 2017 er det anslått at ca. 10.000 kg fisk og ca. 5600 krabber (hovedsakelig kongekrabbe) ble tatt opp (Sundt et al., 2018). Opprenskingsoperasjonene er svært krevende på grunn av store dybder (500-1000m), sterke strømmer og usikkerhet og unøyaktighet i posisjonen til tapte redskaper. Derfor har det i de siste årene blitt fokusert på å utvikle metoder for å redusere tap av redskap, lokalisering av tapte redskap og bruk av biologisk nedbrytbare materialer i fiskeredskap.

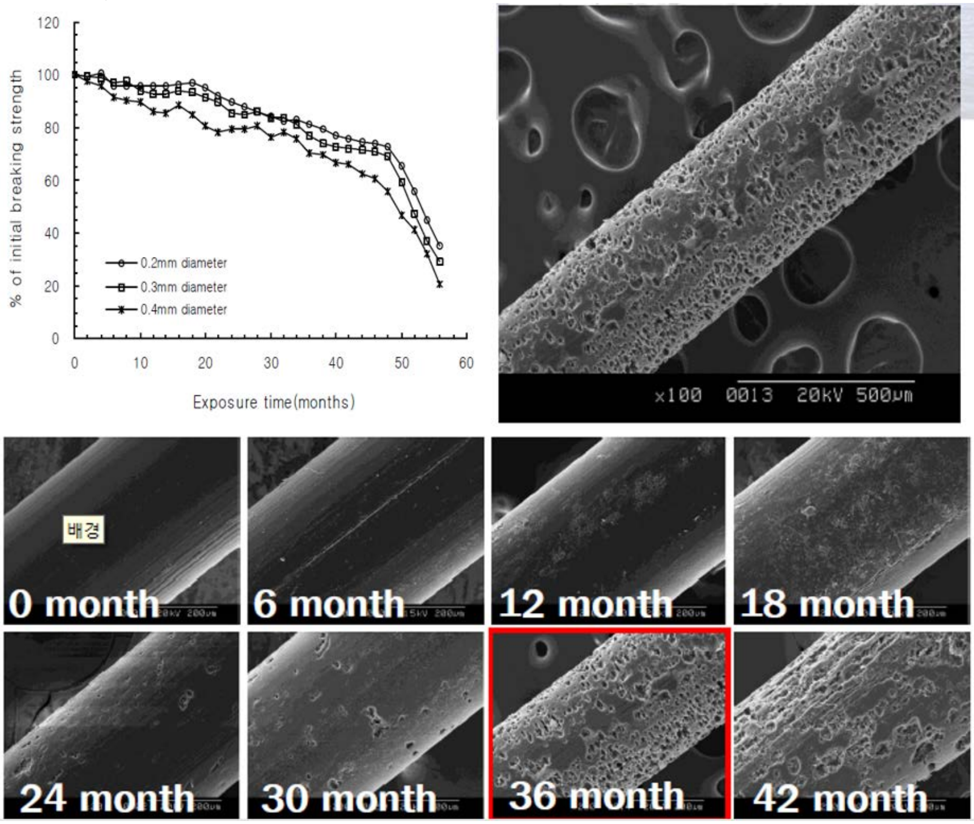
Tabell 1: Opplysninger om bruk av redskaper i fiskeflåten for fartøy under 28 meter. (Kilde: NTNU Sustainability/SALT Lofoten AS)[2]

	Antall eid (ant)	**Antall kjøpt** (Ant/år)	**Tapt til havs** (ant/år)	**Levert som avfall** (ant/år)
Trål	1.569	357	14	342
Ringnot	3.994	190	0	135
Snurrevad	7.559	15.386	147	764
Garn	2.309.384	728.338	13.941	615.902
Line	685.313	269.347	5.949	96.044
Teine	944.891	290.622	5.492	51.664

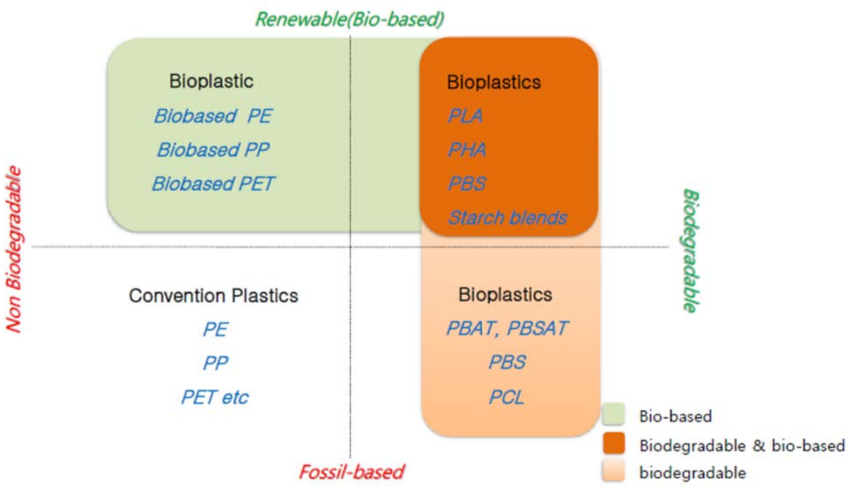
Biologisk nedbrytbare garn (dvs. som brytes ned til vann og CO_2) er de siste årene blitt utviklet i Sør-Korea, og brukes nå i flere garnfiskerier i Sør-Korea. Utviklingen har foregått over en periode på 16 år, i et samarbeid mellom industri, forskningsinstitutter og myndigheter, til et kommersielt produkt som tilbys av Lotte Fine Chemicals Co. Ltd (tidligere Samsung Fine Chemicals Co Ltd.). I koreansk sammenheng er de nedbrytbare garnene oppgitt å ha minst like gode material- og fangstegenskaper som garn laget av nylon. Egenskaper som nedbrytningstid (Figur 1) kan justeres etter behov ved å endre sammensetningen på molekylært nivå i

[1] Standal, D. og Sønvisen, S., 2015. Gear liberalization in the Northeast Arctic cod fisheries – Implications for sustainability, efficiency and legitimacy. Marine Policy 53: 141-148.
[2] Sundt, P., Briedis, R., Skogesal, O., Standal, E., Rødas-Johnsen, H., Shulze, P.E. 2018. Underlag for å utrede produsentansvar ordning for fiskeri- og akvakulturnæringen. Rapport fra Miljødirektoratet MDIR–1310.

materialet. En nærmere kjemisk beskrivelse av det nedbrytbare PBSAT-materialet finnes i (Kim et al., 2017, patent EP 3214133 Al)[3].



Figur 1: Skanning Elektron Mikroskop (SEM) bilder som viser nedbryting av monofilamentet i sjøvann. Øverst til venstre vises nedbrytningshastigheten for 0.2mm, 0.3mm og 0.4mm monofilamenter. Nedbrytningen av PBS/PBAT er en anaerob prosess som ender opp i CO_2 og H_2O. (kilde: Samsung Fine Chemicals Co. Ltd.)



Figur 2: PBSAT tilhører gruppen av nedbrytbare bioplast (Kilde: European bioplastics https://www.european-bioplastics.org/bioplastics/)

[3] Kim, M.K., Yun, K.C., Kang, G.D., Ahn, J.S., Kang, S.M., Kim, Y.J., Yang, M.H. and Byun, K.S. 2017. Biodegradable Resin Composition and Fishing Net Produced From Same. US Patent application publication, US 2017/0112111A1.

2 Aktiviteter og hovedfunn

2.1 Forsøk i kommersiellfiske (vedlegg 1, 2, 3, 7, 8).

Biologisk nedbrytbare PBSAT-garn er blitt testet på blåkveite (mai-juni 2016), sei (oktober-desember 2016, 2017 og 2018) og torsk (januar-mars 2017, 2018 og 2019) (Figur 3). Forsøkene foregikk i kommersielle fiskefelter og under kommersielle fiskeforhold. MS Skreigrunn ble brukt i 2016 for gjennomføring av blåkveitetokt utenfor Senja, mens MS Karoline ble brukt for forsøkene på torsk og sei utenfor Troms i 2016-2019 sesongene. Forskere ombord fiskefartøyene registrerte alt fangstene og lengdemålet alt fisk som ble tatt med nedbrytbare garn og tradisjonelle nylon garn.

Tre typer biologisk nedbrytbare garn ble bruk i fiskeforsøkene. Den første sett av garn var en ufargede (transparent) PBSAT garn som ble brukt i blåkveiteforsøk. Den andre sett av biogarn var grønne garn[4]og ble brukt på sei og torskforsøk i 2017. Den siste sett av biogarn var blå og ble brukt på torsk- og seifiske i 2018 og 2019.

Figur 3. Type fiskeri og periode hvor fiskeforsøk der vi sammenlignet nedbrytbare garn vs. konvensjonelle nylongarn.

Nedenfor presenteres innledningen til de tre vitenskapelige artiklene som er blitt publisert i internasjonale tidsskrifter med resultatene fra fullskala fiskeforsøk. Fulltekstene finnes i vedlegg 1, 2 og 3.

2.1.1 Effekter av å bruke biologisk nedbrytbare garn i blåkveitefiske.

Denne artikkelen studerer effekten av å bruke biologisk nedbrytbare PBSAT-garn i blåkveitefiske (*Reinhardtius hippoglossoides*). Fiskeforsøkene ble gjennomført under kommersielle fiskeforhold i Nord-Norge i 2016. Sammenlignet med konvensjonelle nylongarn, fanget PBSAT-garnet færre fisk. For fisk større enn 65 cm, var reduksjonen i fangsten ganske betydelig. PBSAT-garn fanget ca. 30% færre blåkveiter i disse lengdeklassene (større enn 65cm), enn nylon-garna. Forskjeller i garnas maskestørrelse, bruddstyrke og elastisitet kan imidlertid forklare forskjellene i fangsteffektivitet.

2.1.2 Fangstevne av biologisk nedbrytbare PBSAT-garn og konvensjonelle nylon-garn som brukes i det norske torsk- og seifiskeriet.

Fiskeforsøk ble gjennomført for å sammenligne den relative fangstevnen av biologisk nedbrytbare PBSAT-garn med konvensjonelle nylon-garn. Fiskeforsøket foregikk i to påfølgende fiskesesonger (2016 og 2017) for torsk (*Gadus morhua*) og sei (*Pollachius virens*) i Nord-Norge. Generelt viste resultatene bedre fangstrater for

[4] Fargede PBSAT garn ble utviklet for dette prosjektet av Lotte Fine Chemicals i løpet av 2016 og i 2017 ble det søkt patent på oppfinnelsen: Kim, M.K., Yun, K.C., Kang, G.D., Ahn, J.S., Kang, S.M., Kim, Y.J., Yang, M.H. and Byun, K.S. 2017. Biodegradable Resin Composition and Fishing Net Produced From Same. US Patent application publication, US 2017/0112111A1.

nylon-garn enn for PBSAT-garn. PBSAT-garnene fanget hhv. 50,0% og 26,6% færre torsk, og 41,0% og 22,5% færre sei enn nylon-garnene i henholdsvis 2016 og 2017. Styrketester av nylon- og nedbrytbare PBSAT-garn, viste at begge typer garn hadde betydelig reduksjon i bruddstyrke og forlengelse ved brudd, spesielt i 2017. At nedbrytbare-garn har dårligere fangstevne enn tradisjonelle nylon-garn, kan medvirke til at fiskerne i utgangspunktet trolig vil foretrekke tradisjonelle nylon-garn. Selv om nedbrytbare-garn var mindre effektive enn nylon-garn, viser likevel nedbrytbare-garn et stort potensial for å redusere spøkelsesfiske og plastforurensning i havet. Dette er spesielt relevant for fiske med garn.

2.1.3 Sammenligning av fangstevne mellom nedbrytbare-garn og konvensjonelle nylon-garn.

For å sammenligne fangstevnen for nedbrytbare PBSAT-garn og konvensjonelle nylon-garn, ble de ulike garntypene testet under kommersielle forhold. Den relative fangstevnen mellom de to garntypene ble studert gjennom hele vinter-sesongen for torsk (*Gadus morhua*) i Nord-Norge. Resultatene viser at nylon-garn fanget 21% mer fisk (i antall) enn nedbrytbare-garn, og viste generelt bedre fangstrater for noen lengdeklasser, med unntak av fisk mellom 82 og 90 cm. Forskjellen i elastisitet og bruddstyrke kan forklare den størrelse sammensetningen av fisk som ble fanget av de ulike typene garn. Antall ganger garnene ble brukt gjennom fiskesesongen, påvirket fagstevnen av PBSAT garn og medvirket til at de nedbrytbare garnene ble svakere og dermed fisket litt dårligere enn da garna var nye.

2.1.4 Sammenligning av fangstevne mellom nedbrytbare-garn (0.55 og 0.60 mm monofilament) og konvensjonelle nylon-garn (0.55mm monofilament)

Fiskeforsøk ble gjennomført for å sammenligne fangstevnen til nedbrytbare PBSAT-garn laget av 0.55 mm og 0.60 mm monofilament med konvensjonelle nylon-garn laget av 0.55 mm monofilament. Forsøkene ble gjennomført i oktober-desember 2018 i fiske etter sei og torsk i Nord-Norge. Resultatene viser at for torsk hadde begge typene nedbrytbare garn (0.55 og 0.60 mm) betydelig lavere fangstevne enn konvensjonelle nylon-garn (0.55 mm). De nedbrytbare garnene fanget henholdsvis 62,38% (CI: 50,55-74.04) og 54,96% (CI: 35,42-73,52) av det nylon-garn gjorde (i antall fisk). For sei fanget de nedbrytbare garnene (0.55 og 0.60 mm) henholdsvis 83,40% (CI: 71,34-94,86) og 83,87% (CI: 66,36-104,92) av det 0.55mm nylon garnet gjorde.

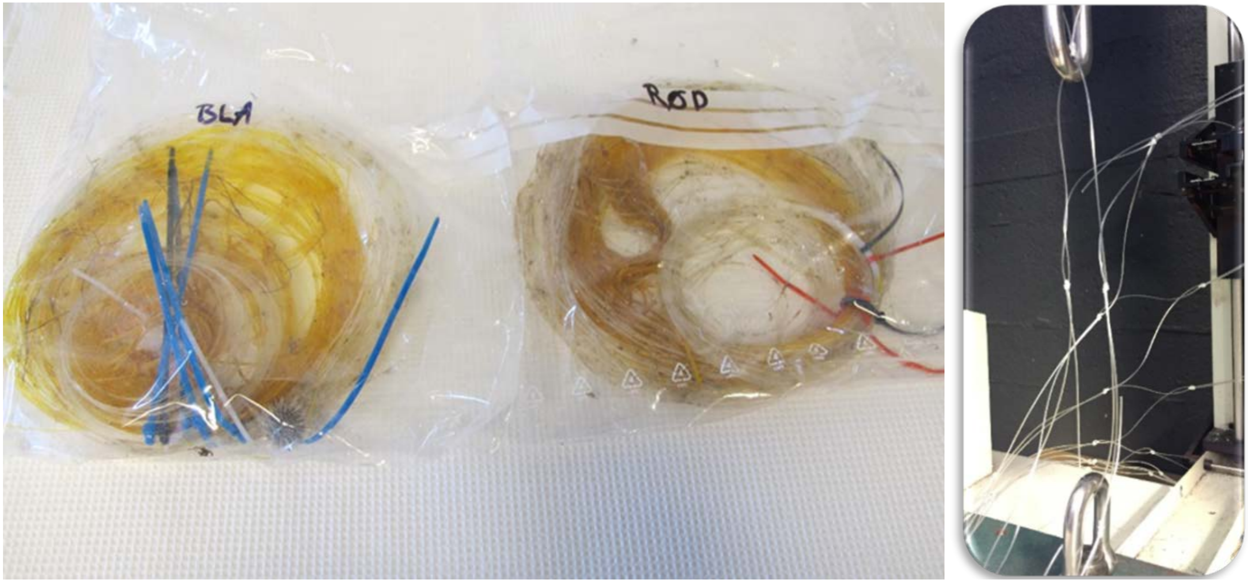
2.1.5 Sammenligning av fangstevne mellom nedbrytbare-garn (0.75 mm monofilament) og konvensjonelle nylon-garn (0.70 mm monofilament)

Fiskeforsøk ble gjennomført for å sammenligne fangstevnen til nedbrytbare PBSAT-garn laget av 0.75 mm monofilament med konvensjonelle nylon-garn laget av 0.70 mm monofilament. Forsøkene ble gjennomført gjennom hele vinterfiske-sesongen for torsk (*Gadus morhua*) i Nord-Norge i 2018. Resultatene viste at det de nedbrytbare garn fanget 80.75% (CI: 73.85-87.64) mer fisk (i antall) enn det nylon garnet gjorde gjennom hele fiskesesongen. Nylon garnet viste generelt bedre fangstevne for de fleste lengdeklasser.

2.2 Degraderingsforsøk i havet (vedlegg 4).

I dette forsøket satt vi sampler av nedbrytbare- og nylon monofilament, samt nedbrytbare- og nylongarn i sjøen, både i Trondheim og i Tromsø. Dybdene samplene ble satt varierte mellom 30 og 70 meter. Forsøket foregikk i to år og samplene ble analysert for styrke og forlengelse hvert tredje måneden (Figur 4 og 5).

Figur 4: Samplene av nedbrytbare- (hvitt) og nylon monofilament (gul) (og netting) ble satt i sjøen i Trondheim (tre teiner) og i Tromsø (to teiner).



Figur 5: Til venstre vises sampler av nedbrytbare og nylon monofilament (og nett) som er blitt tatt ut av teinene for å bli analysert for styrke og forlengelse. Til høyre vises en H10KT universell strekkprøving maskin (Tinius Olsen TMC, PA, USA) som ble brukt til å analysere samplene.

Nedenfor presenteres innledningen til ett vitenskapelig artikkel som er blitt sent til publisering i et internasjonalt tidsskrift med resultatene fra dette forsøk. Fullteksten finnes i vedlegg 4.

2.2.1 Sammenligning av mekaniske egenskaper av PBSAT- og PA-garn.

Dette artikkelen presenterer en komparativ studie av mekaniske egenskaper av biologisk nedbrytbare PBSAT-garn og konvensjonelle polyamid (PA) garn. Et feltforsøk ble gjennomført for å simulere tapte fiskeredskap og endringer i mekaniske egenskaper av PBSAT- og PA-materialet ble studert over en periode av 25 måneder. Prøver av PBSAT-garn og PA-garn (samt PBSAT- og PA-monofilamenter), ble plassert i lukkede teiner og senket i havet på fire forskjellige lokaliteter i Norge. To teiner ble satt i havet utenfor Hitra i Trondheim og to utenfor Tromsø. Sjøvannstemperaturen i hver teine ble logget hver time, og prøver av monofilament og garn ble hentet for å bli analysert hver tredje måned ved starten av forsøket, og deretter hver sjette måned i det siste året av forsøket. Bruddstyrketester ble utført for å sammenligne de mekaniske egenskapene av PBSAT- og PA-monofilamenter og garn. Det ble observert en betydelig reduksjon i bruddstyrke og forlengelse ved brudd. og En liten økning i stivhet av materialet, ble også observert for både PA- og PBSAT-monofilamenter som hadde stått i sjøvann, spesielt i prøvene fra Hitra, Trondheim. Reduksjonene i mekaniske egenskapene indikerer nedbrytning av begge polymermaterialer. PBSAT-garnet viste en signifikant reduksjon (-35%) i bruddstyrken etter å ha stått i sjøvann i 25 måneder. Bruddstyrken av PBSAT-garn var da ca. 26% lavere enn bruddstyrken av PA-garn.

2.3 UV degraderingsforsøk (vedlegg 5 og 6).

Dette forsøket ble gjennomført for å undersøke potensiell degradering av biologisk PBSAT- og nylon monofilamenter for årsaket av UV stråling. Dette forsøket simulerer garn som er eksponert til vanlige værforhold på fiskefartøys dekk eller på kai/land. Nedenfor presenteres innledningen til ett SINTEF-rapport med resultatene fra dette forsøket. Fullteksten finnes i vedlegg 5.

2.3.1 UV-degraderingsforsøk av monofilamenter – Forsøk 1: Utendørstilstand.

To typer monofilamenter ble analysert i dette forsøket. Det ene var laget av nylon (polyamid-66) mens det andre var PBSAT (polybutylensuccinat-co-adipat-co-tereftalat). Begge typer monofilamenter ble eksponert til UV-stråling i 1000 timer i en forvitringsprøve som simulerte utendørstilstand. Nedbrytningen av materialene ble deretter studert av hhv. Fourier Transform Infrared spectroscopy (FTIR-spektroskopi), mekanisk testing, lysmikroskopi og skanning i elektron-mikroskopi (SEM). Resultatene viser at begge materialer viser tegn på nedbrytning allerede etter 200 timers eksponering. PBSAT monofilamentene degraderte raskere enn nylon. Dette indikerer en sterkere reduksjon i mekanisk styrke og materialets integritet. I tillegg endrer PBSAT monofilamentene sin kjemiske struktur mer signifikant under nedbrytning, sammenlignet med nylon.

2.3.2 UV-degraderingsforsøk av monofilamenter – Forsøk 2: Høy relativ fuktighet.

De samme to typene monofilamenter som ble brukt i Forsøk 1 (avsnitt 2.3.1) ble analysert i dette forsøket. Førsøk 2 ble utført med høyere relativ fuktighet enn i Forsøk 1. Nedbrytningen av materialene ble deretter studert ved hhv. FTIR-spektroskopi og mekanisk testing. Resultatene viser at begge materialene viser tegn til nedbrytning allerede etter 200 timers eksponering, noe som er identisk med Forsøk 1 over. PBSAT brytes ned raskere enn nylon og viser dermed en sterkere reduksjon i mekanisk styrke og materialegenskaper. FTIR-analyse viser ikke noen signifikant forskjell når resultatene sammenlignes med Forsøk 1.

2.4 Degraderingsforsøk av monofilamenter i lab.

Følgende er en beskrivelse av forsøksprosedyren for biologisk nedbrytbarhetstesting av PBSAT and nylon monofilamenter ved hjelp av bakteriekulturer og bruken av naturlig sjøvann (SW) fra en norsk fjord som mikrobiell kilde. Fokus er å sammenligne av forskjellige analysemetoder og studere forandringer av polymere i materialet; også kvantifisering av eventuelle løsrevet partikler til sjøvannet (eventuell mikroplast dannelse). Forsøket begynte i september 2017 og skal slutte i september 2019, dermed er resultatene fra dette forsøket ikke klare. Følgende er en beskrivelse av forsøkene som fortsatt pågår i dette prosjektet.

2.4.1 Nedbrytningsstudier med bakterielle anrikningskulturer

Bakterier festet til brukte monofilament og fiskegarn (fra degraderings forsøk i havet, punkt 3.3.) ble brukt i dette eksperimentet. Monofilamentsamplene blir sterilisert før de ble inokulert i testmediet. Monofilamentene ble dyppet i 70% etanol i noen timer, vasket med destillert vann grundig for å fjerne rester og ble tørket senere. Kontrollene uten bakteriekulturer ble tilsatt HgCl2 for å holde dem sterile hver annen måned. Prosedyren for nedbrytnings studier med bakterielle anrikningskulturer ble som følge:

- Bakterielle isolater fra eksperiment 1 ble brukt: Frosne isolater ble tint og tilsatt til dyrkingsmedium Marine Broth (200 ml) til logfase av vekst (OD 595, plate leser), ca. 10-12 timer.
- Bakterier ble tilsatt til 400 ml sterilt sjøvann og 10% Bushnell Haas i dyrkningsflasker sammen med nettene (både nylon og bionedbrytbare)

- Oppsettet ble som følger: a) 3 flasker per prøve. Prøvetaking på 3, 6, 12, 18 og 24 måneder (en kontroll uten bakterier og to for forskjellige analyser), totalt 15 flasker. b) Hver kolbe inkluderer 10 m monofilament, forhåndskutt i 0,5 m lengde.
- Kolberne blir inkubert ved romtemperatur (ca. 20 grader) og med mild risting.
- Medium blir endret etter 2 uker ved å erstatte 50% av mediet med nytt medium (sterilt sjøvann og 10% Bushnell Haas)
- Medium blir byttet en gang i uken.
- Analyse (tabell 2) ved 3, 6, 12, 18 og 24 måneder.

Tabell 2. Test oppsett av studie med bakterielle kulturer. Prøvetaking for fysiske (P), kjemiske (C) og mikrobiologiske (M) analyser er beskrevet. To replikater i normal (R1-R2) og sterilisert SW (SR1-SR2) blir inkludert.

Month Incubat.	Biodegradable net				Nylon net				SW
	R1	R2	SR1	SR2	R1	R2	SR1	SR2	R1
0	P,C	P,C			P,C	P,C			C,M
3	C	C	C	C	C	C	C	C	C
6	P,C,M	P,C,M	P,C	P,C	P,C,M	P,C,M	P,C	P,C	C,M
12	P,C,M	P,C,M	P,C	P,C	P,C,M	P,C,M	P,C	P,C	C,M
18	P,C,M[A)]	P,C,M[A)]	P,CA[A)]	P,C[A)]	P,C,M[A)]	P,C,M[A)]	P,C[A)]	P,C[A)]	C,M[A)]
24	P,C,M[A)]	P,C,M[A)]	P,CA[A)]	P,C[A)]	P,C,M[A)]	P,C,M[A)]	P,C[A)]	P,C[A)]	C,M[A)]

[A)] Valgfritt - hvis finansiert fra andre kilder enn Marinforsk. Hvis ikke finansiert, vil det bli samlet inn og lagret prøver for mulige senere finansieringsmuligheter.

2.4.2 Nedbrytning i naturlig sjøvann

Naturlig SW fra rørledningssystemet av SINTEF Sealab vil bli brukt. SW-kilden er på 80 m dyp, under termoklinen, og ikke påvirket av sesongvariasjoner. SW-kilden anses å være uforurenset, og data om temperatur, saltholdighet, TOC, mineralsk næringsforhold er godt dokumentert. SW blir samlet og akklimatisert til en testtemperatur på 20 °C i 5-7 dager. Før start, vil luften luftes (steril luft). Fine partikkel sedimenter vil bli samlet inn fra tidevannssone til en lokal strand. Sedimenter blir akklimatisert til 20 °C i 5-7 dager.

2.4.3 Nedbrytning i sjøvann med sedimenter

Marine tidevannssedimenter (200 ml) vil bli tilsatt til 1-L Scott-kolks vil, og 400 ml akklimatisert, luftet, ikke-endret SW vil bli anvendt på toppen av sedimentene. Etter at sedimentet har avgjort over natten, vil 20 stykker (0,5 m hver) av biologisk nedbrytbare og nylon fiskenett (sterilisert og tørket) plasseres på sediment overflaten og inkuberes ved 20 ° C i opptil 2 år. I tillegg vil steriliserte kontroller med autoklavert sediment og SW, levert med biocid ($HgCl2$; 100 mg / L) bli inkludert for testing av alternative nedbrytningsprosesser. $HgCl2$ vil bli fornyet annenhver måned. Flaskene (triplikatet) vil bli ofret for fysiske og kjemiske analyser av fiskenettene og sedimentet / SW som beskrevet i Tabell 3. Sedimentet / SV vil bli samplet for å forberede en slurry og deretter avgjøre sedimentet med etterfølgende analyser av SW.

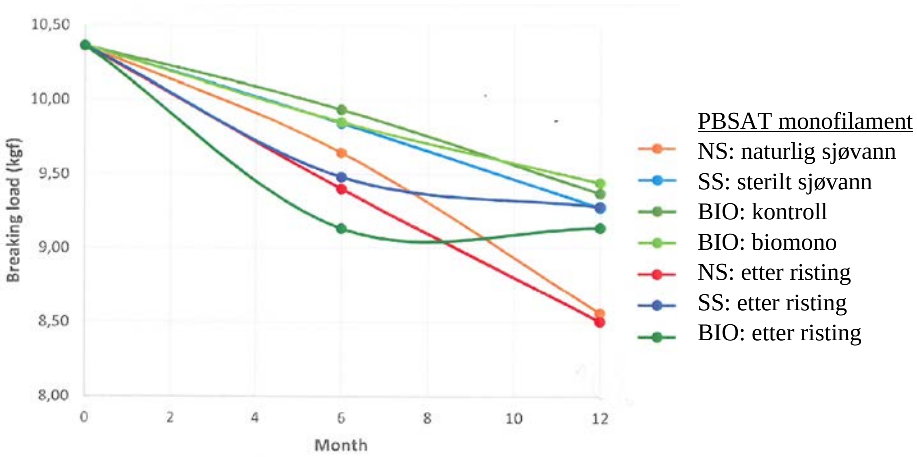
Tabell 3. Test oppsett av eksperiment i sediment-SW system. Prøvetaking for fysiske (P), kjemiske (C) og mikrobiologiske (M) analyser er beskrevet. To replikater i normal (R1-R2) SW vil bli inkludert. Data fra steriliserte kontroller (SR1) og fra dag 0 (replikater med garn) vil bli brukt fra test med bakteriekulturer (se tabell 2).

Month Incubat.	Biodegradable nets			Nylon net			SW
	R1	R2	SR1	R1	R2	SR1	SW1
0							C,M
3	C	C	C	C	C	C	C
6	P,C,M	P,C,M	C	P,C,M	P,C,M	C	C,M
12	P,C,M	P,C,M	C	P,C,M	P,C,M	C	C,M
18	P,C,M[A)]	P,C,M[A)]	C	P,C,M[A)]	P,C,M[A)]	C	C,M[A)]

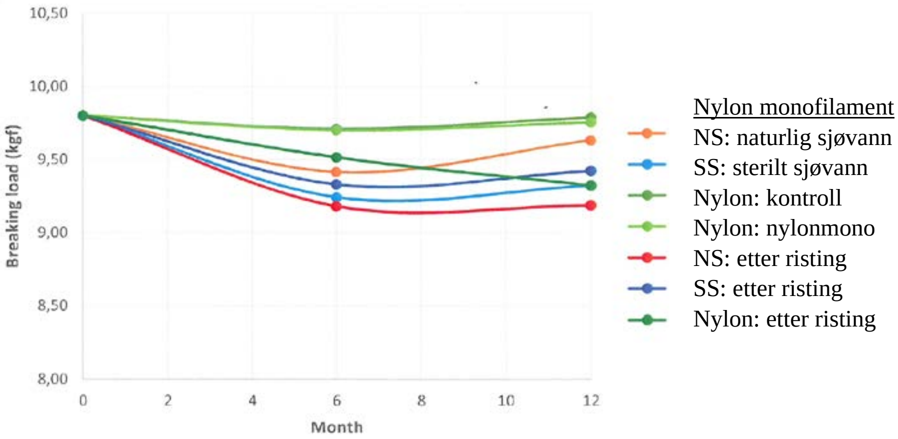
24	P,C,M$^{A)}$	P,C,M$^{A)}$	C	P,C,M$^{A)}$	P,C,M$^{A)}$	C	C,M$^{A)}$

$^{A)}$ Valgfritt - hvis finansiert fra andre kilder enn Marinforsk. Hvis ikke finansiert, vil det bli samlet inn og lagret prøver for mulige senere finansieringsmuligheter.

Foreløpige resultater fra nedbrytningsforsøk med PBSAT monofilamenter og nylon monofilamenter for 12-måneders periode er vist i figur 6 og 7. Styrken av nedbrytbare PBSAT monofilamentet var ca. 20% svakere etter å ha vært et år i naturlig sjøvannet (NS) med og uten risting av sedimenter. Forsøket pågår og resultantene fra kjemiske (C) og mikrobiologiske (M) analyser er ikke enda klare.



Figur 6: Foreløpige resultater fra nedbrytningsforsøk med PBSAT monofilamenter for 12-måneders periode.



Figur 7: Foreløpige resultater fra nedbrytningsforsøk med nylon monofilamenter for 12-måneders periode.

3 Forslag til videre arbeid

Dette prosjektet har fokusert på å utvikle biologisk nedbrytbare garn til norske fiskeri, og på å kvantifisere fangsteffektiviteten, nedbrytningstid og eventuell dannelse av mikroplast i sjøvann. Resultatene fra disse studiene er blitt publisert i internasjonale journaler. Noen nedbrytningsforsøk pågår fortsatt. Per i dag har disse forsøkene pågått i 18 måneder, mens de designet og planlagt for å vare 36 måneder. Det tas sikte på flere publikasjoner basert på disse forsøkene fremover, og det anbefales å videreføre prosjektet og fullføre dette arbeidet.

Et hovedresultat fra fangstforsøken er at biogarn har dårligere fangstevne enn tradisjonelle nylongarn (Grimaldo et al. 2018a, 2018b, 2019; Vedlegg 1, 2, 3). Dette gjør at fiskerne i utgangspunktet trolig vil foretrekke tradisjonelle nylongarn.

Gjennom prosjektet har man imidlertid også sett at fangstprosessen i garnfiske ikke er fullt ut forstått, og at der kan være et potensial for å øke fangstevnen til dette fiskeredskapet. Det foreslås videre studier av forskjellig fangstmodus (dvs. måter fisk fanges i nettet på). Dette krever nye fiskeforsøk og nye analyser av data. Resultatene fra denne aktiviteten kan gi ny grunnleggende kunnskap om fangstevnene til garn generelt, og hvilke parametere som er viktig for de forskjellige modusene.

Et sentralt trekk ved bruk av garn i kommersielt fiske, er at fiskerne taper betydelige mengder garn. Miljødirektoratet (2018)[5] har anslått at om lag 13000 garn mistes hvert år. Tapte garn kan fremdeles ha fangstevne og dermed både øke dødeligheten i bestanden og påføre fiskerne et tap i form av tapte fangstmengder. Det anbefales derfor å gjennomføre en bioøkonomisk analyse av garnfisket, og estimere omfanget og betydningen av utilsiktede dødelighet forårsaket av spøkelsesfiske. Vi foreslår også å undersøke videre om bruk av nedbrytbare garn kan bidra til å redusere spøkelsesfiske og plastforurensning i havet, og på den måten bidra til en mer bærekraftig fiskeriforvaltning i Norge.Problemstillingene i et bioøkonomisk gjennomgang kan være å:

- Estimere mengden av tapte fiskeredskap (garn, teiner) og hvordan kan dette påvirke den biologiske bærekraften.
- Studere i hvilken grad kan normative og regulative insentiver kan knyttes til ressursfordelingsregimet for å implementere nedbrytbare fiskeredskaper.
- Studere hvordan kan vi kan utforme et kvoteregime som bidrar til økonomisk effektivitet og et mer miljøvennlig fiske.

4 Takk

Vi takker Norges Forskningsråd v/MARINFORSK-programmet, Fiskeri- og havbruksnæringens forskningsfond (FHF) og Fiskeridirektoratet for den økonomiske støtten til prosjektet. Takk også til mannskapene på MS Skreigrunn og MS Karoline for bistand og hjelp ved fullskalaforsøkene.

[5] Sundt, P., Briedis, R., Skogesal, O., Standal, E., Rødas-Johnsen, H., Shulze, P.E. 2018. Underlag for å utrede produsentansvar ordning for fiskeri- og akvakulturnæringen. Rapport fra Miljødirektoratet MDIR–1310.

Fishing efficiency of biodegradable PBSAT gillnets and conventional nylon gillnets used in Norwegian cod (*Gadus morhua*) and saithe (*Pollachius virens*) fisheries

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Abstract

Fishing trials were carried out to compare the relative fishing efficiency of gillnets made of a new biodegradable resin (polybutylene succinate co-adipate-co-terephthalate (PBSAT)) with conventional (nylon) nets. The fishing trials covered two consecutive fishing seasons (2016 and 2017) for cod (*Gadus morhua*) and saithe (*Pollachius virens*) in northern Norway. Results generally showed better catch rates for the nylon gillnets. The biodegradable PBSAT gillnets caught 50.0% and 26.6% fewer cod, and 41.0% and 22.5% fewer saithe than the nylon gillnets in 2016 and 2017, respectively. Even though the relative catch efficiency of the biodegradable gillnets was slightly better in 2017 than in 2016, the difference with respect to the catch efficiency of nylon gillnets may be too large for bio degradable gillnets to be accepted by fishermen if they were available commercially. Tensile strength measurements of the nylon and bio degradable PBSAT gillnets carried out before and after the fishing trials showed that the both types of gillnets had significant reductions in tensile strength and elongation at break, especially in 2017. Although less catch efficient than nylon gillnets,

biodegradable PBSAT gillnets show great potential for reducing ghost fishing and plastic pollution at sea which are major problems in these fisheries.

Keywords: Biodegradable gillnet; Ghost fishing; Gillnet fishery; Catch efficiency; Cod fishery; PBSAT resin; Cod; Saithe.

Introduction

Fishing gears that continue fishing after they have been lost (or abandoned) is known as ghost fishing (Breen, 1990). Lost fishing gears, apart from being associated with the catch of target and none-target species, also causes a variety of harmful impacts to coral reefs and benthic fauna, contributes to marine pollution by introducing synthetic (none-biodegradable) plastic materials into the marine food web, causes economic losses from marine species mortalities and due to replacement of lost gears, and diverse costs related to retrieving operations (Al-Masroori et al., 2004; Brown and Macfadyen, 2007; Large et al., 2009; Macfadyen et al., 2009; Gilman, 2015; Gilman et al., 2016; Lusher et al., 2017). From all these problems, marine pollution caused by none-degradable plastics has become one of the most serious problems worldwide (Lusher et al., 2016; Chae and An, 2017). Recognition to all these problems is nowadays demonstrated through the large number of international organizations and agreements that currently focus on reducing the effect of abandoned, lost or otherwise discarded fishing gear (ALDFG) and numerous national initiatives that have being implemented around the world to mitigate their impact on the marine ecosystem (Gilman et al., 2016).

There is extensive literature presenting mitigating measures and methods to reduce the effects of ALDFG on the environment (Al-Masroori et al., 2004; Matsuoka et al., 2005; Brown and Macfadyen, 2007; Large et al., 2009; Macfadyen et al., 2009; Gilman, 2015; Gilman et al., 2016; Lusher et al., 2017). Macfadyen et al. (2009) for instance grouped the methods to reduce the effects of ALDFG into: A) preventive methods that reduce the incidence of fishing gear from becoming abandoned, lost and discarded, such as gear marking, on-board technology to avoid or locate lost gear, onshore collection/reception and/or payment for old/retrieved gear, reduced fishing effort and spatial management; B) mitigating measures that reduce the impact of lost gears in the environment, such as reducing ghost fishing (and plastic pollution) through the use of biodegradable gear, reducing ghost fishing of incidental species by providing escape vents; C) curative measures that are intended to remove the lost gear from the environment, such us electronic and/or acoustic technology for locating lost gear, better reporting of lost gear, gear recovery programs and disposal/recycling of retrieved gear. Many scientists argue that efforts focusing on preventive methods and quick recovery of lost gears are likely to be more effective because curative methods can be highly cost demanding and largely time consuming (Matsushita et al., 2008; Suuronen et al., 2012; Ullmann and Broadhurst, 2015). In addition, preventing gear loss would eliminate ghost fishing mortality (Ullmann and Broadhurst, 2015).

In recent years many studies have documented the physical properties, biodegradability and fishing efficiency of transparent gillnets made of poly butylene succinate (PBS) resin blended with poly butylene adipate-co-terephthalate (PBAT) resin and polybutylene succinate co-adipate-co-terephthalate (PBSAT) resin (Park et al., 2007a, b, 2010; Park and Bae, 2008; Bae et al., 2012, 2013; An and Bae, 2013; Kim et al., 2013, 2016). Ishii et al. (2008) reported that within two years of being submerged in seawater, transparent gillnets made of PBSAT resins were degraded by microorganisms (i.e. natural occurring bacteria, algae and fungi), resulting in low-molecular-weight oligomers, dimers and monomers that ultimately were mineralized into carbon dioxide and water (Tokiwa et al., 2009). However, Kim et al. (2017) argues that gillnets made of PBS and PBAT resins have poor tinting properties and therefore can cause catch efficiency problems such as decreased strength and elasticity due to coloration.

In Norway, gillnetting is one of the most important commercial fishing methods for the coastal fleet, however transparent gillnets are not currently used. Norwegian fishermen prefer coloured gillnets because they provide a better contrast with the metal (aluminium and or stainless steel) sorting boards and make the removal of fish from the nets easier, and also because many fishermen believe that some colours have better catch efficiencies than others depending on the contrast with the seabed. The most important target species in the Norwegian gillnet fishery are cod (*Gadus morhua*) and saithe (*Pollachius virens*). In 2017, 4658 fishing boats (less than 14.9 m LOA) were registered and had licences for gillnetting in Norway. This small-scale coastal fleet caught 89460 tonnes of cod, 17635 tonnes of saithe, and 19869 tonnes of haddock (*Melanogrammus aeglefinus)*, representing 22.3%, 14.7% and 18.1% of the respective annual quota for these species (Norwegian Directorate of Fisheries, 2018). To date, Norway is one of the few countries in the world that has a program for systematic annual retrieval of ALDFG from the most intensively fished areas (Brown et al., 2005; Macfadyen et al., 2009; Cho, 2011). Based on information provided by fishermen, the Norwegian Directorate of Fisheries carry out annual retrieval operations for reported lost fishing gear and deliver it on land to recycling (Humborstad et al., 2003; Gilman et al., 2016). However, these operations are highly challenging because of the depth (500–1000 m) and strong currents in the areas, as well as uncertainties associated with the position of lost gear.

The development of fishing gears made of biodegradable plastic materials, like PBSAT resin, is considered as a potential solution to reduce ghost fishing and plastic pollution at sea caused by ALDFG (Brown and Macfadyen, 2007; Large et al., 2009; Macfadyen et al., 2009; Gilman, 2015; Gilman et al., 2016); however, for an environmentally safe application of such biodegradable plastics at sea it is important to prove that the intermediate break-down products, even those that are degradable, do not have any ecotoxicological effects on the ecosystem. Simultaneously, for biodegradable gillnets to be adopted by the fishing industry, they should prove to be at least as efficient as conventional nylon gillnets and not compromise the profitability of the fishing operations. The present study addresses the second concern: fishing efficiency. The specific objective of this study was therefore to assess the relative catch efficiency of biodegradable PBSAT gillnets with that of conventional nylon gillnets. Our study covered the consecutive fishing seasons of 2016 and 2017, targeting the fall fishery for cod and saithe in Northern Norway.

Materials and Methods

Biodegradable polybutylene succinate-co-adipate-co-terephthalate resin

PBSAT resin is an aliphatic-aromatic co-polyester that is prepared using 1,4-butanediol as an aliphatic glycol (as base materials) and dicarboxylic acids, such as succinic acid and adipic acid (which are aliphatic components) and dimethyl terephthalate (which is an aromatic component) (Kim *et al.*, 2017, patent EP3214133 A1). PBSAT resin is biodegradable, exhibits an excellent coloration effect and does not cause problems such as a decrease in strength due to coloration, as observed in PBS and PBAT resins. The biodegradable PBSAT resin composition includes a colorant at 0.005–0.015 parts by weight. To improve the properties of monofilament yarns formed from the coloured PBSAT resin, additives such as anti-oxidants and UV stabilizers may be included at 0.2–0.5 parts by weight with respect to 100 parts by weight of the PBSAT resin (Kim *et al.*, 2017, patent EP3214133 A1).

Experimental design

A set of experiments were designed to cover two consecutive fishing seasons for saithe and cod. Fishing trials were conducted under commercial fishing conditions on board the coastal gillnet boat "MS Karoline" (10.9 m LOA). The first fishing season was carried out between 24 October 2016 and 11 January 2017, and the second season between 11 October 2017 and 17 January 2018, herein referred to as the 2016 and 2017 seasons, respectively. The fishing grounds were off the coast of Troms (Northern Norway) between 69°55′–70°22′N and 19°39′–21°05′E, which is a common fishing area for coastal vessels from Troms. The fishing depth varied between 29 and 178 m. The sea water temperature was recorded every hour in 2016 with a DST-CTD Star-Oddi logger (Star-Oddi, Iceland) that was set at a depth of approximately 70 m.

In 2016, the fishing performance of 16 green biodegradable PBSAT gillnets, herein called bio gillnets, and 16 conventional green nylon gillnets, herein called nylon gillnets, was compared during fishing trials carried out under commercial fishing conditions. In 2017, the experiment was repeated with a new set of blue gillnets. Each gillnet sheet was made of double knotted 0.55 mm monofilament, had 130 mm nominal mesh opening size and was 50 meshes high by 275 meshes long (approx. 55 m stretched length). Each assembled gillnet was approximately 27.5 m long and had a hanging ratio of 0.5. Since the density of the gillnets materials was similar (1.12 g ml^{-1} for the bio gillnets and 1.14 g ml^{-1} for nylon gillnets) we provided similar buoyancy to both types of gillnets. Each gillnet sheet was fixed to 26 mm diameter SCANFLYT-800 floatlines (made of braided polypropylene rope with a single core of polyurethane floating elements inside) with a buoyancy of 150 g m^{-1}. To provide weight, they were each attached to a 16 mm diameter DANLINE leadline (made of polypropylene rope with a lead core) with a weight of 360 g m^{-1}. The 32 experimental gillnets were divided into two sets, where each set consisted of eight bio gillnets (B) and eight nylon gillnets (N). The gillnets were attached in such a way that they provided the best information for paired comparison. Set 1 was arranged as B–NN–BB–NN–BB–NN–BB–NN–B and set 2 was arranged as N–BB–NN–BB–NN–BB–NN–BB–N (Fig. 1).

FIG. 1

Actual mesh openings were measured with a Vernier caliper without applying tension to the mesh. Two rows of consecutives 20 meshes were measured in each type of gillnet. The mean mesh openings of the bio gillnets and nylon gillnets used in 2016 were 132.8 ± 0.8 mm and 131.4 ± 0.8 mm, respectively. Those used in 2017 were 130.7 ± 0.8 mm and 128.2 ± 0.8 mm, respectively.

Modelling the size-dependent catch efficiency between gillnet types

We used the statistical analysis software SELNET (Sistiaga *et al*., 2010; Herrmann *et al.*, 2012, 2016) to analyse catch data and conduct length-dependent catch comparisons and catch ratio analyses. Using the numbers and sizes of cod and saithe in each gillnet set deployment we determined whether there was a significant difference in the catch efficiency averaged over deployments between the nylon and bio gillnets. We also determined if a potential difference between the gillnet types could be related to the size of the cod or saithe. Specifically, to assess the relative length-dependent catch efficiency effect of changing from nylon gillnet to bio gillnet, we used the method described in Herrmann *et al*. (2017) and compared the catch data for the two types of gillnets. This method models the length-dependent catch comparison rate (CC_l) summed over gillnet set deployments for a full deployment period. The 2016 and 2017 experiments were analysed separately for cod and saithe, respectively:

$$CC_l = \frac{\sum_{j=1}^{m}\{nt_{lj}\}}{\sum_{j=1}^{m}\{nt_{lj}+nc_{lj}\}} \qquad (1)$$

where nc_{lj} and nt_{lj} are the numbers of cod or saithe caught in each length class l for the nylon-gillnet (*control*) and the bio gillnet (*treatment*), in deployment j of a gillnet set. m is the number of deployments carried out for the season (2016 or 2017 experiment separately). Only deployments of the gillnet sets that caught at least 10 individuals in total between the nylon and bio gillnet of the specific species investigated (cod or saithe) was included in the analysis for that species to avoid overinflating confidence intervals for catch comparisons and catch ratio analyses (Krag et al., 2014, 2016). The functional form for the catch comparison rate *CC(l, **v**)* (the experimental being expressed by equation 1), was obtained using maximum likelihood estimation by minimizing the following expression:

$$-\sum_l \left\{ \sum_{j=1}^{m} \left\{ nt_{lj} \times ln\left(CC(l,\boldsymbol{v})\right) + nc_{lj} \times ln\left(1.0 - CC(l,\boldsymbol{v})\right) \right\} \right\} \quad (2)$$

where ***v*** represents the parameters describing the catch comparison curve defined by *CC(l, **v**)*. The outer summation in the equation is the summation over the length classes *l*. When the catch efficiency of the bio gillnet and nylon gillnet is similar, the expected value for the summed catch comparison rate would be 0.5. Therefore, this baseline can be applied to judge whether or not there is a difference in catch efficiency between the two gillnets. The experimental CC_l was modelled by the function *CC(l, **v**)*, on the following form:

$$CC(l,\boldsymbol{v}) = \frac{exp\left(f(l,v_0,\dots,v_k)\right)}{1+exp\left(f(l,v_0,\dots,v_k)\right)} \quad (3)$$

where *f* is a polynomial of order *k* with coefficients v_0 to v_k. The values of the parameters ***v*** describing *CC(l, **v**)* are estimated by minimizing equation (2), which are equivalent to maximizing the likelihood of the observed catch data. We considered *f* of up to an order of 4 with parameters v_0, v_1, v_2, v_3 and v_4. Leaving out one or more of the parameters v_0... v_4 led to 31 additional models that were also considered as potential models for the catch comparison *CC(l,**v**)*. Among these models, estimations of the catch comparison rate were made using multi-model inference to obtain a combined model (Burnham and Anderson, 2002; Herrmann *et al*., 2017).

The ability of the combined model to describe the experimental data was evaluated based on the *p*-value. This *p*-value, which was calculated based on the model deviance and the degrees of freedom, should not be <0.05 for the combined model to describe the experimental data sufficiently well, except from cases where the data were subjected to over-dispersion

(Wileman *et al*., 1996; Herrmann *et al.*, 2017). Based on the estimated catch comparison function $CC(l, \boldsymbol{v})$ we obtained the relative catch efficiency (also named catch ratio) $CR(l, \boldsymbol{v})$ between the two gillnet types by the following relationship:

$$CR(l, \boldsymbol{v}) = \frac{CC(l, \boldsymbol{v})}{(1 - CC(l, \boldsymbol{v}))} \qquad (4)$$

The catch ratio is a value that represents the relationship between catch efficiency between the bio gillnet and that of the nylon gillnet. Thus, if the catch efficiency of both gillnets is equal, $CR(l,\boldsymbol{v})$ should always be 1.0. Thus, $CR(l,\boldsymbol{v})$ = 1.5 would mean that the bio gillnet is catching 50% more cod or saithe with length l than the nylon gillnet. In contrast, if $CR(l,\boldsymbol{v})$ = 0.7 would mean that the bio gillnet is only catching 70% of the cod or saithe with length l that the nylon-gillnet is catching.

The confidence limits for the catch comparison curve and catch ratio curve were estimated using a double bootstrapping method (Herrmann *et al*., 2017). This bootstrapping method accounts for between-set variability (the uncertainty in the estimation resulting from set deployment variation of catch efficiency in the gillnets and in the availability of cod and saithe) as well as within-set variability (uncertainty about the size structure of the catch for the individual deployments). However, contrary to the double bootstrapping method (Herrmann *et al*., 2017) the outer bootstrapping loop in the current study accounting for the between deployment-variation was performed paired for the bio and nylon gillnets, taking full advantage of the experimental design in which both types of net were deployed simultaneously (Fig. 1). By multi-model inference in each bootstrap iteration, the method also accounts for the uncertainty in model selection. We performed 1000 bootstrap repetitions and calculated the Efron 95% (Efron, 1982) confidence limits. To identify sizes of cod or saithe with significant differences in catch efficiency, we checked for length classes in which the 95% confidence limits for the catch ratio curve did not contain 1.0.

Finally, a length-integrated average value for the catch ratio ($CR_{average}$) was estimated directly from the experimental catch data by:

$$CR_{average} = \frac{\sum_l \sum_{j=1}^{m} \{nt_{lj}\}}{\sum_l \sum_{j=1}^{m} \{nc_{lj}\}} \qquad (5)$$

where the outer summation covers the length classes in the catch during the experimental fishing period.

Tensile strength tests

Tensile strength tests were carried out on all the bio and nylon gillnets used in the fishing experiments using a H10KT universal tensile testing machine (Tinius Olsen TMC, PA, USA) equipped with a load cell with 5000 N rated force. The tests were performed in wet conditions on samples collected before and after the experimental fishing (at least 40 replicates for each case) according to ISO 1806:2002. Tensile strength, defined as the stress needed to break the sample, is given in kg, and elongation at break, defined as the length of the sample after it had stretched right when it breaks is given relative to the initial mesh size in percentage.

Assessment of gillnet damage

We assessed the degree of damage in the knots as an indication of the degree of damage of the gillnets. Samples from each type of gillnets used in 2016 and 2017, each measuring 20 x 20 meshes (approx. 2200mm x 2200mm) were visually inspected using a Nalakuvara magnifying glass 3x 45x. All 420 knots from each gillnet sample were individually assessed. The degree of damage was divided into four categories: 1) No damage, 2) slightly damaged, 3) badly damaged and 4) broken knot. The results are given as percentages of the total amount of knots form the sample.

Results

The two experimental gillnets were set at sea 58 and 92 times in the 2016 and 2017 seasons, respectively. Scientists on board the MS Karoline measured the lengths of all fish caught in 34 deployments in each fishing season. Fishermen provided logs (dates, positions and setting-retrieving times) of the remaining deployments, except length measurements of fish caught. The mean effective fishing time (± SD) (the time the gillnets remained at the sea bed) was 19 h, 10 min ± 6 h, 32 min while in 2017 it was 21 h, 58 min ± 6 h, 06 min. The mean (± SD) fishing depth was significantly deeper in 2017 (109 ± 28.9 m) compared to 2016 (61 ± 55.7 m). The temperature of the sea water varied between 8.8ºC and 4.1ºC at the start and end of the experiment. The catch was quite clean, mostly consisting of cod and saithe. These species were caught in sufficient numbers to be included in the analysis. We occasionally caught very few large haddock, but far too few (less than 20 individuals per season) to be included in the study.

Cod

A total of 1057 cod were caught over 33 gillnet deployments during the 2016 and 2017 fishing seasons, of which 407 were caught by the bio gillnets and 650 were caught by the nylon gillnets. Deployments with at least 10 cod in the catch were used in the analysis because gillnets with less than 10 fish would add little information and increase uncertainties to the catch comparison analyses (Table 1).

TABLE 1

The length distribution of cod that were caught with both types of gillnets was very similar in 2016 and 2017. The catch was length-dependent for both types of gillnet, including fish from 50 to 103 cm, but with most of the fish in the range of 65 to 85 cm (Fig. 2). In 2016, the catch efficiency of the bio gillnets was significantly lower than that of the nylon gillnets for almost all cod sizes except for those below 64 cm, while in 2017 significance was only obtained for cod in the size span 90 to 103 cm (Fig. 2). The *CR(l)* was also highly length dependent, with the biggest fish having a lower value for the bio gillnets in 2016, meaning that the nylon gillnets caught significantly more fish in those length classes (Fig. 2). The average *CR* was estimated at 50.0% and 73.4% in 2016 and 2017, respectively, meaning that the bio gillnets on average caught approximately 50.0% fewer fish than the nylon gillnets in 2016 and 26.6% fewer in 2017 (Table 2 and Fig. 2). For 2016 this result was significant as the upper limit for the averaged catch ratio was 73.3% whereas for 2017 it was 102.7% and therefore not significant. The estimated catch ratio curve clearly shows a significant difference in catch efficiency between the bio gillnets and nylon gillnets in 2016, for cod larger than 62 cm. In 2017, this difference was not significant, except for the length classes 90 to 103 cm (Fig. 2).

FIG. 2

TABLE 2.

Saithe

A total of 1965 saithe were caught over 45 gillnet deployments during the 2016 and 2017 fishing seasons, of which 814 were caught by the bio gillnets and 1151 were caught by the nylon gillnets. Only deployments with at least 10 saithe in the catch were used in the analysis to avoid inflate the confidence limits for the catch comparison analysis (Table 3).

TABLE 3.

The length distribution of saithe caught in 2016 and 2017 was length dependent for both types of gillnet, including fish from 50 to 95 cm, but with most of the fish in the range of 65 to 80 cm (Fig. 3). In 2016 and 2017, the catch efficiency of the bio gillnets was very similar to that of the nylon gillnets for fish smaller than 67 cm and 70 cm, respectively. The catch efficiency of the bio gillnets became significant different for larger fish (Fig. 3). The *CR(l)* was also highly length dependent, with the biggest fish having a lower value for the bio gillnets in both

310 2016 and 2017, meaning that the nylon gillnet caught significantly more fish in those length
311 classes (Fig. 3). The average *CR* was estimated at 59.0% and 77.5% in 2016 and 2017,
312 respectively, meaning that the bio gillnets caught on average 41.0% fewer fish in 2016 and
313 22.5% fewer fish in 2017 (Table 4 and Fig. 3). For both 2016 and 2017 this result was
314 significant as the upper limit for the averaged catch ratio was respectively 81.3% and 93.9%.
315 The estimated catch ratio curve clearly shows a significant difference in catch efficiency
316 between the bio gillnets and nylon gillnets in both years, for saithe larger than 69 cm in 2016
317 and larger than 73 cm in 2017 (Fig. 3).

318 FIG 3.

319 TABLE 4.

320

321 **Tensile strength measurements**

322 Tensile strength measurements carried out before and after the fishing experiment showed a
323 significant reduction in tensile strength (t-test, $p < 0.01$) and elongation at break (t-test, $p <$
324 0.01) for both types of gillnet in 2017, but not in 2016 (t-test, $p > 0.05$). In 2017, the nylon
325 gillnets underwent a 13.6% tensile strength reduction (from 11.4 to 9.9 kg) and the bio
326 gillnets underwent an 18.1% strength reduction (from 11.1 to 9.5 kg) (Table 5). Both types of
327 gillnet also showed a significant reduction of elongation at break, 33.9% and 13.2% for the
328 nylon and bio gillnets, respectively.

329 TABLE 5

330

331 **Gillnet damage**

332 The gillnets used in 2017 were more damaged than those used in 2016 (Table 6). The gillnets
333 used in 2017 had more than 26% of badly damaged or broken knots, while this percentage did
334 not exceed 2% in the gillnets used in 2016. The damage in the knots was apparently caused by
335 use and wear throughout the fishing season (i.e. abrasion in the hauling machine, friction due

to contact with hard surfaces when the gillnets were operated on deck), which turned the smooth surface of the materials (when new) into rough surfaces after the fishing trials (Fig 4).

TABLE 6

FIG 4.

Discussion

The bio gillnets caught 50.0% and 26.6% fewer cod, and 41.0% and 22.5% fewer saithe than the nylon gillnets in 2016 and 2017, respectively. Even though the relative catch efficiency of the bio gillnets was slightly better in 2017 than in 2016, the difference with respect to the catch efficiency of nylon gillnets may be too large for bio gillnets to be accepted by fishermen if they were available commercially. Coloured bio gillnets are still in the development process and are not currently a commercial product. The results from these series of experiments at sea suggest the need for further development of biodegradable material to improve their catch efficiency.

The results generally showed better catch rates for the nylon gillnets than for the bio gillnets, especially for large fish, despite having similar (non-significantly different) mesh sizes. Since similar colours were used in nylon and bio gillnets each year (green gillnets in 2016 and blue gillnets in 2017); colour cannot explain the differences in catch efficiency between both types of gillnets. The physical properties of the gillnets material did change over time and may have affected their fishing efficiency. When new, the strength and the elasticity of both types of nets was very similar. By the end of the fishing season, the reduction in tensile strength and the loss of elasticity can explain the major difference in catch efficiency observed between the nylon gillnets and the bio gillnets, especially for larger fish. In 2017, we measured an 18.1% reduction in tensile strength and a 13.2% reduction in elongation in the bio gillnets; while in 2016 these reductions were considerably smaller (Table 5). Visual inspection of the monofilaments and knots of the bio gillnets used in 2017 showed more splintering and other kinds of physical damage than in those used in 2016. Physical damage appeared to be positively correlated with the number of operation days and the fishing depth. In 2017, the experimental gillnets had 59% more deployments, and they were set significantly deeper, than in 2016. Consequently, in 2017 the gillnets were exposed to more physical damage that may have contributed to the greater loss of tensile strength and loss of elasticity which, in turn, made them break more readily. Similar to the bio gillnets, in 2017 the nylon gillnets also experienced a significant reduction in tensile strength (13.2%) and elongation (33.9%), supporting the indication that greater physical damage may be the cause. The reduction in elasticity that was measured in the bio gillnets by the end of the fishing experiments was most likely due to roughening and splintering of the surface due to use and wear of the bio gillnet monofilaments. However, the loss of elasticity is probably also an indication of changes in the physical properties of the PBSAT material due to biodegradation.

Kim et al. (2016) reported that uncoloured bio gillnets (made of a blending of PBS-PBAT resin) slowly degraded in cold sea water (< 5 ºC). The sea water temperature in our fishing experiments oscillated between 4.1 ºC and 8.8 ºC, suggesting that biological degradation was perhaps also a cause of tensile strength and elasticity reduction of the bio gillnets nets. In our experiment we were unable to separate the degree of strength and elasticity reduction caused by biodegradation from that caused by used and wear. However, when we observed monofilaments samples in the electronic scanning microscope we not only saw physical damages caused by friction in both bio and nylon monofilaments, but also, we saw some degree of roughening and splintering of the surface of the bio material. Roughening and splintering of the monofilament surface of the bio gillnets may actually be a consequence of the biodegradation process. A controlled degradation experiment may avoid the damage caused by use and wear of the material and therefore provide the actual loss of strength and elasticity caused by biodegradation. Also, this experiment can provide the degradation speed of the bio gillnets. It is worth to mention that if biodegradation is combined with daily use and wear of the material, the degradation process may be somehow accelerated.

When conventional nylon gillnets get lost at sea, the weakening of the material caused by use and wear, or by environmental factors such as UV radiation, virtually ceases and the degradation process therefore continues slowly. It is well documented that nylon gillnets are highly resistant to degradation, but that they do eventually lose their capability for ghost fishing depending on conditions of the seafloor (i.e. type of substrate, sea temperature, light conditions) (Carr *et al*., 1990; Pawson, 2003; Santos *et al.*, 2003; Humborstad et al., 2003; Tschernij and Larsson, 2003; Nakashima and Matsuoka, 2004; Pham *et al*., 2014). Furthermore, nylon gillnets do not entirely disappear; they just degrade into smaller plastic particles, commonly known as “micro plastics” that may continue to disturb important processes in marine ecosystems (Moore, 2008; Lee *et al*., 2013; Cole and Galloway, 2015; Desforges *et al*., 2015; Chae and Ann, 2017). Contrary to conventional nylon gillnets, if bio gillnets get lost at sea, bacteria, algae and fungi will much more rapidly degrade the material into carbon dioxide, methane and water, and they would therefore not have any further additional impacts on marine ecosystems (Tokiwa *et al*., 2009; Kim *et al*., 2014a, b). According to Kim *et al*. (2017), bio gillnets start degrading after two years of being immersed in seawater. However, this conclusion is based on a degradation experiment with monofilament samples immersed in sea water, thus the samples were not affected by physical damage from daily use and wear. The question of how fast a bio gillnet can lose its ghost fishing capacity depends greatly on the age of the net when lost and how much it had been used.

There is limited literature that quantifies the degradation speed of nylon gillnets, and even fewer studies that assess when a lost nylon gillnet loses its ghost fishing capacity. Some available studies show that nylon gillnets continue to fish for several years after being lost (Carr and Cooper, 1987; Puente et al., 2001; Nakashima and Matsuoka, 2004). Our experiment suggest that the degradation time of bio gillnets could even be shorter if the bio gillnets are weakened by used and wear before they get lost.

Coloured bio gillnets, such as those tested in this study, show potential to become a feasible alternative to conventional nylon gillnets, particularly in the short season Norwegian fisheries like cod, saithe and Greenland halibut, and to reduce the duration of ghost fishing if they do get lost. However, a 26.6% and 22.5% reduction of the cod and saithe catch can considerably affect the cost effectiveness of the fishing operation and the acceptance of bio gillnets by fishermen. Nonetheless, the material is not yet fully developed, and there are challenges and knowledge gaps (i.e. products of degradation, ecotoxicity) that should be addressed before drawing conclusions about the overall benefits of using these new biomaterials in fisheries. Ultimately, it is up to regulatory institutions in Norway to decide whether to introduce bio gillnets in the deep-water gillnet fisheries in order to reduce ghost fishing or let fishermen continue using the most effective nylon gillnets with well-known consequences if they get lost.

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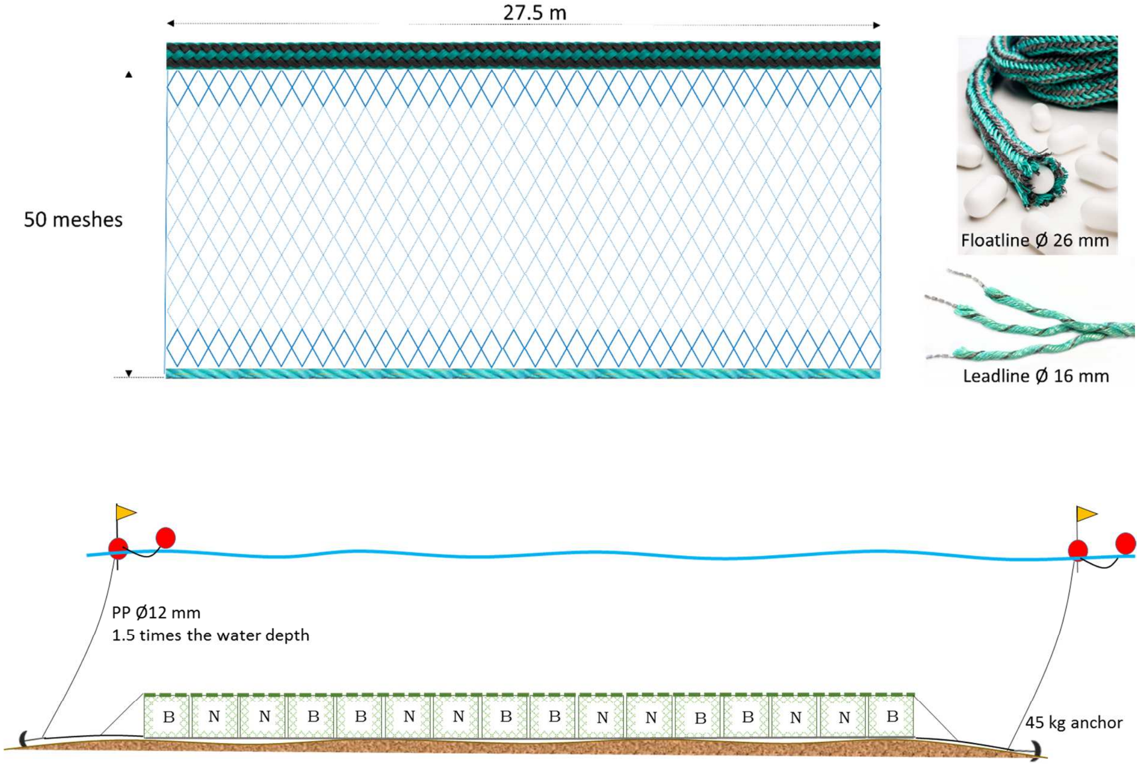

Fig. 1 A schematic representation of the experimental gillnets (set 1) showing the layout (N: nylon gillnet; B: bio gillnet) during the fishing trials.

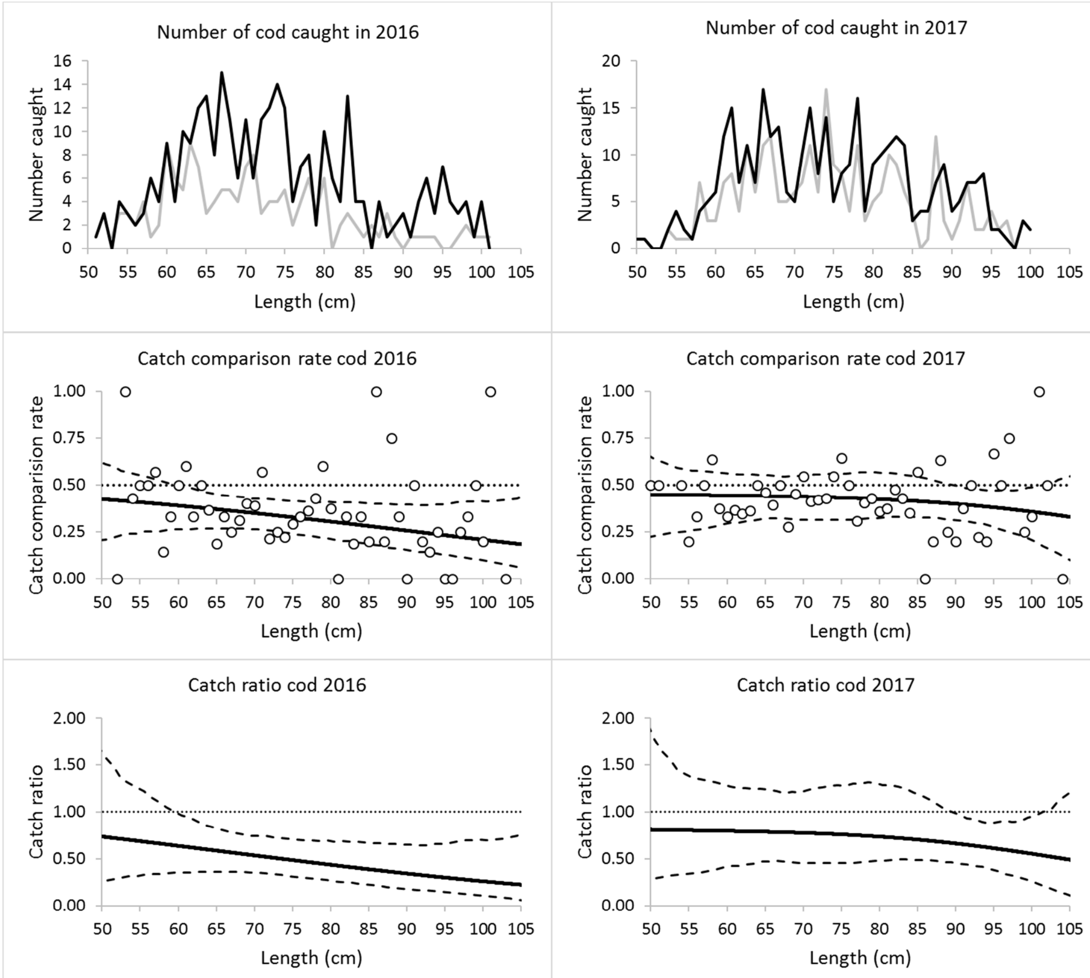

Fig. 2. Top: size distribution of cod caught with each type of gillnet (the black and grey curves represent nylon and bio gillnets, respectively). Centre: Catch comparison rate (*CC*) based on all deployments for 2016 (left) and 2017 (right) with circle marks representing the experimental rate and the curve representing the modelled *CC*. The dotted line at 0.5 represents the baseline at which both types of gillnet have equal catch rates. Stippled curves represent 95% confidence limits for the estimated catch comparison curve. Bottom: Estimated catch ratio (*CR)* curve based on all deployments. The dotted line at 1.0 represents the baseline at which both types of gillnet have equal catch rates. Stippled curves represent 95% confidence limits for the estimated catch ratio curve.

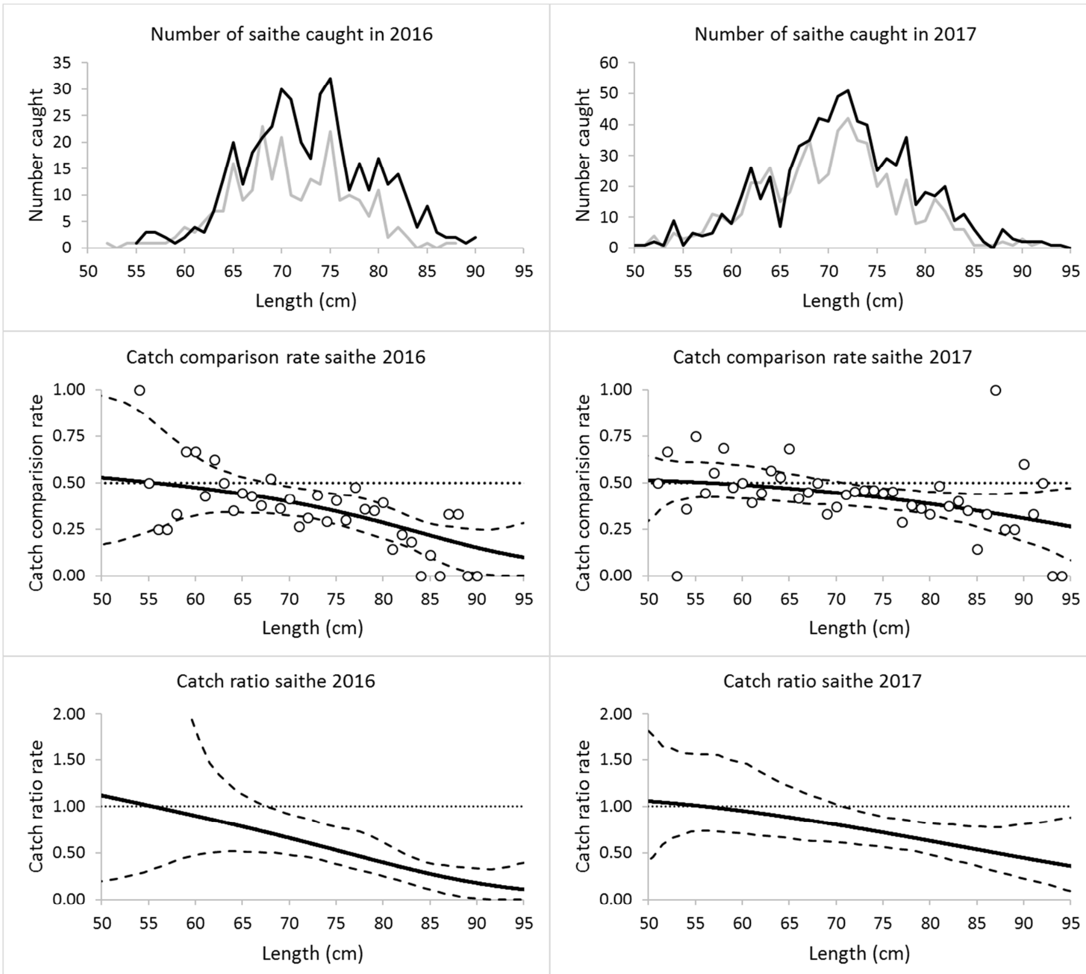

Fig. 3. Top: size distribution of saithe caught with each type of gillnet (the black and grey curves represent nylon and bio gillnets, respectively). Centre: Catch comparison rate (*CC*) based on all deployments for 2016 (left) and 2017 (right) with circle marks representing the experimental rate and the curve representing the modelled (*CC*). The dotted line at 0.5 represents the baseline at which both types of gillnet have equal catch rates. Stippled curves represent 95% confidence limits for the estimated catch comparison curve. Bottom: Estimated catch ratio (*CR)* curve based on all deployments. The dotted line at 1.0 represents the baseline at which both types of gillnet have equal catch rates. Stippled curves represent 95% confidence limits for the estimated *CR* curve.

Fig. 4. Images of the bio gillnets from 2016 (green) and 2017 (blue) showing physical damage of the knots.

Table 1. Catch data for cod. Only sets with at least 10 cod caught were used in the analysis.

Set ID cod	Year	Minimum size (cm)	Maximum size (cm)	Number of cod in Bio gillnet	Number of cod in Nylon gillnet
1	2016	51	89	49	60
2	2016	52	85	7	13
3	2016	52	88	8	9
4	2016	54	90	6	11
5	2016	60	82	3	13
6	2016	56	85	4	7
7	2016	58	86	5	10
8	2016	54	88	8	13
9	2016	57	84	13	29
10	2016	52	87	10	17
11	2016	60	76	3	9
12	2016	58	109	13	60
13	2016	57	100	21	49
14	2017	48	108	13	9
15	2017	58	97	13	32
16	2017	51	78	10	5
17	2017	50	86	9	23
18	2017	59	99	32	25
19	2017	58	94	15	43
20	2017	57	95	44	54
21	2017	50	100	7	7
22	2017	64	91	10	13
23	2017	64	105	8	11
24	2017	54	106	31	12
25	2017	60	104	17	24
26	2017	59	104	5	13
27	2017	58	92	8	13
28	2017	56	94	4	7
29	2017	62	104	2	9
30	2017	62	99	8	15
31	2017	51	100	15	20
32	2017	70	105	3	7
33	2017	62	95	3	8

Table 2. Catalog ratio (*CR(l)*) for cod (%) and fit statistics obtained for the bio gillnets relative to for nylon gillnets in 2016 and 2017. Values in brackets represent 95% confidence limits. DF, degrees of freedom.

Length (cm)	*CR(l)* (%) 2016	*CR(l)* (%) 2017
55	68.9 (33.3–121.9)	80.5 (34.8–136.4)
60	63.9 (35.6–96.2)	79.8 (42.2–127.0)
65	58.8 (36.4–81.2)	79.0 (47.5–123.5)
70	53.7 (35.7–74.6)	77.8 (46.0–122.9)
75	48.7 (31.0–70.9)	76.1 (45.7–127.9)
80	43.7 (26.2–68.6)	73.8 (47.9–128.8)
85	39.9 (22.3–66.8)	70.6 (48.5–117.6)
90	34.4 (17.8–65.6)	66.4 (45.0–96.9)
95	30.1 (14.4–67.1)	61.4 (36.7–89.2)
100	26.1 (10.6–69.6)	55.5 (24.4–96.2)
Average	50.0 (31.4–73.3)	73.4 (51.9–102.7)
p-value	0.2208	0.7037
Deviance	55.21	45.16
DF	48	51

Table 3. Catch data for saithe. Only sets with at least 10 saithe caught were used in the analysis.

Set ID saithe	Year	Minimum size (cm)	Maximum size (cm)	Number of saithe in Bio gillnet	Number of saithe in Nylon gillnet
1	2016	60	83	18	13
2	2016	60	80	17	8
3	2016	52	80	9	2
4	2016	56	87	10	14
5	2016	57	87	27	45
6	2016	63	89	9	12
7	2016	63	90	16	21
8	2016	60	82	9	13
9	2016	56	90	12	56
10	2016	64	85	7	15
11	2016	58	82	7	16
12	2016	64	88	3	11
13	2016	61	88	25	29
14	2016	58	83	12	19
15	2016	68	80	5	8
16	2016	59	78	4	7
17	2016	57	80	7	18
18	2016	57	86	12	18
19	2016	65	85	8	10
20	2016	55	83	25	61
21	2016	62	82	7	26
22	2017	52	92	43	41
23	2017	64	82	5	13
24	2017	54	92	38	51
25	2017	52	88	15	21
26	2017	50	97	27	44
27	2017	62	99	22	37
28	2017	52	85	21	25
29	2017	61	76	7	3
30	2017	51	88	10	16
31	2017	62	94	6	11
32	2017	64	82	7	6
33	2017	52	82	17	24
34	2017	54	86	14	14
35	2017	54	92	39	42
36	2017	54	97	37	19
37	2017	56	87	25	59
38	2017	54	86	41	36
39	2017	54	91	18	27
40	2017	56	82	36	47
41	2017	58	82	4	11
42	2017	55	90	77	78
43	2017	51	84	48	86
44	2017	61	80	3	7
45	2017	58	81	5	11

Table 4. Catch ratios (*CR(l)*) for saithe (%) and fit statistics obtained for the bio gillnets relative to for nylon gillnets in 2016 and 2017. Values in brackets represent 95% confidence limits. DF, degrees of freedom.

Length (cm)	*CR(l)* (%) 2016	*CR(l)* (%) 2017
50	111.9 (20.7–2599.0)	105.8 (45.8–176.9)
55	101.1 (32.8–481.2)	101.2 (73.6–156.3)
60	90.0 (48.7–169.2)	95.3 (70.8–145.4)
65	78.5 (50.9–110.4)	88.4 (65.5–120.1)
70	66.1 (47.4–90.1)	80.5 (61.1–100.7)
75	53.1 (36.9–76.8)	72.0 (55.7–87.9)
80	39.9 (24.0–58.8)	63.0 (47.3–81.9)
85	27.7 (9.4–38.0)	53.8 (34.5–78.2)
90	17.8 (1.0–33.0)	44.7 (21.3–81.3)
95	11.0 (0.1–40.3)	35.9 (8.1–88.6)
average	59.0 (43.1–81.3)	77.5 (62.7–93.9)
p-value	0.7098	0.7127
Deviance	28.10	37.38
DF	33	43

Table 5. Tensile strength (kg) and elongation at break (%), with 95% confident intervals (in brackets) for the gillnets used in 2016 and 2017.

Material	Test	2016				2017			
		New	Used	% reduction	p-value	New	Used	% reduction	p-value
Nylon	Tensile strength	11.9 (0.54)	11.8 (0.68)	-0.8	0,1223	11.4 (0.42)	9.9 (0.97)	-13.2	0.0001
	Elongation at break	36.8 (0.79)	35.9 (1.11)	-2.4	0.0757	36.6 (0.83)	26.2 (1.78)	-33.9	0.0000
Biodegradable	Tensile strength	11.8 (0.39)	11.8 (0.51)	0.0	0.1028	11.1 (0.24)	9.5 (0.66)	-18.1	0.0001
	Elongation at break	39.7 (1.06)	38.4 (1.16)	-3.3	0.0707	38.5 (0.69)	33.4 (2.33)	-13.2	0,0011

Table 6. Percentage of knots with no damage, slightly damaged, badly damaged, and broken knots for gillnets used in 2016 and 2017.

	2016				2017			
	No damage	Slightly damaged	Badly damaged	Broken	No damage	Slightly damaged	Badly damaged	Broken
Bio gillnet	25.95 %	71.90 %	1.90 %	0.00 %	3.81 %	68.57 %	18.81 %	8.57 %
Nylon gillnet	28.81 %	69.76 %	0.48 %	0.00 %	37.38 %	35.24 %	19.52 %	7.86 %

Effect of using biodegradable gillnets on the catch efficiency of Greenland halibut (*Reinhardtius hippoglossoides*)

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Abstract

The effect of using biodegradable polybutylene succinate co-adipate-co-terephthalate (PBSAT) gillnets on the relative catch efficiency was assessed in a commercial gillnet fishery targeting Greenland halibut (*Reinhardtius hippoglossoides*) in northern Norway. Compared to conventional polyamide (PA) gillnets, the PBSAT gillnets caught fewer fish, and the relative catch efficiency decreased with increasing fish size. For fish larger than 65 cm, the reduction in catch efficiency was significant, as the PBSAT gillnets caught 30% fewer Greenland halibut in this size range than the conventional PA gillnets. Differences in mesh size, breaking strength, and elasticity could contribute to the difference in size-dependent catch efficiency between the two types of gillnets.

Keywords: Biodegradable gillnet; Ghost fishing; PBSAT resin; Gillnet fishery; Catch efficiency; Greenland halibut; *Reinhardtius hippoglossoides*

Introduction

When non-biodegradable plastic materials, which are generally more persistent in the environment than natural materials, get lost, are abandoned, and/or are discarded at sea, it causes a series of biological, ecological, and socio-economic problems. In recent decades, numerous studies have focused on assessing the magnitude of the effects of lost fishing gear in the marine environment (Al-Masroori et al., 2004; Brown and Macfadyen, 2007; Large et al., 2009; Macfadyen et al., 2009; Gilman 2015; Gilman et al., 2016). Among the mitigating measures proposed to address the problem is the use of biodegradable fishing gear, which should reduce the time frame of ghost fishing (Macfadyen et al., 2009).

In recent years, many studies have shown that uncoloured (transparent) gillnets made of polybutylene succinate (PBS) resin blended with polybutylene adipate-co-terephthalate (PBAT) resin can be naturally degraded in sea water by the action of bacteria and algae, and simultaneously these studies documented similar fishing efficiency when compared with conventional polyamide (PA) gillnets (Park et al., 2007a; 2007b; 2010; Park and Bae, 2008; Bae et al., 2012, 2013; An and Bae, 2013; Kim et al., 2013, 2016). Kim et al. (2016) reported that within two years of being submerged in sea water, gillnets made of blended PBS and PBAT resin began to degrade and that by then those gillnets would have become weak enough to stop catching fish.

In Norway, gillnets are among the most important fishing methods, especially for the coastal fleet. The main target species are cod (*Gadus morhua*), saithe (*Pollachius virens*), Greenland halibut (*Reinhardtius hippoglossoides*), and monkfish (*Lophius piscatoriusare*), with fisheries for the last two species experiencing the most gear loss (Humborstad et al., 2003). The total international catches of Greenland halibut in 2015 were 25,250 tonnes. Of this, Norwegian catches accounted for 10,800 tonnes and Russian catches 12,950 tonnes. In 2015, about 63% of total catches were taken with bottom trawls, 27% with lines, and 12% with gillnets (Hallfredsson

2017). The coastal fleet, which is mostly composed of vessels smaller than 28 m LOA, can participate in the fishery for Greenland halibut and can land up to 4600 tonnes of Greenland halibut beginning 23 May (from 00.00 hrs.) or until the Norwegian Directorate of Fisheries closes the fishery and up to 2000 tonnes of Greenland halibut beginning 25 July (from 00.00 hrs.) or until the Norwegian Directorate of Fisheries closes the fishery (Norwegian Directorate of Fisheries, 2015). In addition, the individual quota per vessel size is 17.5, 20.0, and 22.5 tonnes for vessels smaller than 13.99 m LOA, between 14.0 m and 19.99 m LOA, and between 20.0 m and 27.99 m LOA, respectively (Norwegian Directorate of Fisheries, 2015).

To date, Norway is one of the few countries in the world that has a program for systematic annual retrieval of lost and abandoned or otherwise discarded fishing gear (LADFG) (Macfadyen et al., 2009) from the most intensively fished areas. Since 1983, more than 20,000 gillnets have been retrieved (Fig. 1); however, they represent only about 40–50% of all gillnets that were reported lost. These retrieval operations are highly demanding because of operation depth (500–1000 m), strong currents in the areas, and uncertainties associated with the accuracy of the lost gear's position. Therefore, and parallel to the gear retrieval program, current research is focused on assessing the possibility of using biodegradable plastic materials to manufacture gillnets.

Fig. 1.

The Norwegian management institution (i.e., Directorate of Fisheries) sees biodegradable plastic materials as a potential solution to reduce ghost fishing and plastic pollution at sea caused by lost gillnets (Langedal, G., Norwegian Directorate of Fisheries, personal communication). For an application of biodegradable plastics at sea to be environmentally safe, the intermediate break-down products, even those that are degradable, must not have any ecotoxicological effects on the ecosystem. Simultaneously, for biodegradable gillnets to be adopted by the fishing industry, they must be as efficient as conventional PA gillnets in order to maintain the profitability of the fishing operation. The present study addressed the second concern: fishing efficiency. The specific objective of this study was to compare the relative catch efficiency of biodegradable PBSAT gillnets versus conventional PA gillnets.

Materials and Methods

Biodegradable PBSAT resin

The new PBSAT resin is an aliphatic-aromatic co-polyester prepared using 1.4-butanediol as an aliphatic glycol (the base material) and dicarboxylic acids such as succinic acid and adipic acid (the aliphatic components) and dimethyl terephthalate (the aromatic component). The PBSAT resin includes multiple dicarboxylic acid residue components; for comparison, PBS resin contains one dicarboxylic acid residue and PBAT resin includes two dicarboxylic acid residues (Kim et al., 2017, patent EP3214133 A1).

Experimental gillnets

The relative fishing efficiency of transparent biodegradable PBSAT gillnets, herein called bio gillnets, was compared with that of conventional yellow PA gillnets, herein called PA gillnets, during fishing trials. Each gillnet had a 210 mm nominal mesh opening, was made of 0.7 mm monofilament, and was 30 meshes in height and 275 meshes long (approximately 55 m stretched length). To provide buoyancy, each gillnet was fixed to a 27.5 m long and 26 mm diameter SCANFLYT-800 float line with a buoyancy of 150 g m^{-1}. To provide weight, they were attached to a 27.5 m long and 16 mm diameter DANLINE lead line with weight of 360 g m^{-1}. Consequently, an assembled gillnet was 27.5 m long and had a hanging ratio of 0.5 (Fig. 2).

Fig. 2.

Because the fishery for Greenland halibut is carried out at the edge of the continental slope at depths that vary between 500 and 700 m, fishermen commonly use long gillnet sets with 30–40 gillnets sheets. In this study, a single set of experimental gillnets was used. The set consisted of 32 gillnets, with 16 bio gillnets (B) and 16 PA gillnets (N) attached in such a way that they provided information for paired comparison analysis. The sheets of gillnets were arranged as B-NN-BB-NN-BB-NN-BB-NN-BB-NN-BB-NN-BB-NN-BB-NN-B. Actual measurements of the mesh openings (four rows of 20 meshes each) were taken using a Vernier calliper without applying tension to the meshes. The mean mesh openings of PA gillnets and bio gillnets were 198.9 mm (95% CI = 198.4–199.4 mm) and 201.7 mm (95% CI = 201.4–202.0 mm), respectively (Fig. 3). The difference in mean mesh sizes between both types of gillnet was highly significant (unpaired t-test: $p = 6.4\times10^{-16}$). So was the difference in variation (F-test, $p = 8.4\times10^{-10}$).

Fig. 3.

Fishing vessel and fishing grounds

The experiment was conducted on board the coastal gillnet boat MS Skreigrunn (14.9 m LOA, 500 HP) between 27 May and 23 June 2016 and covered almost the entire season for Greenland halibut. The experiment stopped when the vessel filled its quota. The fishing grounds chosen for the tests were located off the coast of Troms (Northern Norway) between 69˚24’–69˚45’N and 16˚23’–16˚37’E, which is a common fishing area for coastal vessels from Troms.

Modelling and comparison of the size-dependent catch efficiency of the gillnet types

We used the statistical analysis software SELNET (Sistiaga et al., 2010; Herrmann et al., 2012, 2016) to analyse the catch data and conduct length-dependent catch comparison and catch ratio analyses. We used the catch information (numbers and sizes of Greenland halibut) from each gillnet set deployment to determine whether there was a significant difference in the catch efficiency averaged over deployments between the PA gillnet and the bio gillnet. If a difference between the gillnets was present, we also wanted to determine if this difference could be related to the size of the Greenland halibut. Specifically, to assess the relative length-dependent catch efficiency effect of changing from PA gillnet to bio gillnet, we used the method described in Herrmann et al. (2017) to compare the catch data for the two gillnet types. This method models the length-dependent catch comparison rate (CC_l) summed over gillnet set deployments:

$$CC_l = \frac{\sum_{j=1}^{m}\{nt_{lj}\}}{\sum_{j=1}^{m}\{nt_{lj} + nc_{lj}\}} \qquad (1)$$

where nc_{lj} and nt_{lj} are the numbers of Greenland halibut caught in each length class l for the PA gillnet (*control/baseline*) and the bio gillnet (*treatment*) in deployment j of a gillnet set. m is the number of deployments carried out. The functional form for the catch comparison rate $CC(l,\boldsymbol{v})$ (equation 1) was obtained using maximum likelihood estimation by minimizing the following expression:

$$-\sum_l\left\{\sum_{j=1}^{m}\{nt_{lj} \times ln(CC(l,\boldsymbol{v})) + nc_{lj} \times ln(1.0 - CC(l,\boldsymbol{v}))\}\right\} \qquad (2)$$

where $\boldsymbol{v}$ represents the parameters describing the catch comparison curve defined by $CC(l,\boldsymbol{v})$. The outer summation in the equation is the summation over the length classes l. If the catch efficiency of the bio gillnet and PA gillnet was similar, the expected value for the summed catch comparison rate would be 0.5. Therefore, this value was applied to judge whether or not there was a difference in catch efficiency between the two gillnet types. The experimental CC_l was modelled by the function $CC(l,\boldsymbol{v})$ of the following form:

$$CC(l,\boldsymbol{v}) = \frac{exp(f(l,v_0,\ldots,v_k))}{1 + exp(f(l,v_0,\ldots,v_k))} \qquad (3)$$

where f is a polynomial of order k with coefficients v_0 to v_k. The values of the parameters $\boldsymbol{v}$ describing $CC(l,\boldsymbol{v})$ were estimated by minimizing equation (2), which was equivalent to maximizing the likelihood of the observed catch data. We considered f of up to an order of 4 with parameters v_0, v_1, v_2, v_3, and v_4. Leaving out one or more of the parameters $v_0 \ldots v_4$ led to 31 additional models that were also considered as potential models for the catch comparison *CC(l,**v**)*. Among these models, estimations of the catch comparison rate were made using multi-model inference to obtain a combined model (Burnham and Anderson 2002; Herrmann et al., 2017).

The ability of the combined model to describe the experimental data was evaluated based on the P-value, which quantifies the probability of obtaining by coincidence at least as big a discrepancy between the experimental data and the model as what was observed, assuming that the model is correct. Therefore, this P value, which was calculated based on the model deviance and the degrees of freedom, should not be < 0.05 for the combined model to describe the experimental data sufficiently well, except for cases in which the data were subjected to over-dispersion (Wileman et al., 1996; Herrmann et al., 2017).

Based on the estimated catch comparison function *CC(l,**v**)*, we obtained the relative catch efficiency (also called the catch ratio) *CR(l,**v**)* between the two gillnet types using the following relationship:

$$CR(l,\boldsymbol{v}) = \frac{CC(l,\boldsymbol{v})}{(1 - CC(l,\boldsymbol{v}))} \qquad (4)$$

The catch ratio provided a value for the difference in catch efficiency between the bio gillnet and the PA gillnet. If the catch efficiency of both gillnets is equal, *CR(l,**v**)* should always be 1.0. Thus, *CR(l,**v**)* = 1.5 would mean that the bio gillnet caught 50% more Greenland halibut with length *l* than the PA gillnet. In contrast, *CR(l,**v**)* = 0.8 would mean that the bio gillnet caught only 80% of the Greenland halibut with length *l* that the PA gillnet caught.

The confidence limits for the catch comparison curve and catch ratio curve were estimated using a double bootstrapping method (Herrmann et al., 2017). This bootstrapping method accounts for between-set variability (the uncertainty in the estimation resulting from set deployment variation in catch efficiency in the gillnets and in the availability of Greenland halibut) as well as within-set variability (uncertainty about the size structure of the catch for the individual deployments). However, contrary to the double bootstrapping method described by Herrmann et al. (2017), the outer bootstrapping loop in the current study accounting for the between-deployment variation was performed paired for the bio gillnets and PA gillnets to take full advantage of the experimental design that allowed the two types of gillnet to be deployed simultaneously. By multi-model inference in each bootstrap iteration, this method also accounts for the uncertainty due to uncertainty in model selection. We performed 1000 bootstrap repetitions and calculated the Efron 95% (Efron, 1982) confidence limits. To identify sizes of Greenland halibut with significant difference in catch efficiency, we checked for length classes for which the 95% confidence limits for the catch ratio curve did not contain 1.0.

Finally, a length-integrated average value for the catch ratio was estimated directly from the experimental catch data using the following equation:

$$CR_{average} = \frac{\sum_l \sum_{j=1}^{m} \{nt_{lj}\}}{\sum_l \sum_{j=1}^{m} \{nc_{lj}\}} \quad (5)$$

where the outer summation covers the length classes in the catch during the experimental fishing period. Equation 5 was applied to the full-length span for Greenland halibut caught and separately for sizes below 65 cm ($CR_{average65-}$) and above 65 cm ($CR_{average65+}$) to determine if the average relative catch efficiency differed for the smaller and bigger Greenland halibut.

Finally, for explorative purposes, we looked for any sign of loss in relative fishing efficiency for the bio gillnets compared to the PA gillnets during the deployment period by comparing catch ratios for the last three deployments with those obtained for the first three deployments.

Tensile strength tests

To compare the physical properties of the biodegradable and conventional PA monofilaments, tensile strength measurements were carried out on samples before and after the fishing experiments using a H10KT universal tensile testing machine (Tinius Olsen TMC, Horsham, PA, USA). Spools of monofilament were provided by the producers of the gillnets. Samples of gillnets measuring approximately 20 × 20 meshes were cut from the centre of the new and used gillnets. The tests were performed in dry and wet conditions (at least 40 replicates for each case) according to ISO 1806 (2002). Tensile strength, defined as the stress needed to break the sample, is given in kg, and elongation at break, defined as the length of the sample after it has stretched and right when it breaks (L), is given relative to the initial size in percentage. T-tests were used to compare the means of the two populations (PA or biodegradable). F-tests were performed to determine the equality of the variances of the two populations.

Results

The experimental gillnet set was lost on the first deployment carried out on 27 May 2016 and was recovered three days later on 30 May 2016. Length measurements of Greenland halibut caught in this set of gillnets were not recorded and therefore not included in the analysis. Scientists on board the MS Skreigrunn measured the lengths of all fish caught in the next seven deployments. A total of 698 Greenland halibut were caught, with 316 caught in the bio gillnets and 382 in the nylon gillnets. The mean effective soaking time (± standard deviation (SD)) was 21 h 29 min ± 0 h 52 min. The mean (± SD) fishing depth was 664.1 ± 12.6 m, and sea temperature varied between 5 and 6 ºC. Table 1 shows catch data including set number, date, soaking time, number of fish caught, and minimum and maximum length of fish caught.

Table 1.

Length-dependent catch efficiency

The length distribution of fish shows that the catch of Greenland halibut was length-dependent for both types of gillnet, with most of the fish being in the range of 47 to 80 cm (Fig. 4). The catch comparison rate was also highly length dependent, with fish larger than 65 cm having a lower value for the bio gillnets; this means that the PA gillnets caught significantly more fish in those length classes. The modelled catch comparison curve follows the main trend of the experimental points, which is supported by the fit statistics presented in Table 2. When analysing the size-dependent catch efficiency in the first three and the last three gillnets deployments, the results show a very similar tendency to that than when including all seven deployments. The size-dependent catch efficiency from the first three deployments shows that for fish larger than 65 cm in length, the catch rates for the bio gillnets were significantly lower than those for the PA gillnets. The size-dependent catch efficiency from the last three deployments shows that catch rates for the bio gillnets were significantly lower than those for the PA gillnets for fish between 64 and 74 cm (Fig. 4).

Fig. 4.

Table 2.

The length-integrated average value for the catch ratio of the bio gillnets with respect to the PA gillnets (including all deployments) was 82.7%, meaning that the bio gillnets caught 17.3% fewer fish than the PA gillnets. However, this difference was not statistically significant, as expressed by the wide confidence limits (62.4–110.2) (Table 2). However, the average catch ratio for sizes of Greenland halibut above 65 cm ($CR_{average65+}$) was 29.8% (CI = 15.5–44.4), which indicates that the bio gillnets were catching significantly fewer bigger fish than the PA gillnets. For sizes of Greenland halibut below 65 cm, the average catch efficiency ($CR_{average65-}$) was similar between the two gillnet types (Table 2). Individual analysis of the length classes of 45, 50, 55, 60, 65, 70, 75, and 80 cm revealed significant differences in the catch ratio for fish larger than 65 cm. In the length classes 70 and 80 cm, for instance, the bio gillnets caught 23.5% (CI = 1.2–43.3) and 2.1% (CI = 0.0–17.5) of what the PA gillnets caught, respectively (Table 2).

The length-integrated average values for the catch ratio of the bio gillnets with respect to the PA gillnets for the first three and the last three deployments were 94.6% (CI =81.8–173.7%) and 75.0 % (CI = 60.5–123.8%), respectively. This means that the bio gillnets caught 5.4% and 25.0% fewer fish than the PA gillnets in the first three and the last three deployments, respectively (Table 2). However, as is evident from the highly overlapping confidence bands, this result was not significant and likely was a coincidence.

Tensile strength

The average breaking strength of the dry knotless PA monofilaments was 27.6 kg (CI = 27.4–27.8 kg), and that of dry biodegradable monofilaments was 17.7 kg (CI = 17.5–17.8 kg). Thus, the PA monofilaments were significantly 35.8% stronger (t-test, $p = 7.7\times10^{-21}$) than the biodegradable monofilaments. The average elongation at break of dry PA monofilaments was 27.7% (26.9–28.5%) and that of dry biodegradable monofilaments was 25.2% (CI = 25.1–25.2%), meaning that the dry bio monofilaments were significantly (t-test, $p = 3.3\times10^{-4}$) 9.2% less elastic than dry PA monofilaments (Table 3 and Fig. 5).

The average breaking strength of the wet knotless PA monofilaments was 22.2 kg (CI = 22.1–22.4 kg) and that of wet biodegradable monofilaments was 19.3 kg (CI = 19.2–19.4 kg), representing a significant difference (t-test, $p =3.3\times10^{-4}$) of 13.2% in favour of the PA monofilament. The average elongation at break of the wet knotless PA monofilaments was 32.1% (31.4–32.8%) and that of biodegradable monofilaments was 25.0% (CI = 24.7–25.3%), meaning that the wet biodegradable monofilaments were significantly (t-test, $p = 1.9\text{x}10^{-8}$) 22.3% less elastic than the wet PA monofilaments (Table 3 and Fig. 5).

The average breaking strength of the wet PA netting was 22.5 kg (CI = 22.0–23.0 kg), while that of biodegradable netting was 20.0 kg (CI = 19.1–20.9 kg), representing a significant difference (t-test, $p = 7.9\times10^{-4}$) of 11.0% in favour of the PA netting. The average elongation at break of PA netting was 30.6% (29.9–31.3%), while that of biodegradable netting was 34.2% (CI = 33.4–35.0%), meaning that the biodegradable netting was significantly (t-test, $p = 3.2\times10^{-6}$) 11.6% less elastic than PA netting (Table 3 and Fig. 5).

The difference in the average tensile strength between new and used gillnets (measured in wet conditions) was significant for PA gillnets (t-test, $p = 3.2\times10^{-10}$), and for bio gillnets (t-test, $p = 3.2\times10^{-2}$). The elasticity of used bio gillnets (32.9%, CI = 31.6–34.1%) was significantly reduced (t-test, $p = 2.7\times10^{-2}$) by 3.9% with respect to new bio nets (34.2%, CI = 33.4–35.0%) (Table 3 and Fig. 5). Used bio gillnets were significantly (12.3%) weaker and 8.5% less elastic than used PA gillnets.

Table 3.

Fig. 5.

Discussion

Compared to conventional PA gillnets, the bio gillnets caught fewer Greenland halibut, the relative catch efficiency decreased with increasing fish size, and for sizes above 65 cm in length this reduction in catch efficiency was statistically significant. Specifically, it was estimated that the bio gillnets caught 30% fewer Greenland halibut above 65 cm than the conventional PA gillnets (Table 2). The difference in tensile strength and elasticity between the two net types could have had a strong effect on their relative catch efficiencies. Material testing revealed that the bio gillnets were considerably weaker (11.0%) and less elastic (11.9%) than the PA gillnets. Thus, large Greenland halibut (> 65 cm) may have managed to break the meshes of bio gillnets and avoid getting caught. Our results agree with those reported by Grimaldo et al. (2018) who assessed the catch characteristics of bio gillnets for cod and saithe, Bae et al. (2013) for flounder, and Kim et al. (2013, 2016) for yellow croaker. These scientists reported that the catch efficiency of PA gillnets was 1.1–1.4 times greater than that of the biodegradable nets and concluded that the flexibility of bio gillnets was positively correlated with fishing capacity (i.e., greater flexibility means greater fishing capacity).

We also investigated whether there were any signs of temporal loss in relative fishing efficiency for the bio gillnets and the PA gillnets during the deployment period by comparing catch ratios for the last three deployments with those obtained for the first three deployments. We did not find any clear signs of such an effect. However, the deployment period during this study was short, so this result cannot be taken as evidence that bio gillnets do not lose catch efficiency compared to the traditional gillnets over the course of a complete fishing season that consists of many more deployments.

The results obtained in this study need to be interpreted with caution, as they are based on a data set composed of only seven gillnet deployments that caught 698 Greenland halibut. This small sample size leads to uncertainties regarding the estimated catch ratios of the bio gillnets and the PA gillnets. However, these uncertainties are reflected in the confidence bands around the catch ratio curves. Therefore, as long as these confidence bands are considered when drawing conclusions, the limited number of Greenland halibut caught should not be a major problem if it is valid to assume that the seven gillnet deployments reflect how the two gillnet types on average would perform, at least relative to each other regarding catch efficiency for Greenland halibut. We have no reason to believe that our gillnet deployments were atypical for the fishery. Therefore, despite the limited data set we believe that this study provides relevant and reliable information as long as the above described precautions are respected.

Tensile strength measurements of the used bio gillnets showed that some meshes broke at 15.6 kg load, whereas the weakest PA mesh broke at 18.2 kg load. Based on the length distributions of fish caught with both types of gillnet, it seems possible that the weakest PA meshes were still strong enough to retain Greenland halibut of large length classes, whereas the weakest bio gillnets meshes were not. The elasticity of the used PA gillnets was unchanged over time (around 30%), but that of the used bio gillnets was significantly reduced by 3.9% with respect to new nets. This reduction in elasticity in the bio gillnets (and not in the PA gillnets) over the course of the four-week experiment (27 May and 23 June 2016) suggests that changes in the physical properties of the bio gillnets occur over time due to degradation. Biological degradation was not assessed in this study, but it should be studied because it may confound the effect of use and wear of the gillnets on the weakening of the bio gillnets.

If lost, biodegradable PBSAT and PA gillnets are no longer affected by use and wear (i.e., abrasion in the hauling machine, friction due to contact with hard surfaces when gillnets are operated on deck). In the case of bio gillnets, bacteria, algae, and fungi take over and further degrade the material. Because the biodegradable materials are degraded into carbon dioxide, methane, and water, they do not have any additional impact on the marine ecosystems (Tokiwa et al., 2009; Kim et al., 2014a, b). In the case of PA gillnets, weakening of the material nearly stops when the gear is lost, and degradation then occurs very slowly. PA gillnets are highly resistant to degradation, but they eventually lose their capability for ghost fishing depending on conditions of the seafloor (Carr et al., 1990; Humborstad et al., 2003; Pawson, 2003; Santos et al., 2003; Tschernij and Larsson, 2003; Nakashima and Matsuoka, 2004; Pham et al., 2014). Furthermore, PA gillnets do not entirely disappear; they just degrade into smaller plastic particles that may continue to disturb various processes in the marine ecosystem (Moore, 2008). According to Kim et al. (2017), biodegradable PBS-PBAT gillnets would stop catching fish after two years of being immersed in seawater. However, this conclusion is based on a degradation experiment with monofilament samples immersed in sea water, thus the samples were not affected by use and wear. The question of "how fast a biodegradable gillnet loses its ghost fishing capacity" depends greatly on when it is lost (new or old gillnet) and how much it has been used (use and wear).

The lifespan of gillnets, in this case defined as the amount of time they can be used for fishing, depends greatly on their durability and the degree of damage that they suffer when fishing. In the Norwegian deep-water gillnet fishery for Greenland halibut, a conventional PA gillnet generally is used for one season, and one season normally lasts between one and two months depending on the boat, the quota, and the availability and catchability of fish. When the fishing season is over, fishermen normally exchange most of the sheets of nets for new ones because the cost of repairing the nets is much greater than the cost of buying new relatively inexpensive PA gillnets. Therefore, the use of short lifespan bio gillnets could be an alternative to conventional PA gillnets if the profitability of the fishing operations is not compromised.

However, in the current study, the cost of the bio gillnets was approximately twice that of PA gillnets, and the catch of Greenland halibut obtained with the bio gillnets was approx.19% lower than that caught with PA gillnets. One set of PA gillnets (32 sheets) for fishing Greenland halibut costs approximately USD 3104, thus the cost of replacing them with bio gillnets would have been approximately USD 6208. Based on the length-weight relationship for Greenland halibut ($w = 4.538 \times 10^{-6} \times (l)^{3,158}$, Gundersen and Brodie, (1999)), the weight of the fish caught with the experimental gillnets was approximately 1390 kg, and according to the price in June 2016 (USD 3.06/kg) the catch had a value of USD 5006. The fact that the bio gillnets caught only 82.3% of what the PA gillnets did was equivalent to approximately 197 kg less Greenland halibut, which represented a loss of USD 709. The MS Skreigrunn used five sets of gillnets in the 2016 fishing season (one of which was the experimental gillnet set) and landed 16,136 kg of Greenland halibut in the period 27 May and 23 June 2016, with a value of USD 58,225. If all gillnets used in this period had been bio gillnets, the 19% reduction in catch would have represented approximately USD 8150 less income for the crew of the MS Skreigrunn.

In conclusion, biodegradable PBSAT gillnets have potential to be used as a feasible alternative to conventional PA gillnets, especially in short-seasoned fisheries such as that for Greenland halibut, and they would reduce the effect of ghost fishing if they are lost. However, a 17.3% reduction of the catch would negatively impact the cost-effectiveness of the fishing operation and the acceptance of biodegradable gillnets by fishermen. Nonetheless, the material is not yet fully developed, and there are challenges and knowledge gaps (i.e., beads, products of degradation, ecotoxicity) that should be addressed before drawing conclusions about the overall benefits of these new materials in gillnet fisheries.

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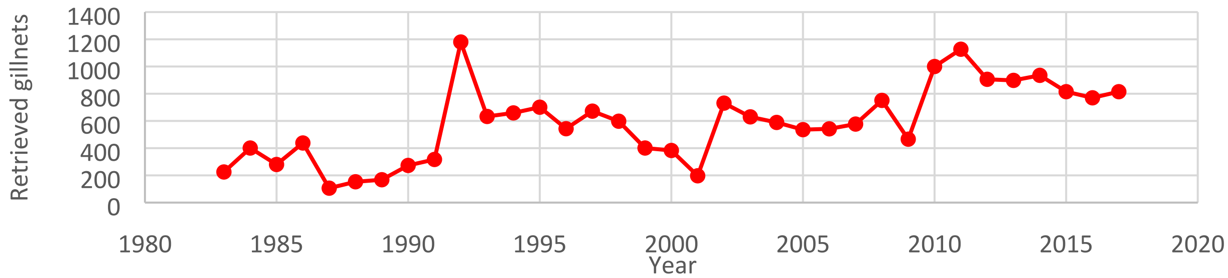

Fig 1: Number of retrieved gillnets in Norway (1983-2017). Source: Norwegian Directorate of Fisheries.

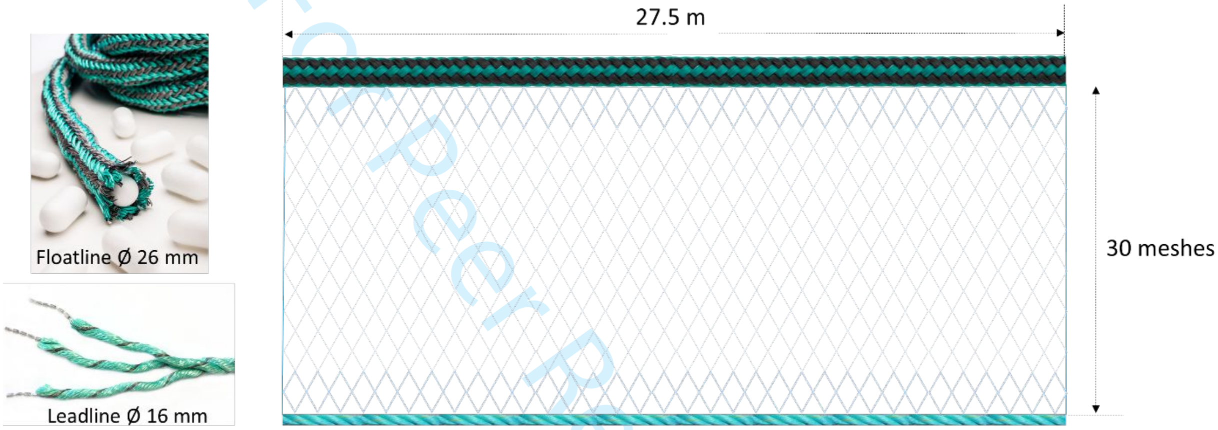

Fig 2. One sheet of gillnets illustrating the main components and dimensions.

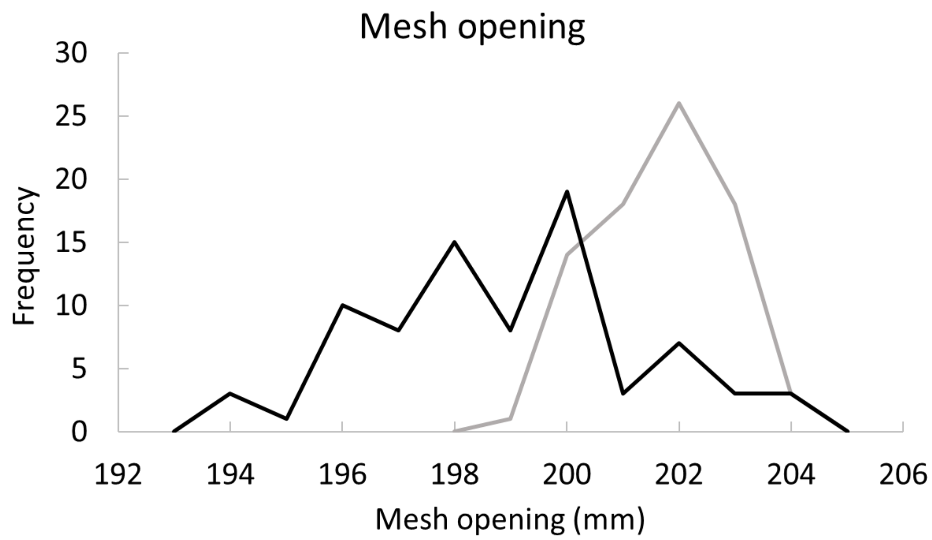

Fig. 3 Mesh opening distribution for PA (black line) and biodegradable gillnets (grey line).

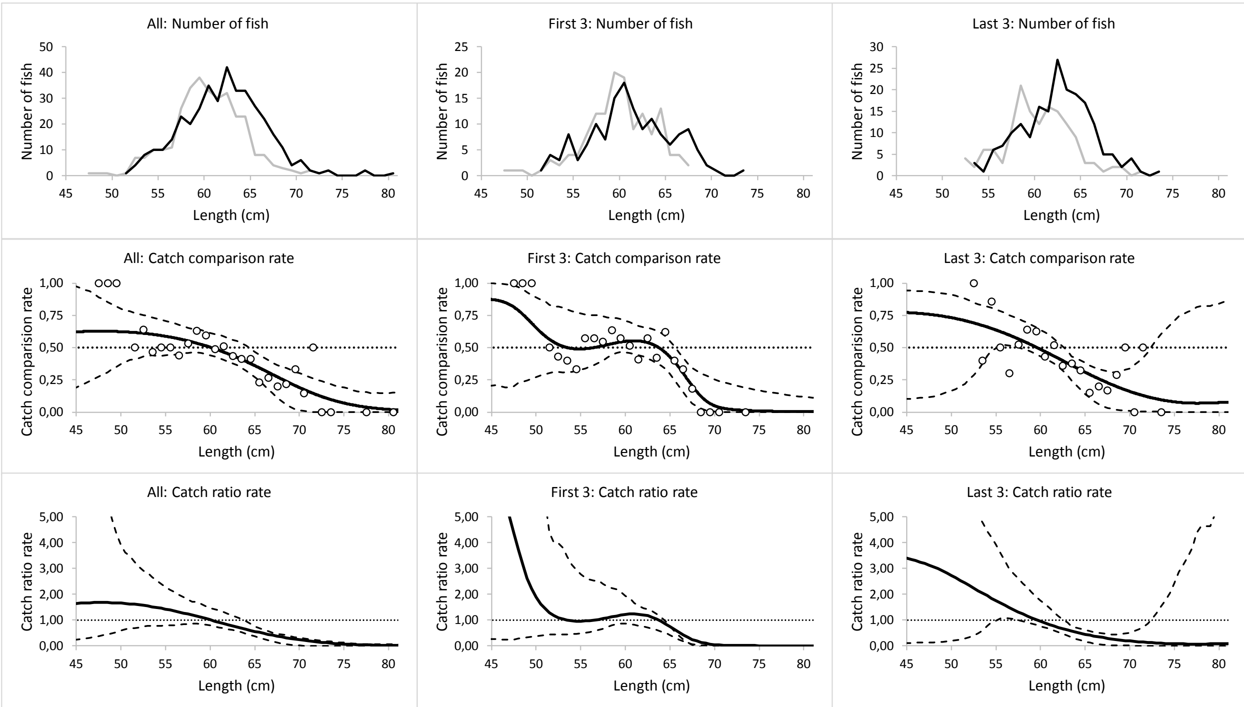

Fig. 4: Top: size distribution of Greenland halibut caught with each type of gillnets (black curve for PA gillnets and grey curve for bio gillnet). Centre: Catch comparison rate based on all seven deployments with circle marks representing the experimental rate and the curve the modelled catch comparison rate. Dotted line at 0.5 represent the baseline where both types of gillnets catch equally for Greenland halibut. Stipple curves represent 95% confidence limits for the estimated catch comparison curve. Bottom: Estimated catch ratio curve based on all deployments. Dotted line at 1.0 represent the baseline where both types of gillnets catch equally for Greenland halibut. Stipple curves represent 95% confidence limits for the estimated catch ratio curve.

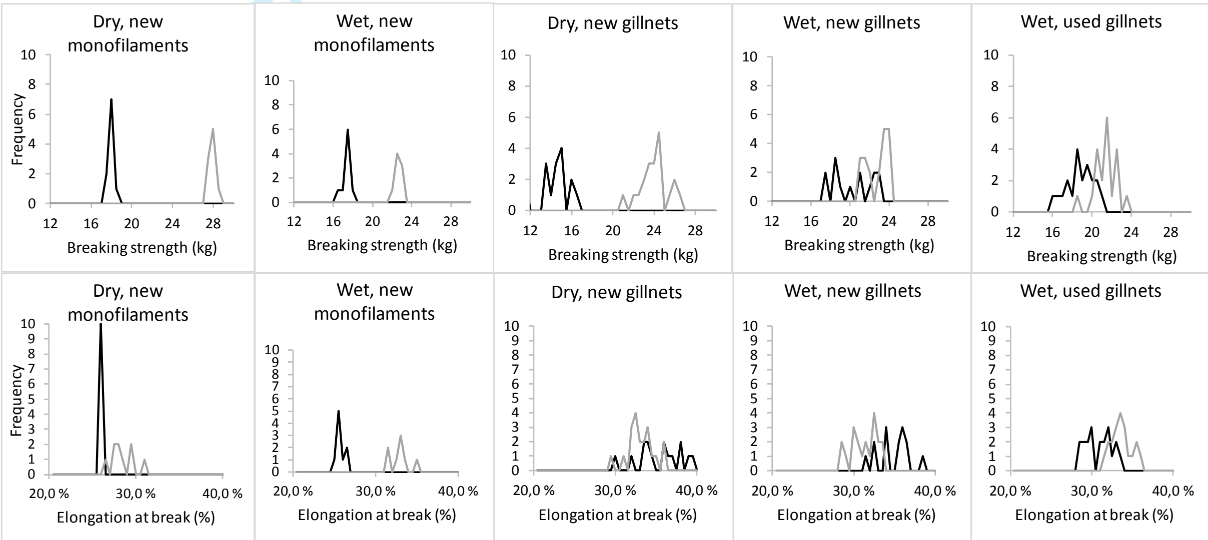

Fig 5. Tensile strength and elongation at break measurements for monofilaments and netting carried out in dry and wet conditions for PA (grey lines) and biodegradable materials (black line).

Table 1: Information about the seven gillnet deployments.

Set ID	Date	Fishing depth (m)	Soaking time (hh:mm)	Minimum size (cm)	Maximum size (cm)	Number of fish in bio gillnet	Number of fish in PA gillnet
Lost*	27.05.2016						
1	31.05.2016	640–672	22h 30min	47	68	45	55
2	01.06.2016	655–687	22h 10min	52	67	33	19
3	02.06.2016	645–689	22h 56min	48	73	62	74
4	13.06.2016	630–657	21h 45min	53	80	32	42
5	16.06.2016	658–664	22h 15min	54	73	26	21
6	20.06.2016	670–698	21h 25min	52	71	95	133
7	23.06.2016	655–678	20h 05min	54	68	23	38

* The experimental gillnet set got lost and was recovered on 30.05.2016. The catch data was not recorded and therefore was not included in the analysis

Table 2: Catch ratio *cr* in % and fit statistics obtained for the bio gradable design vs nylon for all data, first three and last three deployments. The catch ratio provided value for the difference in catch efficiency between the bio gillnet and nylon gillnet. If the catch efficiency of both gillnets is equal, *cr* should always be 100%. Thus, *cr* = 150% would mean that the bio gillnet caught 50% more Greenland halibut than the PA gillnet. In contrast, *cr* = 80% would mean that the bio gillnet caught only 80% of the Greenland halibut with length l that the PA gillnet caught. Values in ( ) represent 95% confidence limits. DOF denotes degrees of freedom.

Length (cm)	*cr* (%) All data	*cr* (%) First 3 sets	*cr* (%) Last 3 sets
45	164.9 (24.0–363.1)	690.8 (25.8-67920.1)	338.9 (11.4-1634.4)
50	165.7 (59.5–400.6)	188.7 (37.4-803.9)	273.4 (19.4-1012.8)
55	142.7 (78.9–239.1.7)	95.9 (49.2-324.3)	175.2 (98.0-392.9)
60	101.0 (79.0–158.1)	121.7 (86.6-241.0)	94.8 (76.5-174.6)
65	56.2 (37.4–86.9)	74.6 (42.0-123.7)	44.7 (15.9-62.0)
70	23.5 (1.2–43.3)	5.2 (0.3-34.3)	19.0 (1.0-51.5)
75	7.5 (0.0–23.7)	0.9 (0.0-20.1)	8.6 (0.1-243.2)
80	2.1 (0.0–17.5)	0.4 (0.0-13.4)	31.3 (0.0- 532.8)
Average65-	100.0 (85.9-129.5)	112.1 (90.9-202.0)	91.0 (71.9-173.2)
Average65+	29.8 (15.5-44.4)	31.3 (0.0-55.6)	25.5 (0.0-44.4)
Average	82.7 (62.1–112.9)	94.6 (81.8-173.7)	75.0 (60.5-123.8)
p–value	0.7141	0.9082	0.1143
Deviance	18.78	11.44	22.98
DOF	23	19	16

Table 3. Average tensile strength (kg) and elongation at break (%) measurements with 95% confident intervals (in brackets) for the monofilaments and meshes of the gillnets used for fishing Greenland halibut in 2016.

	Tensile strength (kg)		Elongation at break (%)	
	New	Used	New	Used
Dry PA monofilament	27.6 (27.4–27.8)		27.7 (26.9–28.5)	
Dry biodegradable monofilament	17.7 (17.5–17.8)		25.2 (25.1–25.2)	
Wet PA monofilament	22.2 (22.1–22.4)		32.1 (31.4–32.8)	
Wet biodegradable monofilament	19.3 (19.2–19.4)		25.0 (24.7–25.3)	
Wet PA netting	22.5 (22.0–23.0)	21.1 (21.1–21.1)	30.6 (29.9–31.3)	30.1 (30.1–30.2)
Wet biodegradable netting	20.0 (19.1–20.9)	18.5 (18.5–18.6)	34.2 (33.4–35.0)	32.9 (32.9–32.9)

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Comparison of fishing efficiency between biodegradable gillnets and conventional nylon gillnets

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ABSTRACT

Gillnets made of a new biodegradable resin (polybutylene succinate co-adipate-co-terephthalate (PBSAT) were tested under commercial fishing conditions to compare their fishing performance with that of conventional nylon (PA) nets. The relative catch efficiency between the two gillnet types was evaluated over the entirewinter fishing season for cod (*Gadus morhua*) in northern Norway. The nylon gillnets caught 21% more fish (in numbers) than the biodegradable gillnets throughout the fishing season and generally showed better catch rates for most length classes, except for sizes between 82 and 90 cm. The difference in elasticity and breaking strength could explain the major difference in the size structure of fish caught by each type of gillnets, especially for larger fish. The number of times that the gillnets were deployed affected the relative catch efficiency of the gillnets with the biodegradable continuously loosing efficiency compared to the nylon. Although less catch efficient than nylon gillnets, biodegradable gillnets still show great potential for reduction of ghost fishing and plastic pollution at sea caused by this fishery.

1. Introduction

Gillnets are among the most widely used fishing gears in the world and are commonly used by the commercial and artisanal fleets in all the oceans, fresh water and estuaries areas (Brandt, 2005). The effect of lost gillnets on the ecosystem is not well understood, although investigations have shown that lost gillnets can fish for years after they have been lost, a problem known as ghost fishing (Macfaden et al., 2009). International recognition of this problem is demonstrated through the large number of international organizations and agreements that now focus on lost gillnets and numerous national initiatives that have being implemented around the world (Gilman et al., 2016).

Also, in Norway gillnets are among the most important fishing methods, especially for the coastal fleet, however transparent gillnets are not used at all by the Norwegian fishermen. Instead, coloured gillnets are favoured because fishermen believe that certain colours reduce the contrast between the net and its background and therefore increase the fishing efficiency of the gillnet; also, because coloured gillnets provide a better contrast with the aluminium and/or stainless-steel sorting boards and make the removal of fish from the nets easier. Gillnetting is mostly carried out by the coastal fleet, and in 2017, this fleet was integrated by 5 705 boats smaller than 28 m (length overall, LOA) and used approx. 2.3 million gillnets. Of them, 13 941 gillnets were reported lost at sea in 2017 (Norwegian Environment Agency, 2018) (according to the Norwegian legislation every lost net should be reported). Based on information provided by fishermen, the Norwegian Directorate of Fisheries carry out systematic annual retrieval operation of lost gillnets (and other fishing gears) from the most intensively fished areas along the coast (Humbolstad et al., 2003; Gilman et al., 2016). Despite more than 20 400 lost gillnets have been retrieved since 1983, the recovery rate is considered to be low. Of the 13 941 gillnets that were reported lost at sea in 2017 (Norwegian Environment Agency, 2018), only 815 nets were retrieved in 2017 (Norwegian Directorate of Fisheries, 2018). This low recovery rate is because the low rate of reporting of lost gears and the highly demanding retrieving operations, especially if they are carried out in deep waters (400–1000 m) with strong currents in the areas, and uncertainties associated with the accuracy of the lost gear's position (Norwegian Environment Agency, 2018). Therefore, and parallel to the gear retrieval program, research has also focused on assessing the possibility of using biodegradable

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plastic materials to manufacture gillnets.

In the last decade, a large number of studies have shown that uncoloured (transparent) gillnets made of poly butylene succinate (PBS) resin blended with poly butylene adipate-co-terephthalate (PBAT) resin can be naturally degraded in sea water by the action of bacteria and algae, and simultaneously these studies documented the fishing efficiency of the new nets by direct comparison with conventional nylon gillnets (Park et al., 2007a, 2007b; 2010; Park and Bae, 2008; Bae et al., 2012, 2013; An and Bae, 2013; Kim et al., 2013, 2016). In addition, Kim et al. (2016) reported that gillnets made of blended PBS and PBAT resin began to degrade within two years of being submerged in sea water and that by then those gillnets would have become weak enough to stop catching fish. However, gillnets made of blended PBS and PBTA resins have poor tinting strength and can cause problems such as decreased strength and elasticity due to coloration (Kim et al., 2017).

Gillnets made of biodegradable plastic materials, like PBS and PBAT, have been considered as potential mitigation measures to reduce ghost fishing and plastic pollution at sea caused by lost gears (Brown and Macfadyen, 2007; Large et al., 2009; Macfadyen et al., 2009; Gilman, 2015; Gilman et al., 2016). However, for an environmentally safe application of such biodegradable plastics at sea it is important to prove that the intermediate breakdown products, even those that are degradable, do not have any ecotoxicological effects on the ecosystem. Simultaneously, for biodegradable gillnets to be adopted by the industry, they should prove to be at least as efficient as conventional nylon gillnets and not compromise the profitability of the fishing operations. The present study addresses the second concern: fishing efficiency. This study was designed to assess the relative catch efficiency and changes of catch efficiency due to use (aging) of gillnets made of a new biodegradable resin (polybutylene succinate co-adipate-co-terephthalate (PBSAT)) throughout the entire winter fishing season for cod in northern Norway. The catch efficiency, catch rate, and effect of use and wear of the biodegradable PBSAT gillnets were directly compared to those of conventional nylon gillnets.

2. Materials and methods

2.1. Biodegradable PBSAT resin

The new PBSAT resin is an aliphatic-aromatic co-polyester prepared using 1.4-butanediol as an aliphatic glycol (as base materials) and dicarboxylic acids such as succinic acid and adipic acid (which are aliphatic components) and dimethyl terephthalate (which is an aromatic component). The PBSAT resin includes multiple dicarboxylic acid residue components, unlike the polybutylene succinate (PBS) resin that includes one dicarboxylic acid residue or the polybutylene adipate-co-terephthalate (PBAT) resin that includes two dicarboxylic acid residues (Kim et al., 2017, patent EP3214133 A1). The new PBSAT resin has biodegradability properties, exhibits an excellent coloration effect, and does not cause problems such as a decrease in strength due to coloration, which occurs with PBS and PBAT resins. The biodegradable PBSAT resin composition includes a colorant at 0.005–0.015 parts by weight. To improve the properties of monofilament yarn formed from the coloured resin, additives such as anti-oxidants and UV stabilizers may be included at 0.2–0.5 parts by weight with respect to 100 parts by weight of the PBSAT resin (Kim et al., 2017).

2.2. Experimental gillnets

Features of green biodegradable PBSAT gillnets, herein called bio gillnets, were compared with those of conventional blue nylon gillnets, herein called nylon gillnets, during fishing trials. Each gillnet had 210 mm nominal mesh opening, was made of 0.7 mm monofilament, and was 30 meshes in height and 275 meshes long (approx. 55 m stretched length). To provide buoyancy, each gillnet was fixed to a 27.5-meter-long and 26 mm diameter SCANFLYT-800 float line with a buoyancy of 150 g m^{-1}. To provide weight, they were attached to 27.5-meter-long and 16 mm diameter DANLINE lead line with weight of 360 g m^{-1}. Consequently, an assembled gillnet was 27.5 m long and had a hanging ratio of 0.5. We used two sets of gillnets in the experiments. Each set consisted of 16 gillnets, with eight bio gillnets (B) and eight nylon gillnets (N). The gillnets were arranged in such a way that they provided the best information for paired comparison, nylon versus bio net, accounting for spatial and temporal variation in the availability of cod. With individual sets being the basic unit for the subsequently paired analysis (described in Section 2.4), it was important that within each gillnet set averaged over nets that the bio and nylon nets were approximately exposed to the same spatial variability in cod availability. This could in principle be achieved by alternating between the two types of nets after each net sheet as B-N-B-N-B-N-B-N-B-N-B-N-B-N-B-N. However, for easing of registration of fish on board in relation to the type of net in which it was caught, the alternation in net types were only applied after each second net sheet. Therefore, to make conditions as equal between net types a possible set 1 was arranged as N-BB-NN-BB-NN-BB-NN-BB-N and set 2 as B-NN-BB-NN-BB-NN-BB-NN-B. Each set was deployed at least 3.6 km (two nautical miles) from each other to guarantee sampling independence. Actual measurements of the mesh openings (four rows of 20 meshes each) were taken with a Vernier calliper without applying tension to the meshes and showed that the mean mesh openings of nylon gillnets and bio gillnets were 210.6 ± 1.1 mm and 204.3 ± 2.1 mm, respectively.

2.3. Fishing vessel, fishing grounds and catch

The experiment was designed to cover the entire winter season for migrating cod and was conducted on board the coastal gillnet boat "MS Karoline" (10.9 m LOA) between 24 January and 8 March 2017, except on 16 February when the research vessel "Johan Ruud" (30 m LOA) was used to operate the gillnets due to bad weather conditions. The fishing grounds chosen for the tests were located off the coast of Troms (Northern Norway) between 70°21′–70°22′N and 19°39′–19°42′E, which is a common fishing area for coastal vessels from Troms (Fig. 1). The fishing depth varied between 55 and 145 m, and sea temperature varied between 4 and 6 °C.

A total of 88 gillnet deployments were carried out during the experimental period. Scientists on board the "MS Karoline" sorted out the catch by type of gillnet and measured the total lengths (to the nearest cm) of all fish caught in 44 deployments. Data from two deployments were lost. One additional data set was collected on board the research vessel "Johan Rudd" on 16 February (deployment no. 24) using the same sets of experimental gillnets and in the same fishing ground as the "MS Karoline."

2.4. Modelling the size-dependent catch efficiency between gillnet types

We used the statistical analysis software SELNET (Sistiaga et al., 2010; Herrmann et al., 2012, 2016) to analyze the catch data and conduct length-dependent catch comparison and catch ratio analyses. Using the catch information (numbers and sizes of cod in each gillnet set deployment), we wanted to determine whether there was a significant difference in the catch efficiency averaged over deployments between the nylon gillnet and the bio gillnet. We also wanted to determine if a potential difference between the gillnet types could be related to the size of the cod. Specifically, to assess the relative length-dependent catch efficiency effect of changing from nylon gillnet to bio gillnet, we used the method described in Herrmann et al. (2017) and compared the catch data for the two net types. This method models the length-dependent catch comparison rate (CC_l) summed over gillnet set deployments (for the full deployment period):

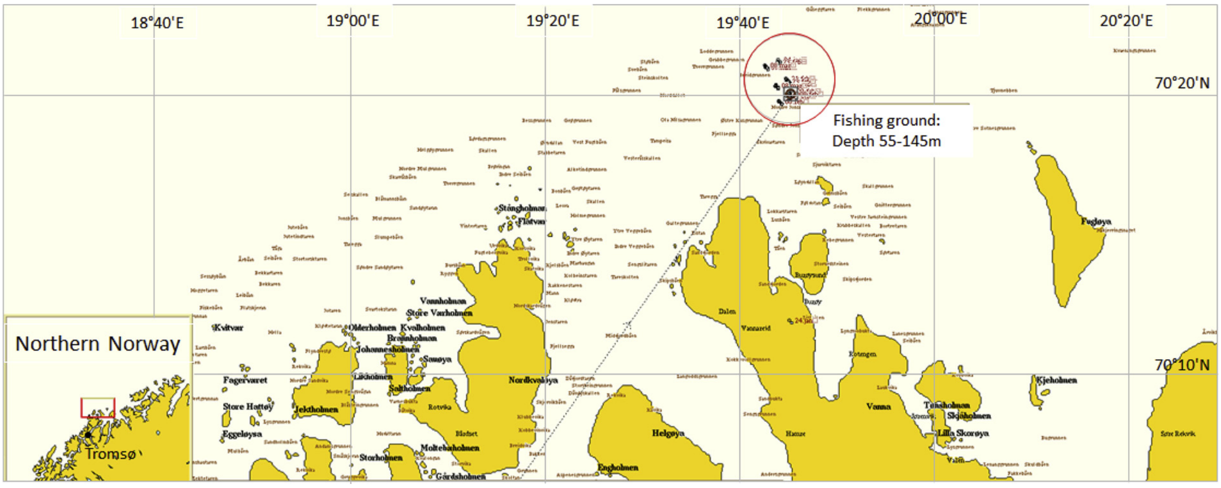

Fig. 1. The fishing grounds in Northern Norway: the red circle shows the position of each of the gillnet settings. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

$$CC_l = \frac{\sum_{j=1}^{m} \{nt_{lj}\}}{\sum_{j=1}^{m} \{nt_{lj} + nc_{lj}\}} \tag{1}$$

where nc_{lj} and nt_{lj} are the numbers of cod caught in each length class l for the nylon gillnet (*control*) and the bio gillnet (*treatment*) in deployment j of a gillnet set (first or second set). m is the number of deployments carried out with one of the two sets. The functional form for the catch comparison rate $CC(l,v)$ (the experimental being expressed by Eq. (1)) was obtained using maximum likelihood estimation by minimizing the following expression:

$$-\sum_{l}\left\{\sum_{j=1}^{m}\{nt_{lj} \times ln(CC(l, v)) + nc_{lj} \times ln(1.0 - CC(l, v))\}\right\} \tag{2}$$

where v represents the parameters describing the catch comparison curve defined by $CC(l,v)$. The outer summation in the equation is the summation over length classes l. When the catch efficiency of the bio gillnet and nylon gillnet is similar, the expected value for the summed catch comparison rate would be 0.5. Therefore, this baseline can be applied to judge whether or not there is a difference in catch efficiency between the two gillnet types. The experimental CC_l was modelled by the function $CC(l,v)$ using the following equation:

$$CC(l, v) = \frac{exp(f(l, v_0, \ldots, v_k))}{1 + exp(f(l, v_0, \ldots, v_k))} \tag{3}$$

where f is a polynomial of order k with coefficients v_0 to v_k. The values of the parameters v describing $CC(l,v)$ were estimated by minimizing Eq. (2), which was equivalent to maximizing the likelihood of the observed catch data. We considered f of up to an order of 4 with parameters v_0, v_1, v_2, v_3, and v_4. Leaving out one or more of the parameters $v_0 \ldots v_4$ led to 31 additional models that were also considered as potential models for the catch comparison $CC(l,v)$. Among these models, estimations of the catch comparison rate were made using multi-model inference to obtain a combined model (Burnham and Anderson, 2002; Herrmann et al., 2017).

The ability of the combined model to describe the experimental data was evaluated based on the p-value. The p-value, which was calculated based on the model deviance and the degrees of freedom, should not be < 0.05 for the combined model to describe the experimental data sufficiently well, except for cases for which the data are subject to over-dispersion (Wileman et al., 1996; Herrmann et al., 2017). Based on the estimated catch comparison function $CC(l,v)$ we obtained the relative catch efficiency (also named catch ratio) $CR(l,v)$ between the two gillnet types using the following relationship:

$$CR(l, v) = \frac{CC(l, v)}{(1 - CC(l, v))} \tag{4}$$

The catch ratio is a value that represents the relationship between catch efficiency of the bio gillnet and that of the nylon gillnet. Thus, if the catch efficiency of both gillnets is equal, $CR(l,v)$ should always be 1.0. $CR(l,v) = 1.5$ would mean that the bio gillnet is catching 50% more cod with length l than the nylon gillnet. In contrast, $CR(l,v) = 0.8$ would mean that the bio gillnet is only catching 80% of the cod with length l that the nylon gillnet is catching.

The confidence limits for the catch comparison curve and catch ratio curve were estimated using a double bootstrapping method (Herrmann et al., 2017). This bootstrapping method accounts for between-set variability (the uncertainty in the estimation resulting from set deployment variation of catch efficiency in the gillnets and in the availability of cod) as well as within-set variability (uncertainty about the size structure of the catch for the individual deployments). However, contrary to the double bootstrapping method (Herrmann et al., 2017), the outer bootstrapping loop in the current study accounting for the between deployment variation was performed paired for the bio gillnet and nylon gillnet, taking full advantage of the experimental design with the bio gillnet and nylon gillnet being deployed simultaneously (see Fig. 1). By multi-model inference in each bootstrap iteration, the method also accounted for the uncertainty due to uncertainty in model selection. We performed 1000 bootstrap repetitions and calculated the Efron 95% (Efron, 1982) confidence limits. To identify sizes of cod with significant differences in catch efficiency, we checked for length classes in which the 95% confidence limits for the catch ratio curve did not contain 1.0.

Finally, a length-integrated average value for the catch ratio was estimated directly from the experimental catch data using the following equation:

$$CR_{average} = \frac{\sum_l \sum_{j=1}^{m} \{nt_{lj}\}}{\sum_l \sum_{j=1}^{m} \{nc_{lj}\}} \tag{5}$$

where the outer summation covers the length classes in the catch during the experimental fishing period.

2.5. Modelling the effect of number of times deployed on the length-integrated catch ratio

To investigate the effect of the number of times the gillnets were the deployed on the length-integrated catch ratio, the Eq. (5) was calculated for individual deployment sets such without the summation over gillnet sets. This led to a dataset consisting of pair values for number of times the gillnets were deployed and corresponding values for $CR_{average}$. Based on this dataset, we tested if the value for $CR_{average}$ changed linearly with number of deployment times (*DNO*) using the following equation:

$$CR_{average}(DNO) = \alpha \times DNO + \beta_l \tag{6}$$

The last part of the analysis using model (6) was conducted using the linear model function (lm) in statistical package R (version 2.15.2; www.r-project.org).

2.6. Tensile strength tests

Tensile strength tests were carried out on samples of the bio and nylon gillnets used in before and after fishing experiments using a H10KT universal tensile testing machine (Tinius Olsen TMC, PA, USA). Samples of gillnets measuring approx. 20 × 20 meshes were cut from the centre of the new and used gillnets. The tests were performed in wet conditions (at least 40 replicates for each case) according to ISO, 1086. Tensile strength, defined as the stress needed to break the sample, is given in kg, and elongation at break, defined as the length of the sample after it had stretched right when it breaks (L) is given relative to the initial mesh size in percentage.

2.7. Assessment of gillnet damage

The tensile strength tests showed that most of the meshes broke in the knots. We therefore assessed the degree of damage in the knots as an indication of the degree of damage of the gillnets. Two additional samples from each type of gillnets, each measuring 20 × 20 meshes, were visually inspected using a 20× magnifying glass. All knots from each gillnet sample were individually assessed; in total, 840 knots for each type of gillnet. The degree of damage was divided into four categories: 1) No damage, if the knot has a smooth and glossy surface; 2) slightly damaged, knots with roughened surface and/or with tightened knots; 3) badly damaged; knots with visible scratches and/or is peel off; 4) broken knot. The results are given as percentages of the total amount of knots from the sample. Some samples from each type of material were observed with a scanning electron microscope (SEM) to assess the changes in the surface.

3. Results

A total of 5103 cod were caught in the 43 gillnets deployments that were included in the analysis, with 2243 and 2850 cod caught by the bio gillnets and nylon gillnets respectively. Daily catches that varied between 73 and 498 cod. The mean effective fishing time (SD) (the time the gillnets remained at the sea bed) was 21 h 14 min (4 h 54 min). The mean (SD) fishing depth was 95.7 m (10.8 m). Table 1 shows catch data including set number, date, fishing time, number of fish caught, and minimum and maximum length of fish caught.

The catch was length-dependent for both types of gillnet, including fish from 70 to 120 cm, but with most of the fish being in the range of 85 to 110 cm (Fig. 2). The catch comparison rate was also highly length dependent, with smallest and biggest fish having a lower value for the bio gillnets, meaning that the nylon gillnet caught significantly more fish in those length classes (Fig. 2). The modelled catch comparison curve follows the main trend of the experimental points, which is supported by the fit statistics presented in Table 2. The estimated catch ratio curve clearly shows a significant difference between the bio gillnets and nylon gillnets for fish of certain length cases. The catch ratio curve of the bio gillnets was significantly lower than that of the nylon gillnets for almost all cod sizes except for those between 82 and 90 cm. In those length classes, the bio gillnets caught significantly more fish than the nylon gillnets (Fig. 2).

The length-integrated average value for the catch ratio of the bio gillnets with respect to the nylon gillnets (including all deployments) was 79.05%, meaning that the bio gillnets caught significantly 20.95% fewer fish than the nylon gillnets, as expressed by the narrow confidence limits (70.75–86.83) (Table 2). Individual analysis of the length-classes of 100, 105, 110, 115 and 120 cm revealed significant differences in the catch ratio for fish larger than 100 cm. In the length-classes of 100 and 110 cm, for instance, the bio gillnets caught 67.98% (CI = 59.88–75.79) and 46.32% (CI = 34.52–59.84) of what the nylon gillnets caught, respectively (Table 2).

The effect of number of times that the gillnets were deployed (parameter α) on the length-integrated catch ratio showed a significant (p-value < 0.03, R^2 value = 0.1948) decrease in relative catch efficiency for the bio gillnet compared to the nylon gillnet Fig. 3), meaning that the accumulated number of deployments did affect the relative catch efficiency between the gillnets.

The average breaking strength of the new nylon gillnets was 22.6 kg (CI = 21.1–24.2 kg), while that of bio gillnets was 18.8 kg (CI = 17.8–19.8 kg), representing a significant difference (t-test, $p = 2.2 \times 10^{-15}$) of 16.9% in favour of the nylon gillnets. The average elongation at break of nylon gillnets was 40.0% (CI = 37.7–42.3%), while that of bio gillnets was 37.3% (CI = 36.4–38.2%), meaning that the bio gillnets was significantly (t-test, $p = 5.0 \times 10^{-7}$) 6.8% less elastic than the nylon gillnets (Table 3).

The difference in the average tensile strength between new and used gillnets was significant for the bio gillnets (t-test, $p = 1.5 \times 10^{-3}$), but not for the nylon gillnets (t-test, $p = 3.5 \times 10^{-7}$). The elongation at break of used bio gillnets (17.2%, CI = 14.6–19.8%) was significantly (t-test, $p = 6.9 \times 10^{-7}$) reduced by 10% with respect to the new bio gillnets (18.8% CI = 17.8–19.8%) (Table 3) Used bio gillnets were significantly (t-test, $p = 1.6 \times 10^{-6}$) 10.4% weaker and (t-test, $p = 1.3 \times 10^{-11}$) 17.3% less elastic than used nylon gillnets.

Both types of gillnets were considerably more damaged after the fishing experiments, showing several more knots with visible surface damage than new gillnets. Bio gillnets had 66% and 19% of slightly and badly damaged knots; while nylon gillnets showed 74.5% and 16% respectively. In addition, the bio gillnets had 8.6% of broken knots while the nylon gillnets only 3.3% (Table 4). SEM images revealed physical damages that apparently were caused by use and wear throughout the fishing season (i.e., abrasion in the hauling machine, friction due to contact with hard surfaces when the gillnets were operated on deck), which turned the smooth and glossy surface of the materials (when new) into very rough surfaces after the fishing trials.

4. Discussion

The model used to analyse the length-dependent catch efficiency of the gillnets provided a good description of the catch data set. Considering that the gillnets were used in 88 deployments over a period of approximately two months, the use of a linear model was useful to specifically investigate the effect of number of gillnet deployments on the length-averaged catch ratio and showed a significant decrease in catch efficiency for the bio gillnet compared to the traditional nylon gillnet. Laboratory material testing and assessment of gillnets damage helped explaining the differences in catch efficiency between the two types of gillnet and the loss of catch efficiency due to use and wear.

On average, the bio gillnets caught 21% fewer fish (in numbers) than the nylon gillnets throughout the fishing season. The results generally showed better catch rates for the nylon gillnets than for the bio gillnets for most of the length classes; however, catch rates for the bio gillnets for cod between 82 and 90 cm were significantly better than those of the nylon gillnets. The differences in mesh size can account for some of the difference in the size distributions of fish caught by each type of gillnets. However, the difference in elasticity and tensile strength could explain the major difference in catch efficiency observed between the two types of gillnets, especially for larger fish. The two type of gillnet used in our experiments had different colours (blue for nylon and green for bio nets) which could potentially affect their

Table 1
Catch data.

Set no.	Setting date	Fishing time (hh:mm)	Fishing depth (m) (min. - max.)	Accumulated number of deployments	Number of cod in bio gillnets	Number of cod in nylon (PA) gillnets	Minimum fish length (cm)	Maximum fish length (cm)
1	24.01.2018	9h 20m	90–125	1	81	80	70	120
2	24.01.2018	10 h 10m	85–125	1	48	57	73	119
1	01.02.2018	6h 00m	55–110	9	94	104	70	120
2	01.02.2018	5h 30m	80–130	9	42	57	70	112
1	02.02.2018	24 h 00m	55–110	10	36	26	70	120
2	02.02.2018	24 h 00m	75–130	10	61	48	70	120
1	03.02.2018	22 h 00m	55–110	11	93	91	70	117
2	03.02.2018	22 h 30m	75–110	11	135	142	70	120
1	04.02.2018	22 h 25m	55–110	12	87	116	70	112
2	04.02.2018	22 h 10m	75–130	12	85	103	70	120
1	06.02.2018	20 h 50m	55–110	14	41	63	70	116
2	06.02.2018	20 h 50m	75–130	14	69	89	70	116
1	07.02.2018	22 h 45m	55–110	15	49	80	70	114
2	07.02.2018	22 h 45m	75–130	15	75	85	73	115
1	08.02.2018	22 h 40m	55–110	16	6	12	70	113
2	08.02.2018	22. 35m	75–130	16	36	44	70	120
1	09.02.2018	23 h 05m	55–110	17	1	4	70	118
2	09.02.2018	23 h 35m	75–130	17	31	37	72	117
1	16.02.2018	24 h 00m	55–130	24	148	207	72	119
1	20.02.2018	19 h 05m	75–130	28	8	7	76	120
2	20.02.2018	19 h 15m	55–110	28	74	115	81	120
1	21.02.2018	26 h 25m	75–130	29	28	24	70	110
2	21.02.2018	27 h 05m	55–110	29	144	155	77	120
1	22.02.2018	21 h 10m	75–130	30	124	150	83	120
2	22.02.2018	21 h 00m	100–145	30	105	119	73	120
1	23.02.2018	21 h 35m	55–110	31	23	32	71	119
2	23.02.2018	19 h 05m	100–145	31	66	77	70	120
1	01.03.2018	21 h 05m	55–110	37	19	43	83	110
2	01.03.2018	21 h 35m	76–130	37	18	27	86	119
1	02.03.2018	21 h 50m	66–120	38	14	25	80	120
2	02.03.2018	22 h 50m	76–130	38	7	32	80	120
1	03.03.2018	23 h 20m	66–120	39	39	83	76	120
2	03.03.2018	24 h 25m	76–132	39	124	132	72	116
1	04.03.2018	23 h 00m	66–122	40	4	7	89	110
2	04.03.2018	23 h 00m	74–130	40	7	13	93	116
1	05.03.2018	23 h 20m	60–120	41	11	18	88	109
2	05.03.2018	23 h 00m	74–130	41	13	21	89	118
1	06.03.2018	23 h 15m	60–120	42	25	36	79	118
2	06.03.2018	23 h 20m	75–130	42	27	50	80	120
1	07.03.2018	23 h 05m	65–120	43	59	84	76	119
2	07.03.2018	23 h 05m	75–130	43	27	31	76	118
1	08.03.2018	23h05m	65–120	44	37	77	77	120
2	08.03.2018	23 h 00m	76–130	44	32	47	77	118

relative fishing efficiency (Balik and Cubuk, 2001). However, compared to what was reported by Balik and Cubuk (2001) gillnetting in shallow (< 6 m) Mediterranean lake waters the depths in our experiments were much larger (55–145 m) and also was carried out during the end of the darkest period in northern Norway (natural phenomenon known as polar night). During this period of the year, the Sun's path goes completely under the horizon, even when it is at its highest (about midday). Therefore, we expect that none of the gillnets would be visible for the cod during the capture process leading us to assume that difference in gillnet colour is not responsible for the difference in catch efficiency observed. Other differences in catch efficiency may be related to different modes of catching fish (snagging—caught by the mouth or teeth or other part of the head region; gilling—caught with the mesh behind the gill cover (no twine in the mouth); wedging—caught by the largest part of the body (no twine in the mouth); entangling—caught by the spine, fins, or other parts of the body as a result of struggling) (Grati et al., 2015), these were not assessed in this experiment.

The lower catch efficiency observed in the bio gillnets respect to the nylon nets, especially for larger fish could be explained by the difference in braking strength and elasticity. Material testing of the new gillnets revealed that the bio gillnets were indeed considerable weaker (16.9%) and less elastic (6.8%) than nylon gillnets. Large cod (> 100 cm) may have managed to break the meshes of bio gillnets and avoid getting caught. Our results are in agreement with those reported by Grimaldo et al. (2018a,2018b) while assessing the catch characteristic of gillnets for cod, saithe *Pollachius virens* and Greenland halibut *Reinhardtius hippoglossoides*, Bae et al. (2013) for flounder *Cleisthenes pinetorum*, and those by Kim et al. (2016) for yellow croaker *Larimichthys polyactis*. The scientists found that the fishing efficiency of nylon gillnets were 1.1–1.4 times higher than those of the biodegradable nets and concluded that the flexibility of a bio gillnets was proved to be positively correlated to the fishing capacity, thus higher flexibility, the higher fishing capacity.

The effect of number of times deployed on the average catch ratio was significant at 95% confidence, meaning that the catch efficiency of the bio gillnets (relative to the nylon gillnets) was negatively correlated with number of gillnet deployments. Use and wear of the gillnets throughout the fishing season made the bio gillnet loss on average 9% of their original tensile strength, although variability was high. Visual inspection of the monofilaments and knots of the bio gillnets showed splintering and weakening, thus they stretched less and broke more easily. Tensile strength measurements of used PBSAT gillnets showed some meshes breaking at 11.7 kg load, whereas the weakest nylon (PA) mesh broke at 16.1 kg load. Although the nylon gillnet monofilaments also showed an 11% reduction of tensile strength, the gillnets were still strong enough to retain cod of large length classes. Curiously, elasticity

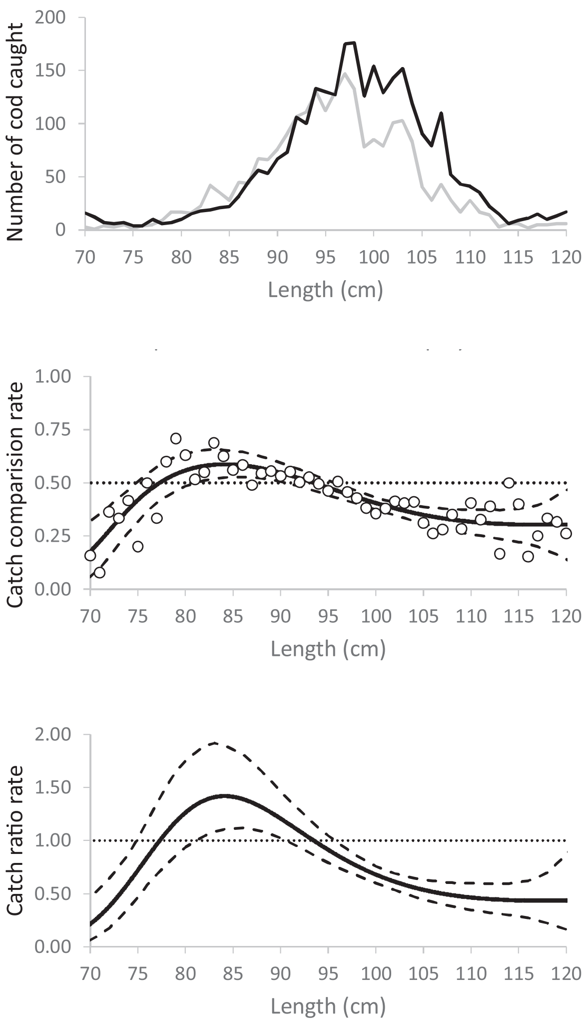

Fig. 2. Top: size distribution of fish caught with each type of gillnet (black curve for nylon (PA) gillnet and grey curve for bio gillnet). Centre: Catch comparison rate based on all deployments, with circle marks representing the experimental rate and the curve representing the modelled catch comparison rate. Dotted line at 0.5 represent the baseline where both types of gillnets fish equally. Stippled curves represent 95% confidence limits for the estimated catch comparison curve. Bottom: Estimated catch ratio curve based on all deployments. Dotted line at 1.0 represent the baseline where both types of gillnets fish equally. Stippled curves represent 95% confidence limits for the estimated catch ratio curve. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 2
Catch rate results and fit statistics obtained for the bio gillnet vs. nylon (PA) gillnet based on all deployments. Values in parentheses represent 95% confidence limits. DOF denotes degrees of freedom.

Length (cm)	Catch ratio (%)
70	21.42 (6.25–46.92)
75	71.96 (46.28–101.92)
80	126.27 (93.59–174.99)
85	141.18 (111.40–185.52)
90	120.71 (102.29–146.30)
95	91.25 (79.14–104.54)
100	67.98 (59.88–75.79)
105	53.61 (44.37–63.04)
110	46.32 (34.52–59.84)
115	43.68 (28.45–607.04)
120	43.51 (16.31–86.60)
Average	79.05 (70.75–86.83)
p-value	0.5447
Deviance	44.28
DOF	46

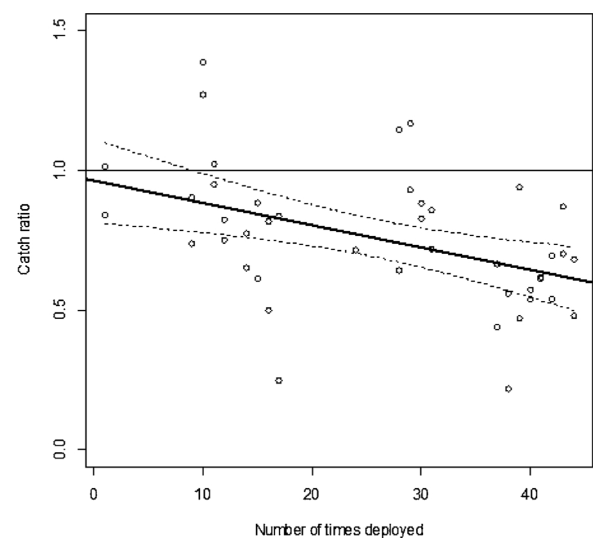

Fig. 3. Fit of linear model testing of the effect of number of times deployed on average catch ratio. At 1.0, both biodegradable gillnets and nylon (PA) gillnets fish equally. Circle marks represent the experimental length-integrated catch ratio (average catch ratio) for individual deployments. The thick line represents the modelled effect of number of times deployed on the average catch ratio. The two stipple curves represent 95% confidence bands for the linear model.

of the used nylon gillnets was unchanged over time, which likely contributed to these nets not reducing their catch efficiency. Furthermore, biological degradation, which was not assessed in this study, may be confounded with the effect of use and wear of the bio gillnets and probably also contributed to the weakening of the material.

The reduction in elasticity that was measured in the bio gillnets by the end of the fishing experiments was most likely due to roughening and splintering of the surface due to use and wear of the bio gillnet monofilaments. However, the loss of elasticity is probably also an indication of changes in the physical properties of the PBSAT material due to biodegradation. Kim et al. (2016) reported that uncoloured biodegradable PBS-PBAT gillnets slowly degraded in cold sea water ($< 5\,^{\circ}C$). The temperature of the sea water where the fishing experiments were carried out in the current study oscillated between 4 and 6 °C, suggesting that biological degradation was perhaps also a cause of tensile strength and elasticity reduction of the PBSAT nets.

If lost, the biodegradable PBSAT and nylon gillnets will no longer be affected by use and wear (i.e., abrasion in the hauling machine, friction due to contact with hard surfaces when gillnets are operated on deck). In the case of bio gillnets, bacteria, algae, and fungi will take over and further degrade the material. Because the biodegradable materials are degraded into carbon dioxide, methane, and water, they do not have any additional impact on marine ecosystems (Kim et al., 2014a, b). In the case of nylon gillnets, weakening of the material nearly stops when the gear is lost, and degradation then occurs very slowly. It is well documented how nylon gillnets are highly resistant to degradation and how they eventually lose their capability for ghost fishing depending on conditions of the seafloor (Carr et al., 1990; Humborstad et al., 2003; Pawson, 2003; Santos et al., 2003; Tschernij and Larsson, 2003; Nakashima and Matsuoka, 2004; Pham et al., 2014). Furthermore, nylon gillnets do not entirely disappear; they just degrade into smaller plastic particles that may continue to disturb various processes in the marine ecosystem (Moore, 2008). According to Kim et al. (2016), biodegradable PBS-PBAT gillnets would stop catching fish after two years of being immersed in seawater. However, this conclusion is based on a

Table 3
Tensile strength (kg), elongation at break (%), with 95% confidence intervals (in brackets), for new and used gillnets.

	Tensile strength (kg)		Elongation at break (%)	
	New	Used	New	Used
Nylon netting	22.6 (21.1–24.2)	20.2 (18.4–21.9)	40.0 (37.7–42.3)	40.6 (37.6–43.6)
Biodegradable netting	18.8 (17.8–19.8)	17.2 (14.6–19.8)	37.3 (36.4–38.2)	32.6 (28.4–36.9)

Table 4
Assessment of gillnet damage after the fishing experiments. Values are given in percentage.

	No damage	Slightly damaged	Badly damaged	Broken
Bio gillnet	6.4	66.0	18.8	8.6
Nylon gillnet	6.0	74.5	16.2	3.3

degradation experiment with monofilament samples immersed in sea water, thus the samples were not affected by use and wear. The question of "how fast a biodegradable gillnet loses its ghost fishing capacity" depends greatly on when it is lost (new or old gillnet) and how much it has been used (use and wear).

The lifespan of the gillnets, in this case defined as the time the gillnets can be used for fishing, highly depends on their durability and the degree of damage that they suffer when fishing. In the Norwegian gillnet fishery for winter cod, a conventional nylon gillnet is mostly used for one season, and one season normally lasts between two and four months depending on the boat, the quota and the availability and catchability of fish. When the fishing season is over, fishermen normally change the sheets of nets for new ones. This is done because the cost of repairing the nets is by far larger than the costs of buying relative unexpensive nylon gillnets. In these circumstances the use of short lifespan bio gillnets could easily be an alternative to conventional nylon gillnets without representing a big investment for the fishermen and as long as the profitability of the fishing operations is not compromised. However, the results from the fishing trials did show that the bio gillnets caught 21% less fish than nylon gillnets. Based on the total length–gutted weight relationship for northeast Atlantic cod $W = 0.013 \times L^{2.86}$ (Walsh and Hiscock, 2005), the weight of the fish caught with the two experimental gillnets sets was approximately 29,291 kg, and according to the price in January-March 2016 ($2.75/kg) the catch had a value of approx. $80,552. The fact that the bio gillnets caught only 79% of what the nylon gillnets did was equivalent to approximately 3321 kg less of cod, which represented a loss of $9134. The "MS Karoline" used eight sets of gillnets in the 2016 fishing season (two of which were the experimental gillnet sets). If all gillnets used in this period had been bio gillnets, the 21% reduction in catch would have represented approximately $36,536 less income for the crew of the "MS Karoline".

The results of this study suggest that the difference in of the catch efficiency between the two types of gillnets may be explained by the initial differences in breaking strength and elasticity, and that this difference got bigger as the gillnets were more used. The changes in the physical properties of the material are not only due to use and wear when fishing but also, to a certain extent, to biological degradation. The new biodegradable PBSAT gillnets show potential to become a feasible alternative to conventional nylon gillnets, especially in short-seasoned fisheries such as those for cod, saithe and Greenland halibut, and they might contribute to reducing the duration of ghost fishing when lost. However, a 21% reduction of the catch can considerably affect the cost effectiveness of the fishing operation and the acceptance of biodegradable gillnets by fishermen. Nonetheless, the material is not yet fully developed, and there are challenges and knowledge gaps (i.e. beads, products of degradation, ecotoxicity) that should be addressed before drawing conclusions about the overall benefits of these new materials in gillnet fisheries. Ultimately, it is up to regulatory institutions to decide whether to introduce biodegradable gillnets in the deep-water gillnet fishery in Norway in order to reduce ghost fishing or to let fishermen continue using the most effective nylon gillnets with well-known consequences if they are lost.

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A COMPARATIVE STUDY OF MECHANICAL PROPERTIES OF BIODEGRADABLE PBSAT AND PA GILLNETS IN NORWEGIAN COASTAL WATERS

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ABSTRACT

This paper presents a comparative study of mechanical properties of biodegradable PBSAT (polybutylene succinate co-adipate-co-terephthalate) and conventional polyamide (PA) gillnets used in Norwegian fisheries. Field tests were performed to simulate abandoned, lost, or otherwise discarded fishing gear. Changes in mechanical properties of PBSAT and PA nets in two Norwegian coastal environments were studied. Samples of biodegradable PBSAT gillnets and PA gillnets were placed inside modified lobster pots at four different locations: two outside the island Hitra in the middle of Norway and two outside Tromsø in the north of Norway. For each pot, seawater temperature was logged each hour, and net samples were retrieved for analyses at 3 to 9 months intervals.

Tensile strength testing was performed to determine and compare mechanical properties of biodegradable and PA monofilaments and gillnets. Comparative analyses were conducted, aimed at investigating the different behaviors of biodegradable material and conventional PA material, and the possible influence of seawater temperature on the degradation process of biodegradable PBSAT gillnets. Reduced tensile strength and elongation at break, and a slight increase in stiffness was observed for both PA and PBSAT monofilaments after the field trial at Hitra, indicating degradation of both polymer materials. After 25 months immersion in seawater, the PBSAT gillnets exhibited a significant reduction of tensile strength due to seawater exposure (35%), and the tensile strength of PBSAT gillnets was then 26% lower than the average strength of the PA net samples.

NOMENCLATURE

ALDFG	Abandoned, lost, or otherwise discarded fishing gear
PA	Polyamide
PBS	Polybutylene succinate
PBAT	Polybutylene adipate-co-terephthalate
PBSAT	Polybutylene succinate co-adipate-co-terephthalate
t-test	Student's t-test
SEM	Scanning electron microscope

INTRODUCTION

When fishing nets are lost, abandoned or discarded at sea, they may continue to catch fish and other animals for a long period of time. This phenomenon is known as "ghost fishing" [1]. Lost fishing gears also cause a variety of harmful impacts to coral reefs and benthic fauna, and marine pollution may introduce synthetic (non-biodegradable) plastic materials into the marine food web. There are also economic consequences due to marine species mortalities, replacement of lost gear, and diverse costs related to retrieving operations. Recognition of all these problems is nowadays demonstrated through the large number of international organizations and agreements that currently focus on reducing the effect of abandoned, lost, or otherwise discarded fishing gear (ALDFG). In addition to numerous national initiatives that have been implemented around the world to mitigate the ALDFG impact on the marine ecosystem [2]. To date, Norway is one of the few countries in the world that has a program for systematic annual retrieval of ALDFG from the most intensively fished areas [3–5]. Based on information provided by fishermen, the Norwegian Directorate of Fisheries carry out annual retrieval operations for reported lost fishing gear and deliver it on land to recycling [6, 2]. However, these operations are highly challenging because of the depth (500–1000 m) and strong currents in the areas, as well as uncertainties associated with the position of lost gear.

The development of fishing gears made of biodegradable plastic materials is considered as a potential solution to reduce "ghost fishing" and plastic pollution at sea caused by ALDFG [7–10]. In recent years, many studies have documented the mechanical properties, biodegradability, and fishing efficiency of colorless gillnets made of polybutylene succinate (PBS) resin blended with polybutylene adipate-co-terephthalate (PBAT) resin and polybutylene succinate co-adipate-co-terephthalate (PBSAT) resin [11–21]. In Norway, gillnets are among the most important commercial fishing methods for the coastal fleet, however colorless gillnets are not currently used. Norwegian fishermen prefer colored gillnets because they provide a better contrast with the sorting boards and make removal of fish from nets easier, and also because many fishermen believe that some colors have better catch efficiencies than others depending on the contrast with the seabed and surroundings.

In 2016 and 2017, a set of fishing trials were carried out to compare the relative fishing efficiency of colored gillnets made of a new biodegradable PBSAT resin (Patent EP3214133 A1) with conventional PA gillnets. This new biodegradable resin was designed for better coloring properties which does not give rise to problems such as reduced strength due to coloration [22]. The fishing trials covered two consecutive fishing seasons for cod (*Gadus morhua*) and saithe (*Pollachius virens*) in northern Norway. The corresponding catch rates were assessed in a previous study [23].

The present study focuses on the mechanical properties of ALDFG due to degradation of gillnet materials. Field tests were performed to simulate abandoned, lost, or otherwise discarded fishing gear. Changes in mechanical properties of PBSAT and PA nets in two Norwegian coastal environments were studied.

MATERIALS AND METHODS

Materials

Polybutylene succinate-co-adipate-co-terephthalate (PBSAT) resin is an aliphatic-aromatic co-polyester. According to the patent application, it is biodegradable, exhibits an excellent coloration effect and does not cause problems such as a decrease in strength due to coloration, as observed in PBS and PBAT resins [22]. Anti-oxidants and UV stabilizers are applied in production of monofilaments for gillnets and fishing lines.

Test samples

Gillnets and monofilaments of both PBSAT and PA (Polyamide) were applied in the experiments (Figure 1 and 2). Conventional nets and fishing lines of PA were included as reference (Vónin Refa gillnets and Sølvkroken sea fishing line). Monofilaments had a diameter of 0.7 mm, and gillnets had been produced by similar monofilaments and double knots. Mesh size was 200 mm for PBSAT nets, and 215 or 330 mm for PA nets.

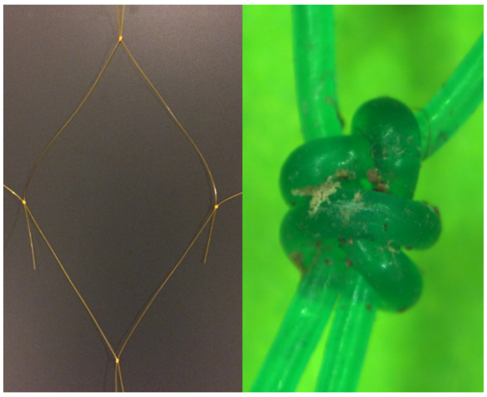

Figure 1. Gillnet made of double knotted monofilaments. Left: PA (new); Right: PBSAT (used).

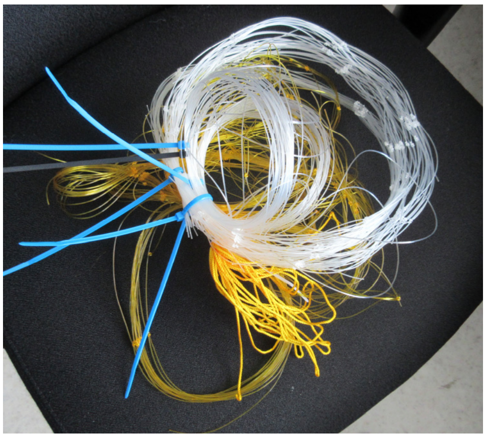

Figure 2. Set of test samples: Gillnets of PA (yellow) and PBSAT (white), and monofilaments of PA and PBSAT (both white).

Field test in coastal environment

Field tests were performed to assess changes in mechanical properties of biodegradable ALDFG PBSAT gillnets in Norwegian coastal environments. Test samples were attached inside modified lobster pots at four different locations: two outside the island Hitra in the middle of Norway (Figure 3) and two outside Tromsø in the north of Norway.

The PA gillnets deployed had a nominal mesh size of 330 mm at Hitra and 215 mm in Tromsø. In addition to gillnets, monofilament samples of PBSAT and PA were deployed at the two sites outside Hitra. The monofilaments may provide a more direct measure of material degradation, excluding the effect of knots [21]. All the conducted degradation tests are listed in Table 1 by the locations, deployed samples and durations.

The samples were deployed on May 30th, 2016 at the two sites outside Hitra and one month later at the two sites outside Tromsø. The pots containing the samples were placed at water depths of 35–50 m. For each pot, seawater temperature was logged each hour, and samples were retrieved for analyses at 3 to 9 months intervals.

Figure 3. Modified lobster pot with 8 sets of test samples (at Hitra).

Table 1. List of the conducted degradation tests in seawater.

	Location	Samples	Duration
Location 1	Hitra	gillnets and monofilaments	25 months
Location 2	Hitra	gillnets and monofilaments	25 months
Location 3	Tromsø	gillnets	15 months
Location 4	Tromsø	gillnets	6 months

Tensile testing of nets and monofilaments

Tensile testing was performed to determine and compare mechanical properties of PBSAT and PA gillnets and monofilaments before and after the field test. Both tensile strength, elongation at break and stiffness found from a force-elongation curve can be applied to assess degradation of mechanical properties. All measurements were performed in compliance with ISO 1806:2002 (gillnets) and ISO 1805:1973 (monofilaments), using a universal testing machine (H10KT, Tinius Olsen TMC, PA, USA) equipped with a load cell of 5000 N capacity.

Tensile properties of the gillnet samples were found by mesh strength tests, while monofilaments were tested using bollard grips. Initial mesh length of gillnets was found as the mesh opening at pretension. For monofilaments, the initial length of each sample was defined as the monofilament length between the clamps at pretension, which was approximately 450 mm. Pretension was applied as 2 N for gillnets and 1 N for monofilaments.

For gillnets, testing speed was adjusted according to the mesh size: 200 mm/min for gillnets with mesh size 200-215 mm, and 300 mm/min for mesh size of 330 mm. Testing speed for monofilaments was 400 mm/min between grips.

Tensile properties were measured and found based on at least 20 replicates for nets and at least 10 replicates for monofilaments.

Tensile testing was performed in wet condition, with samples that had been wetted for 48-72 hours in room tempered tap water. New samples were also tested in dry condition to consider the effect of water on tensile properties. In dry condition, the specimens were acclimated to the laboratory atmosphere for at least 48 hours.

Figure 4 shows an example of force-elongation curves obtained from tensile testing of PBSAT monofilaments after 25 months immersion in seawater (10 replicates). For each replicate, the tensile strength was determined as the peak of the force-elongation curve, and the corresponding elongation was taken as the elongation at break. For a set of samples, the tensile strength was determined as the average of all replicates, and polynomial fitting was performed to determine the average force-elongation curve.

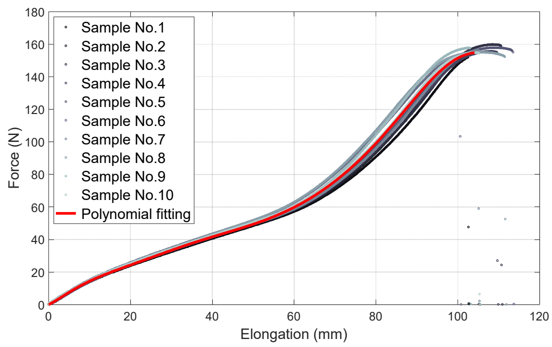

Figure 4. Polynomial fitting of the force-elongation curves obtained from tensile strength tests of the PBSAT monofilaments after 25 months immersion in seawater.

RESULTS AND DISCUSSION

Results from the field degradation tests are given as changes in strength and elongation of gillnet and monofilament samples. In addition, stiffness properties were assessed for a selected location (Location 1). Possible effect of temperature on degradation was assessed, and finally possible degradation mechanisms and observations were presented and discussed.

Changes in strength and elongation at break after field trial

After the field trial, most samples from Location 1 and 2 (Hitra) showed reduced strength and elongation at break, indicating degradation of the material (Table 2 and 3). The strength loss was up to 43% for the PBSAT net at Location 2. A contributing source of this strength loss is possibly mechanical damage due to crabs, which is discussed later. Reduction in elongation corresponds with reduction in strength. At Location 3 and 4, no significant changes in average strength have been found for PA and PBSAT gillnets after 6-15 months in sea. For the PA netting at Location 4, an increased average strength value was found after the field test. This may be explained by naturally varying properties of PA gillnets.

The results show that after 25 months of exposure to coastal seawater, PBSAT gillnets showed larger reduction in average strength and elongation than comparable PA nets. At location 3 and 4, no significant reduction in strength or elongation was found. Thus, there were no signs of degradation of the samples at Location 3 and 4.

Monofilaments showed reduced strength and elongation at break at approximately the same level as the gillnets, except the PBSAT monofilaments at Location 1, which had significantly less reduction in properties.

Tensile strength and elongation at break as a function of time is given for test samples at Location 1 in Figure 5-8. Data is given for "new" material, i.e. new specimens not subjected to degradation test in seawater, and material samples retrieved 3, 9, 16 and 25 months after being immersed in seawater. PA nets and monofilaments experienced reduced properties after 3 months in sea, after that, no significant changes were found throughout the total test duration of 25 months. After having been immersed in seawater for 3 months, the tensile strength of PA nets and monofilaments was reduced by 16% and 19% respectively.

When new (and wet), the measured tensile strength of PBSAT gillnets was 11% lower than for PA nets. After being immersed in seawater from 3 to 16 months, no significant difference in strength was found using a 95% confidence interval (Kolmogorov–Smirnov test, $P = 0.146, > 0.05$; t-test, $P = 0.065, > 0.05$). However, after 25 months immersion in seawater, the PBSAT gillnets exhibited a significant reduction of tensile strength due to seawater exposure (35%), and the tensile strength of PBSAT gillnets was then 26% lower than the average strength of the PA net samples.

When new (and wet), the measured tensile strength of PBSAT monofilaments was 23% lower than for PA monofilaments. After 3 months of submergence and throughout the test, the tensile strength of PBSAT and PA monofilaments were at the same level (except at Location 2 after 25 months). No significant reduction was found from the 9^{th} to 25^{th} month in the 95% confidence interval (Kolmogorov–Smirnov test, $P = 0.241, > 0.05$; t-test, $P = 0.174, > 0.05$) for the PA monofilaments. The PBSAT monofilaments exhibited a slight strength reduction over time: reduced by 8% after having been immersed in seawater for 25 months.

Figure 7 compares the elongation at break of PA and PBSAT gillnets. When new (and wet), the elongation of PBSAT gillnets was 12% higher than PA. After 16 months in seawater, the elongation of PBSAT gillnets was still 14% higher than PA. The elongation of PBSAT gillnets showed a significant reduction (27%) after 25 months in seawater, and elongation at break was then at the same level as for PA gillnets.

Figure 8 compares the elongation at break of PA and PBSAT monofilaments. When new (and wet), the elongation of PBSAT monofilaments was 22% lower than PA, while no significant difference was found when they were immersed in seawater between 3 and 25 months. After having been immersed in seawater for 3 months, the elongation of PA monofilaments was reduced by 24%. No significant reduction was found from the 9^{th} to 25^{th} month in the 95% confidence interval (Kolmogorov–Smirnov test, $P = 0.678, > 0.05$; t-test, $P = 0.566, > 0.05$). The elongation of PBSAT monofilaments was on average reduced by 7% after having been immersed in seawater for 25 months.

Figures 9-12 compare changes in strength and elongation for PBSAT gillnets and monofilaments at Location 1 and 2. Results are given relative to new material in percentage. The degradation tests at the two different locations gave similar results during the first 16 months. During the last time period (16-25 months), some of the PBSAT samples at Location 2 showed larger reduction in tensile properties: Several of the individual strength tests of the gillnet and monofilament samples yielded relatively low strength and elongation. This was probably due to observed mechanical damage to the nets and monofilaments caused by crabs.

Table 2. Changes in measured average strength and elongation of gillnets after field test. Mean value / standard deviation [%].

	PA		PBSAT	
	Strength	**Elongation**	**Strength**	**Elongation**
Location 1	-22 / 8	-17 / 8	-35 / 7	-27 / 8
Location 2	-21 / 10	-15 / 9	-43 / 15	-37 / 17
Location 3	2 / 7	-9 / 6	-3 / 3	-6 / 3
Location 4	11 / 5	-2 / 4	0 / 4	-3 / 3

Table 3. Changes in measured average strength and elongation of monofilaments after field test. Mean value / standard deviation [%].

	PA		PBSAT	
	Strength	**Elongation**	**Strength**	**Elongation**
Location 1	-22 / 3	-26 / 8	-8 / 1	-7 / 2
Location 2	-35 / 12	-33 / 12	-34 / 15	-14 / 7

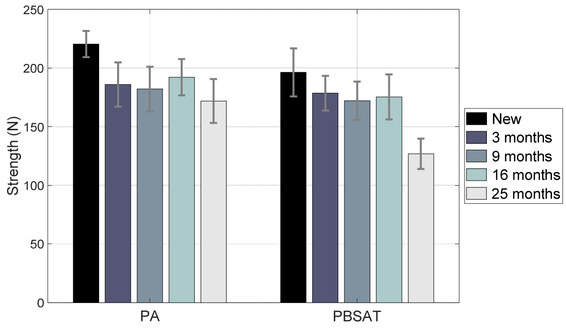

Figure 5. Tensile strength of PA and PBSAT gillnets at Location 1 as a function of time. Given as average value with standard deviation.

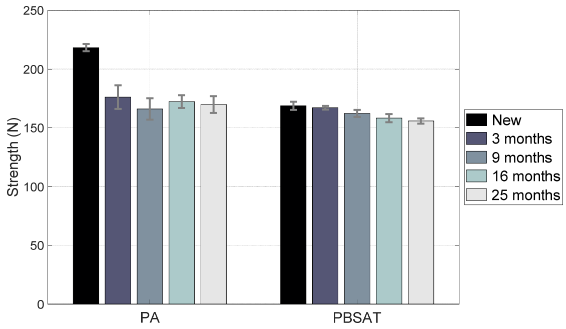

Figure 6. Tensile strength of PA and PBSAT monofilaments at Location 1 as a function of time. Given as average value with standard deviation.

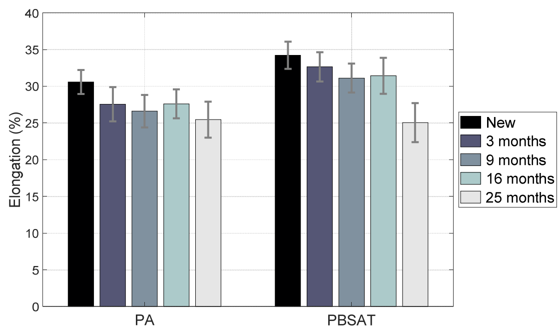

Figure 7. Elongation at break of PA and PBSAT gillnets at Location 1. Given as average value with standard deviation.

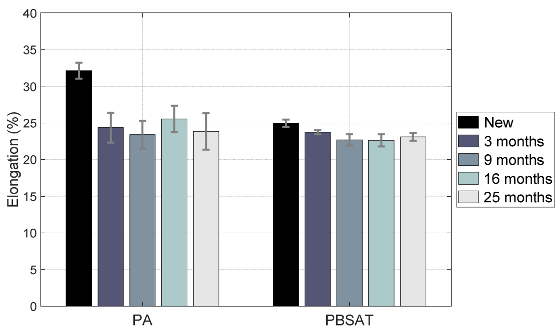

Figure 8. Elongation at break of PA and PBSAT monofilaments at Location 1. Given as average value with standard deviation.

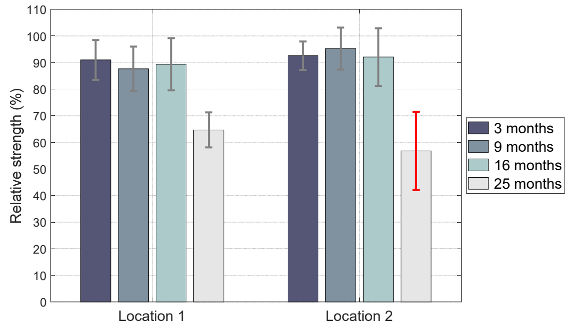

Figure 9. Relative tensile strength of PBSAT gillnets at Location 1 and 2. Given as average value with standard deviation.

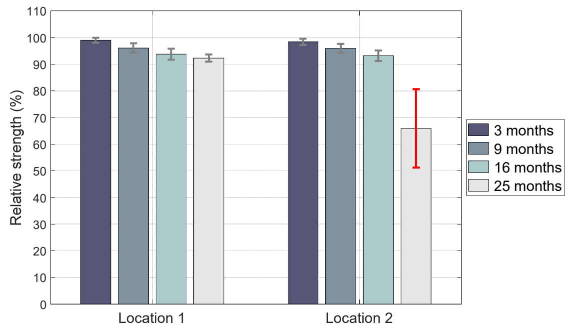

Figure 10. Relative tensile strength of PBSAT monofilaments at Location 1 and 2. Given as average value with standard deviation.

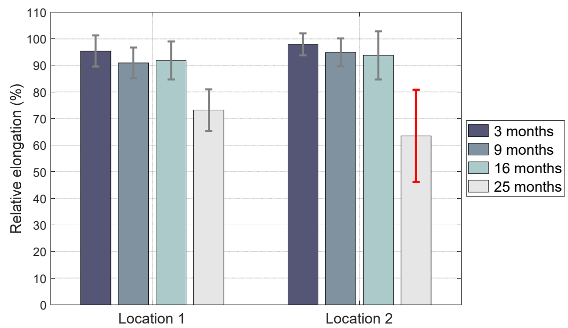

Figure 11. Relative elongation of PBSAT gillnets at Location 1 and 2. Given as average value with standard deviation.

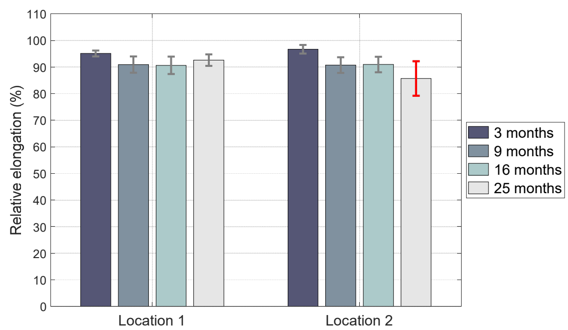

Figure 12. Relative elongation of PBSAT monofilaments at Location 1 and 2. Given as average value with standard deviation.

Tensile properties

Changed stiffness properties for the monofilaments may indicate degradation of the polymer material. Increased stiffness can be identified as an increased slope in a force-elongation curve from tensile testing of the materials and vice versa. Fitted force-elongation curves from tensile testing are shown for samples from Location 1 after 25 months of submergence in Figure 13-16. Elongation is given in percentage relative to the initial length of the samples. For comparison, curves are also given for new material, both in dry and wet conditions.

The gillnets have different tensile properties in dry and wet condition. This is due to different behaviors of the knots; the knots will tighten during the first part of a mesh strength test and will behave differently depending on their condition. PA will absorb water, which has a significant effect on tensile properties as stiffness at low elongation (Figure 15), also affecting the behavior of the knot. Wetting of new PA monofilaments reduced the average tensile strength by 19%. Properties of PBSAT monofilaments are not affected by wetting (Figure 16), however the knots slipped in dry state, resulting in reduced stiffness and strength for the gillnets (Figure 14). It was observed that the knots in the PBSAT nets were not as tight as in the PA nets.

Wetting of new PBSAT gillnets led to an increase in average tensile strength by 42%, while the strength was reduced by 6% for the PA gillnets. After having been immersed in seawater for 25 months, both the PA and PBSAT gillnets exhibited a significant reduction in tensile strength while no noticeable difference in stiffness was found.

A slight increase in stiffness, reduced tensile strength and elongation at break was observed for both PA and PBSAT monofilaments after the field trial, indicating degradation of both polymer materials.

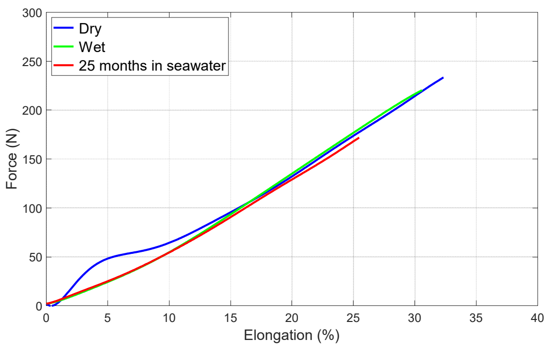

Figure 13. Force-elongation curves of the PA gillnets before (Dry and Wet) and after field trial at Location 1. Elongation is given relative to initial length in percentage.

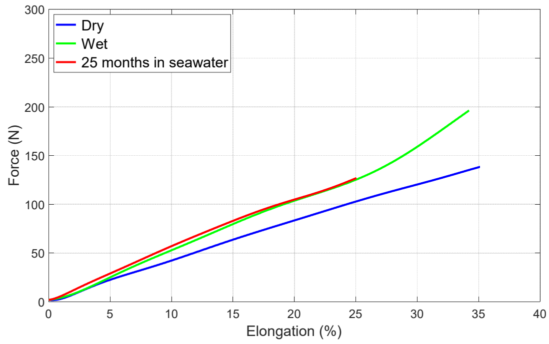

Figure 14. Force-elongation curves of the PBSAT gillnets before (Dry and Wet) and after field trial at Location 1. Elongation is given relative to initial length in percentage.

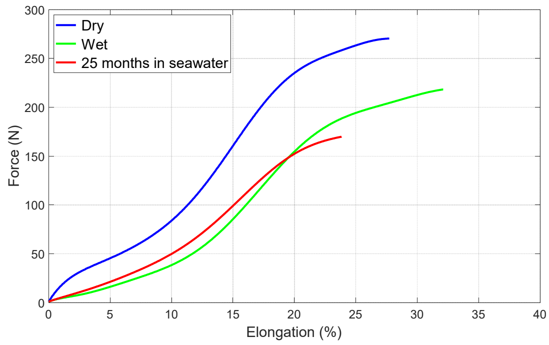

Figure 15. Force-elongation curves of PA monofilaments before (Dry and Wet) and after field trial at Location 1. Elongation is given relative to initial length in percentage.

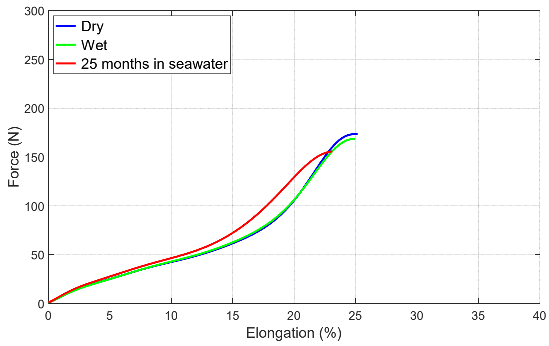

Figure 16. Force-elongation curves of PBSAT monofilaments before (Dry and Wet) and after field trial at Location 1. Elongation is given relative to initial length in percentage.

Influence of water temperature on the degradation process

Figure 17 shows recorded water temperatures at two different locations, where the water temperature at Location 2 was on average 2 to 4 °C higher than at Location 3. Location 1 had similar temperature as Location 2, and Location 4 had similar temperature as Location 3. Temperature varied between 6-15 °C at Location 1 and 3-9 °C at Location 3. Figure 18 and 19 show the change in strength and elongation of PBSAT gillnets at the two locations. During the field trial, the strength of PBSAT gillnets at Location 2 was on average 5% lower than at Location 3 (which showed no significant change in strength of PBSAT gillnets). Gillnets at both locations showed similar reduced elongation at break, increasing in time up to 6 % after 15 months immersion.

It was shown in a previous study [21] that biodegradable gillnets made of a blending of PBS-PBAT resin had a higher degradation rate in higher water temperatures in summer, and slowly degraded in cold seawater (< 5 °C). In our study, we do not see such correlation. However, no degradation of the gillnets was observed at Location 3, while both PA and PBSAT gillnets degraded at Location 1. This imply that degradation of PBSAT may be a temperature dependent process. It is well-known that degradation of polymers will increase with increased temperature.

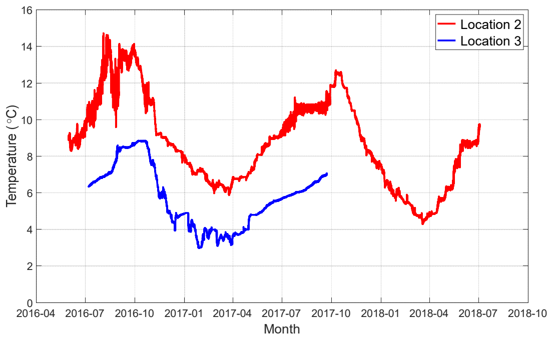

Figure 17. Water temperature during the degradation test at Location 2 (middle Norway) and Location 3 (northern Norway).

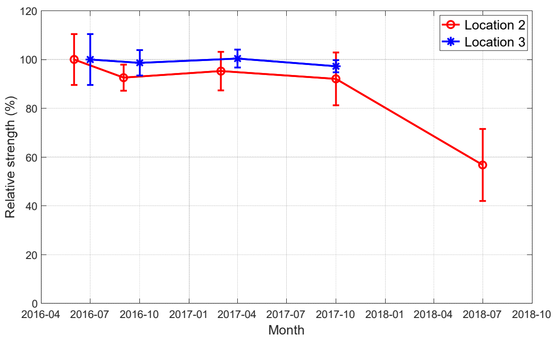

Figure 18. Relative tensile strength of the PBSAT gillnets after the degradation test at Location 2 and Location 3. Given by the average value with standard deviation.

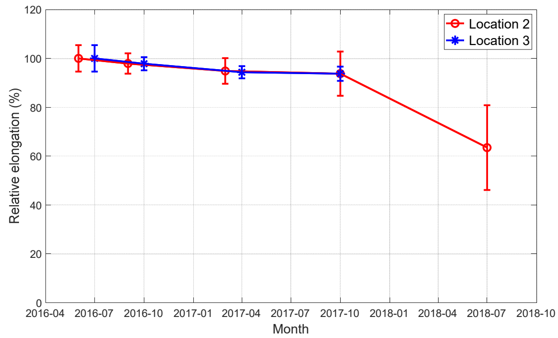

Figure 19. Relative elongation of the PBSAT gillnets after the degradation test at Location 2 and Location 3. Given by the average value with standard deviation.

Possible degradation mechanisms and observations

The degradation of PA and PBSAT fibers used in this experiment was the result of chemical and mechanical changes that occurred during the 25 months' experimental period. The degradation led to loss of strength and elongation, and distortion and discoloration of fibers was observed. Different mechanisms of degradation might have acted simultaneously on the PA and PBSAT fibers, and some of them probably had a stronger effect than others. Although this experiment was unable to identify and quantify the effect of specific mechanisms of degradation of the samples that were studied, possible degradation mechanisms are discussed below.

As shown by the results, both PA and PBSAT gillnets exhibited a reduction in tensile strength and elongation at break after having been immersed in seawater. The PA gillnets exhibited a significant strength reduction in the first 3 months while there was no significant reduction from the 9th to 25th month. The PBSAT gillnets showed a slight strength reduction during the first 16 months, while a large reduction was found after having been immersed in seawater for 25 months. This finding is consistent with a previous study [21], which showed that the biodegradable gillnets (made of a blending of PBS-PBAT resin) began to degrade after about 2 years when immersed in seawater.

Possible degradation mechanisms during the field experiments are microbiological degradation, hydrolysis, oxidation, and mechanical damage from crabs. Polymers are also known to also be vulnerable to UV-exposure, however at more than 25 meters depth we consider the UV-radiation to be negligible. Abandoned, lost, or otherwise discarded fishing gear will in addition experience wear and abrasion damages. The damages will be similar as found in used nets. During fishing trials [23], damages due to use and wear was documented (i.e. abrasion in the hauling machine, friction due to contact with hard surfaces when the gillnets were operated on deck). Figure 20 shows a representative example of the gillnet damages observed with a scanning electron microscope (SEM). It was found that the gillnet damages had contributed to loss of tensile strength.

For microbial degradation to take place, it is crucial that the right types of microbes are present at the location and are established on the samples. The samples from the Locations outside Tromsø did not have any visible bio-fouling or bio-film, opposed to the samples from Hitra that contained visible biologic material. Especially the last samples after 25 months submergence contained significant biofouling, including algae, spirorbis worms (Figure 21) and starfish. Biofouling was also observed inside the knots of the gillnets, which may affect the strength of the knots during mesh strength tests [24].

At Location 2, several crabs were found entangled in the specimens when retrieving samples after 25 months. It was observed that the PBSAT samples were entangled, and the filaments were bent and crushed (Figure 21 and 22). In comparison, the PA filaments seemed undisturbed. This indicates that the degraded PBSAT was vulnerable to mechanical damage due to compressive loads and bending. This was also experienced during mesh strength tests: The size of the grips had to be increased in order to reduce compressive loads on the fibres and fracture in the grips. The fractures after tensile testing were frayed (Figure 23), the degraded PBSAT appears to be fragmented into axial fibers.

During a mesh strength test, gillnets usually break in the knots, where the material is subjected to compressive, bending and shear loading. In the present study, it was found that PBSAT gillnets had a higher reduction in strength and elongation than the monofilaments (Figure 5 and 6), which may be due to compressive loads in the knots during stretching and biofouling particles inside the knots.

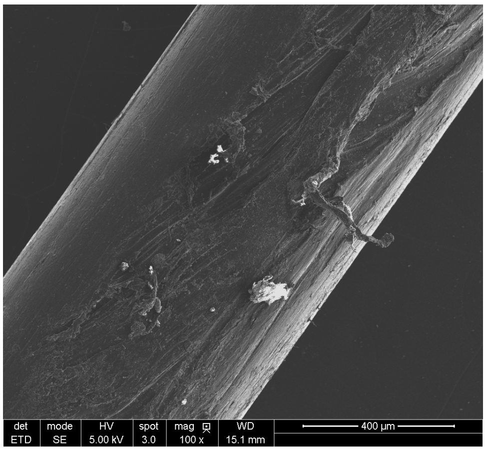

Figure 20. Scanning electron microscope (SEM) image showing a representative example abrasion damages caused by use and wear throughout fishing trials [23].

Figure 21. Net samples retrieved from Location 2 after 25 months of submergence. PBSAT samples were entangled (left).

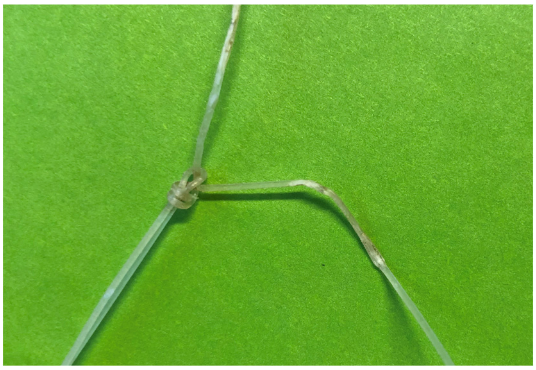

Figure 22. Bent and crushed PBSAT fiber from Location 2 after 25 months of submergence.

Figure 23. Frayed fracture of PBSAT fiber from Location 2 after 25 months of submergence.

CONCLUSION

After the field trial, most samples from Location 1 and 2 showed reduced strength and elongation at break, indicating degradation of the material. The strength loss was up to 43 % for the PBSAT gillnets at location 2. There were no signs of degradation of the samples at Location 3 and 4.

PA nets and monofilaments experience reduced properties after 3 months in sea, after that, no significant changes are found throughout the total test duration of 25 months. The PBSAT gillnets showed a slight strength reduction during the first 16 months, while a large reduction was found after having been immersed in seawater for 25 months. After 25 months immersion in seawater, the PBSAT gillnets exhibited a significant reduction of tensile strength due to seawater exposure (35%), and the tensile strength of PBSAT gillnets was then 26% lower than the average strength of the PA net samples. Reduction in elongation corresponds with reduction in strength. In the present study, a possible correlation between the degradation of PBSAT gillnets and water temperature was not significant.

Reduced tensile strength and elongation at break, and a slight increase in stiffness was observed for both PA and PBSAT monofilaments after the field trial, indicating degradation of both polymer materials. Possible degradation mechanisms during the field experiments are microbiological degradation, hydrolysis, oxidation, and mechanical damage from crabs.

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Test report

Aging test of monofilament fishing line

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Eduardo Grimaldo

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TEST OBJECT
Monofilament fishing line (nylon and PBSAT)

TEST OBJECT RECEIVED
Week 39

TEST PROGRAM
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Oct.-Dec.

ABSTRACT
Two types of monofilament fishing line were received. One line was made of nylon (polyamide-6) and the other was PBSAT (polybutylene succinate co-adipate-co-terephthalate). Both materials were aged for 1000 hours in a weathering test, simulating outdoor condition. The degradation of the materials was characterised by FTIR spectroscopy, mechanical testing, light microscopy, and scanning electron microscopy. The analyses reveal that both materials show signs of degradation already after 200 hours of exposure. PBSAT degrades faster than nylon and thus shows a stronger reduction in mechanical strength and material integrity. In addition, PBSAT is changing its chemical structure more significantly during degradation compared to nylon, as revealed by FTIR.

The test results relate only to the items tested

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REPORT NO.
n.a.

CLASSIFICATION

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1 Experiment

Two types of monofilament fishing line were received. One line was made of nylon (polyamide-6) and the other was PBSAT (polybutylene succinate co-adipate-co-terephthalate). From both lines, 36 pieces of approx. 35 cm length were cut for the weathering test, yielding 72 samples in total. One set of 6 pieces from each material was kept aside as reference. The other pieces were fixed on to the sample holders of the weather-o-meter in groups of 6. The weathering was done according to ISO 4892-2 (outdoor) using an Atlas Xenotest 440 weather-o-meter. The total exposure time was 1000 hours and the parameters for the weathering cycle are summarized in Table 1.

Table 1: Weathering cycle according to ISO 4892-2 (2013).

Exposure period	**Irradiance**		**Black-standard temperature [°C]**	**Chamber temperature [°C]**	**Relative humidity [%]**
	Broadband UV300-400 [W/m^2]	**Narrowband [W/m^2 nm)]**			
102 min dry	60 ± 2	0,51 ± 0,02 (@340 nm)	65 ± 3	38 ± 3	50 ± 10
18 min water spray	60 ± 2	0,51 ± 0,02 (@340 nm)	-	38 ± 3	-

During the weathering test one set of samples (6 pieces) from each material was removed after 196h, 431h, 626h, 817h, and finally after 1000h for further analysis.
Tensile testing of the fishing lines samples was performed using a Zwick/Roell Z250 universal test machine and three parallels from each set of samples were analysed.
FTIR spectra were recorded using an Agilent Cary 670 equipped with an ATR crystal.

2 Results and discussion

2.1 Tensile test

Figure 1 shows the stress-strain curves of both nylon and PBSAT samples when new (non-aged) and after 1000 hours of exposure.

(a) (b)

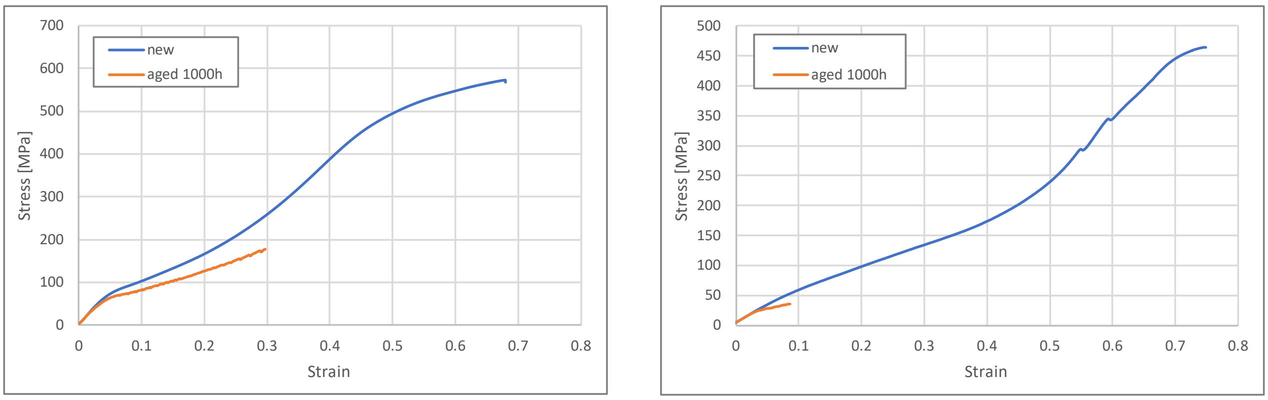
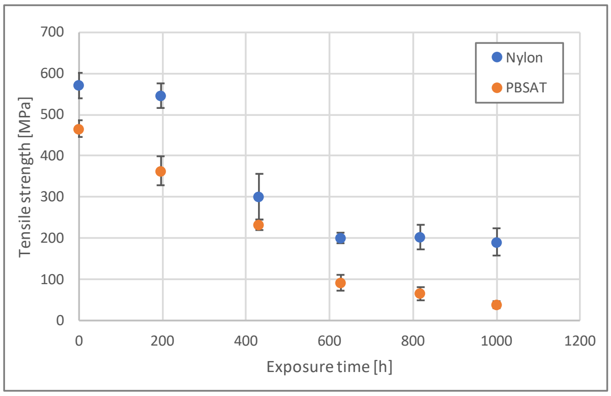


Figure 1: Stress-strain curve of nylon (a) and PBSAT (b). The strain is the engineering strain ($\Delta L/L_0$ where L_0 is the initial grip-to-grip distance). The stress is the engineering stress (force divided by initial cross-sectional area).

The strain at break is reduced after aging, i.e. the material loses ductility, which is an expected sign of degradation. This aging effect is strongest for the PBSAT fishing line. The change in tensile strength and strain at break are shown in Figure 2a and b, respectively. Before aging, the tensile strength of nylon is about 23% higher than the one of PBSAT. Already after 200 hours exposure the tensile strength of both materials starts to decline, and the deterioration is strongest for PBSAT. However, after 600 hours exposure the values for nylon seem to level off whereas those of PBSAT continue to decline.

(a)



(b)

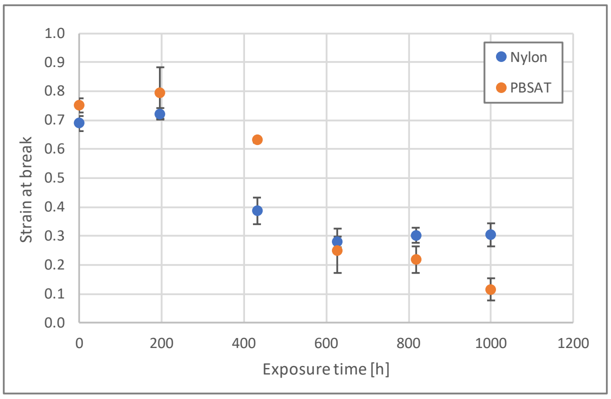


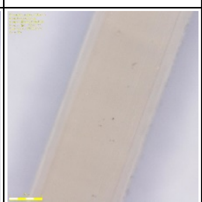
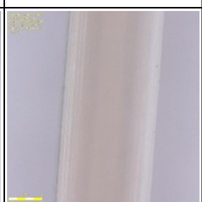
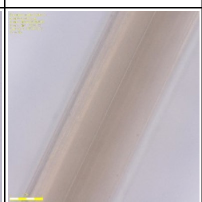
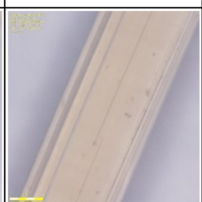
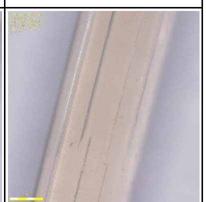
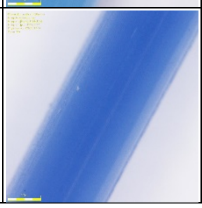
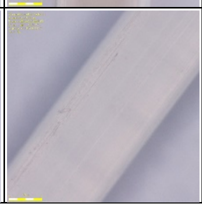
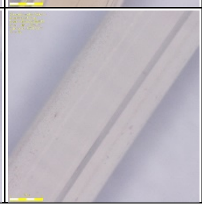
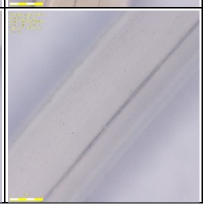
Figure 2: Change of tensile strength (a) and strain at break (b) during aging.

Before aging, the elongation at break is about 9% higher for PBSAT compared to nylon, indicating that this material has a slightly higher ability for plastic deformation. For both materials the elongation at break increases slightly during the first 200 hours of exposure and then declines significantly. Like the tensile strength, the elongation at break for nylon seems to level off after about 600 hours exposure whereas PBSAT continues to decline.

2.2 Light microscopy

Table 2 shows light microscopy images of the two materials at different times during the aging test. It can be seen easily, that both materials lose their colour quickly. Already after around 200 hours of exposure the blue colour is faded away and the materials become colourless to slightly yellowish. Also, the formation of cracks at the surface can be observed, which starts at around 600 hours of exposure and is more prominent for the PBSAT sample.

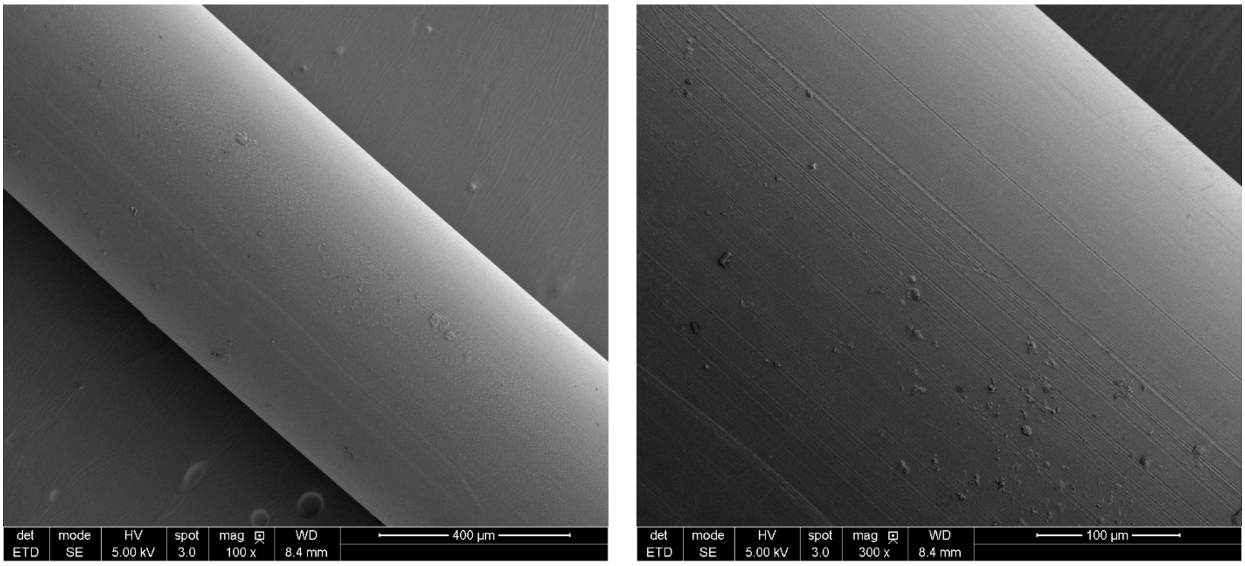
Table 2: Light microscopy images of nylon and PBSAT samples at different points during the aging test.

	new	196h	431h	626h	817h	1000h
Nylon						
PBSAT						

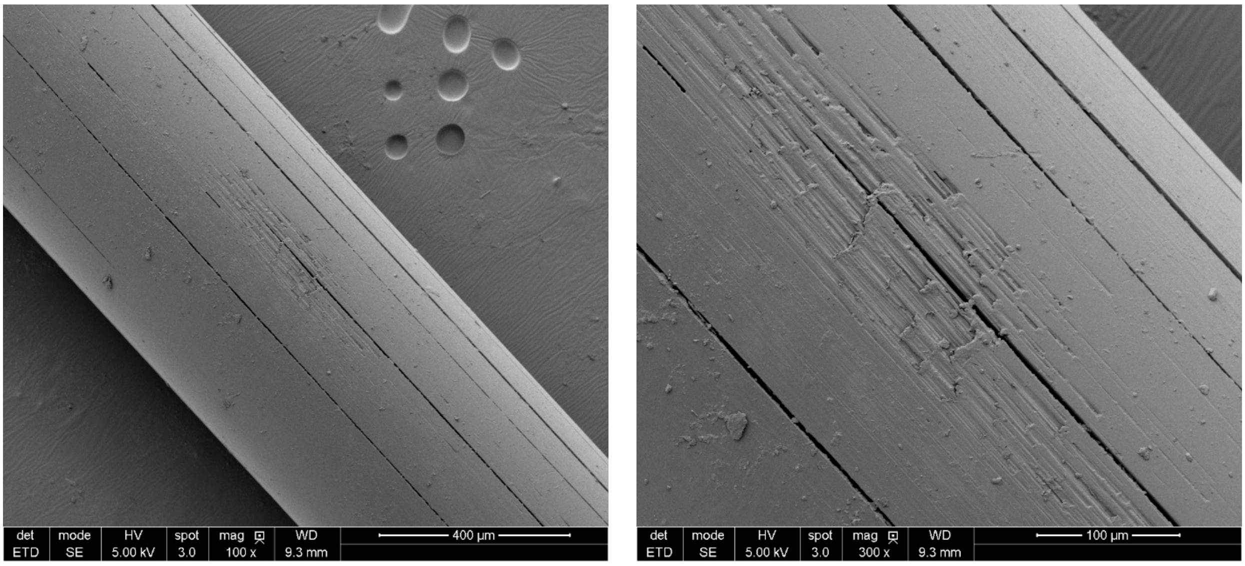
2.3 Scanning electron microscopy (SEM)

Figure 3 shows SEM micrographs of the nylon sample before and after 1000 hours aging. The new nylon line has a smooth surface showing only some scratches originating most likely from the manufacturing process. After 1000 hours of exposure the surface of the nylon line shows long cracks along the fibre axis and the line starts to fragmentate, showing large areas where material is broken off (Figure 3b).

(a)



(b)



(b)

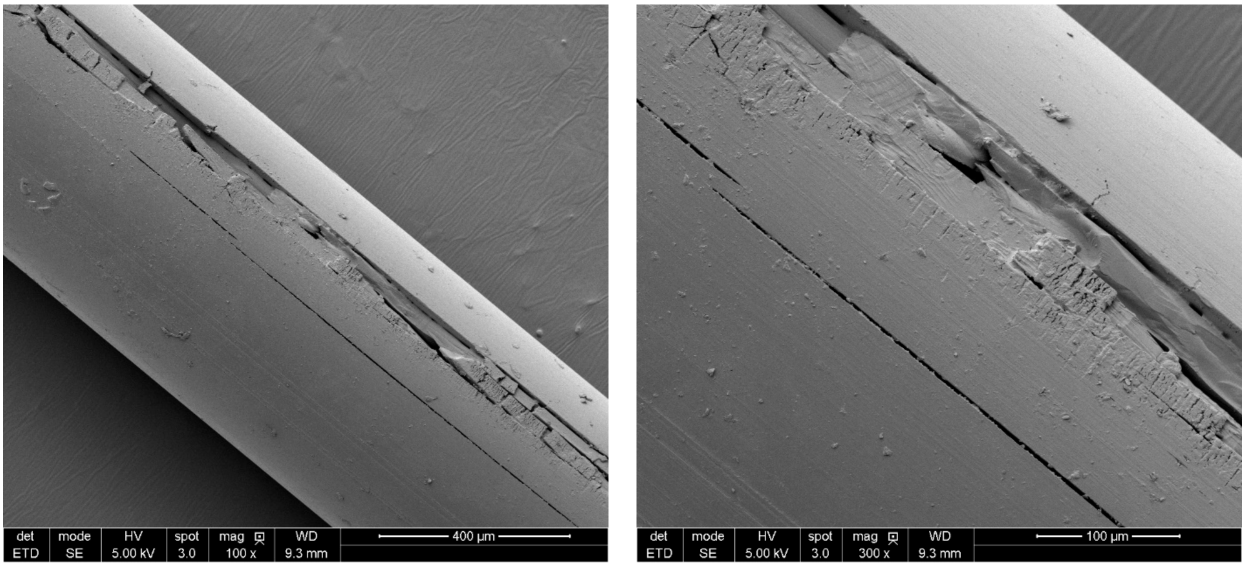
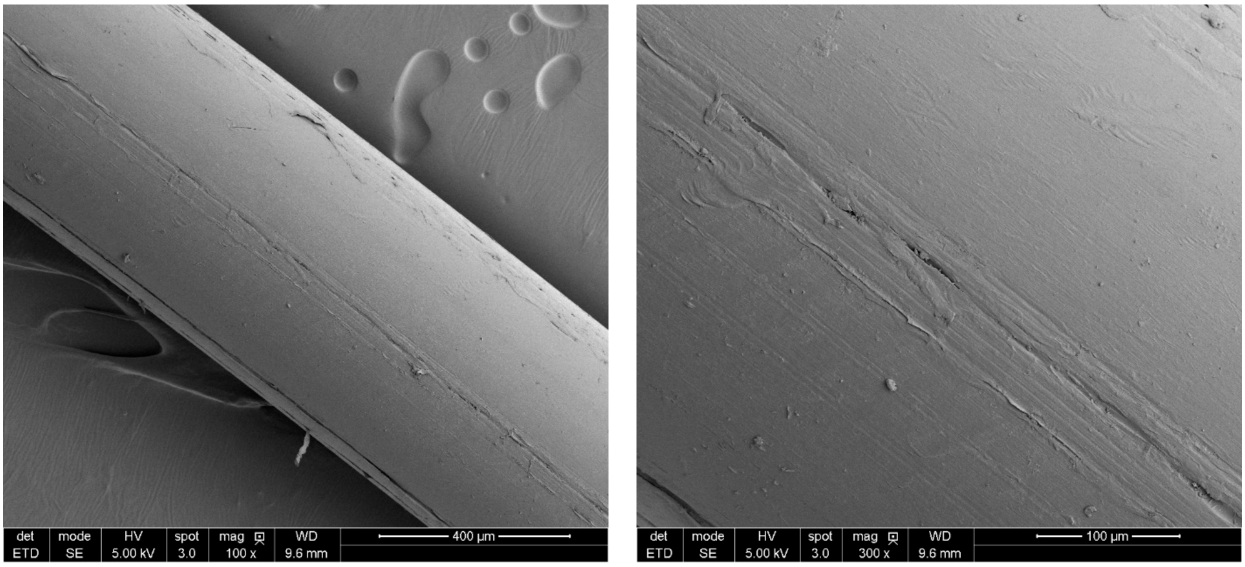


Figure 3: SEM micrographs of the nylon fishing line sample before (a) and after 1000 hours aging (b).

The surface of the non-exposed fishing line made of PBSAT is slightly rougher compared to the nylon sample and it shows already some cracks along the fibre axis (Figure 4a). After 1000 hours of exposure the degradation of the fishing line is clearly visible. The material has started to fragmentate and large pieces from the surface have started to break off (Figure 4b).

(a)



(b)

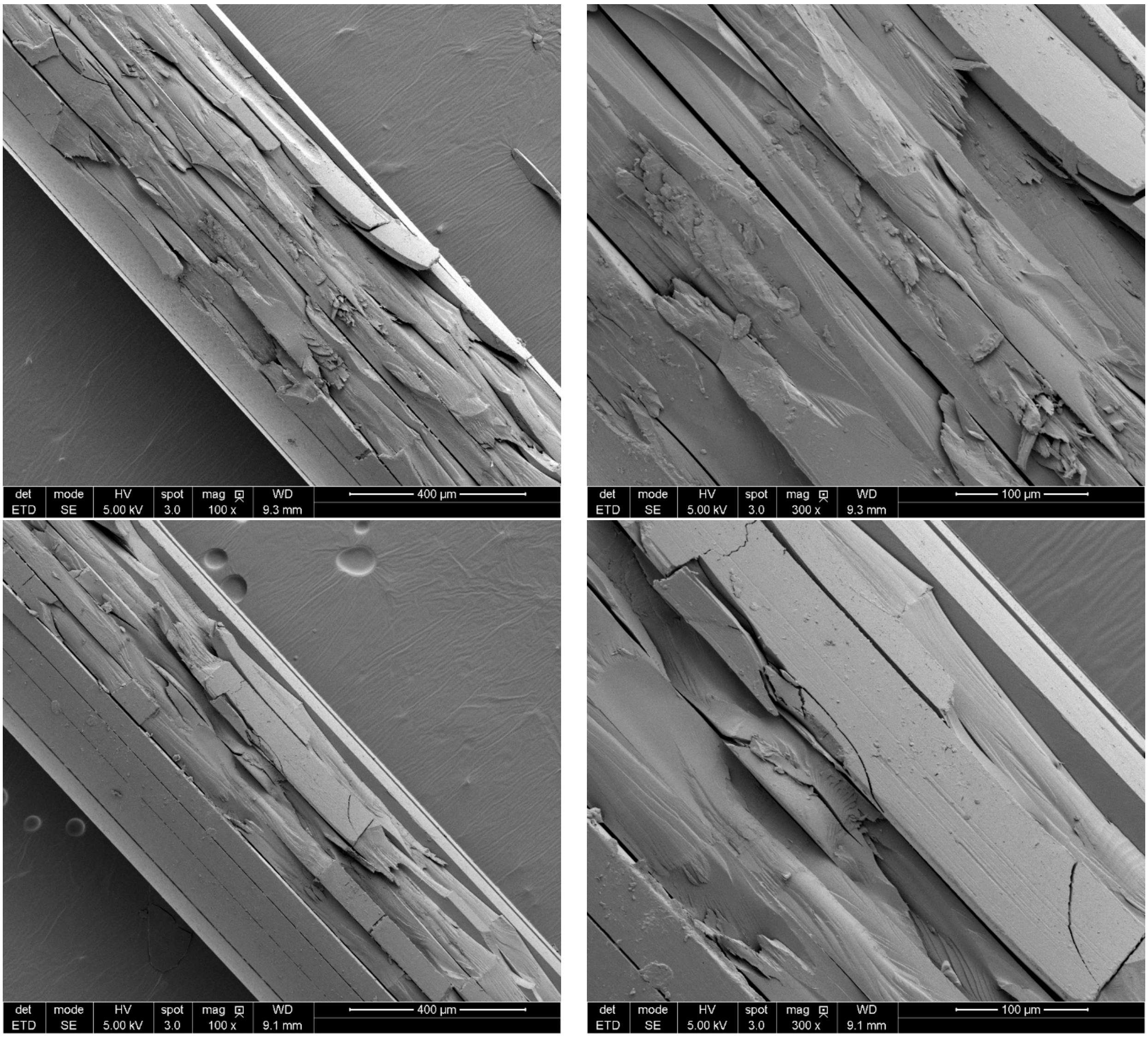
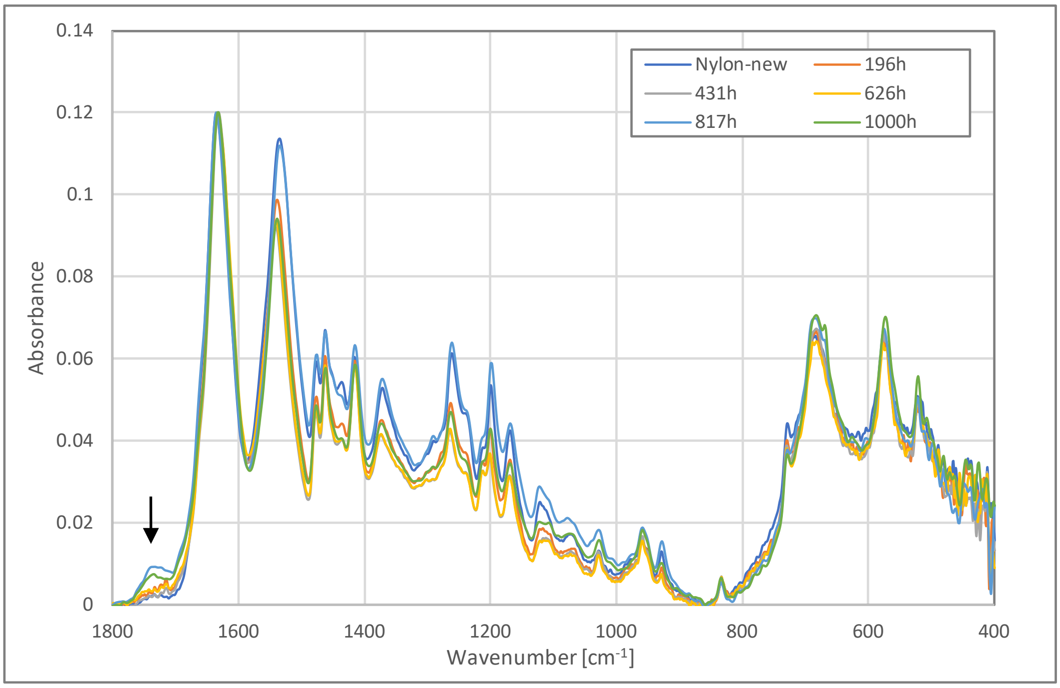


Figure 4: SEM micrographs of the PBSAT fishing line sample before (a) and after 1000 hours aging (b).

2.4 FTIR

Figure 5a shows the FTIR spectra of the nylon samples. The aging leads to an oxidation of the material and introduces carbonyl groups, which appear in the spectra as a peak at around 1730 cm^{-1} (indicated by an arrow). Besides that, there are no significant changes observed in the spectra. The FTIR spectra of the PBSAT samples are shown in Figure 5b. The main changes in the spectra during aging are the reduction of the two peaks at 1245 and 1267 cm^{-1} (stretching vibrations of C–O) and the reduction of the peak at 731 cm^{-1} (bending vibration of CH-plane of a benzene ring), both indicated by an arrow. In addition, the peaks between 750-1200 cm-1 are all slightly reduced. These peaks are related to stretching vibrations of C-O bonds as well as to bending vibration at the surface of adjacent hydrogen atoms on a phenyl ring. The findings indicate that the chemical structure of PBSAT is changing more significantly during degradation compared to nylon.

(a)



(b)

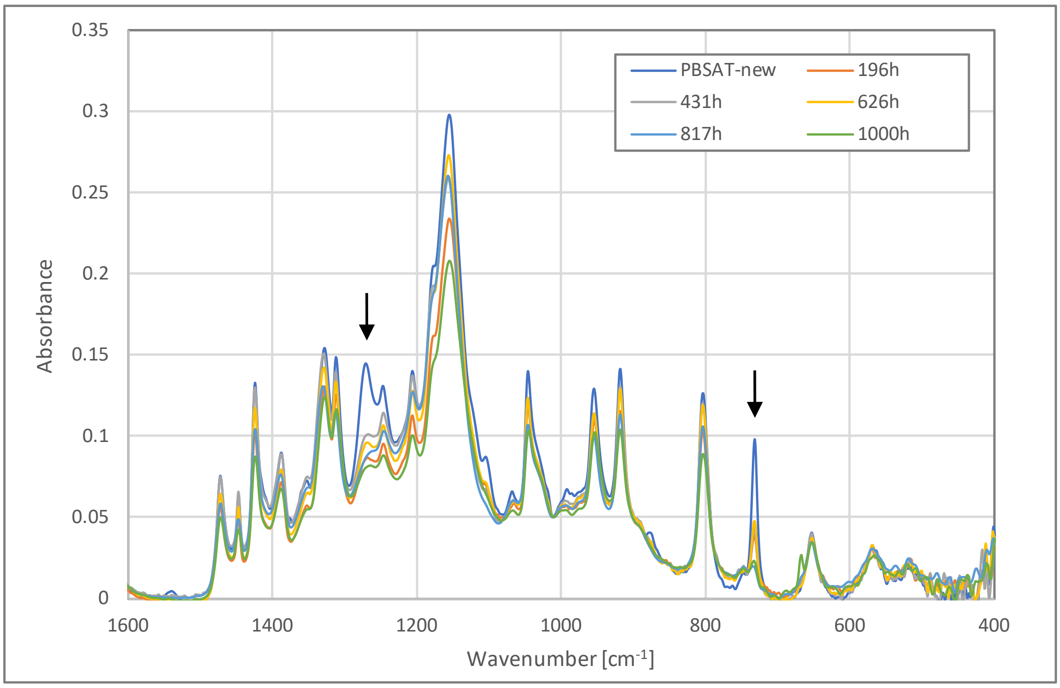


Figure 5: FTIR spectra of nylon (a) and PBSAT (b).

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KEYWORDS
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Weathering
Nylon
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Test report

Aging test of monofilament fishing line

VERSION 1.0	**DATE** 2019-08-02
AUTHOR(S) Stephan Kubowicz	
CLIENT(S) SINTEF Ocean	**CLIENT'S REF.** Eduardo Grimaldo
PROJECT NO. 822000116	**NUMBER OF PAGES/APPENDICES** 4
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ABSTRACT

Two types of monofilament fishing line were received. One line was made of nylon (polyamide-6) and the other was PBSAT (polybutylene succinate co-adipate-co-terephthalate). Both materials were aged for about 1000 hours in a weathering test, simulating outdoor condition. Compared to a previous test run in autumn 2018, this test was performed at higher relative humidity. The degradation of the materials was characterised by FTIR spectroscopy and mechanical testing. The analyses reveal that both materials show signs of degradation already after 200 hours of exposure, which is identical to the previous test. PBSAT degrades faster than nylon and thus shows a stronger reduction in mechanical strength and material integrity. Compared to the previous test, PBSAT seems to be slightly affected by the higher humidity as its mechanical properties are reduced slightly more. FTIR analysis has not shown a significant difference when comparing the results with the previous test. In conclusion, the results indicate that the wetter aging conditions did not have a significant impact. Hence, the effect of photo oxidation as aging mechanism is stronger than hydrolysis.

The test results relate only to the items tested

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APPROVED BY -	SIGNATURE
REPORT NO.	**CLASSIFICATION**

1 Experiment

Two types of monofilament fishing line were received. One line was made of nylon (polyamide-6) and the other was PBSAT (polybutylene succinate co-adipate-co-terephthalate). From both lines, 36 pieces of approx. 35 cm length were cut for the weathering test, yielding 72 samples in total. One set of 6 pieces from each material was kept aside as reference. The other pieces were fixed on to the sample holders of the weather-o-meter in groups of 6. The weathering was done using an Atlas Xenotest 440 weather-o-meter and a modified weathering cycle, which was based on ISO 4892-2 (outdoor). The total exposure time was about 1000 hours and the parameters for the weathering cycle are summarized in Table 1.

Table 1: Weathering cycle.

Exposure period	Irradiance		Black-standard temperature [°C]	Chamber temperature [°C]	Relative humidity [%]
	Broadband UV300-400 [W/m²]	Narrowband [W/m² nm)]			
2 min water spray	60 ± 2	0,51 ± 0,02 (@340 nm)	65 ± 3	38 ± 3	80 ± 10
8 min dry	60 ± 2	0,51 ± 0,02 (@340 nm)	-	38 ± 3	-

The frequent water spraying and the high humidity in the chamber ensured that the samples were always wet during the weathering test. The length of the spraying and dry cycles had to be adjusted slightly during the test to match the water supply rate of the water purifier. Spray cycle lengths varied between 2-3 min and dry times between 7-9 min. The values in Table 1 are the final ones.
During the weathering test one set of samples (6 pieces) from each material was removed after 176h, 434h, 567h, 757h, and finally after 998h for further analysis.
Tensile testing of the fishing lines samples was performed using a Zwick/Roell Z250 universal test machine and three parallels from each set of samples were analysed.

2 Results and discussion

2.1 Tensile test

The strain at break is reduced after aging, i.e. the material loses ductility, which is an expected sign of degradation. This aging effect is strongest for the PBSAT fishing line. The change in tensile strength and strain at break are shown in Figure 2a and b, respectively. The strain is the engineering strain, $\Delta L/L_0$, where L_0 is the initial grip-to-grip distance.
Before aging, the tensile strength of nylon is about 24% higher than the one of PBSAT. Already after 200 hours exposure the tensile strength of both materials starts to decline, and the deterioration is strongest for PBSAT. However, after 600 hours exposure the values for PBSAT seem to level off whereas those of nylon continue to decline.
The elongation at break of the pristine material is about 9% higher for PBSAT compared to nylon, indicating that this material has a slightly higher ability for plastic deformation. For both materials the elongation at break increases slightly during the first 200 hours of exposure and then declines significantly. Like the tensile strength, the elongation at break for PBSAT seems to level off after about 600 hours exposure whereas nylon continues to decline until about 800 hours before it seems to level off as well.

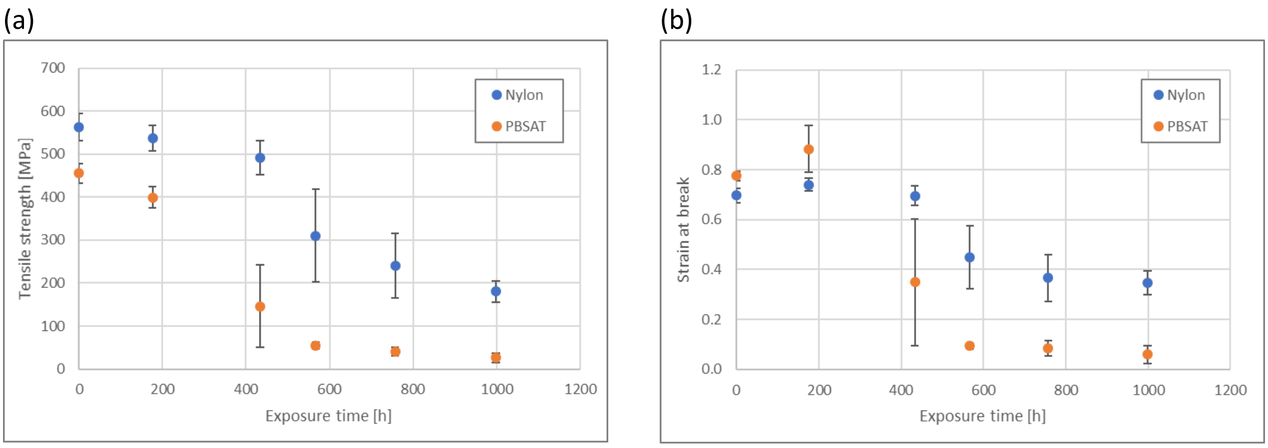

Figure 1: Change of tensile strength (a) and strain at break (b) during aging.

In a previous aging test, which was run in autumn 2018, identical samples of these fishing line materials were used. The test in 2018 was according to the weathering cycle described in ISO 4892-2 (outdoor), which has a much longer dry cycle (18 min vs 8 min) and a lower relative humidity (50% vs 80%) than the one used for this recent test. Figure 2 shows the new results in comparison to the results from last year.

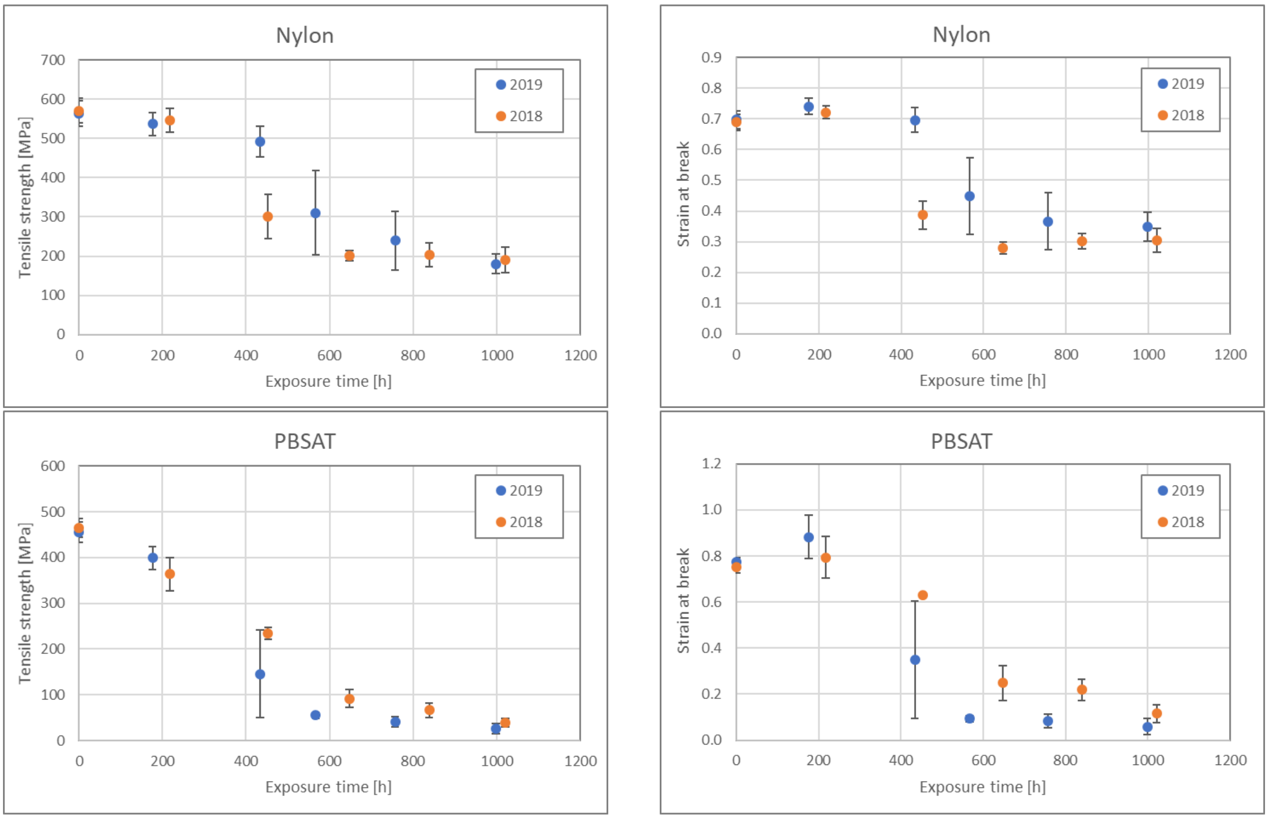

Figure 2: Comparison of the two aging tests, autumn 2018 and spring 2019. Change of tensile strength (left) and strain at break (right) during aging.

Overall, the samples show a very similar aging behaviour in both tests. The latest test was much wetter than the previous one and PBSAT seems to be slightly affected by that. Its tensile strength and strain at break decreased more compared to the previous test but the time until a decline was observed was about the same. Nylon seems to be less affected by the higher humidity and it looks like it even degrades a bit slower.

2.2 FTIR

Figure 3 shows FTIR spectra of nylon and PBSAT after 1000h of aging. In comparison, the spectra from the respective samples from last year are shown. The spectra look very similar, which is in line with the results from mechanical testing. That means, the wetter aging conditions did not have a significant impact on the degradation process of nylon and PBSAT.

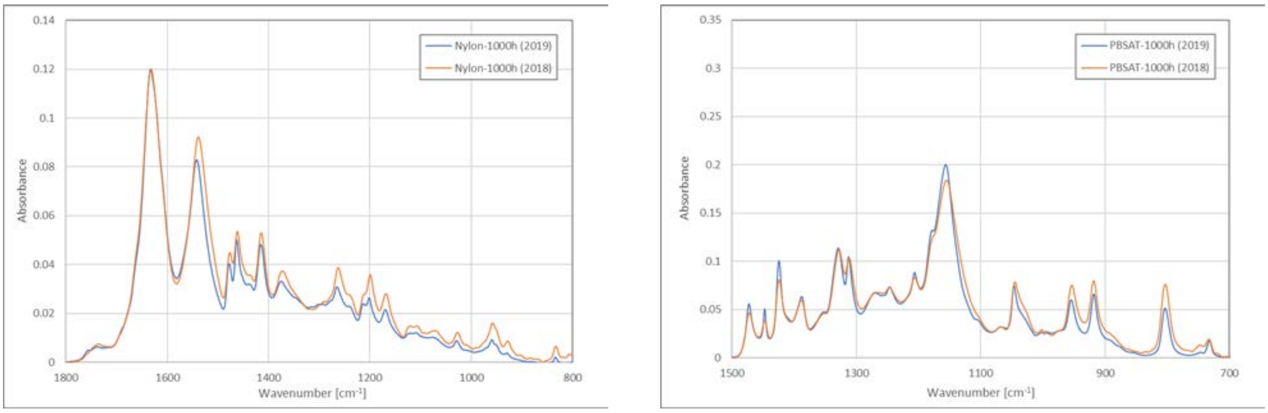

Figure 3: FTIR spectra of nylon (left) and PBSAT (right) in comparison to the results from the previous test in 2018.

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Sea trials report

Results from sea trials made using biodegradable gillnets on saithe and cod, October – December 2018

KEYWORDS:
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Ghost fishing

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DATE
2019-12-13

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ABSTRACT

Gillnets made of a new biodegradable resin (polybutylene succinate co-adipate-co-terephthalate (PBSAT) were tested under commercial fishing conditions to compare their fishing performance with that of conventional nylon (PA) nets. The relative catch efficiency between the two gillnet types was evaluated over the 2018's fall fishing season for saithe and cod in northern Norway.

For cod both biodegradable gillnets (0.55 and 0.60mm) had a significantly lower catch efficiency compared to the traditional nylon net (0.55mm) with estimated efficiencies at respectively 62.38% (CI: 50.55-74.04) and 54.96% (CI: 35.42-73.52) of with the nylon net.

For saithe, there were 15 sets for analysis of the 0.55 mm setup and 11 for the 0.60 mm setup (table 1 and table 4). Also for saithe results showed a lower catch efficiency for the biodegradable gillnets had a significantly lower catch efficiency compared to the traditional nylon net with estimated efficiencies at respectively 83.40% (71.34-94.86) and 83.87% (66.36-104.92) of with the nylon net.

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1 Experimental setup

Sea trials were conducted on board the coastal gillnet boat "MS Karoline" (10.9 m LOA) throughout October and December in 2018 with the aim to further investigate the relative catch efficiency between gillnets made using biodegradable and nylon twine. The fishing grounds chosen for the tests were located off the coast of Troms (Northern Norway) between 70°21'–70°22'N and 19°39'–19°42'E, which is a common fishing area for coastal vessels from Troms.

Gillnets with a 130 mm nominal mesh opening was used for both types of gillnets, with monofilament twine thickness of 0.55 and 0.60 mm in the biodegradable gillnets and 0.55 mm in the nylon gillnets. Since the biodegradable monofilament is considered to be approximately 10% weaker than nylon monofilament (at equal monofilament thickness), we increased the monofilament thickness from 0.55mm to 0.60 mm to compensate for the difference in tensile strength.

We used two sets of gillnets in the experiments. Each set consisted of 16 gillnets, with eight bio gillnets (B) and eight nylon gillnets (N). The gillnets were arranged in such a way that they provided the best information for paired comparison, nylon versus bio net, accounting for spatial and temporal variation in the availability of cod. With individual sets being the basic unit for the subsequently paired analysis (described in section 2.4), it was important that within each gillnet set averaged over nets that the bio and nylon nets were approximately exposed to the same spatial variability in cod availability. This could in principle be achieved by alternating between the two types of nets after each net sheet as B-N-B-N-B-N-B-N-B-N-B-N-B-N-B-N. However, for easing of registration of fish on board in relation to the type of net in which it was caught, the alternation in net types were only applied after each second net sheet. Therefore, to make conditions as equal between net types a possible set 1 was arranged as N-BB-NN-BB-NN-BB-NN-BB-N and set 2 as B-NN-BB-NN-BB-NN-BB-NN-B. Actual measurements of the mesh openings (four rows of 20 meshes each) were taken with a Vernier calliper without applying tension to the meshes and showed that the mean mesh openings of 0.55mm nylon gillnets and 0.55mm and 0.60mm bio gillnets were 131.6 ± 0.72mm, 131.5 ± 1.0mm and 132.5 ± 0.8mm respectively.

2 Data analysis

We used the statistical analysis software SELNET (Herrmann et al., 2012, 2016) to analyze the catch data and conduct length-dependent catch comparison and catch ratio analyses. Using the catch information (numbers and sizes of cod in each gillnet set deployment), we wanted to determine whether there was a significant difference in the catch efficiency averaged over deployments between the nylon gillnet and the bio gillnet. We also wanted to determine if a potential difference between the gillnet types could be related to the size of the cod. Specifically, to assess the relative length-dependent catch efficiency effect of changing from nylon gillnet to bio gillnet, we used the method described in Herrmann et al. (2017) and compared the catch data for the two net types. This method models the length-dependent catch comparison rate (CCl) summed over gillnet set deployments (for the full deployment period):

$$CC_l = \frac{\sum_{j=1}^{m}\{nt_{lj}\}}{\sum_{j=1}^{m}\{nt_{lj}+nc_{lj}\}} \qquad (1)$$

where nclj and ntlj are the numbers of cod caught in each length class l for the nylon gillnet (control) and the bio gillnet (treatment) in deployment j of a gillnet set (first or second set). m is the number of deployments carried out with one of the two sets. The functional form for the catch comparison rate CC(l,v) (the experimental being expressed by equation 1) was obtained using maximum likelihood estimation by minimizing the following expression:

$$-\sum_l\left\{\sum_{j=1}^{m}\left\{nt_{lj} \times ln\big(CC(l,v)\big) + nc_{lj} \times ln\big(1.0 - CC(l,v)\big)\right\}\right\} \qquad (2)$$

where v represents the parameters describing the catch comparison curve defined by CC(l,v). The outer summation in the equation is the summation over length classes l. When the catch efficiency of the bio gillnet and nylon gillnet is similar, the expected value for the summed catch comparison rate would be 0.5. Therefore, this baseline can be applied to judge whether or not there is a difference in catch efficiency between the two gillnet types. The experimental CCl was modelled by the function CC(l,v) using the following equation:

$$CC(l,v) = \frac{exp(f(l,v_0,\ldots,v_k))}{1+exp(f(l,v_0,\ldots,v_k))} \quad (3)$$

where f is a polynomial of order k with coefficients v0 to vk. The values of the parameters v describing CC(l,v) were estimated by minimizing equation (2), which was equivalent to maximizing the likelihood of the observed catch data. We considered f of up to an order of 4 with parameters v0, v1, v2, v3, and v4. Leaving out one or more of the parameters v0…v4 led to 31 additional models that were also considered as potential models for the catch comparison CC(l,v). Among these models, estimations of the catch comparison rate were made using multi-model inference to obtain a combined model (Burnham and Anderson 2002; Herrmann et al., 2017).

The ability of the combined model to describe the experimental data was evaluated based on the p-value. The p-value, which was calculated based on the model deviance and the degrees of freedom, should not be < 0.05 for the combined model to describe the experimental data sufficiently well, except for cases for which the data are subject to over-dispersion (Wileman et al., 1996; Herrmann et al., 2017). Based on the estimated catch comparison function CC(l,v) we obtained the relative catch efficiency (also named catch ratio) CR(l,v) between the two gillnet types using the following relationship:

$$CR(l,v) = \frac{CC(l,v)}{(1-CC(l,v))} \quad (4)$$

The catch ratio is a value that represents the relationship between catch efficiency of the bio gillnet and that of the nylon gillnet. Thus, if the catch efficiency of both gillnets is equal, CR(l,v) should always be 1.0. CR(l,v) = 1.5 would mean that the bio gillnet is catching 50% more cod with length l than the nylon gillnet. In contrast, CR(l,v) = 0.8 would mean that the bio gillnet is only catching 80% of the cod with length l that the nylon gillnet is catching.

The confidence limits for the catch comparison curve and catch ratio curve were estimated using a double bootstrapping method (Herrmann et al., 2017). This bootstrapping method accounts for between-set variability (the uncertainty in the estimation resulting from set deployment variation of catch efficiency in the gillnets and in the availability of cod) as well as within-set variability (uncertainty about the size structure of the catch for the individual deployments). However, contrary to the double bootstrapping method (Herrmann et al., 2017), the outer bootstrapping loop in the current study accounting for the between deployment variation was performed paired for the bio gillnet and nylon gillnet, taking full advantage of the experimental design with the bio gillnet and nylon gillnet being deployed simultaneously (see Fig. 1). By multi-model inference in each bootstrap iteration, the method also accounted for the uncertainty due to uncertainty in model selection. We performed 1000 bootstrap repetitions and calculated the Efron 95% (Efron, 1982) confidence limits. To identify sizes of cod with significant differences in catch efficiency, we checked for length classes in which the 95% confidence limits for the catch ratio curve did not contain 1.0.

Finally, a length-integrated average value for the catch ratio was estimated directly from the experimental catch data using the following equation:

$$CR_{average} = \frac{\sum_l \sum_{j=1}^{m} \{nt_{lj}\}}{\sum_l \sum_{j=1}^{m} \{nc_{lj}\}} \quad (5)$$

where the outer summation covers the length classes in the catch during the experimental fishing period.

2.5. Modelling the effect of number of times deployed on the length-integrated catch ratio
To investigate the effect of the number of times the gillnets were the deployed on the length-integrated catch ratio, the equation (5) was calculated for individual deployment sets such without the summation over gillnet sets. This led to a dataset consisting of pair values for number of times the gillnets were deployed and corresponding values for CRaverage. Based on this dataset, we tested if the value for CRaverage changed linearly with number of deployment times (DNO) using the following equation:

$$CR_{average}(DNO) = \alpha \times DNO + \beta_l \qquad (6)$$

The last part of the analysis using model (6) was conducted using the linear model function (lm) in statistical package R (version 2.15.2; www.r-project.org).

3 Tensile strength tests

Tensile strength tests were carried out on samples of the bio and nylon gillnets used in before and after fishing experiments using a H10KT universal tensile testing machine (Tinius Olsen TMC, PA, USA). Samples of gillnets measuring approx. 20 x 20 meshes were cut from the centre of the new and used gillnets. The tests were performed in wet conditions (at least 40 replicates for each case) according to ISO 1806. Tensile strength, defined as the stress needed to break the sample, is given in kg, and elongation at break, defined as the length of the sample after it had stretched right when it breaks (L) is given relative to the initial mesh size in percentage.

4 Results

Sufficient data was collected for two species throughout the trial period, cod and saithe. A total of 1200 cod were caught, 780 using the nylon gillnet and 420 in the biodegradable gillnet. 1328 saithe individuals were collected, of these, 736 were caught in the nylon gillnets and the remaining 592 were caught in the biodegradable gillnet. Data was collected for 21 catches for both cod and saithe, but the analysis was conducted based on catches that were greater than 10 in each set (Table 1). This was done in order to not add additional uncertainty to the results and has been a method used successfully in previous catch comparison studies. For cod this resulted in a total of 15 sets for analysis of the 0.55 mm setup and 12 for the 0.60 mm setup. For cod both biodegradable gillnets (0.55 and 0.60mm) had a significantly lower catch efficiency compared to the traditional nylon net (0.55mm) with estimated efficiencies at respectively 62.38% (CI: 50.55-74.04) and 54.96% (CI: 35.42-73.52) of with the nylon net (Tables 2-3 and figures 1-6).

For saithe, there were 15 sets for analysis of the 0.55 mm setup and 11 for the 0.60 mm setup (table 1 and table 4). Also for saithe results showed a lower catch efficiency for the biodegradable gillnets had a significantly lower catch efficiency compared to the traditional nylon net (0.55mm) with estimated efficiencies at respectively 83.40% (71.34-94.86) and 83.87% (66.36-104.92) of with the nylon net (Tables 4-6 and Figures 7-12).

Table 1: Catch data of all deployments for cod, rows highlighted in grey indicate sets used in the analysis (sets containing catches of 10 or more cod).

Set	Setup	Setting date	Fishing time	Fishing depth (m) (min - max)	Acc. no. of deployments	No. of cod in nylon gillnets	No. of cod in bio gillnets	Min cod length in nylon gillnets	Max cod length in nylon gillnets	Min cod length in bio gillnets	Max cod length in bio gillnets
1	55/55	06/09/18	19h 45min	140	1	1	1	87	87	60	60
1	55/60	06/09/18	19h 45min	120	1	0	0	0	0	0	0
2	55/55	10/09/18	21h 45min	110	2	3	1	60	85	64	64
2	55/60	10/09/18	22h 10min	130	2	2	3	66	76	60	101
3	55/55	30/10/18	27h 30min	170-140	3	15	7	51	88	50	73
3	55/60	30/10/18	26h 15min	130-110	3	1	2	80	80	61	63
4	55/55	31/10/18	22h 40min	180-160	4	6	2	59	69	60	64
4	55/60	31/10/18	24h 15min	110-130	4	1	2	65	65	50	67
5	55/55	01/11/18	22h 40min	100-120	5	3	2	63	73	65	68
5	55/60	01/11/18	23h 55min	105-125	5	2	2	63	68	60	64
6	55/55	10/11/18	24h 50min	25-30	6	40	28	60	88	59	84
6	55/60	10/11/18	24h 15min	50-70	6	6	3	61	81	67	73
7	55/55	12/11/18	21h 20min	25-30	7	4	1	56	66	78	78
7	55/60	12/11/18	21h 45min	50-70	7	4	0	60	68	59	91
8	55/55	13/11/18	22h	50-70	8	2	4	59	69	60	90
8	55/60	13/11/18	18h 20min	50-70	8	1	3	74	74	56	83
9	55/55	26/11/18	22h 20min	35-20	9	27	11	52	86	55	92
9	55/60	26/11/18	23h 20min	95-45	9	11	0	55	77	0	0
10	55/55	27/11/18	23h 20min	35-20	10	14	6	53	76	56	75
10	55/60	27/11/18	22h 20min	50-85	10	1	2	66	66	64	69
11	55/55	28/11/18	23h 40min	38-25	11	30	9	53	68	56	75
11	55/60	28/11/18	26h 20min	55-45	11	12	7	50	74	56	71
12	55/55	29/11/18	18h 5min	30-75	12	36	23	52	92	54	87
12	55/60	29/11/18	18h 55min	45-48	12	11	13	57	98	53	84
13	55/55	30/11/18	25h 40min	30-75	13	26	18	56	96	66	96
13	55/60	30/11/18	26h	45-48	13	24	8	51	94	67	95

14	55/55	01/12/18	18h 5min	30-76	14	20	7	50	85	54	67
14	55/60	01/12/18	18h 15min	45-49	14	100	12	50	92	51	95
15	55/55	02/12/18	26h 10min	35-20	15	33	17	50	95	56	78
15	55/60	02/12/18	28h 5min	50-85	15	16	11	51	96	58	87
16	55/55	03/12/18	16h	30-75	16	28	14	50	84	55	66
16	55/60	03/12/18	16h 15min	45-48	16	11	6	52	92	62	96
17	55/55	04/12/18	23h	30-75	17	46	47	52	95	51	76
17	55/60	04/12/18	23h 25min	45-48	17	50	44	55	94	50	94
18	55/55	06/12/18	25h 20min	30-75	18	19	12	54	67	52	72
18	55/60	06/12/18	22h 20min	45-48	18	26	4	52	95	64	85
19	55/55	07/12/18	24h 5min	30-75	19	26	22	50	74	52	67
19	55/60	07/12/18	27h 55min	45-48	19	15	10	56	85	55	86
20	55/55	08/12/18	22h 50min	30-75	20	27	12	52	87	50	89
20	55/60	08/12/18	18h 10 min	45-48	20	32	9	54	92	59	87
21	55/55	09/12/18	16h 30min	30-75	21	26	25	54	71	51	82
21	55/60	09/12/18	16h 5min	45-48	21	22	10	55	96	51	95

Table 2: Catch rate and fit statistics results from the 0.55 mm biodegradable and nylon set based on the valid deployments for cod. Values in parentheses indicate a 95% confidence interval. DOF denotes the degrees of freedom

Length (cm)	Catch ratio (%)
50	74.59 (24.39-269.67)
55	70.97 (46.14-96.63)
60	66.97 (47.25-87.92)
65	62.66 (47.73-84.43)
70	58.17 (40.29-82.65)
75	53.72 (29.74-80.38)
80	48.70 (21.37-70.54)
85	45.71 (13.67-72.52)
90	42.56 (4.97-93.69)
95	40.37 (1.62-320.05)
Average	62.38 (50.55-74.04)
P-value	0.2915
Deviance	45.46
DOF	41

Table 3: Catch rate and fit statistics results from the 0.60 mm biodegradable and 0.55 mm nylon set based on the valid deployments for cod. Values in parentheses indicate a 95% confidence interval. DOF denotes the degrees of freedom. *: In case only best model is used and not the model averaging P-value would be 0.077.

Length (cm)	Catch ratio (%)
50	65.93 (24.43-410.77)
55	58.57 (28.60-139.11)
60	54.41 (29.05-94.91)
65	52.63 (29.65-74.56)
70	52.61 (30.64-70.73)
75	53.90 (31.20-83.56)
80	55.90 (33.45-106.62)
85	57.63 (33.27-126.53)
90	57.74 (28.19-116.21)
95	55.26 (9.76-109.90)
100	52.01 (0.68-134.61)
105	51.88 (0.00-185.15)
Average	54.96 (35.42-73.52)
P-value	0.0334*
Deviance	60.29
DOF	42

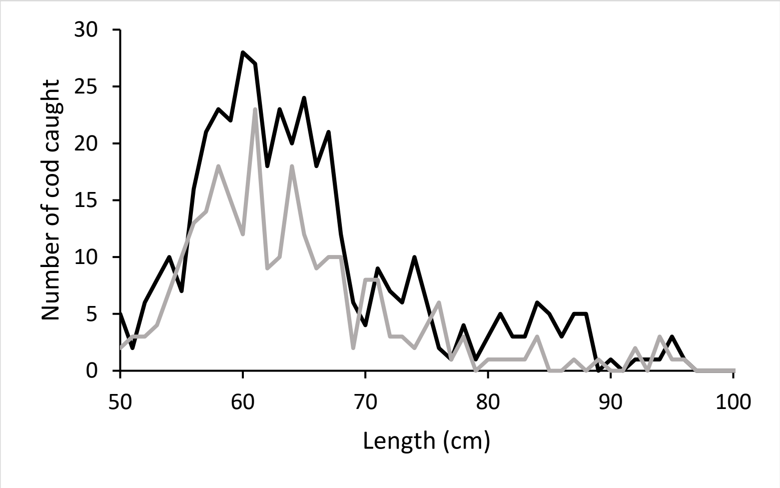

Fig 1: The size distribution of cod caught using 0.55 mm nylon (black) and biodegradable (grey) twine gillnets

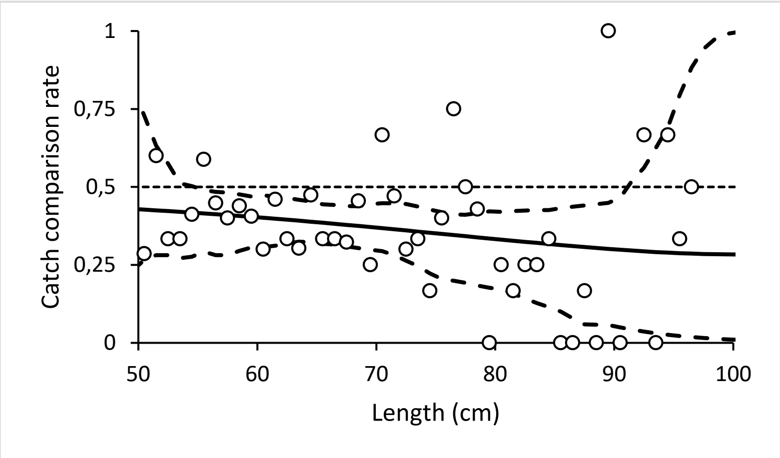

Fig 2: The catch comparison curve for cod with circle marks indicating the experimental rate and the curve indicates the modelled catch comparison rate. The dotted line at 0.5 indicates the baseline where both 0.55 mm gillnets fish the same amount. The stippled curve indicates a 95% confidence interval for the estimated catch comparison curve.

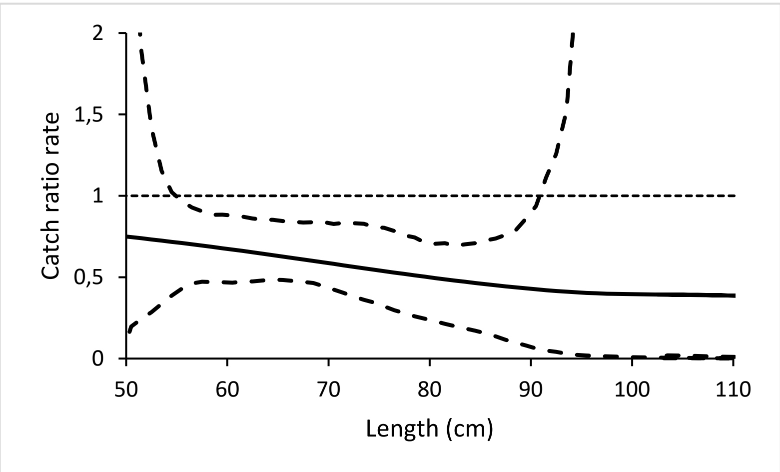

Fig 3: The estimated catch ratio curve for cod (solid line). The dotted line at 1.0 indicates the baseline where fishing efficiency of both 0.55 mm gillnet types is equal. The stippled curves represent a 95% confidence interval of the estimated catch ratio curve.

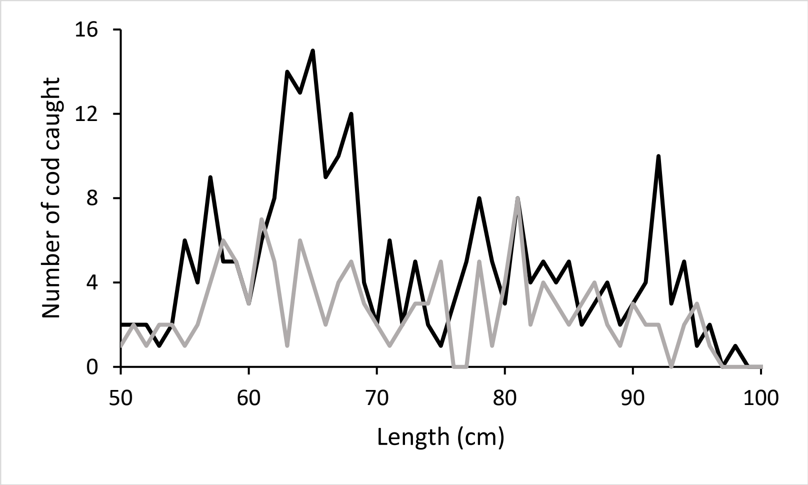

Fig 4: The size distribution of cod caught using 0.60 mm nylon (black) and biodegradable (grey) twine gillnets

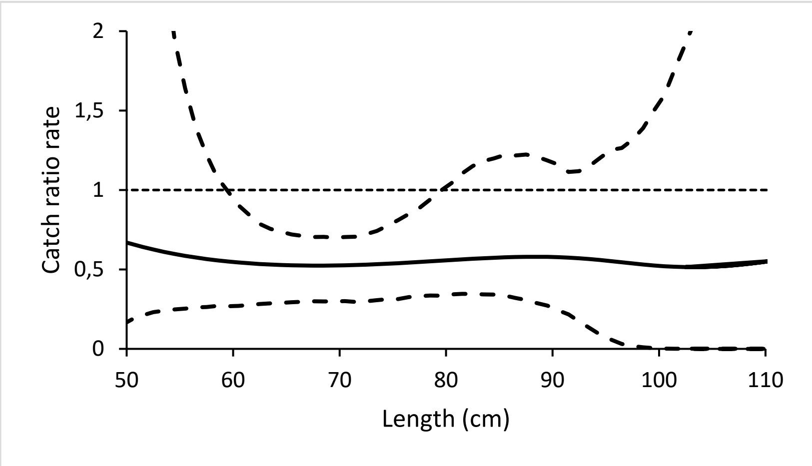

Fig 5: The estimated catch ratio curve for cod (solid line). The dotted line at 1.0 indicates the baseline where fishing efficiency of the 0.55 mm nylon and the 0.60 mm biodegradable gillnet types is equal. The stippled curves represent a 95% confidence interval of the estimated catch ratio curve.

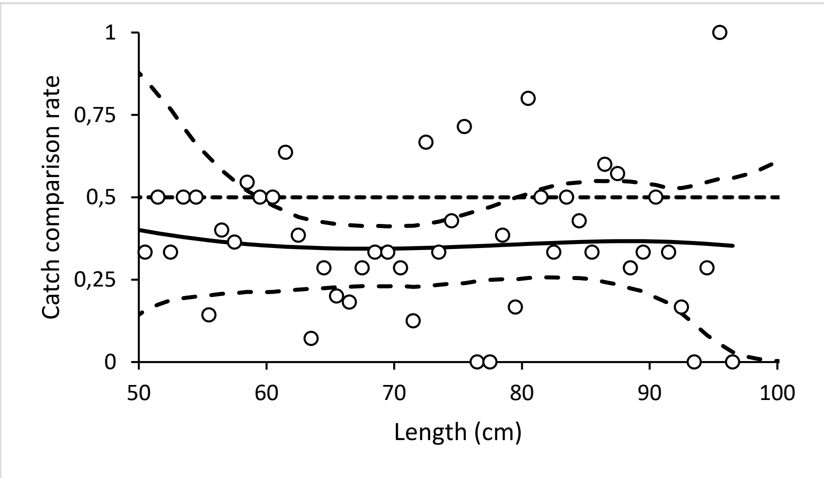

Fig 6: The catch comparison curve for cod with circle marks indicating the experimental rate and the curve indicates the modelled catch comparison rate. The dotted line at 0.5 indicates the baseline where the 0.55 mm nylon and the 0.60 mm biodegradable gillnets fish the same amount. The stippled curve indicates a 95% confidence interval for the estimated catch comparison curve.

Table 4: Catch data of all deployments for saithe, rows highlighted in grey indicates sets used in the analysis (sets containing catches of 10 or more saithe).

Set	Setup	Setting date	Fishing time	Fishing depth (m) (min - max)	Acc. no. of deployments	No. of saithe in nylon gillnets	No. of saithe in bio gillnets	Min saithe length in nylon gillnets	Max saithe length in nylon gillnets	Min saithe length in bio gillnets	Max saithe length in bio gillnets
1	55/55	06/09/18	19h 45min	140	1	4	2	64	74	64	67
1	55/60	06/09/18	19h 45min	120	1	0	0	0	0	0	0
2	55/55	10/09/18	21h 45min	110	2	3	0	73	83	0	0
2	55/60	10/09/18	22h 10min	130	2	3	2	67	70	69	73
3	55/55	30/10/18	27h 30min	170-140	3	9	4	54	69	50	75
3	55/60	30/10/18	26h 15min	130-110	3	3	0	50	75	0	0
4	55/55	31/10/18	22h 40min	180-160	4	3	1	65	76	70	70
4	55/60	31/10/18	24h 15min	110-130	4	0	1	0	0	50	50
5	55/55	01/11/18	22h 40min	100-120	5	4	2	62	77	63	70
5	55/60	01/11/18	23h 55min	105-125	5	5	3	61	71	59	68
6	55/55	10/11/18	24h 50min	25-30	6	21	13	59	83	59	86
6	55/60	10/11/18	24h 15min	50-70	6	17	8	52	87	56	77
7	55/55	12/11/18	21h 20min	25-30	7	3	1	67	72	68	68
7	55/60	12/11/18	21h 45min	50-70	7	10	3	64	88	65	81
8	55/55	13/11/18	22h	50-70	8	4	0	65	82	0	0
8	55/60	13/11/18	18h 20min	50-70	8	6	0	65	86	0	0
9	55/55	26/11/18	22h 20min	35-20	9	47	42	50	91	50	86
9	55/60	26/11/18	23h 20min	95-45	9	8	3	62	79	58	76
10	55/55	27/11/18	23h 20min	35-20	10	17	13	51	72	50	63
10	55/60	27/11/18	22h 20min	50-85	10	0	0	0	0	0	0
11	55/55	28/11/18	23h 40min	38-25	11	25	33	50	81	50	85
11	55/60	28/11/18	26h 20min	55-45	11	27	17	53	80	54	77
12	55/55	29/11/18	18h 5min	30-75	12	34	30	50	81	50	88
12	55/60	29/11/18	18h 55min	45-48	12	2	6	70	80	65	77
13	55/55	30/11/18	25h 40min	30-75	13	28	23	50	92	60	85

13	55/60	30/11/18	26h	45-48	13	6	3	61	72	67	80
14	55/55	01/12/18	18h 5min	30-76	14	26	20	50	82	54	77
14	55/60	01/12/18	18h 15min	45-49	14	2	7	75	75	57	79
15	55/55	02/12/18	26h 10min	35-20	15	44	33	50	78	51	80
15	55/60	02/12/18	28h 5min	50-85	15	20	19	61	88	55	81
16	55/55	03/12/18	16h	30-75	16	16	15	50	78	53	73
16	55/60	03/12/18	16h 15min	45-48	16	9	12	54	85	58	84
17	55/55	04/12/18	23h	30-75	17	26	23	51	78	51	76
17	55/60	04/12/18	23h 25min	45-48	17	61	52	59	96	55	87
18	55/55	06/12/18	25h 20min	30-75	18	31	11	50	73	50	70
18	55/60	06/12/18	22h 20min	45-48	18	3	11	62	75	57	77
19	55/55	07/12/18	24h 5min	30-75	19	51	40	50	86	50	84
19	55/60	07/12/18	27h 55min	45-48	19	20	12	53	88	61	81
20	55/55	08/12/18	22h 50min	30-75	20	54	39	50	81	50	82
20	55/60	08/12/18	18h 10 min	45-48	20	15	9	53	77	54	85
21	55/55	09/12/18	16h 30min	30-75	21	47	58	52	76	50	86
21	55/60	09/12/18	16h 5min	45-48	21	22	21	50	82	55	72

Table 5: Catch rate and fit statistics results from the 0.55 mm biodegradable and 0.55 mm nylon set based on the valid deployments for saithe. Values in parentheses indicate a 95% confidence interval. DOF denotes the degrees of freedom.

Length (cm)	Catch ratio (%)
50	103.33 (64.00-199.22)
55	94.42 (73.90-140.63)
60	86.58 (70.16-110.11)
65	80.20 (63.52-92.19)
70	75.54 (53.68-88.66)
75	72.85 (46.76-95.12)
80	72.49 (47.52-119.27)
85	75.14 (43.22-261.02)
90	81.86 (31.08-1550.13)
95	93.83 (19.72-8043.05)
Average	83.40 (71.34-94.86)
P-value	0.6438
Deviance	33.29
DOF	37

Table 6: Catch rate and fit statistics results from the 0.60 mm biodegradable and 0.55 mm nylon set based on the valid deployments for saithe. Values in parentheses indicate a 95% confidence interval. DOF denotes the degrees of freedom.

Length (cm)	Catch ratio (%)
50	126.66 (70.30-608.14)
55	124.11 (76.96-319.85)
60	110.00 (70.75-186.24)
65	93.93 (60.67-137.33)
70	79.96 (53.35-110.59)
75	68.32 (46.18-97.93)
80	57.43 (36.45-96.40)
85	45.23 (25.14-79.05)
90	32.05 (8.66-67.15)
95	23.18 (1.29-62.48)
100	17.57 (0.83-64.05)
Average	83.87 (66.36-104.92)
P-value	0.4114
Deviance	35.19
DOF	34

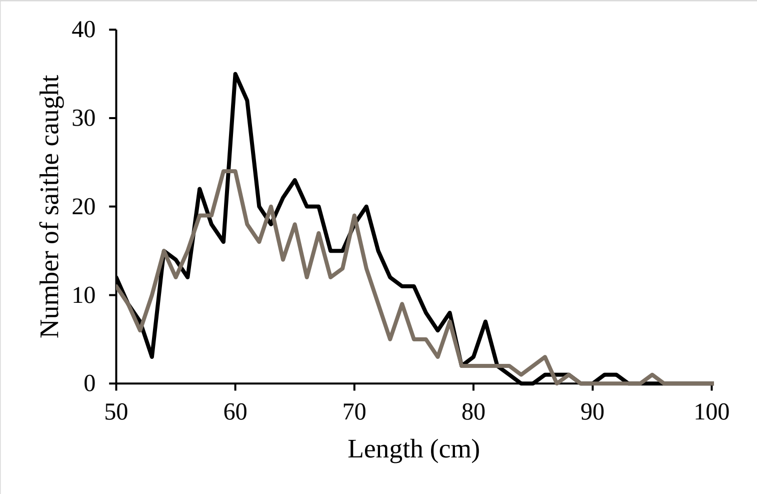

Fig 7: The size distribution of saithe caught using 0.55 mm nylon (black) and biodegradable (grey) twine gillnets

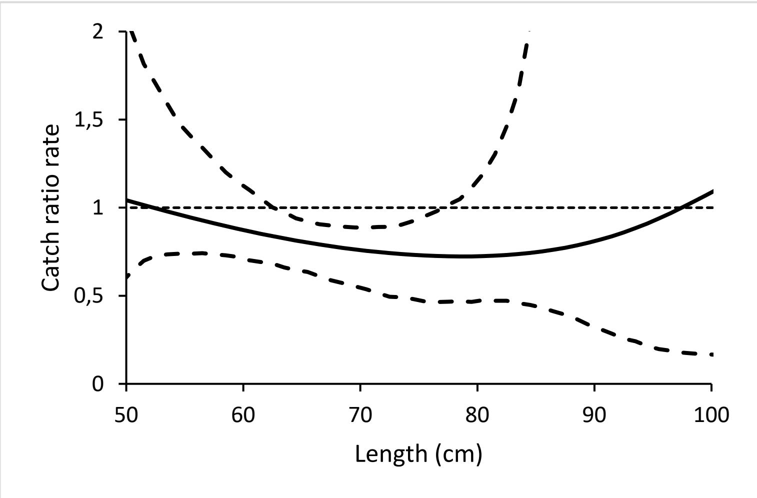

Fig 8: The estimated catch ratio curve for saithe (solid line). The dotted line at 1.0 indicates the baseline where fishing efficiency of both 0.55 mm gillnet types is equal. The stippled curves represent a 95% confidence interval of the estimated catch ratio curve.

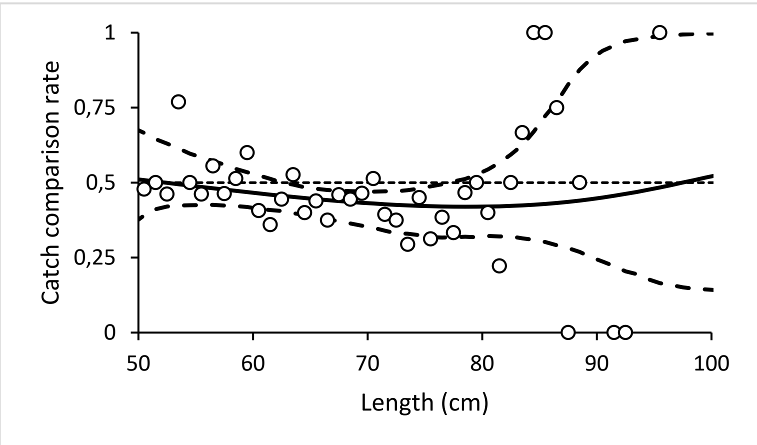

Fig 9: The catch comparison curve for saithe with circle marks indicating the experimental rate and the curve indicates the modelled catch comparison rate. The dotted line at 0.5 indicates the baseline where the 0.55 mm nylon and biodegradable gillnets fish the same amount. The stippled curve indicates a 95% confidence interval for the estimated catch comparison curve.

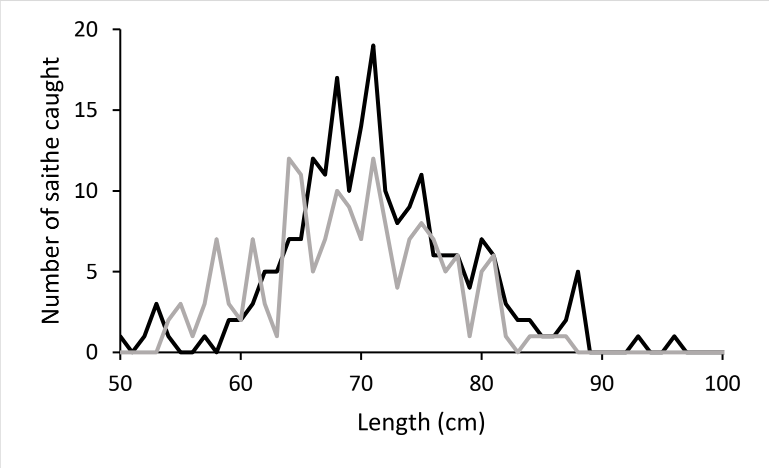

Fig 10: The size distribution of saithe caught using 0.60 mm nylon (black) and biodegradable (grey) twine gillnets

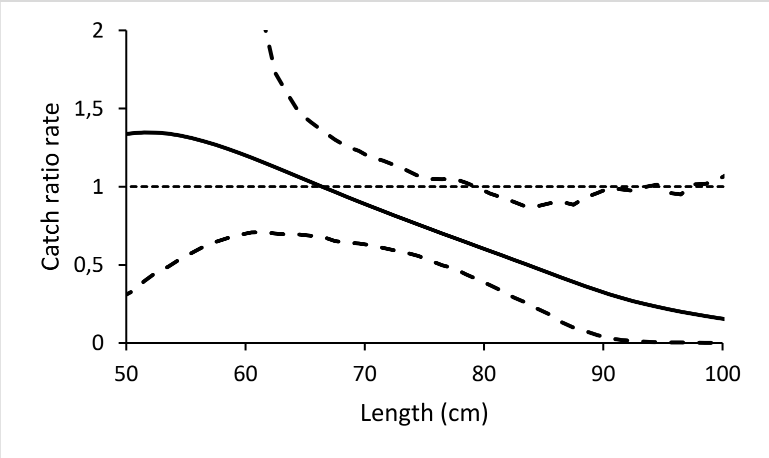

Fig 11: The estimated catch ratio curve for saithe (solid line). The dotted line at 1.0 indicates the baseline where fishing efficiency of both the 0.55 mm nylon and the 0.60 mm biodegradable gillnet types is equal. The stippled curves represent a 95% confidence interval of the estimated catch ratio curve.

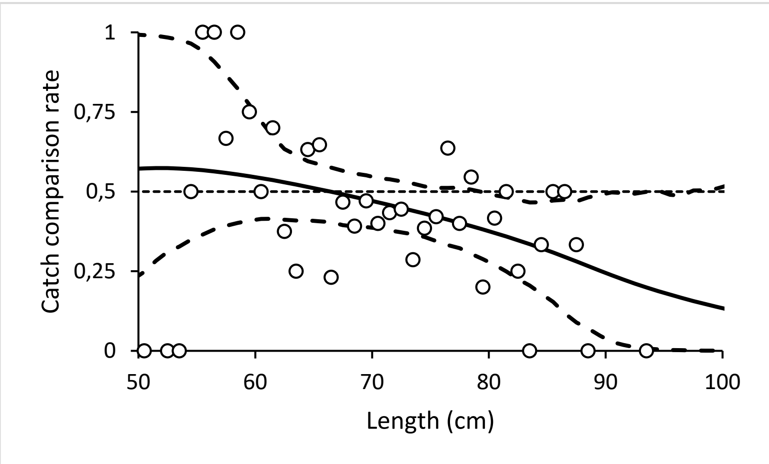

Fig 12: The catch comparison curve for saithe with circle marks indicating the experimental rate and the curve indicates the modelled catch comparison rate. The dotted line at 0.5 indicates the baseline where the 0.55 mm nylon and the 0.60 mm biodegradable gillnets fish the same amount. The stippled curve indicates a 95% confidence interval for the estimated catch comparison curve

When new, nylon gillnets made of 0.55 mm monofilaments were significantly (8.9%) stronger than bionets of 0.55mm monofilaments, and equally stronger than bionets of 0.60 mm monofilament. When used, nylon gillnets were 21.2% and 15.1 % stronger than bionets of 0.55mm and 0.60mm monofilaments. Used nylon nets did not lose strength but lost 14.6% elongation at break. Used bionets lose 13.5% and 16.7% strength and 4 and 8% elongation at break (Table 3).

Table 3: Mean tensile strength (kg) and elongation at break (%) with 95 % confidence intervals (in brackets) for new and used gillnets.

Sea trial	Netting	Tensile strength (kg)			Elongation at break (%)		
		New	Used	%	New	Used	%
Autumn 2018	0.55mm Nylon	14.6 (14.2–15.1)	14.6 (13.9–15.1)	−0.0	32.7 (31.9–33.4)	27.9 (26.9–28.9)	−14.6
	0.55mm Biodegradable	13.3 (13.1–13.5)	11.5 (10.9–12.1)	−13.5	39.4 (38.8–39.9)	37.8 (36.6–39.1)	−4.0
	0.60mm Biodegradable	14.9 (14.5–15.3)	12.4 (11.7–13.0)	−16.7	39.2 (38.5–39.8)	37.9 (36.3–39.4)	−8.1

5 Discussion and conclusion

The nylon gillnets caught significantly more cod and saithe than the biodegradable gillnets throughout the fishing season and generally showed better catch rates for most length classes. Any difference in breaking strength and elongation a break between 0.55mm nylon-nets and 0.60mm bio-nets was detected when nets were new, and therefore it is unclear what caused the catch differences between the nets.

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Sea trials report

Results from sea trials made using biodegradable gillnets on cod, January – March 2019

KEYWORDS:
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ABSTRACT
Gillnets made of a new biodegradable resin (polybutylene succinate co-adipate-co-terephthalate (PBSAT) were tested under commercial fishing conditions to compare their fishing performance with that of conventional nylon (PA) nets. The relative catch efficiency between the two gillnet types was evaluated over the entire 2019's winter fishing season for cod (Gadus morhua) in northern Norway.

The nylon gillnets caught 19% more fish (in numbers) than the biodegradable gillnets throughout the fishing season and generally showed better catch rates for most length classes. Any difference in breaking strength and elongation a break was detected when nets were new, and therefore it is unclear what caused the catch differences between the nets. The number of times that the gillnets were deployed affected the relative catch efficiency of the gillnets with the nylon continuously loosing efficiency compared to the biodegradable. The biodegradable gillnet catch efficiency became more similar to that of the nylon gillnet as the number of times it was deployed increased.

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1 Experimental setup

Sea trials were conducted on board the coastal gillnet boat "MS Karoline" (10.9 m LOA) throughout January and March in 2019 with the aim to further investigate the relative catch efficiency between gillnets made using biodegradable and nylon twine. The fishing grounds chosen for the tests were located off the coast of Troms (Northern Norway) between 70°21'–70°22'N and 19°39'–19°42'E, which is a common fishing area for coastal vessels from Troms.

Gillnets with a 210 mm nominal mesh opening was used for both types of gillnets, with monofilament twine thickness of 0.75 mm in the biodegradable gillnet and 0.7 mm thickness in the nylon gillnet. Since the biodegradable monofilament is approximately 10% weaker than nylon (at the same monofilemant thickness), we increased the thickness of the bionet's monofilament from 0.7 to 0.75mm expecting to match the tensile strength of the nylon nets.

We used two sets of gillnets in the experiments. Each set consisted of 16 gillnets, with eight bio gillnets (B) and eight nylon gillnets (N). The gillnets were arranged in such a way that they provided the best information for paired comparison, nylon versus bio net, accounting for spatial and temporal variation in the availability of cod. With individual sets being the basic unit for the subsequently paired analysis (described in section 2.4), it was important that within each gillnet set averaged over nets that the bio and nylon nets were approximately exposed to the same spatial variability in cod availability. This could in principle be achieved by alternating between the two types of nets after each net sheet as B-N-B-N-B-N-B-N-B-N-B-N-B-N-B-N. However, for easing of registration of fish on board in relation to the type of net in which it was caught, the alternation in net types were only applied after each second net sheet. Therefore, to make conditions as equal between net types a possible set 1 was arranged as N-BB-NN-BB-NN-BB-NN-BB-N and set 2 as B-NN-BB-NN-BB-NN-BB-NN-B. Actual measurements of the mesh openings (four rows of 20 meshes each) were taken with a Vernier calliper without applying tension to the meshes and showed that the mean mesh openings of nylon gillnets and bio gillnets were 210.6 ± 1.1 mm and 204.3 ± 2.1 mm, respectively.

2 Data analysis

We used the statistical analysis software SELNET (Herrmann et al., 2012, 2016) to analyze the catch data and conduct length-dependent catch comparison and catch ratio analyses. Using the catch information (numbers and sizes of cod in each gillnet set deployment), we wanted to determine whether there was a significant difference in the catch efficiency averaged over deployments between the nylon gillnet and the bio gillnet. We also wanted to determine if a potential difference between the gillnet types could be related to the size of the cod. Specifically, to assess the relative length-dependent catch efficiency effect of changing from nylon gillnet to bio gillnet, we used the method described in Herrmann et al. (2017) and compared the catch data for the two net types. This method models the length-dependent catch comparison rate (CCl) summed over gillnet set deployments (for the full deployment period):

$$CC_l = \frac{\sum_{j=1}^{m}\{nt_{lj}\}}{\sum_{j=1}^{m}\{nt_{lj}+nc_{lj}\}} \qquad (1)$$

where nclj and ntlj are the numbers of cod caught in each length class l for the nylon gillnet (control) and the bio gillnet (treatment) in deployment j of a gillnet set (first or second set). m is the number of deployments carried out with one of the two sets. The functional form for the catch comparison rate CC(l,v) (the experimental being expressed by equation 1) was obtained using maximum likelihood estimation by minimizing the following expression:

$$-\sum_l\{\sum_{j=1}^{m}\{nt_{lj}\times ln\big(CC(l,v)\big)+nc_{lj}\times ln\big(1.0-CC(l,v)\big)\}\} \qquad (2)$$

where v represents the parameters describing the catch comparison curve defined by CC(l,v). The outer summation in the equation is the summation over length classes l. When the catch efficiency of the bio gillnet and nylon gillnet is similar, the expected value for the summed catch comparison rate would be 0.5. Therefore, this baseline can be applied to judge whether or not there is a difference in catch efficiency between the two gillnet types. The experimental CCl was modelled by the function CC(l,v) using the following equation:

$$CC(l,v) = \frac{exp(f(l,v_0,\ldots,v_k))}{1+exp(f(l,v_0,\ldots,v_k))} \quad (3)$$

where f is a polynomial of order k with coefficients v0 to vk. The values of the parameters v describing CC(l,v) were estimated by minimizing equation (2), which was equivalent to maximizing the likelihood of the observed catch data. We considered f of up to an order of 4 with parameters v0, v1, v2, v3, and v4. Leaving out one or more of the parameters v0…v4 led to 31 additional models that were also considered as potential models for the catch comparison CC(l,v). Among these models, estimations of the catch comparison rate were made using multi-model inference to obtain a combined model (Burnham and Anderson 2002; Herrmann et al., 2017).

The ability of the combined model to describe the experimental data was evaluated based on the p-value. The p-value, which was calculated based on the model deviance and the degrees of freedom, should not be < 0.05 for the combined model to describe the experimental data sufficiently well, except for cases for which the data are subject to over-dispersion (Wileman et al., 1996; Herrmann et al., 2017). Based on the estimated catch comparison function CC(l,v) we obtained the relative catch efficiency (also named catch ratio) CR(l,v) between the two gillnet types using the following relationship:

$$CR(l,v) = \frac{CC(l,v)}{(1-CC(l,v))} \quad (4)$$

The catch ratio is a value that represents the relationship between catch efficiency of the bio gillnet and that of the nylon gillnet. Thus, if the catch efficiency of both gillnets is equal, CR(l,v) should always be 1.0. CR(l,v) = 1.5 would mean that the bio gillnet is catching 50% more cod with length l than the nylon gillnet. In contrast, CR(l,v) = 0.8 would mean that the bio gillnet is only catching 80% of the cod with length l that the nylon gillnet is catching.

The confidence limits for the catch comparison curve and catch ratio curve were estimated using a double bootstrapping method (Herrmann et al., 2017). This bootstrapping method accounts for between-set variability (the uncertainty in the estimation resulting from set deployment variation of catch efficiency in the gillnets and in the availability of cod) as well as within-set variability (uncertainty about the size structure of the catch for the individual deployments). However, contrary to the double bootstrapping method (Herrmann et al., 2017), the outer bootstrapping loop in the current study accounting for the between deployment variation was performed paired for the bio gillnet and nylon gillnet, taking full advantage of the experimental design with the bio gillnet and nylon gillnet being deployed simultaneously (see Fig. 1). By multi-model inference in each bootstrap iteration, the method also accounted for the uncertainty due to uncertainty in model selection. We performed 1000 bootstrap repetitions and calculated the Efron 95% (Efron, 1982) confidence limits. To identify sizes of cod with significant differences in catch efficiency, we checked for length classes in which the 95% confidence limits for the catch ratio curve did not contain 1.0.

Finally, a length-integrated average value for the catch ratio was estimated directly from the experimental catch data using the following equation:

$$CR_{average} = \frac{\sum_l \sum_{j=1}^{m} \{nt_{lj}\}}{\sum_l \sum_{j=1}^{m} \{nc_{lj}\}} \quad (5)$$

where the outer summation covers the length classes in the catch during the experimental fishing period.

2.5. Modelling the effect of number of times deployed on the length-integrated catch ratio

To investigate the effect of the number of times the gillnets were the deployed on the length-integrated catch ratio, the equation (5) was calculated for individual deployment sets such without the summation over gillnet sets. This led to a dataset consisting of pair values for number of times the gillnets were deployed and corresponding values for CRaverage. Based on this dataset, we tested if the value for CRaverage changed linearly with number of deployment times (DNO) using the following equation:

$$CR_{average}(DNO) = \alpha \times DNO + \beta_l \quad (6)$$

The last part of the analysis using model (6) was conducted using the linear model function (lm) in statistical package R (version 2.15.2; www.r-project.org).

3 Tensile strength tests

Tensile strength tests were carried out on samples of the bio and nylon gillnets used in before and after fishing experiments using a H10KT universal tensile testing machine (Tinius Olsen TMC, PA, USA). Samples of gillnets measuring approx. 20 x 20 meshes were cut from the centre of the new and used gillnets. The tests were performed in wet conditions (at least 40 replicates for each case) according to ISO 1806. Tensile strength, defined as the stress needed to break the sample, is given in kg, and elongation at break, defined as the length of the sample after it had stretched right when it breaks (L) is given relative to the initial mesh size in percentage.

4 Results

A total of 5332 cod (*Gadus Morhua*) were caught during the 18 deployments of the two gears with 2382 individuals caught in the biodegradable gillnet and 2950 caught in the nylon net (table 1). Figure 1 outlines the length dependency for the number of cod caught within each length class and by each gillnet. The biodegradable and nylon gillnet curves each have the same frequency tendency across length classes, while the biodegradable caught less for most length classes, the most fish for both gears were caught for length classes between 88 cm and 108 cm (fig. 1).

The catch comparison curve indicated a significant difference in catch efficiency between the two materials for individuals between 92 and 111 cm (fig 2). Within this range the nylon gillnet caught a significantly higher amount of cod as these length classes had a lower value for the biodegradable gillnets. The remaining length classes were caught at approximately the same frequency by the two gillnets. The curve provides a good fit to the catch data and this can be confirmed by the fit statistics in table 2. The trend outlined in figure 2 is further emphasized in the estimated catch ratio curve (fig. 3) as the nylon catches significantly more cod for these central length classes (92 cm – 111 cm). This interval is further explained in analysis of the individual length classes of 95, 100, 105 and 110 cm where the significant difference is shown by the narrow confidence limits. For example, in the length classes of 95 and 105 cm, the biodegradable gillnets caught 80.96% (CI = 71.05-89.01) and 72.53% (CI = 63.03-85.02) of what the nylon gillnets caught, respectively (table 2). The length integrated average value for the catch ratio of the biodegradable gillnet with respect to the nylon gillnet across all deployments was 80.75%. This indicates a reduction in catch by the biodegradable gillnet on average of 19.25% compared to the nylon gillnet.

The curve provided in figure 4 displays a trend opposite to that observed in previous sea trials testing biodegradable gillnets (Grimaldo et al., 2019, 2018). The biodegradable gillnet catch efficiency became more similar to that of the nylon gillnet as the number of times it was deployed increased. As this was seen to be size dependent from the catch ratio curve of figure 3 it could be explained if the mean size distribution changed throughout the fishing season. However, it was actually found that there was a slight tendency for the mean size to increase before it stabilized (table not given). So, we have two sets of results. Regarding the overall catch efficiency, we see a length dependency. The pattern is not the same but has the same tendency as in previous studies. Regarding the number of deployments, we have managed to obtain results that are exactly opposite to those in previous studies (Grimaldo et al., 2019, 2018).

Table 1: Catch data over all deployments

Set no.	Setting date	Fishing time (hh:mm)	Fishing depth (m) (min - max)	Accumulated number of deployments	Number of cod in bio gillnets	Number of cod in nylon (PA) gillnets	Minimum cod Length	Maximum cod length
1	24/01/19	43h 55m	40-115	1	30	38	66	124
2	24/01/19	46h 00m	48-85	1	14	30	61	124
1	26/01/19	46h 55m	40-115	2	21	31	77	113
2	26/01/19	47h 10m	48-85	2	41	47	71	123
1	28/01/19	24h 15m	40-115	3	15	20	75	114
2	28/01/19	24h 45m	48-85	3	7	13	81	112
1	29/01/19	47h 10m	40-115	4	29	37	68	118
2	29/01/19	47h 10m	48-85	4	13	30	76	109
1	31/01/19	23h 30m	40-115	5	13	20	71	107
2	31/01/19	23h 35m	48-85	5	5	10	89	106
1	04/02/19	19h 00m	40-115	6	51	54	78	120
2	04/02/19	19h 45m	48-85	6	97	99	78	118
1	05/02/19	20h 05m	40-115	7	29	55	80	110
2	05/02/19	20h 10m	48-85	7	74	103	71	120
1	06/02/19	22h 50m	40-115	8	50	49	79	122
2	06/02/19	22h 30m	48-85	8	55	95	65	121
1	07/02/19	23h 05m	40-115	9	81	107	78	121
2	07/02/19	24h 15m	48-85	9	107	125	74	125
1	08/02/19	22h 45m	40-115	10	130	133	78	116
2	08/02/19	21h 40m	48-85	10	112	125	64	123
1	09/02/19	22h 45m	40-115	11	51	77	72	122
2	09/02/19	23h 25m	48-85	11	67	71	79	124
1	10/02/19	23h 20m	40-115	12	81	100	74	125
2	10/02/19	23h 20m	48-85	12	27	33	81	117
1	11/02/19	24h 50m	40-115	13	238	286	68	127
2	11/02/19	22h 10m	48-85	13	186	225	68	126
1	12/02/19	22h 10m	40-115	14	169	213	78	122
2	12/02/19	22h 20m	48-85	14	88	125	74	123
1	13/02/19	18h 00m	40-115	15	142	157	81	121
2	13/02/19	18h 15m	48-85	15	107	125	74	118
1	28/02/19	17h 00m	40-115	16	64	71	77	123
2	28/02/19	17h 20m	48-85	16	59	73	68	118
1	02/03/19	23h 15m	40-115	18	57	73	72	121
2	02/03/19	23h 05m	48-85	18	72	100	79	125

Table 2: Catch rate and fit statistics results from the bio gillnet vs. nylon (PA) gillnet based on all deployments. Values in parentheses indicate 95% confidence intervals. DOF denotes the degrees of freedom.

Length (cm)	Catch ratio (%)
70	133.93 (69.35-228.18)
75	121.98 (83.59-196.40)
80	108.48 (82.92-163.15)
85	97.39 (79.49-127.52)
90	88.17 (75.45-101.07)
95	80.96 (71.05-89.01)
100	75.78 (66.87-83.90)
105	72.53 (63.03-85.02)
110	71.19 (58.50-94.23)
115	71.74 (54.58-105.68)
120	74.26 (47.67-114.94)
Average	80.75 (73.85-87.64)
p-value	0.2483
Deviance	64.92
DOF	58

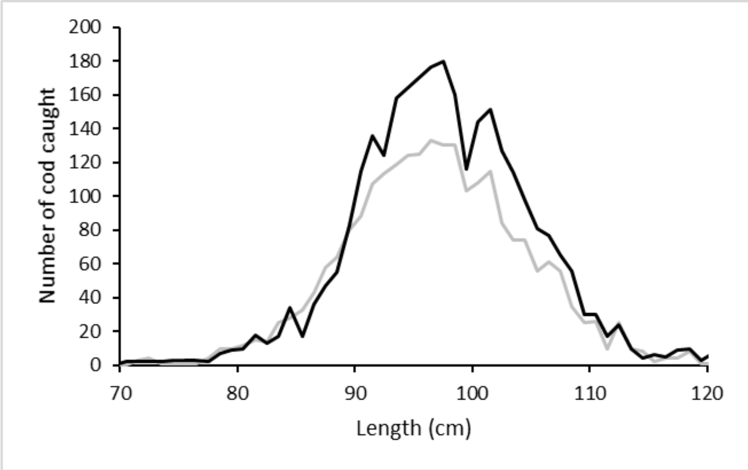

Fig. 1: The size distribution of fish caught with each type of gillnet (the black curve is for the nylon gillnet and the grey curve is for the bio gillnet).

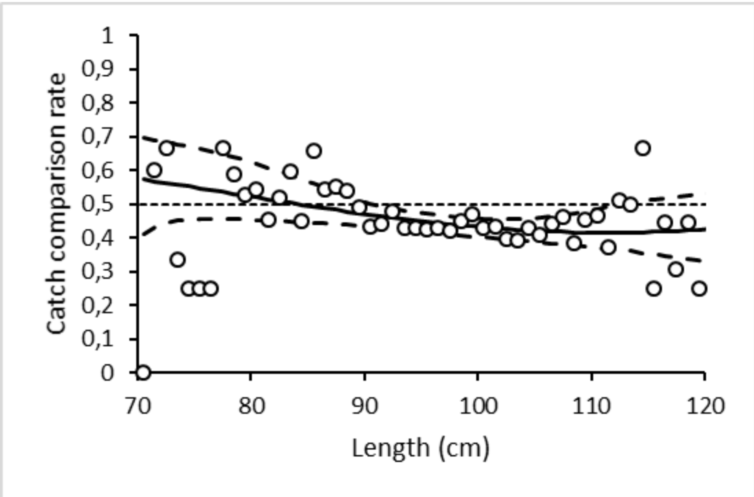

Fig 2: The catch comparison based on the total deployments, circle marks indicate the experimental rate and the curve indicates the modelled catch comparison rate. The dotted line at 0.5 indicates the baseline where both types of gillnets fish the same amount. The stippled curves indicate a 95% confidence interval for the estimated catch comparison curve.

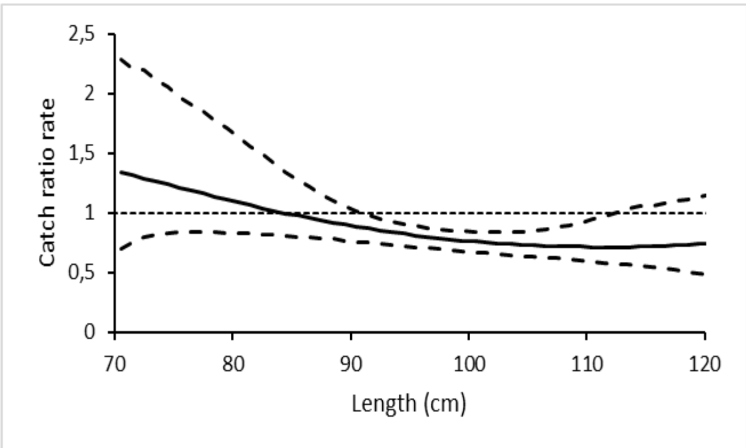

Fig 3: The estimated catch ratio curve based on all of the deployments (solid line). The dotted line at 1.0 indicates the baseline where fishing efficiency of both gillnet types is equal. The stippled curves represent a 95% confidence interval of the estimated catch ratio curve.

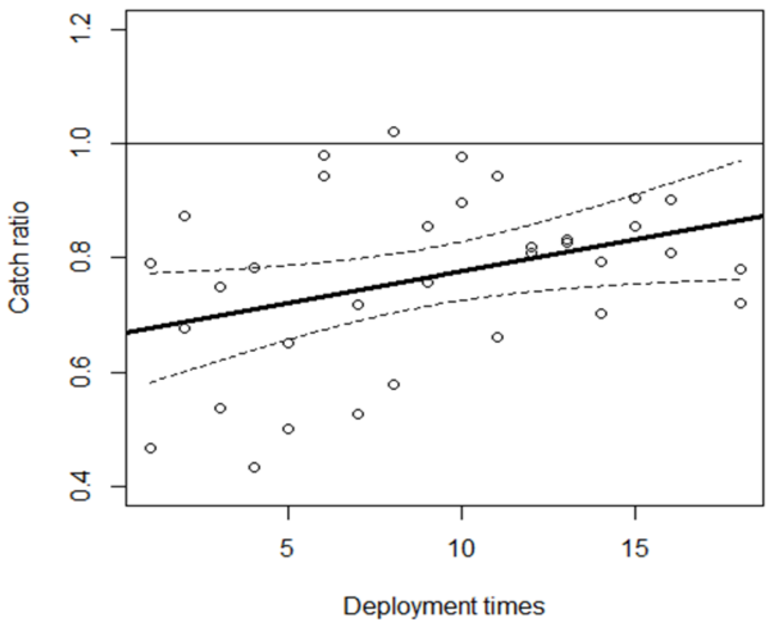

Fig. 4: The fit of linear model testing of the effect of the times deployed on the average catch ratio. The horizontal line at 1.0 indicates the point at which both the biodegradable and the nylon gillnets fish equally. The circle marks indicate the experimental length-integrated catch ratio (average catch ratio) for the individual deployments. The thick line indicates the modelled effect of times deployment on the average catch ratio. The two stipple curves indicate a 95% confidence interval for the linear model.

Tensile strength tests shoved no significant differences in tensile strength and elongation at break between new bio and nylon nets. When used, nylon and bionets lose 3.6% and 5.3 % of their tensile strength and 18% and 4.6% of their elongation at break (Table 3).

Table 3: Mean tensile strength (kg) and elongation at break (%) with 95 % confidence intervals (in brackets) for new and used gillnets.

Sea trial	Netting	Tensile strength (kg)			Elongation at break (%)		
		New	Used	%	New	Used	%
Winter season 2019	0.70mm Nylon	22.6 (22.9–23.2)	21.7 (20.9–22.4)	−3.6	40.0 (39.2–40.9)	32.6 (24.6–25.9)	−18.5
	0.75mm Biodegradable	22.5 (22.0–22.9)	21.3 (20.7–21.9)	−5.3	39.2 (38.5–39.8)	37.3 (36.7–37.9)	−4.6

5 Discussion and conclusion

The nylon gillnets caught 19% more fish (in numbers) than the biodegradable gillnets throughout the fishing season and generally showed better catch rates for most length classes. Any difference in breaking strength and elongation a break was detected when nets were new, and therefore it is unclear what caused the catch differences between the nets.

The number of times that the gillnets were deployed affected the relative catch efficiency of the gillnets with the nylon continuously loosing efficiency compared to the biodegradable. The curve provided in figure 4 displays a trend opposite to that observed in previous sea trials testing biodegradable gillnets (Grimaldo et al., 2019, 2018). The biodegradable gillnet catch efficiency became more similar to that of the nylon gillnet as the number of times it was deployed increased. As this was seen to be size dependent from the catch ratio curve of figure 3 it could be explained if the mean size distribution changed throughout the fishing season.

6 References

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