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Use of biodegradable materials to reduce marine plastic pollution in small scale coastal longline fisheries

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ABSTRACT

Pollution from lost, abandoned, or discarded fishing gear is recognized as a global nature conservation concern. Longlining with hooks is a commonly applied fishing method in fisheries around the world. The longline gear consists of a mainline with a number of baited hooks that are attached to it by thinner twine (snoods) which are often made of plastic material such as polyamide (nylon) or polyester that degrades very slowly in the marine environment. During longline fishing, some of the snoods are lost at sea contributing to marine macro- and micro-plastic pollution. The extent of the snood loss is often unknown and can vary between different longline fisheries and fishing grounds. In this study, we estimated and compared the risk for the biodegradable and nylon snood loss in an Adriatic small scale longline fishery. Further, we compared the catch composition and estimated catch efficiency between biodegradable and nylon snoods for capture of common pandora (*Pagellus erythrinus*), two-banded seabream (*Diplodus vulgaris*) and axillary seabream (*Pagellus acarne*). The risk for nylon snood loss in this longline fishery (3 % for each snood for each deployment), demonstrate that the use of more environmentally friendly materials is necessary for nature conservation. No significant differences between the performance of the two materials regarding snood loss rate, hook loss rate, catch efficiency and catch composition were found during short-term usage in the fishery. Based on these results, future long-term testing is encouraged to investigate whether this promising performance of the biodegradable snood material is persistent over longer fishing periods.

1. Introduction

Marine debris comprise of different materials among which plastic is considered as the most represented marine litter category due to its resistance to degradation and thus the persistence in the environment (Strafella, Fabi, Depalatovic, Cvitković, & Fortibuoni, 2019). At a global level, it is estimated that 640 000 tons of fishing gear is lost, abandoned, or discarded each year, contributing to the marine plastic pollution (Macfadyen, Huntington, & Cappell, 2009). Abandoned, lost, or otherwise discarded fishing gear (ALDFG) is recognized as a problem of global concern due to increasing fishing effort and the use of non-degradable materials for the fishing gear, primarily plastics. Such ALDFG has negative ecological impacts on the marine environment due to macro- and microplastic pollution (Gilman, 2015). Therefore, pollution resulting from fishing gear losses is now considered as an important threat to the marine ecosystem (Strafella et al., 2019).

The rate of littering can vary greatly among regional areas depending on the scale of fishing activities at the local level and on the specific hydrological and geomorphological conditions (Pham, Ramirez-Llondra, Alt, & Amaro, 2014; Moschino et al., 2019; Strafella et al., 2019). In the Adriatic Sea, pollution resulting from lost, abandoned, or discarded fishing gear (such as longlines and gillnets) and aquaculture related debris accounts for half of the total plastic litter (Strafella et al., 2019). Specifically, in a study conducted in the western part of the Adriatic Sea, results showed that 78 % of the total marine debris consisted of derelict fishing gear where longlines were the most abundant

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gear identified (61 %) (Consoli, Romeo, Angiolillo, Canese, & Esposito, 2019).

Longlines with hooks are commonly used fishing gears in the world (He, Chopin, Suuronen, Ferro, & Lansley, 2021). One example of such fishery is the small-scale coastal longline fishery in the Adriatic targeting Sparidae species such as common pandora (*Pagellus erythrinus*) and two-banded seabream (*Diplodus vulgaris*). Each longline consists of a mainline and baited hooks that are connected to it by thinner twines called snoods. In demersal longline fisheries, snoods are often lost at sea during fishing because of, for example, snagging at the seafloor during the deployment or when the fish break the snood material (Cerbule et al., 2022). In many longline fisheries, the mainline and snoods are made from monofilament or multifilament polyamide (nylon) or multifilament polyester. Such plastic materials degrade slowly in the seawater in case of being lost. The ALDFG resulting from longlines and snoods do not represent a ghost fishing risk to the same extent as other fishing gear types such as gillnets. However, they can cause considerable long-term negative effects on the marine environment (Consoli et al., 2019) such as macro- and micro-plastic pollution when the material from lost snoods degrades into smaller plastic particles that can be ingested by marine organisms.

To limit the pollution caused by ALDFG, new biodegradable plastic materials are being tested in longline and gillnet fisheries (e.g., Kim et al., 2014a; 2014b; Grimaldo et al., 2019; Grimaldo et al., 2020; Cerbule et al., 2022; Cerbule et al., 2022). The aim of the biodegradable material is to limit marine plastic pollution as the material degrades in a shorter period when lost at sea compared to non-biodegradable materials such as nylon (Brakstad et al., 2022) and is aimed to degrade into components that are not harmful to the marine environment (Lucas et al., 2008).

Use of biodegradable materials such as polybutylene succinate-*co*-adipate-co-terephthalate (PBSAT) to replace non-biodegradable material (nylon) in snoods has earlier been tested in the Barents Sea fishery targeting cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) for reducing the plastic pollution resulting from lost snoods in this longline fishery (Cerbule et al., 2022). The results from these trials showed no differences in the short-term performance between the new and the traditionally used nylon material regarding capture efficiency and the snood loss rate. Therefore, this biodegradable material may be used to reduce the marine pollution resulting from the longline fisheries. However, such experiments could potentially show differences when testing the material performance in different fisheries and in different regions such as the coastal demersal longline fishery in the Eastern Adriatic. Specifically, the differences between environmental factors such as temperature and salinity between the two regions can affect the degradation of the biodegradable material and thus result in lower performance of the material in this fishery.

To be accepted commercially, the biodegradable snood loss should not exceed the loss of snoods made of nylon. Furthermore, the fishing gear performance of the biodegradable gear should be comparable to the traditionally used gear regarding the catch efficiency of the targeted species. Also, since the longline fishery in the Adriatic Sea addressed in the present study targets several fish species, the effect on the entire catch composition has to be investigated rather than focusing only on the primary target species. Specifically, although the commonly captured species are common pandora, two-banded seabream and axillary seabream (*Pagellus acarne*), several other species with a commercial value are caught in this fishery. Thus, the assessment of the whole composition of the species diversity in the catches, captured with both nylon and biodegradable snoods, would allow making a more holistic evaluation of the performance of the longlines in this fishery and of the effect of the gear on the full species community. Specifically, such approach would enable evaluating the effect of the gear changes on the full species community instead of focusing on a few target species.

Thus, the aims of this study were to address the following research questions:

- What is the risk of loss of conventional nylon snoods and snoods constructed of biodegradable PBSAT material in the Adriatic longline fishery?
- Is there any difference in catch efficiency of common pandora, two-banded seabream and axillary seabream if the snood material is changed from nylon to biodegradable PBSAT plastic material?
- What is the catch composition in small-scale longline fisheries in the Eastern Adriatic, and can material properties of PBSAT snoods change the catch composition in this fishery?

2. Materials and methods

2.1. Sea trials and experimental design

Sea trials were conducted with a small-scale fishing vessel (6.6 m LOA, 25.6 kW) during October 2022 in Croatia. The fishing grounds were located between N43°95854-44°12371 and E15°02750-15°18495 (Fig. 1a). The fishing depth varied between 33.0 and 64.7 m (Supplementary material 1).

During each deployment day, eight separate mainlines with snoods were deployed close together on a rocky substrate at the edge of a reef. Therefore, the deployment pattern varied with some of the mainlines being deployed parallel to each other while others were deployed in a consecutive order (in a row) depending on the variations in the seabed conditions. The mainlines were made of monofilament nylon with twine diameter of 1 mm. Each mainline consisted of 25 biodegradable and 25 nylon snoods (50 snoods and hooks in total) with twine diameter of 0.44 mm. We used the same twine thickness in both biodegradable and nylon snoods in this experiment to avoid differences in catch efficiency that can potentially be caused by alternating snood diameter (Herrmann, Sistiaga, Rindahl, & Tatone, 2017).

Biodegradable (B) and nylon (N) snoods were attached in an alternated order on the mainline so that each material type was exposed to the same spatial variability regarding fish availability: N-B-N-B-N-B-N-(..) (Fig. 1b). The distance between each snood was ~ 6.4 m. Therefore, the total length of each mainline was 314 m. In all longlines, same type of hooks was used (J-hooks, VMC 9746S, no. 13). Prior to each deployment, hooks on all longlines were baited manually using squid and stored in tubs.

During retrieval of the longlines, catches were sorted and counted by species and separated according to type of the snoods (biodegradable or nylon). Further, all individuals of common pandora (minimum conservation reference size (MCRS) = 15 cm), axillary seabream (MCRS = 18 cm) and two-banded seabream (MCRS = 17 cm) were measured for the total length to the closest 0.5 cm below.

After each fishing trip, the numbers of lost hooks and lost snoods with hooks were recorded for each snood type (biodegradable and nylon, respectively). Specifically, we separately recorded two situations regarding hook and snood losses. First, the situation where the snood was broken close to the hook resulting in a hook loss and need of attachment of new hook on the existing snood. Second, a situation where the snood was broken closer to the mainline, resulting in need for replacement of snood and attachment of a new hook. Before new deployments with the same mainlines, new hooks or snoods with hooks, respectively, were attached where necessary so that the number of snoods was identical for each longline deployment and consisted of 50 snoods on each mainline.

2.2. Estimating probabilities of hook and snood loss

To estimate probabilities for losing the hook or the hook together with the snood k for mainline i, during deployment j, we recorded the damage status of the specific nylon snood on the specific mainline and specific deployment sN_{ijk} according to:

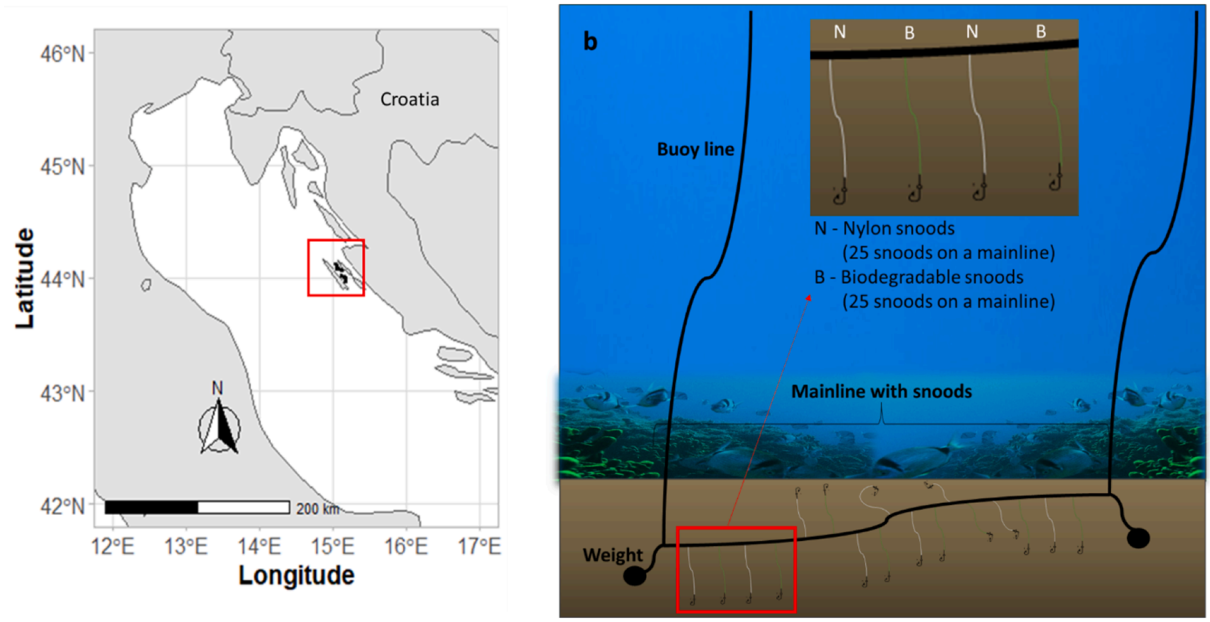

Fig. 1. Map of the location where the experiments were conducted (a) and illustration of experimental setup (b) showing longline components.

$$sN_{ijk} = \begin{cases} 0 & : \quad \textit{snood line and hook intact} \\ 1 & : \quad \textit{hook lost but snood intact} \\ 2 & : \quad \textit{hook and part or entire snood lost} \end{cases} . \tag{1}$$

For the biodegradable snoods, we used the same approach and scored the status sB_{ijk} as for the nylon snoods (Eq. (1)).

The probabilities for losing only the hook for nylon (phN_{ij}) and biodegradable (phB_{ij}) snoods during one specific deployment j of mainline i were estimated by:

$$\begin{gathered} phN_{ij} = \frac{1}{m}\sum\nolimits_{k=1}^{m} g\left(sN_{ijk}\right) \\ phB_{ij} = \frac{1}{m}\sum\nolimits_{k=1}^{m} g\left(sB_{ijk}\right) \\ \textit{with} \\ g(s) = \begin{cases} 0 & \forall \quad s = 0 \\ 1 & \forall \quad s > 0 \end{cases} \end{gathered} \tag{2}$$

where m is the number of snoods on the mainline made of nylon or biodegradable materials, respectively ($m = 25$).

For estimating the probability of losing both the hook and the snood for nylon ($pshN_{ij}$) and biodegradable ($pshB_{ij}$) materials, respectively, during one specific deployment j of mainline i, we used:

$$\begin{gathered} pshN_{ij} = \frac{1}{m}\sum\nolimits_{k=1}^{m} g\left(sN_{ijk}\right) \\ pshB_{ij} = \frac{1}{m}\sum\nolimits_{k=1}^{m} g\left(sB_{ijk}\right) \\ \textit{with} \\ g(s) = \begin{cases} 0 & \forall \quad s < 2 \\ 1 & \forall \quad s = 2 \end{cases} \end{gathered} . \tag{3}$$

The uncertainties for probabilities of losing the hook or the snood together with the hook during one deployment j for the specific mainline i were estimated by bootstrapping for nylon and biodegradable snoods separately by resampling (1000 bootstrap repetitions) the individual snoods on the mainline and applying Eq. (1)–(3). Uncertainties were given as Efron 95 % confidence intervals (CI) (Efron, 1982) similar as in Cerbule et al. (2022).

For inferring the effect on probability for hook loss or snood and hook loss by changing the snood material for one specific deployment j of specific mainline i, we used:

$$\begin{aligned} \Delta ph_{ij} &= phB_{ij} - phN_{ij} \\ \Delta psh_{ij} &= pshB_{ij} - pshN_{ij} \end{aligned} . \tag{4}$$

The advantage of inferring the difference in probability for hook and snood and hook loss between the two materials for the individual deployments is that the two materials are exposed to the same varying fishing conditions. This increases the power in inferring differences regarding the material type used in snoods.

Efron 95 % percentile CIs for Δph_{ij} and Δpsh_{ij} were obtained based on the two bootstrap populations of results (1000 bootstrap repetitions in each). As they were obtained independently, a new bootstrap population of results was created by (Herrmann, Krag, & Krafft, 2018):

$$\begin{aligned} \Delta ph_{ij_q} &= phB_{ij_q} - phN_{ij_q} \, q \in [1 \cdots 1000] \\ \Delta psh_{ij_q} &= pshB_{ij_q} - pshN_{ij_q} \, q \in [1 \cdots 1000] \end{aligned} \tag{5}$$

where q denotes the bootstrap repetition index. As the bootstrap resampling were independent for the two materials, it is valid to generate the bootstrap population of results for the difference based on Eq. (5) using the two independently generated bootstrap files (Herrmann et al., 2018; Cerbule et al., 2022). In case Δph_{ij_q} or Δpsh_{ij_q} do not include the value 0.0 in the CIs, the hook or snood and hook loss probability between biodegradable and nylon material would be significantly different.

During each experimental fishing day j, the mainlines were deployed on slightly different fishing grounds with some similarities in the conditions the fishing took place. Therefore, it is relevant also to quantify the mean values for hook and snood and hook loss probability based on the results for individual mainlines deployed during the same day j. Therefore, we used the following equation:

$$
\begin{aligned}
phN_j &= \frac{1}{a}\sum_{i=1}^{a} phN_{ij} \\
pshN_j &= \frac{1}{a}\sum_{i=1}^{a} pshN_{ij} \\
phB_j &= \frac{1}{a}\sum_{i=1}^{a} phB_{ij} \\
pshB_j &= \frac{1}{a}\sum_{i=1}^{a} pshB_{ij} \\
\Delta ph_j &= \frac{1}{a}\sum_{i=1}^{a} \Delta ph_{ij} \\
\Delta psh_j &= \frac{1}{a}\sum_{i=1}^{a} \Delta psh_{ij}
\end{aligned}
\tag{6}
$$

where a is the number of mainlines fished during the specific deployment day. In Eq. (6), we applied Eq. (2)–(4). Uncertainties for the values estimated by Eq. (6) were obtained by bootstrapping by resampling results for the a mainlines deployed for the specific day j. We used Efron 95 % CIs which were obtained by using 1000 bootstrap repetitions.

Further, to quantify the mean probabilities for hook loss and snood and hook loss, respectively, for the complete fishing trials, we used Eq. (6) in:

$$
\begin{aligned}
phN &= \frac{1}{u}\sum_{j=1}^{u} phN_j \\
pshN &= \frac{1}{u}\sum_{j=1}^{u} pshN_j \\
phB &= \frac{1}{u}\sum_{j=1}^{u} phB_j \\
pshB &= \frac{1}{u}\sum_{j=1}^{u} pshB_j \\
\Delta ph &= \frac{1}{u}\sum_{j=1}^{u} \Delta ph_j \\
\Delta psh &= \frac{1}{u}\sum_{j=1}^{u} \Delta psh_j
\end{aligned}
\tag{7}
$$

where u is the total number of deployment days. Uncertainties for the values estimated by Eq. (7) were obtained by bootstrapping results for the u deployment days. We used Efron 95 % CIs which were obtained by using 1000 bootstrap repetitions.

2.3. *Estimating the length-dependent catch efficiency between longlines with different snood materials*

Comparison of catch efficiency for the three target species (two-banded seabream, axillary seabream and common pandora) between biodegradable and nylon snoods was estimated by analysing the relative catch efficiency between biodegradable and nylon snoods separately for each species following procedure descried below. Specifically, we estimated the length-dependent catch comparison rate $CC(l,\boldsymbol{v})$ and catch ratio $CR(l,\boldsymbol{v})$ for deployment of all mainlines during all deployment days to investigate potential differences in catch efficiency when using biodegradable instead of nylon snoods (Herrmann et al., 2017; Cerbule et al., 2022). We assumed the same fish availability regarding the abundance and size structure for both biodegradable and nylon snoods since they were deployed in an alternated order on each mainline. Therefore, we used paired catch comparison analysis for estimating the catch efficiency (Lomeli et al., 2021). Specifically, we used the count numbers of the three most frequently species caught with biodegradable and nylon snoods, separately) to determine whether there was a significant difference in the catch efficiency between the two snood types.

To assess the relative length dependent catch comparison rate (CC_l) of changing from nylon to biodegradable snoods, we used Eq. (8) (i.e., Lomeli et al., 2021):

$$CC_l = \frac{\sum_{j=1}^{u}\sum_{i=1}^{m} nB_{lij}}{\sum_{j=1}^{u}\sum_{i=1}^{m}\left\{nB_{lij} + nN_{lij}\right\}}. \tag{8}$$

In Eq. (8), $\boldsymbol{nB_{lij}}$ and $\boldsymbol{nN_{lij}}$ are the number (n) of fish of the selected species with length l, caught in deployments j for mainlines i with the biodegradable (B) and nylon (N) snoods, respectively. The functional description of the catch comparison rate $CC(l,\boldsymbol{v})$ that experimentally was expressed by Eq. (8) was attained using maximum likelihood estimation by minimizing the Expression (9) (Lomeli et al., 2021):

$$-\sum_{j=1}^{u}\sum_{i=1}^{m}\sum_{l}\left\{nB_{lij}\times ln[CC(l,\boldsymbol{v})] + nN_{lij}ln[1.0 - CC(l,\boldsymbol{v})]\right\}. \tag{9}$$

In Expression (9), $\boldsymbol{v}$ represents the parameters describing the catch comparison curve defined by $CC(l,\boldsymbol{v})$ (Lomeli et al., 2021). The experimental CC_l was modelled by the function $CC(l,\boldsymbol{v})$ using the following equation (Herrmann et al., 2017):

$$CC(l,\boldsymbol{v}) = \frac{exp[f(l, v_0, \cdots, v_k)]}{1 + exp[f(l, v_0, \cdots, v_k)]}. \tag{10}$$

In Eq. (10), f is a polynomial of order k with coefficients v_0-v_k, such that $\boldsymbol{v} = (v_0,\ldots,v_k)$ (Lomeli et al., 2021). We considered f of up to an order of 4. Leaving out one or more of the parameters $v_0 \ldots v_4$, at a time resulted in 31 additional candidate models for $CC(l,\boldsymbol{v})$. Among these models, the catch comparison rate was estimated using the multi-model inference to obtain a combined model (Burnham & Anderson, 2002; Herrmann et al., 2017). The ability of the combined model to describe the experimental data was based on the p-value. The p-value is calculated based on the model deviance and degrees of freedom (DOF) (Wileman, Ferro, Fonteyne, & Millar, 1996; Herrmann et al., 2017). Therefore, suitable fit statistics for the combined model to describe the experimental data sufficiently well should include a p-value > 0.05 (Lomeli et al., 2021). If the p-value exceeded 0.05, the deviance and the DOF were assessed to determine if the result was due to structural problems when modelling the experimental data, or due to overdispersion. Further, to provide a direct relative value of the catch efficiency between the two snood materials, we used the following catch ratio $CR(l,\boldsymbol{v})$ equation (Lomeli et al., 2023):

$$CR(l,\boldsymbol{v}) = \frac{CC(l,\boldsymbol{v})}{[1 - CC(l,\boldsymbol{v})]}. \tag{11}$$

We used a double bootstrapping method with 1000 bootstrap repetitions to estimate the Efron 95 % CIs for the catch comparison and catch ratio (Efron, 1982). If the catch efficiency of the biodegradable and nylon snoods is equal, the catch comparison rate is equal to 0.5 and the catch ratio is 1.0 (Lomeli et al., 2023; Cerbule et al., 2022).

2.4. *Estimation of length-integrated average catch ratio*

Based on the experimental catch data, length-integrated average values for the catch ratio for target sized fish of each species above the MCRS ($CR_{average+}$) were assessed utilizing the following equation (Eq. (12) (Herrmann, Grimaldo, Brčić, & Cerbule, 2021):

$$CR_{average+} = 100 \times \frac{\sum_{j=1}^{u}\sum_{i=1}^{m}\sum_{l \geq MLS} nB_{lij}}{\sum_{j=1}^{u}\sum_{i=1}^{m}\sum_{l \geq MLS} nN_{lij}}. \quad (12)$$

In case the estimated $CR_{average+}$ value includes 100 % within the CIs, this implies no significant differences in the length-integrated average values between biodegradable and nylon snoods, while values significantly higher than 100 % would mean that biodegradable snoods are retaining significantly more target sized fish compared to gear with nylon snoods (Herrmann et al., 2017). Contrary to the length-dependent evaluation of $CR(l,\boldsymbol{v})$, the $CR_{average+}$ is specific for the fish population structure encountered during the fishing trials (Herrmann et al., 2017). Therefore, it cannot be extrapolated to other scenarios in which the size structure of the three fish species may be different.

2.5. Quantification of species composition in longline catches

To quantify the species composition observed in longline catches with biodegradable and nylon snoods, respectively, we used species dominance estimation (Cerbule et al., 2022; Herrmann et al., 2022). This estimate takes into consideration all observed species in the catch and is measuring how much one or few species dominate among the other species in the catches (Maurer & McGill, 2011). In this study, we estimated the catch composition for each snood type (biodegradable and nylon) separately by estimating the dominance patterns of species observed in our samples averaged over snood deployments.

The species dominance patterns in catch composition retained by biodegradable and nylon snoods were estimated separately, by using the following equation (Cerbule et al., 2022; Herrmann et al., 2022):

$$d_e = \frac{\sum_{j=1}^{u}\sum_{i=1}^{m} n_{eij}}{\sum_{e=1}^{t}\sum_{j=1}^{u}\sum_{i=1}^{m} n_{eij}}. \quad (13)$$

In Eq. (13), n_{eij} is the count number of individuals of species e caught in deployment j for mainline i with the specific snood material (biodegradable or nylon). t is the maximum species ID following the approach for species ranking as outlined in Herrmann et al. (2022).

Further, we used cumulative dominance curves to represent species dominance patterns by showing the cumulative proportional abundances of the species plotted against the species rank (Warwick, Clarke, & Somerfield, 2008). Cumulative dominance is estimated as follows (Eq. (14) (Cerbule et al., 2022; Herrmann et al., 2022):

$$D_E = \frac{\sum_{e=1}^{E}\sum_{j=1}^{u}\sum_{i=1}^{m} n_{eij}}{\sum_{e=1}^{t}\sum_{j=1}^{u}\sum_{i=1}^{m} n_{eij}} \quad \text{with} \quad 1 \leq E \leq t \quad (14)$$

In Eq. (14) E is the species ID summed up in the nominator (Cerbule et al., 2022; Herrmann et al., 2022). Following the approach in Herrmann et al. (2022) and Cerbule et al. (2022), we kept a fixed species IDs for species in all catches in the cumulative dominance curves to allow comparison of the steepness of the cumulative dominance curves. This approach allows obtaining an overview of how many species are dominant and the distribution of their relative dominance in longline catches with biodegradable and nylon snoods, respectively. The steeper the resulting cumulative dominance curve is, the more dominated the particular species is in the sample. On the contrary, the horizontal parts in cumulative dominance curves would show that the particular species are not abundant (Cerbule et al., 2022).

We applied the same approach for uncertainty estimation for the observed catch compositions as in Herrmann et al. (2022) and Cerbule et al. (2022). Specifically, we obtained Efron 95 % CIs (Efron, 1982) for dominance patterns following the procedure described in Herrmann et al. (2022). This procedure enables estimation of the uncertainty around the dominance values induced by limited sample sizes for individual deployments as well as for between deployment variation in species dominance values.

The difference Δd in species dominance d in the nylon (N) and biodegradable (B) snoods was estimated by (Cerbule et al., 2022; Herrmann et al., 2022):

$$\Delta d_e = dB_e - dN_e \quad (15)$$

where dB_e and dN_e are obtained by using Eq. (13). CIs for Eq. (15) were obtained based on separate bootstrap populations for dB_e and dN_e similar as in Cerbule et al. (2022). When inferring for significance, we inspected if the CIs for the difference contained the value 0.0. If 0.0 value was within the CIs, no significant difference was detected (Cerbule et al., 2022; Herrmann et al., 2022). The analyses described above in sections 2.3-2.5 were conducted using the software tool SELNET (Herrmann, Sistiaga, Nielsen, & Larsen, 2012), software version date 27 March 2023.

3. Results

3.1. Risk of hook and snood loss

During the experiments, eight mainlines with 50 snoods each were deployed during six fishing trips, resulting in 48 longline deployments. Each deployment had 200 biodegradable and 200 nylon snoods. During our trials, we observed both situations of loosing snoods together with hooks (Fig. 2a) and loosing hooks without the snoods (Fig. 2b).

The total number of observed lost hooks over all deployments were 95 and 69 for the snoods with biodegradable and nylon material, respectively. Of those, cases where the hook was lost together with part of the snood was 53 for the biodegradable snoods and 36 for the nylon snoods.

The estimated probabilities for losing a hook or a snood together with hook during each deployment separately varied over the deployments. However, the results did not show any significant differences between the two materials (Fig. 3a and 4a) except of one instance during deployment on day 4 where a higher loss of hooks from snoods of biodegradable (phB_{ij}) material compared to nylon (phN_{ij}) was shown (Fig. 3a). However, no other significant differences for hook or snood and hook loss probabilities between the two materials during the deployments were observed. Furthermore, these differences were not significant either when compared for each deployment day based on the results for the individual mainlines deployed (Fig. 3b and 4b), although there was an indication that more snoods of biodegradable materials were lost during each deployment day.

Finally, for the whole fishing trials with biodegradable and nylon snoods, the estimated probabilities for losing a hook attached to the mainline by biodegradable (phB) or nylon (phN) snoods were 7.91 % (CI: 5.17–11.17 %) and 5.75 % (CI: 2.75–9.83 %), respectively. Similarly, as when considering the snood loss for each deployment or deployment day, the pairwise difference between the probabilities for hook losses between the two material types (Δph_{ij}) for the whole fishing trials did not show any statistically significant differences (Fig. 3c). Further, the pairwise difference between the probabilities for loss of snoods together with hooks (Δpsh_{ij}) showed an indication that the probability of snood and hook loss is higher for the biodegradable material. Specifically, the estimated snood and hook loss for the whole fishing trials was 4.42 % (CI: 2.58–6.50 %) for biodegradable snoods and 3.00 % (CI: 1.00–5.92 %) for snoods of nylon material (Fig. 4c).

3.2. Catch efficiency of biodegradable versus nylon snoods

In total, 347 common pandora, 167 axillary seabream and 87 individuals of two-banded seabream, were captured and included in the analysis (Table 1). The fit statistics for the catch comparison analysis showed that the modelled curve fitted the experimental data well for

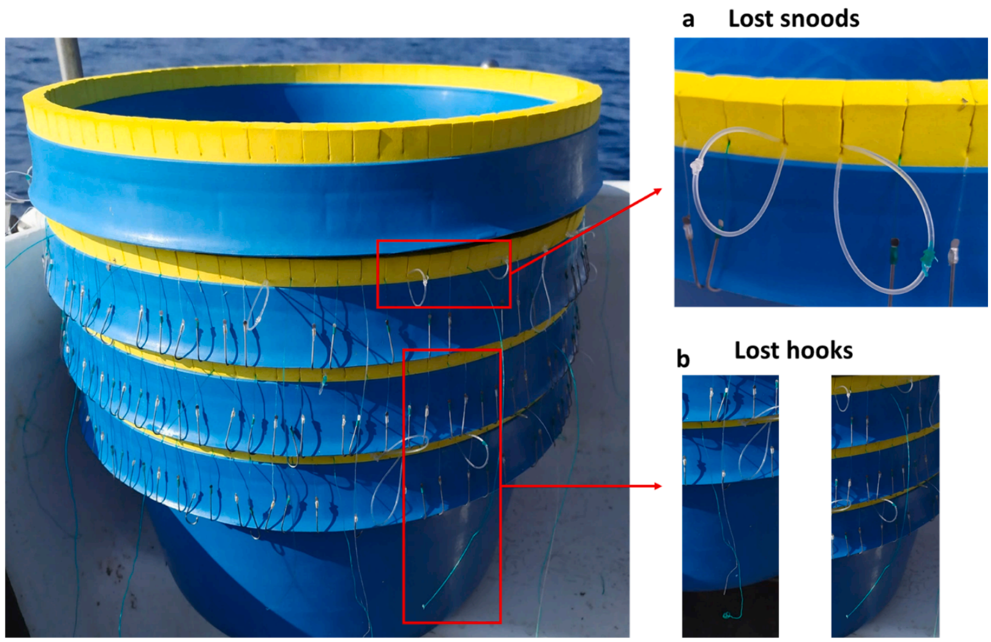

Fig. 2. Examples of cases with snood (a) and hook (b) loss after longline retrieval.

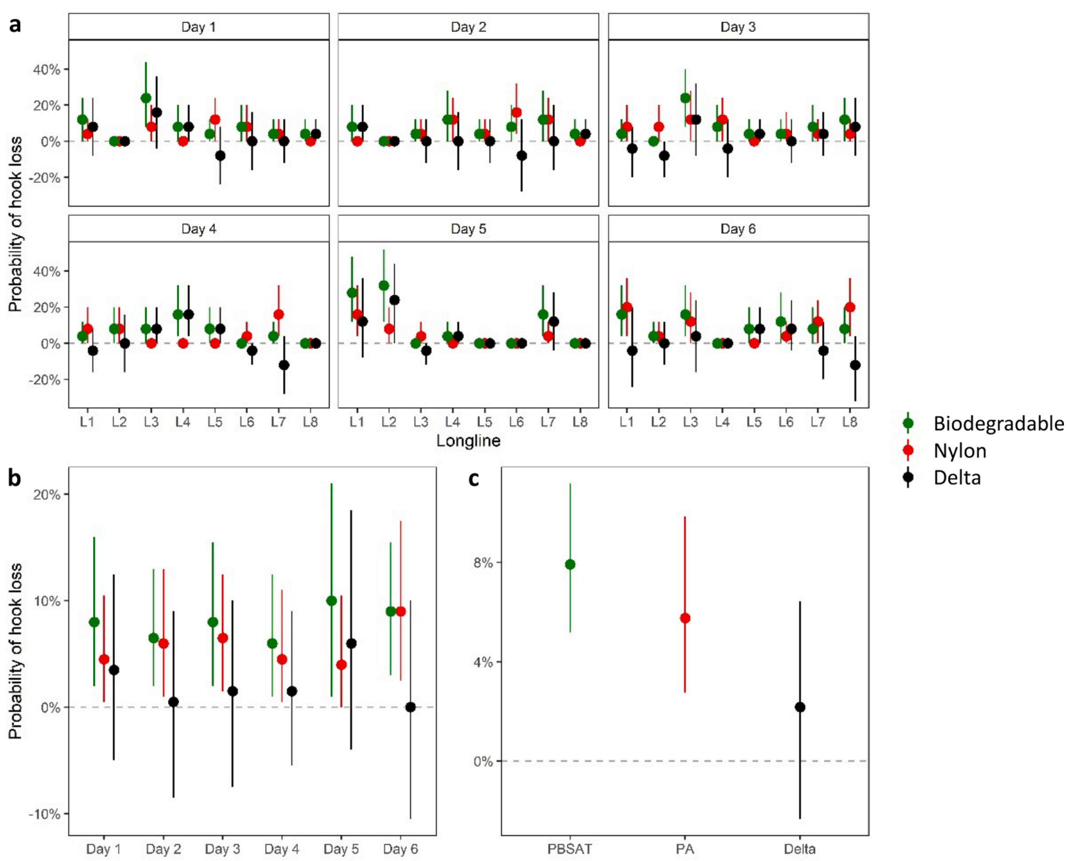

Fig. 3. Probabilities (in %) for losing a hook of biodegradable (green) and nylon (red) material. a: Probabilities estimated for each deployment in each day (L 1–8). b: Probabilities estimated for each deployment day (Day 1–6). c: Mean probabilities for hook loss for the complete fishing trials for the two snood materials separately. Black points are pairwise difference inferring the effect on probability for hook loss by changing the snood materials.

axillary seabream since the *p*-value was > 0.05 (Wileman et al., 1996). For two-banded seabream and common pandora, the *p*-value was < 0.05 (Table 1); however, the catch comparison curves represented the trends in experimental data well (Fig. 5), therefore, the low *p*-value was assumed to be due to overdispersion in the data.

Both snood material types had similar patterns of capturing all three species regarding the fish length, with most individuals being above the MCRS for all species (Fig. 5). Further, biodegradable snoods did not

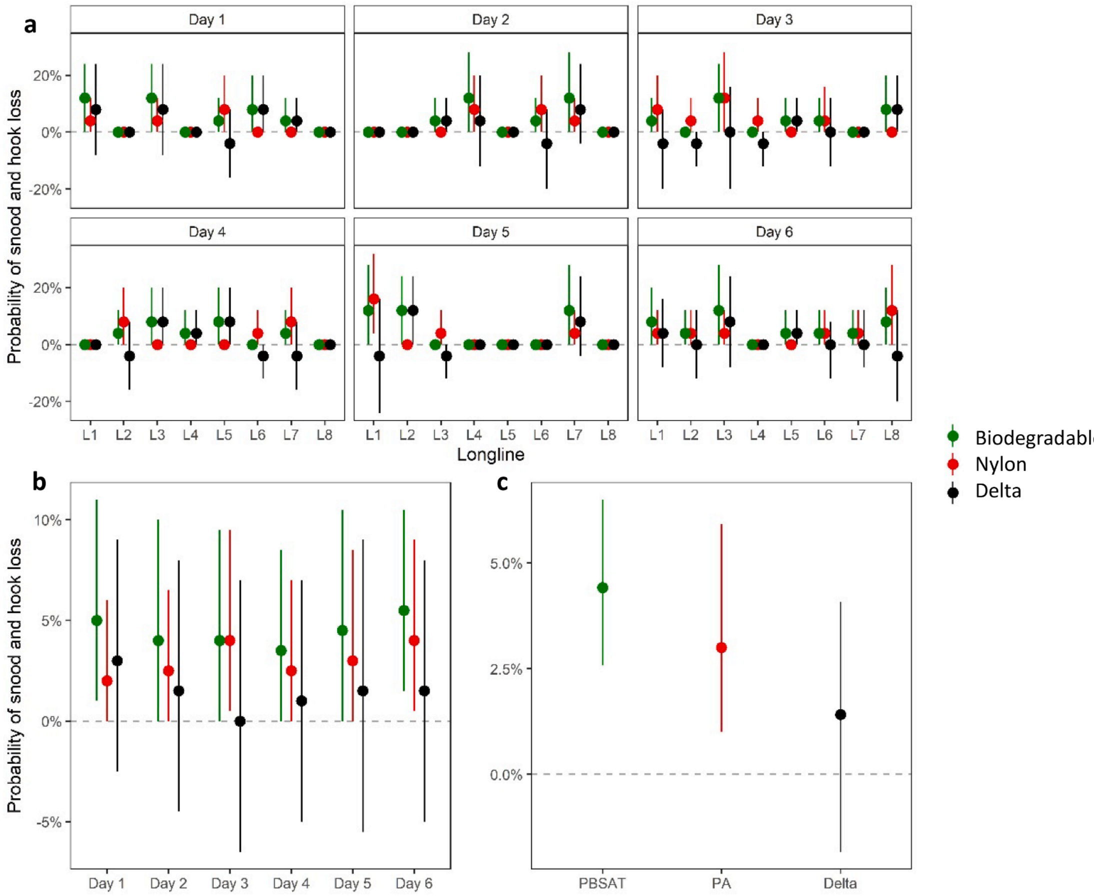

Fig. 4. Probabilities (in %) for losing a snood together with hook of biodegradable (green) and nylon (red) material. a: Probabilities estimated for each deployment (L 1–8). b: Probabilities estimated for each deployment day (Day 1–6). c: Mean probabilities for snood and hook loss for the complete fishing trials for the two snood materials separately. Black points are pairwise difference inferring the effect on probability for snood and hook loss by changing the snood materials.

Table 1
Number of fish observed, fit statistics, and catch comparison results. Values in brackets represent 95 % Efron confidence CIs. DOF denotes degrees of freedom.

	Common pandora	Two-banded seabream	Axillary seabream
Number of individuals; biodegradable snoods	169	50	83
Number of individuals; nylon snoods	178	37	84
p-value	0.0020	0.0290	0.1481
Deviance	59.98	28.32	20.66
DOF	32	16	15
CRaverage+ (%)	96.08 (75.44–117.39)	108.33 (81.81–138.09)	96.08 (72.41–132.56)

show significant differences in catch efficiency for any of the three species when compared to the nylon snoods (Fig. 5). Specifically, the average catch ratio (*CRaverage+*) for target sized individuals (i.e., over MCRS) of the three species did not show any significant differences when using biodegradable instead of nylon snood material (Table 1).

3.3. Species dominance pattern in catch compositions

During the trials in this coastal longline fishery, a total of 338 and 347 individuals belonging to 21 species were captured by biodegradable and nylon snoods, respectively (Table 2).

The species cumulative dominance patterns (Fig. 6) and species dominance values (Supplementary material 2) showed that the longline catch in this fishery is dominated by the three main target species, the two-banded seabream, axillary seabream and common pandora. However, during our experiments, other species contributed to the catches to a small extent as shown by the dominance curves for the cumulative dominance values. Thus, some species were recorded in only few deployments (Table 2). The species cumulative dominance patterns did not differ significantly between catches using biodegradable or nylon snood material (Fig. 6; Supplementary material 2). The pairwise difference in cumulative dominance (delta) curves (Fig. 6) is used for inferring for differences in catch composition between longline catches with snoods of biodegradable and nylon materials. No significant differences between the two materials were detected regarding the catch composition in species dominance as the results included 0.0 within the obtained CIs.

4. Discussion

In this study, we investigated whether biodegradable PBSAT material can be used to reduce marine macro- and micro-plastic pollution caused by lost snoods in the Adriatic small scale longline fishery. Specifically, we investigated the short term differences in performance between the materials by estimating the risk of hook and snood and hook losses, catch efficiency, and catch composition in this fishery.

During this study, we differentiated between hook loss and snood and hook loss probability. The hook loss alone implies an attachment of new hook on an existing snood for the next deployment of the longline which results in additional work and expenses for the fishers regarding use of new hooks. However, the second situation when the hooks are lost

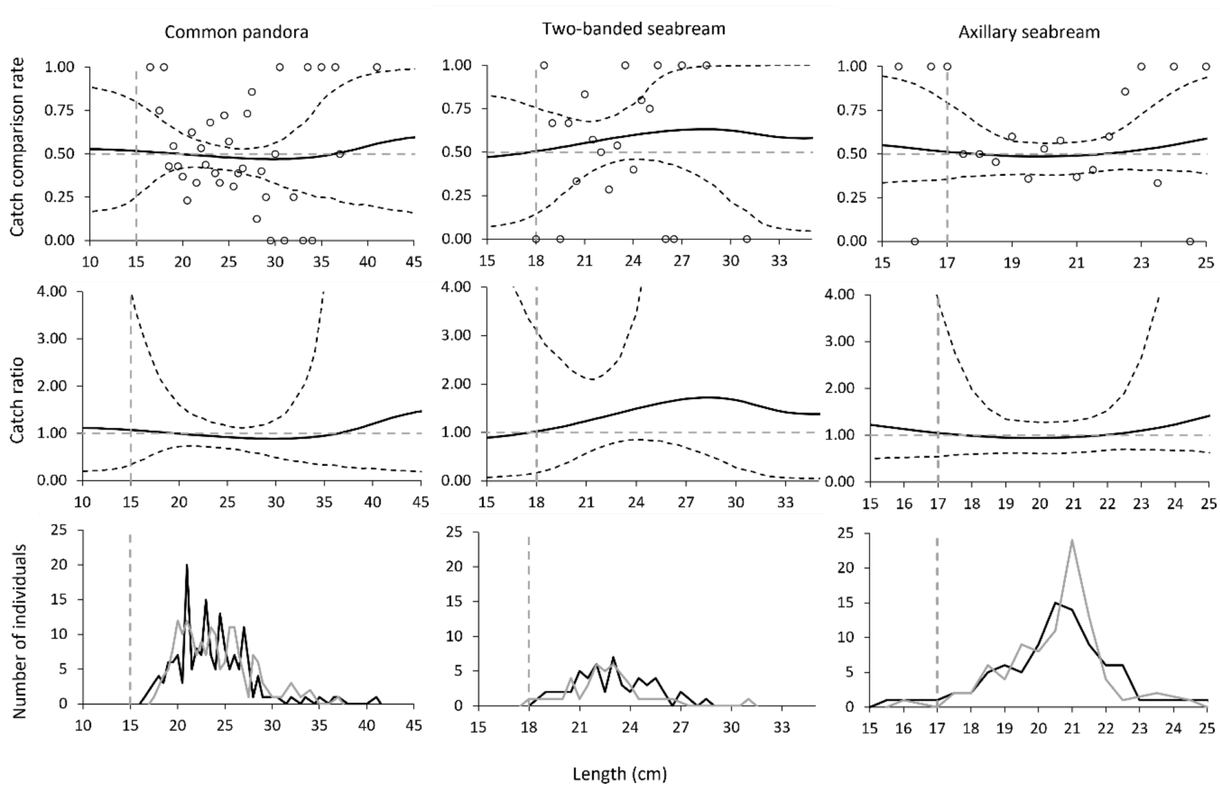

Fig. 5. Catch comparison and catch ratio analysis for common pandora, two-banded seabream and axillary seabream. Upper graphs: the modelled catch comparison rates (black curves) with 95 % CIs (black stippled curves). Circles represent experimental rate. Middle graphs: the estimated catch ratio curves (black curves) with 95 % CIs (black stippled curves). The grey stippled lines at 0.5 and 1.0 represent the point at which both gears have an equal catch rate. Lower graphs: the length frequency distribution of fish captured with the biodegradable snoods (black line) and nylon snoods (gray line). Vertical stippled lines show the minimum conservation reference size for each species.

Table 2
List of species and number of individuals sampled during the experiments with biodegradable and nylon snood.

Species ID	Species name	Common name	Number of individuals	
			Biodegradable	Nylon
1	*Pagellus erythrinus*	Common pandora	173	179
2	*Pagellus acarne*	Axillary seabream	88	90
3	*Diplodus vulgaris*	Common two-banded seabream	50	37
4	*Trachurus trachurus*	Atlantic horse mackerel	3	9
5	*Echelus myrus*	Painted eel	6	3
6	*Sparus aurata*	Gilthead seabream	2	7
7	*Conger conger*	European conger	4	3
8	*Mustelus punctulatus*	Blackspotted smooth-hound	2	4
9	*Boops boops*	Bogue	2	1
10	*Merluccius merluccius*	European hake	2	1
11	*Scorpaena notata*	Small red scorpionfish	1	2
12	*Diplodus annularis*	Annular seabream	0	2
13	*Myliobatis aquila*	Common eagle ray	0	2
14	*Scyliorhinus stellaris*	Nursehound	1	1
15	*Serranus hepatus*	Brown comber	1	1
16	*Spondyliosoma cantharus*	Black seabream	0	2
17	*Squilla mantis*	Spottail mantis squillid	0	2
18	*Pagrus pagrus*	Red porgy	0	1
19	*Raja miraletus*	Brown ray	1	0
20	*Serranus scriba*	Painted comber	1	0
21	*Spicara smaris*	Picarel	1	0

together with whole or part of the snoods, would imply that the plastic material of lost snoods stays in the marine environment. Therefore, in longline fisheries this situation is more critical regarding the increase of plastic pollution. In this longline fishery in the Adriatic Sea, the estimated mean snood loss for the whole fishing trials reached 3.00 % (CI: 1.00–5.92 %) during a longline deployment when using traditional nylon material. Taking into consideration that there are several vessels operating in a relatively small area with regular longline deployments, this amount implies a considerable source of plastic pollution. The Adriatic Sea is one of the areas highly affected by benthic litter (Pasquini, Ronchi, Strafella, Scarcella, & Fortibuoni, 2016). Microplastic pollution in the Adriatic Sea has been demonstrated in the marine environment, including surface waters, sediments, and biota (Schmid, Cozzarini, & Zambello, 2021). In longline fisheries, the amount of snood loss can vary over the fishing grounds and the way how the longlines are being operated. For example, in earlier study estimating the snood loss in a coastal longline fishery in the Barents Sea, the fraction of lost nylon monofilament snoods was close to 5 % during each longline deployment (Cerbule et al., 2022). However, Lomeli et al. (2023), reported an observation of hook damage and snood loss (e.g., due to breaking of snood) to be around 1.3 % in the fishery targeting Pacific halibut (*Hippoglossus stenolepis*) when using hard-lay twine (Powers #72 braided nylon cover with a Dyneema® polyester core).

In this study, the estimated loss of snoods when using the biodegradable material did not differ significantly when compared to nylon and was 4.42 % (CI: 2.58–6.50 %). This difference was neither significant when considered over deployment days or single longline deployments. Furthermore, there were no significant differences between biodegradable and nylon snoods except for only one instance when the hook loss probability for a single mainline in a single deployment between the two materials was significant. However, since no significant

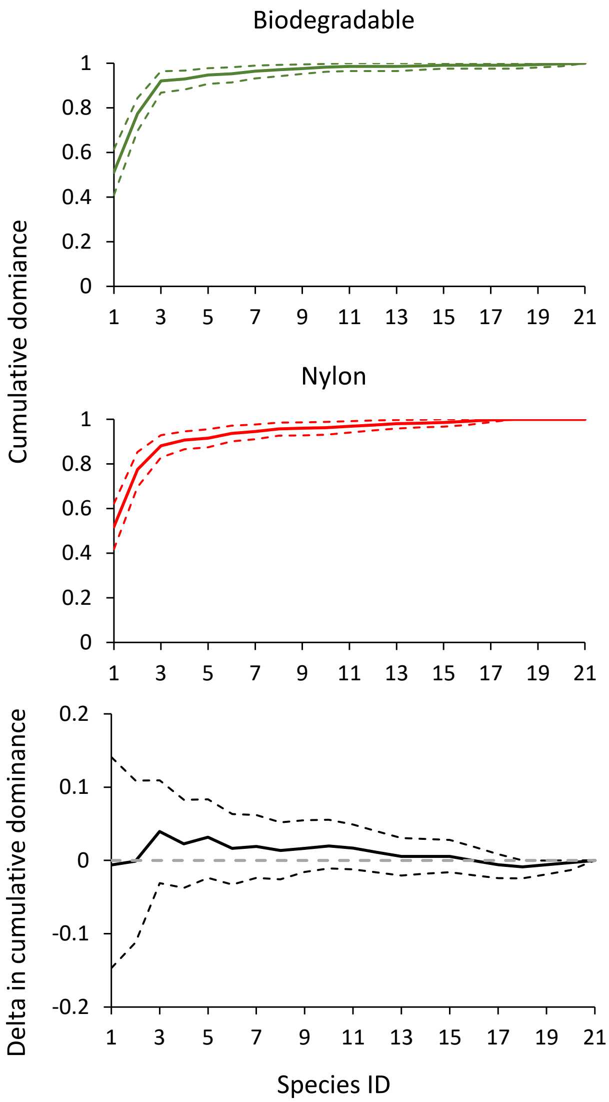

Fig. 6. Cumulative dominance curves for catch composition of biodegradable snoods (green; upper graph) and nylon snoods (red; middle graph) and pairwise difference (delta) in cumulative dominance curves for biodegradable versus nylon snoods (lower graph). Dashed lines are 95 % CIs.

differences in hook loss between snoods of the two materials were observed in any of the remaining 47 longline deployments, this difference can be coincidental. Therefore, the results of this study are in line with the earlier study in the Barents Sea where no significant differences in snood losses were observed in initial trials comparing nylon and biodegradable PBSAT plastic snoods during the initial trials (Cerbule et al., 2022).

For the three most frequently captured species (common pandora, two-banded seabream and axillary seabream), no significant differences in catch efficiency were observed when comparing the two snood materials for initial use. Specifically, snoods of both materials showed similar efficiency at capturing individuals of the three species of all sizes observed. The average catch efficiency for target sized individuals (*CRaverage+*) did not show any significant difference between the snood materials for any of the species.

Our obtained results showed no initial significant differences in performance between biodegradable and nylon snoods in line with results from a Norwegian longline fishery (Cerbule et al., 2022) which showed no significant differences between snoods of nylon and PBSAT materials. The degradation of the PBSAT is taking place faster compared to nylon (Brakstad et al., 2022), which would imply that snoods of such material would degrade faster compared to nylon snoods if exposed to the marine environment in case of being lost. Furthermore, due to biodegradation by naturally occurring microorganisms (Tokiwa, Calabia, Ugwu, & Aiba, 2009), this material is aimed at degrading into substances that would not affect marine environment negatively even if the snoods are lost at similar quantities as when using traditional non-biodegradable materials (Cerbule et al., 2022). However, the production of PBSAT is currently limited due to further material development. Therefore, the costs of it are higher when compared to nylon (Standal et al., 2020). Despite that, a reduction in costs of this material could take place when the production of the biodegradable material is scaled up and put in mass production (Cerbule et al., 2022).

Performing and reporting preliminary results as done in this study are important for investigating whether the biodegradable plastic material has potential to be developed to commercial use thereby avoiding unsuccessful research and development work in further comprehensive studies and select the materials that have the potential to be used in further experiments (Thabane et al., 2016). However, these short-term positive results should further be followed up by studies estimating material performance over long-term use. Differences in material properties such as tensile strength of the biodegradable PBSAT material compared to nylon are estimated to increase over time (i.e., Grimaldo et al., 2020) due to faster material degradation and reduced breaking strength of the biodegradable material (Brakstad et al., 2022). This has previously shown to affect the material performance when used in gillnet fishery (Grimaldo et al., 2020; Cerbule et al., 2022). Therefore, such degradation process might also have an effect on material performance in the longline fishery when tested over several deployments regarding loss of the snoods and the fishing performance of the gear.

The results from the Adriatic Sea showed potential for the biodegradable materials to be used to reduce the marine plastic pollution from the longline fishery and thus contribute to the nature conservation. Therefore, this should further be investigated by a follow-up study assessing long-term performance of the material before a final conclusion can be made regarding whether the biodegradable materials can solve the plastic pollution problem created by the longline fishery.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jnc.2023.126438.

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