Switching to bioplastics may exacerbate ingestion of lost and discarded fishing gear by marine invertebrates

Sandra Powell [1], Benjamin Mos [1,2]

[1] Moreton Bay Research Station (MBRS), School of the Environment, The University of Queensland, 37 Fraser Street, Dunwich, Minjerribah, QLD 4183, Australia

[2] Centre for Marine Science (CMS), The University of Queensland, Brisbane, QLD, 4072, Australia

Corresponding Author: Benjamin Mos

Postal Address: Moreton Bay Research Station (MBRS), The University of Queensland, 37 Fraser Street, Dunwich, QLD 4183, Australia

Email: b.mos@uq.edu.au

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Abstract

Bioplastics are argued to be more environmentally sustainable than conventional plastics. Yet, little is known about how bioplastics degrade in marine environments or their likelihood of being ingested by animals. We measured changes in the weight of biodegradable, semi-biodegradable, and non-biodegradable fishing gears (soft plastic lures, SPLs) in or out of seawater over 14 days. We then exposed new and preconditioned SPLs to soldier crabs *Mictyris longicarpus* and green paddle worms *Phyllodoce novaehollandiae.* Biodegradable SPLs gained or lost up to 70% of their weight, likely due to changes in water content, but there was little change in nonbiodegradable and semi-biodegradable SPLs. Both animals ingested biodegradable SPLs, but not non-biodegradable SPLs. Crabs also ingested semi-biodegradable SPLs. Biodegradable SPLs shed up to 8 times more glitter microplastics when crabs were present than absent. Switching from conventional plastics to bioplastics may make lost/discarded fishing gear more likely to be ingested by marine invertebrates.

1. Introduction

Plastic is now found in every marine habitat on Earth (e.g., Bergmann et al., 2017; Chiba et al., 2018). The volume of plastic entering the marine environment is estimated at 4.8–12.7 million Mt per year (Jambeck et al., 2015), with lost or discarded fishing gears a significant source (Lebreton et al., 2018; Richardson et al, 2022). Plastic is particularly prevalent in intertidal marine habitats due to the proximity of these habitats to human settlements and the tendency of plastic to concentrate in sediments (Worm et al., 2017). Plastic pollution can have substantial negative impacts on the organisms that live in marine ecosystems, with the most documented effects associated with ingestion and entanglement (Worm et al., 2017).

One of the ways that the impacts of marine plastic pollution might be reduced is through switching to alternative materials, such as bioplastics. The term bioplastic is unresolved, but generally refers to plastics made from biological material, plastic that can be broken down by living organisms, typically microbes (i.e., biodegradable), or plastics that feature both properties (Goel et al., 2021; Venâncio et al., 2022). Bioplastic production was 2.2 Mt $year^{-1}$ in 2022 and is expected to reach 6.3 Mt $year^{-1}$ in 2027 (European Bioplastics, 2022). It is argued bioplastics may have lower environmental impacts than conventional plastics because bioplastics break down quicker; months to years instead of centuries or millennia (Goel et al., 2021; Venâncio et al., 2022). However, many bioplastics are not biodegradable in marine environments (Goel et al., 2021; Venâncio et al., 2022), and biodegradable bioplastics in marine habitats appear to degrade up to four times slower than in terrestrial environments (Dilkes-Hoffman et al., 2019; Goel et al., 2021), suggesting marine organisms may be among the life forms most likely to interact with bioplastics.

Little is known about the ways in which marine life interact with bioplastics (Venâncio et al., 2022). Bioplastics are colonised by marine microbes, which can enhance biodegradation (Emadian et al., 2017) and inhibit photodegradation (Delacuvellerie et al., 2023), and alter the likelihood that bioplastic will be ingested by animals (Hodgson et al., 2018). Most research testing whether bioplastics are ingested by marine life examined the impacts of micro-sized particles (i.e., microplastics) on filter feeding bivalve molluscs, worms, tunicates, and copepods (Venâncio et al., 2022). Few studies have examined the ingestion of large pieces of bioplastic. Müller et al. (2012) found the gastrointestinal fluids of two species of sea turtles were unable to digest bioplastic shopping bags. Amphipods living on marine sandy shores bite, ingest, fragment, and partially digest large pieces of bioplastic, with negative impacts on their survival (e.g., Hodgson et al., 2018; Martellini et al., 2023). To understand real-world degradation rates and better compare the environmental impacts of conventional plastics and bioplastics, additional work is needed to test whether other marine organisms ingest large bioplastics.

To help fill knowledge gaps about the fate of large bioplastics in marine ecosystems, this study examined short-term degradation and ingestion of conventional plastic and biodegradable fishing gears. Lost or discarded fishing gear may account for more than 46% of the plastic litter in some marine habitats (e.g., Lebreton et al., 2018) and has proven detrimental to a wide variety of taxa, including ingestion of fishing-derived plastic impacting at least 208 species (Worm et al., 2017). We focused on soft plastic lures (hereafter SPLs) (Fig. 1), a type of fishing gear commonly used by recreational anglers (Raison et al., 2014; Skaggs and Allen, 2015). In heavily fished locales, lost or discarded SPLs accumulate in littoral zones at rates exceeding 80 km^{-1} $year^{-1}$ (Raison et al., 2014). In laboratory studies, SPLs made from conventional plastics were voluntarily ingested by up to 63% of brook trout, *Salvelinus fontinalis* (Danner et al., 2009) and 85% of largemouth bass, *Micropterus salmoides* (Sanft et al., 2018), though in the wild the percentage of freshwater fish within a population that have SPLs in their digestive tract is generally <4% (Raison et al., 2014; Sanft et al., 2018). Nothing is known about the way in which animals other than freshwater fish interact with lost or discarded SPLs.

We kept conventional plastic and bioplastic SPLs in and out of seawater for 14 days and monitored changes in their wet weight (WW) in comparison to organic matter (pieces of fish, *Sardinops sagax*). We then tested whether new and preconditioned SPLs were ingested by two common marine invertebrates found in intertidal soft sediment habitats on the east coast of Australia, the soldier crab, *Mictyris longicarpus* and the green paddle worm, *Phyllodoce novaehollandiae.*

2. Methods

2.1 Effects of time, type of plastic, and condition treatment on SPL degradation

To understand how conventional plastic and bioplastic soft plastic lures (SPLs) degrade in comparison to organic natural bait (fish) when in or out of seawater, a degradation experiment was performed. Three types of SPLs were tested (Fig. 1) representing three of the most common types of SPLs available at Australian outdoor and angling retailers (pers. obs.): (1) ElaZtech Zman Slim SwimZ, 64 or 75mm, colours watermelon red, bad shad, and motor oil, made of an unspecified thermoplastic elastomer (TPE), hereafter referred to as 'non-biodegradable'; (2) Shimano Squidgies Bio-Tough, 70 mm, colour watermelon red, marketed on the package as "50% biodegradable synthetic bioplastic", and hereafter referred to as 'semi-biodegradable'; and (3) Berkley Gulp! Paddleshad, size 75mm, colours 'black & gold' and 'silver & gold', marketed as "100% biodegradable" by retailers in Australia (pers. obs.) and as "biodegradable" in North America (Raison et al., 2014), and hereafter referred to as 'biodegradable'. Pieces of pilchard, *Sardinops sagax* (Tweed Bait Pty Ltd), approximately the same dimensions as the SPLs, were used as an organic reference material (hereafter referred to as 'organic matter').

Each material (non-biodegradable, semi-biodegradable, biodegradable, and organic matter) was exposed to three condition treatments in all combinations (4 types × 3 conditions = 12 treatments). All materials were either exposed to air (dry), placed in unfiltered seawater, or placed in seawater that had been filtered to 0.22µm to remove microbes. There were seven replicates per treatment. Each replicate consisted of a polypropylene 560-mL bucket (Chanrol C20) containing one whole SPL newly removed from its packaging or a piece of organic matter (previously described), and either 200 mL of seawater (filtered or unfiltered) or nothing. Replicates were left uncovered in the laboratory at The University of Queensland's Moreton Bay Research Station (MBRS) for 14 days under ambient conditions (photoperiod 13:11 h light/dark, 19.2 °C ± 1.7 SD, HOBO MX Temp/Light MX 2202 set to record every 60 min). Seawater was exchanged every 72 h using water that had been prepared at the beginning of the experiment (filtered or unfiltered) and stored in the same room as the experiment.

To assess degradation, each SPL or organic matter was weighed to the nearest mg at the beginning of the experiment and after 24 h, 7 days, and 14 days had elapsed using a Shimadzu AX 2000 N595. Materials that were exposed to seawater were placed on dry paper towel for 10 s each side to remove excess water before weighing. Data on change in the wet weight (WW) of the SPLs and organic matter were calculated for each replicate bucket at each time point as a percentage of the WW at the beginning of the experiment.

2.2 Study species

Soldier crabs of the genus *Mictyris* are a common sight on sandy and muddy beaches in the Indo-West Pacific (Davie et al., 2010). At present, six species have been described, with those from the east coast of Australia (Cape York, Queensland to at least Waratah Bay, Victoria) assigned to *Mictyris longicarpus* (Davie et al., 2010). Mictyrids are primarily deposit feeders, separating organic material from sediment using their mouthparts, and discarding inedible sediment as pellets (Cameron, 1966; Quinn, 1986). However, we observed some *M. longicarpus* within travelling armies pause briefly to scavenge organic material using chelae from the carcases of pilchards, *Sardinops sagax* as they passed by (pers. obs.), and observed some individuals feed on small pieces of biodegradable SPLs in pilot trials in the laboratory (pers. obs.).

The green paddle worm *Phyllodoce novaehollandiae* is common on sand flats and beaches on the east coast of Australia (Davie et al., 2011; Hutchings and Rainer, 1979), though the full extent of their distribution is not known. *P. novaehollandiae* is a carnivorous predator and scavenger, and feeds using an eversible proboscis, similar to its congener *Phyllodoce mucosa* (Lee et al., 2004). *P. novaehollandiae* were observed feeding on the carcases of pilchard, *Sardinops sagax* and biodegradable SPLs in the field (Fig. S1, pers. obs.).

M. longicarpus and *P. novaehollandiae* were chosen for this study because of their high abundance and conspicuousness on intertidal flats in Moreton Bay, Quandamooka, South-East

Queensland (QLD), Australia where this study was done. *M. longicarpus* and *P. novaehollandiae* were collected in July 2023 from Bradbury's Beach, North Stradbroke Island, QLD, Australia (27.4956S, 153.4003E) and held for ~48 h prior to experiments to standardise the amount of material in their digestive tracts (permit MPP18-001092). The mean mass of *M. longicarpus* was 3.37 g ± 0.88 SD, mean carapace width 1.66 cm ± 0.24 SD (N = 20). The mean mass of *P. novaehollandiae* was 0.29 g ± 0.13 SD, mean length 12.07 cm ± 3.56 SD (N = 20). At the end of the experiments, all animals were allowed to clear their digestive tract and then returned to where they were collected.

2.3 Effects of conditioning and SPL type on ingestion by soldier crabs

To understand how different types of materials and preexposure to varied physicochemical conditions influence the likelihood that SPLs are consumed by intertidal marine invertebrates, we exposed SPLs to *M. longicarpus* and measured how much of the SPLs the crabs consumed. SPLs (non-biodegradable, semi-biodegradable, biodegradable) were conditioned either by exposing them to air for 7 days (dry), exposing them to unfiltered seawater for 7 days (wet), or not conditioned (fresh) in all combinations before they were fed to *M. longicarpus* (3 types × 3 conditions = 9 treatments).

Each treatment had five replicates, consisting of a white round polypropylene 2-L bucket (Chanrol 08FB02W) housing three *M. longicarpus*, an SPL or organic matter, clean beach sand, and seawater to a depth of 2 cm. The sand was sloped to one side of the bucket to provide areas where the *M. longicarpus* could bury or climb out of the water while retaining access to water. For each treatment, an additional five replicate buckets that did not have *M. longicarpus* present were used to measure changes in the SPLs that was not attributable to the crabs (i.e., autogenic controls). Buckets containing sand, seawater, and organic matter (pilchard fillet approximately the same dimensions as the SPLs) were used as a positive control treatment (five replicates with *M. longicarpus* present) and corresponding autogenic control treatment (five replicates without crabs). Four replicate buckets containing *M. longicarpus*, sand, and seawater, but no SPLs or organic matter, were also used to monitor for mortality not attributable to treatments. All replicate buckets were held in the laboratory at MBRS for 48 h under ambient conditions (photoperiod 13:11 h light/dark; temperature mean 20.3°C ± 0.8 SD; HOBO MX Temp/Light MX 2202). Seawater was exchanged in all buckets every 24 h using fresh seawater at the same temperature.

Each SPL or organic matter was weighed at the beginning of the experiment and after 6, 24, and 48 h had elapsed using a Shimadzu AX 2000 N595. All materials were placed on dry paper towel for 10 s each side to remove excess water before weighing. Data on change in the wet weight (WW) of the SPLs and organic matter were calculated for each replicate bucket at each time point as a percentage of the WW at the beginning of the experiment.

At the end of the experiment, the number of glitter particles present in all replicate buckets was counted. After SPLs and crabs were removed, water was added, and the sand stirred and swirled to

concentrate all glitter particles at the centre of the surface of the sand. All crabs were alive at the end of the experiment.

2.4 Effects of conditioning and SPL type on ingestion by green paddle worms

To understand whether marine invertebrate taxa differ in their propensity to consume SPLs made of different materials or pre-exposed to varied physicochemical conditions, we fed SPLs to *P. novaehollandiae* and measured how much of the SPLs they consumed. The same experimental design previously described for *M. longicarpus* was used, except each replicate bucket contained sand to a depth of 1 cm and unfiltered seawater to a depth of 0.5 cm above the level of the sand. All replicate buckets were held in the laboratory at MBRS for 48 h under ambient conditions (photoperiod 13:11 h light/dark; temperature mean 20.9°C ± 1.0 SD; HOBO MX Temp/Light MX 2202). The WW of each SPL or organic matter was measured at the beginning of the experiment and after 6, 24, and 48 h in the same way as for *M. longicarpus*. Change in the wet weight (ΔWW) of the SPLs and organic material were calculated in the same way as for *M. longicarpus*. The number of glitter particles present in each replicate was also counted at the end of the experiment in the same way as for *M. longicarpus*. All green paddle worms were alive at the end of the experiment.

2.5 Statistical Analysis

Data on the change in the WW of SPLs and organic matter in all experiments were not normal and were therefore analysed using non-parametric permutational analysis of variance (PERMANOVA) (Anderson, 2001) in PRIMER v7. Change in the WW of SPLs and organic matter from the degradation experiment were analysed using a repeated measures ANOVA design with 'time' as a random factor and 'conditioning treatment' and 'type of SPL' as fixed factors. Replicate (bucket) was included in the model to account for non-independence of measurements taken from the same replicate over time. Change in the WW of SPLs from the ingestion experiments were analysed using a repeated measures ANOVA design with 'time' as a random factor and 'conditioning treatment' and 'type of SPL' as fixed factors. Replicate (bucket) was included in the model to account for non-independence of measurements taken from the same replicate over time. Data on the number of glitter particles present after 48 h were analysed by three-way ANOVA design using 'presence/absence of animals', 'conditioning treatment', and 'type of SPL' as fixed factors, and bucket as the level of replication. Data on the change in the WW of organic matter in ingestion experiments were analysed using a repeated measures ANOVA design with time as a random factor and 'presence/absence of animals' as a fixed factor. A covariate of initial WW of the organic matter was included, and replicate (bucket) was included in the model to account for non-independence of measurements taken from the same replicate over time.

For all ANOVAs, assumptions of normality and heterogeneity of variance were initially examined using Q-Q residual plots, values for skewness and kurtosis, and Kolmogorov-Smirnov and

Shapiro-Wilk tests in IBM SPSS v29.0 (Field, 2018; Quinn and Keough, 2002). Pair-wise comparisons of untransformed data were generated using Euclidean distance and 9999 permutations of the raw data. The default sum of squares was used (Type III for ANOVA and Type I for repeated measures ANOVA). Significant interactions ($p < .05$) of interest were interpreted by examining 95% CI (confidence intervals) of estimated marginal means generated in SPSS 29.0 as per Garofalo et al. (2022).

3. Results

3.1 Effects of time, type of plastic, and condition treatment on SPL degradation

Over 14 days, some SPLs experienced little change in their WW, while others gained 5–9% mass or lost 47–88% of their mass (Fig. 2). Changes in the WW of different materials depended on a complex interaction between the type of SPL or organic matter, the condition they were exposed to, and how long they had been exposed to those conditions (Fig. 2, Table 1).

Pieces of organic matter in seawater for 24 h gained 6% (unfiltered) or 9% (filtered) WW, but pieces held out of water lost 45% of their WW (Fig. 2, Table 1). After 7 days, there was no difference in the percentage of WW lost by the pieces of organic matter in the air (-64%) or unfiltered seawater (-63%), which was significantly greater than pieces in filtered seawater (-3%) (Fig. 2, Table 1). After 14 days, organic matter in unfiltered seawater had lost 89% of its initial WW, a significantly greater loss than for pieces exposed to air (-65%). Pieces in filtered seawater (-48%) lost significantly less of their initial WW compared to pieces in unfiltered seawater or air (Fig. 2, Table 1).

After 24 h, biodegradable SPLs in seawater gained 10% (unfiltered) or 12% (filtered) WW, but biodegradable SPLs held out of water lost 36% of their initial WW (Fig. 2, Table 1). After 7 days, there was no difference in the percentage of WW gained by biodegradable SPLs in filtered seawater (7%) or unfiltered seawater (6%), whereas SPLs held out of water lost 64% of their initial WW (Fig. 2, Table 1). After 14 days, biodegradable SPLs displayed little change from the previous week, maintaining a gain in WW of 6–7% in filtered and unfiltered seawater respectively and a loss of 65% of their initial WW when held out of water (Fig. 2, Table 1).

In contrast to the organic matter and biodegradable SPLs, there was little change in the WW of the semi-biodegradable and non-biodegradable SPLs at any time (Fig. 2). For instance, after 14 days the change in the WW of the non-biodegradable and semi-biodegradable lures exposed to seawater was <1.5% of their initial WW and did not significantly differ regardless of which conditions they were exposed to (Fig. 2, Table 1).

3.2 Effects of conditioning and SPL type on ingestion by soldier crabs

Changes in WW of SPLs depended on a significant interaction among the presence/absence of *M. longicarpus*, the type of SPL, and how the SPL was conditioned (Fig. 3, Fig. S2, Table 2). There were significantly lower WWs recorded in all biodegradable SPL treatments and the semi-biodegradable SPL treatment conditioned dry when *M. longicarpus* were present compared to corresponding control treatments without *M. longicarpus* (Fig. 3, Table 2). Thus *M. longicarpus* ingested biodegradable SPLs and semi-biodegradable SPLs that had been conditioned in air for 7 days. All other treatments showed little change in WW (< 3%) and did not significantly differ among treatments regardless of whether *M. longicarpus* were present or not (Fig. 3, Fig. S2, Table 2). Thus *M. longicarpus* did not consume non-biodegradable SPLs or semi-biodegradable SPLs that were not conditioned or conditioned in seawater for 7 days.

The WW of organic matter fluctuated over time, with an initial increase at 6 h followed by a general decline over time (Fig. S2). Changes in the WW of organic matter depended on a significant interaction between the presence/absence of *M. longicarpus* and time (Fig. S2, Table S1). After 48 h, organic matter where *M. longicarpus* was present had a mean 15% lower WW compared to organic matter in the absence of *M. longicarpus* (Fig. S2, Table S1), indicating *M. longicarpus* consumed organic matter.

3.3 Effects of conditioning and SPL type on ingestion by green paddle worms

Changes in the WWs of SPLs depended on a significant interaction among the presence/absence of *P. novaehollandiae,* the type of SPL, and how the SPL was conditioned (Fig. 4, Fig. S3, Table 2). There were significantly lower WWs recorded in the biodegradable SPL treatment conditioned dry when *P. novaehollandiae* were present compared to corresponding control treatments without *P. novaehollandiae* (Fig. 4, Table 2). Thus *P. novaehollandiae* ingested biodegradable SPLs that had been conditioned in air for 7 days. For all other treatments regardless of how they were conditioned, there was little difference in WW between replicates where *P. novaehollandiae* were present and corresponding control replicates without *P. novaehollandiae* (Fig. 3, Fig. S2, Table 2). Thus *P. novaehollandiae* did not consume any non-biodegradable SPLs, any semi-biodegradable SPLs, or biodegradable SPLs that were not conditioned or conditioned in seawater for 7 days.

The WW of organic matter fluctuated over time, with an initial increase at 6 h followed by a general decline over time (Fig. S3). Changes in the WW of organic matter depended on a significant interaction between the presence/absence of *P. novahollandiae* and time (Fig. S3, Table S1). After 48 h, organic matter where *P. novaehollandiae* was present had a mean ~12% greater WW compared to organic matter in the absence of *P. novaehollandiae* (Fig. S3, Table S1). Thus, the presence of *P. novaehollandiae* led to an increase in the WW of organic matter.

3.4 Effects of invertebrates, conditioning, and SPL type on glitter shedding

For SPLs in the *M. longicarpus* experiment, the mean number of glitter particles shed from SPLS after 48 h varied between 0 and 43 (Fig. S4, Fig. 5). The number of glitter particles found depended on a significant interaction between the presence/absence of *M. longicarpus* and the type of SPL (Fig. 5, Table 2). Biodegradable SPLs shed more glitter particles than all other types of SPLs and shed >6 times more glitter particles when *M. longicarpus* were present than when the soldier crabs were absent (Fig. 5, Table 2). Non-biodegradable and semi-biodegradable SPLs shed few glitter particles regardless of whether *M. longicarpus* was present or absent (Fig. 5, Table 2).

The presence of *P. novaehollandiae* did not affect the number of glitter particles shed from SPLs (Fig. 6, Table 2). The number of glitter particles was greatest in the biodegradable-absent-no pre-condition treatment, which had significantly more glitter particles present than all other treatments, which did not differ (Fig. 6, Table 2).

4. Discussion

Biodegradable SPLs displayed substantial gains or losses in weight over 14 days depending on whether they were held in or out of seawater respectively. Similar to our results, Raison et al. (2014) reported that SPLs from eight different brands swelled but showed little decomposition over a two-year period, with some showing an increase in weight of 205%. Legault et al. (2023) found biodegradable SPLs absorbed water over time, swelling and increasing in weight by at least 181%. In contrast, Pander et al. (2022) found 'rotten' SPLs collected from a drained freshwater lake weighed on average 75% less than new SPLs, though it is not clear what materials the SPLs were made from or how long the SPLs had been in the lake. Overall, it appears bioplastic SPLs are unlikely to quickly degrade in aquatic environments but may undergo rapid increases or decreases in size and weight as they absorb or lose water. The consequences of changes in water content on the rates of degradation of bioplastics is not clear and important to investigate because, for example, reduced water levels can impede microbial degradation (Allison and Treseder, 2008; Briassoulis, 2007).

We found there was negligible change in the weights of non-biodegradable and semi-biodegradable SPLs over 14 days regardless of whether they were in or out of seawater. It was unsurprising to find little evidence of degradation in the non-biodegradable SPL made of a thermoplastic elastomer (TPE). These types of materials are often employed in situations that take advantage of their high resistance to degradation (Downey et al., 2019; Prathumrat et al., 2022). Information on the chemical makeup of the non-biodegradable and semi-biodegradable SPLs is not publicly available, though the manufacturer of the semi-biodegradable SPL states the material is colonised by microbes in water or soil and degrades by 50% in 3 years (Shimano, 2024). Our findings add to growing evidence that when lost or discarded, non-biodegradable and semi-biodegradable

SPLs are likely to be around for a substantial amount of time (years) with the potential to interact with aquatic life (Raison et al., 2014, Pander et al., 2022).

Organic matter (pieces of fish) rapidly decreased in weight in all experiments except for when they were housed with *P. novaehollandiae*, and in some treatments almost disappeared by 14 days. Microbes likely played the major role. Degradation rates of organic matter in unfiltered seawater were almost double compared to pieces held in seawater filtered to 0.22 µM to remove microbes. In contrast, SPLs of the same type held in filtered and unfiltered seawater did not differ in weight. This finding adds to growing evidence suggesting that despite high abundances, microbes in aquatic ecosystems are less capable of degrading bioplastics compared to microbial communities living in soil and compost (Dilkes-Hoffman et al., 2019; Goel et al., 2021). Pieces of fish exposed to *P. novaehollandiae* likely increased in weight due to being covered in mucous which is excreted in copious amounts by the green paddle worm (Davie et al., 2011).

We found little evidence that *M. longicarpus* and *P. novaehollandiae* ingest non-biodegradable SPLs. This contrasts with freshwater fishes which readily consume SPLs in the laboratory and to a lesser extent in the wild (Danner et al., 2009; Raison et al., 2014; Sanft et al., 2018). One reason for why *M. longicarpus* and *P. novaehollandiae* ignored non-biodegradable SPLs is that intertidal marine invertebrates do not rely on sight to find food (Lee et al., 2004; Quinn, 1986; Zimmer-Faust, 1987). SPLs mimic the size, shape, and swimming behaviour of animal prey but are unlikely to smell or taste like food (i.e., organic matter) unless a chemical attractant is used (Diggles et al., 2022) or the plastic is colonised by microbes (Savoca et al., 2016). It should be noted however that we only tested one type of non-biodegradable SPL made of TPE. It is possible other types of non-biodegradable SPLs may be ingested by marine invertebrates, and warrants further investigation.

M. longicarpus and *P. novaehollandiae* consumed up to 8% of the initial mass of biodegradable SPLs within 48 h, though the amount of material they ingested varied depending on how the SPLs were conditioned. To our knowledge, this is the first study to demonstrate ingestion of biodegradable fishing gear by marine invertebrates, though several studies have previously demonstrated marine fauna eat large pieces of bioplastic (e.g., Hodgson et al., 2018; Martellini et al., 2023). Biodegradable SPLs may have been consumed more than any other SPL tested as they contain a chemical attractant (Berkley, 2023). Chemical attractants enhance the ingestion of SPLs by fish (Diggles et al., 2022), and it is possible these chemicals also stimulate feeding in invertebrates. This may also explain why biodegradable SPLS that had been conditioned dry for 7 days were consumed by both *P. novaehollandiae* and *M. longicarpus* at a higher rate than new biodegradable SPLs or biodegradable SPLs condition in seawater for 7 days. Shrinking and expansion related to changes in water content of the biodegradable SPL may have concentrated and/or enhanced the release of the chemical attractant.

It would be interesting to test whether different chemical attractants influence the likelihood that invertebrates ingest biodegradable and non-biodegradable SPLs.

M. longicarpus consumed a greater variety of SPLs than *P. novaehollandiae*. It is not clear why this result occurred, but might be influenced by food preferences, morphology of feeding structures, and/or the physico-chemical characteristics of SPLs in different precondition treatments. To our knowledge, no study has directly compared the rates of ingestion of macroplastic between marine taxa, but both crustaceans and annelids have been shown to ingest microplastics made of conventional plastic and bioplastic at similar rates (Venâncio et al., 2022). Our result demonstrates that marine invertebrates may vary in their likelihood of ingesting large bioplastics. Therefore, we need to test widely to see which taxa are most likely to eat bioplastic, which will also help focus research efforts on groups of organisms that are most likely to experience negative impacts of bioplastics.

Glitter is a type of microplastic known to have negative impacts on marine organisms (Abessa et al., 2023; Piccardo et al., 2022; Provenza et al., 2022). Biodegradable SPLs released up to 8 times more glitter particles when *M. longicarpus* were present compared to absent. In contrast, the presence of *P. novaehollandiae* had no effect on the release of glitter from SPLs. We observed *M. longicarpus* frequently climb over SPLs and move SPLs using their chelae. It is possible that these behaviours mechanically released glitter from the biodegradable SPLs which were generally more prone to releasing glitter than other types of SPLs tested here. Other studies have also found crustaceans play a key role in mechanically degrading plastics (e.g., Hodgson et al., 2018; Martellini et al., 2023; Zheng et al., 2023). For instance, Zheng et al. (2023) found isopods, clamworms, and the crab *Chinomantes dehaani* release microplastics when boring holes into Styrofoam floats. Our experiments were conducted in a laboratory setting using small numbers of animals in a confined space and it is unclear how well our setup mimics an army of *M. longicarpus* trampling SPLs in intertidal habitats. Further research is warranted to better understand how the presence and absence of invertebrates affects the rate at which SPLs release glitter and other microplastics in the field.

We examined the ingestion of SPLs using an experimental design which incorporated autogenic controls, similar to the experimental designs recommended for ecological feeding studies (Peterson and Renaud, 1989; Roa, 1992). Our results and the findings of previous studies (Legault et al., 2023; Raison et al., 2014) demonstrate that biodegradable SPLs may undergo substantial changes in mass depending on the conditions that they are exposed to. Til now, autogenic controls have not been frequently used in studies examining the ingestion of plastic, perhaps because conventional plastics are unlikely to degrade substantially over the duration of a short-term feeding experiment. Our results highlight the need for researchers examining the decomposition of bioplastic in the presence of fauna or using bioplastics in feeding experiments to consider the use of appropriate autogenic controls.

In advocating for a switch from conventional plastics to biodegradable plastics to reduce the environmental impacts of plastic, we could be creating a situation in which marine life is more likely to ingest plastic pollution. If our results are representative of broader patterns of plastic ingestion across invertebrate taxa, it is unlikely SPLs made of conventional plastics are frequently ingested by marine invertebrates. Conversely, fishing gears made from biodegradable materials appear much more likely to be ingested, with rates of ingestion dependent on the type of material and the taxa involved. While additional work is needed to quantify rates of deposition and ingestion of SPLs in marine habitats, this study provides further evidence to support concerns that switching from conventional plastics to bioplastics is unlikely to reduce the impacts of plastic pollution in marine environments.

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CRediT authorship contribution statement

Sandra Powell: Methodology, Investigation, Formal Analysis, Data Curation, Visualization, Writing – Original Draft. **Benjamin Mos:** Supervision, Conceptualization, Methodology, Software, Validation, Visualization, Formal Analysis, Writing – Review & Editing.

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Figures

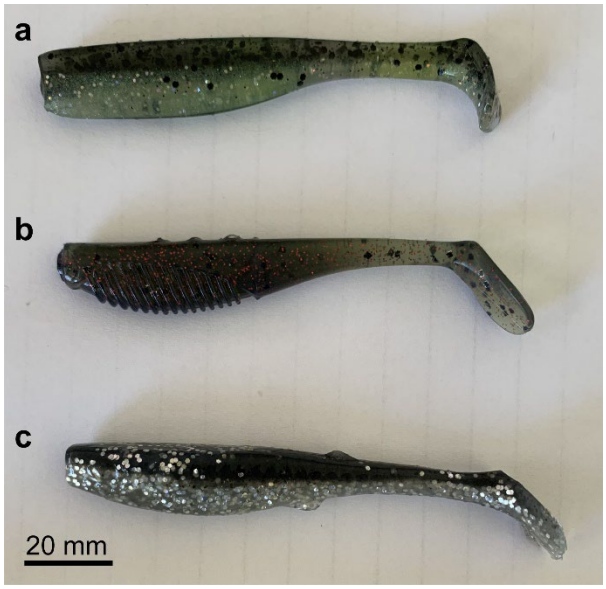
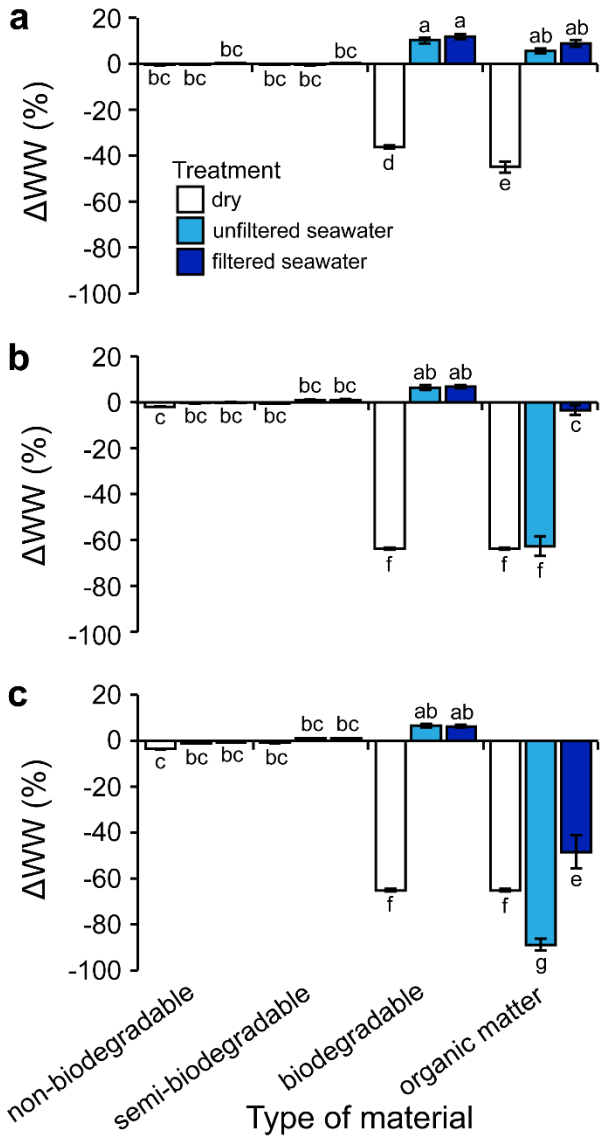


Fig. 1. Illustrative size, colour, and glitter content of three soft plastic lures (SPL) used in this study. **a**) non-biodegradable. **b**) semi-biodegradable. **c**) biodegradable.



520

521 **Fig. 2.** Change in the wet weight (ΔWW) of non-biodegradable, semi-biodegradable, and
522 biodegradable soft plastic lures (SPL) and similar sized pieces of fish, *Sardinops sagax* (organic
523 matter) held out of water (dry) or kept in unfiltered seawater or filtered seawater (0.22 µM) in a
524 laboratory experiment for **a**) 1 day, **b**) 7 days, and **c**) 14 days. **a-c**) Letters above or below bars denote
525 statistical significance (both within and between panels). Bars that have a common letter are not
526 significantly different according to ANOVA (Table 1, *treatment* × *type of material* × *time* interaction,
527 $p < .05$) followed by examination of 95% confidence intervals of estimated marginal means ($p < .01$).
528 Data are means ± SE, $n = 7$.

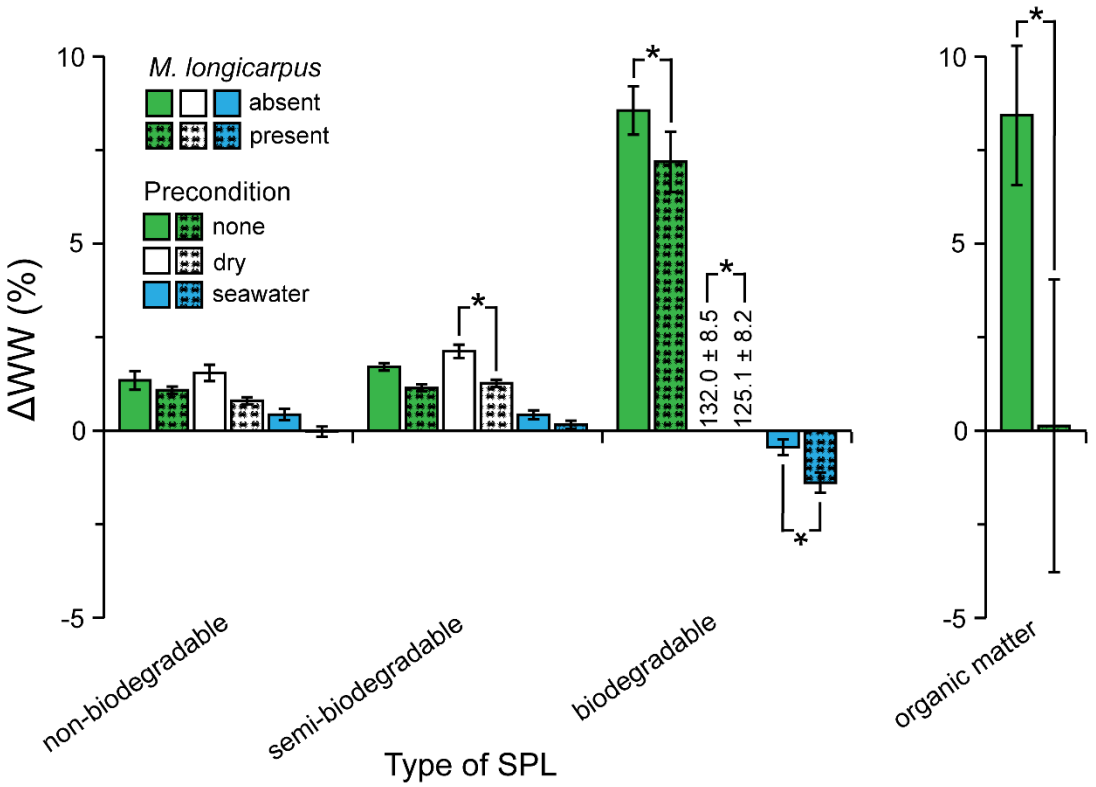


Fig. 3. Change in the wet weight (ΔWW) of new and preconditioned non-biodegradable, semi-biodegradable, and biodegradable soft plastic lures (SPL) and similar sized pieces of fish, *Sardinops sagax* (organic matter) in the presence and absence of soldier crabs, *Mictyris longicarpus*, in a laboratory experiment. SPLs were preconditioned in seawater for 7 days (seawater, blue bars), held out of water for 7 days (dry, white bars), or were not conditioned (none, green bars). For ease of illustration, data for the *presence/absence* × *precondition* × *type of SPL* interaction are presented here, and the full data set is presented in Supplementary Material (Fig. S2). Values for biodegradable-dry treatments are an order of magnitude larger than all other treatments and therefore presented as numerals (mean ± SE). Asterisks denote a significant difference between the bars/numerals connected by lines according to ANOVA (Table 2; Table S1; followed by examination of 95% confidence intervals of estimated marginal means, $p < .01$). Data are means ± SE, $n = 15$.

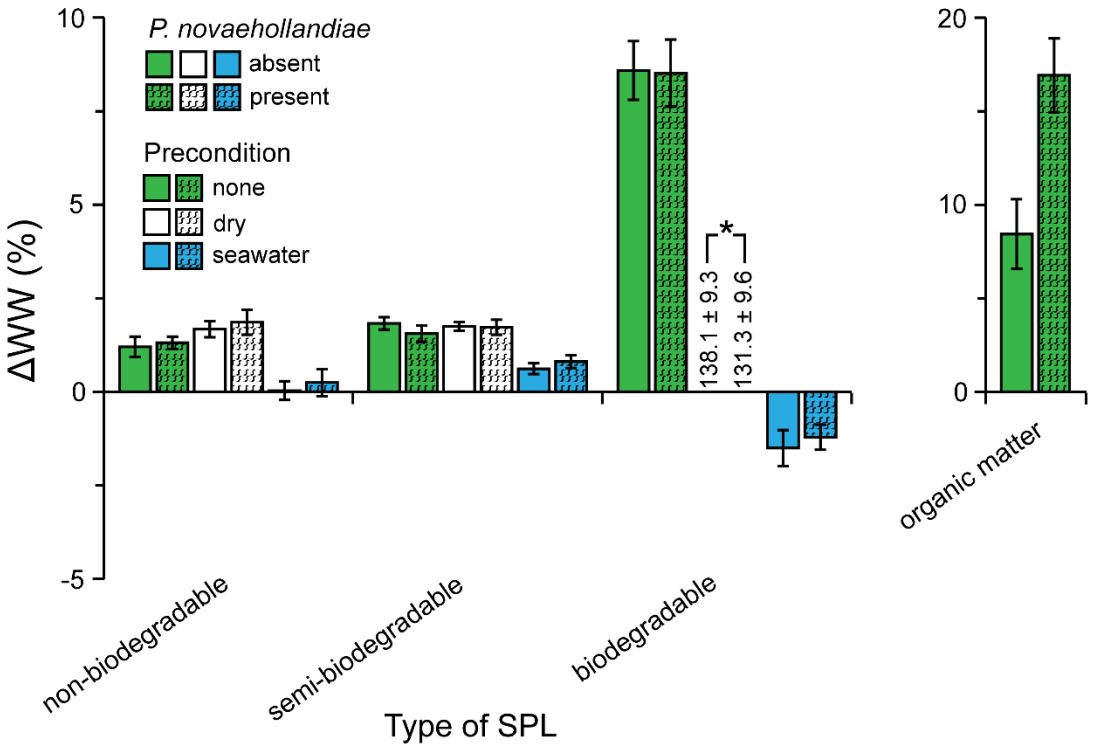


Fig. 4. Change in the wet weight (ΔWW) of new and preconditioned non-biodegradable, semi-biodegradable, and biodegradable soft plastic lures (SPL) and similar sized pieces of fish, *Sardinops sagax* (organic matter) in the presence and absence of green paddle worms, *Phyllodoce novaehollandiae*, in a laboratory experiment. SPLs were preconditioned in seawater for 7 days (seawater, blue bars), held out of water for 7 days (dry, white bars), or were not conditioned (none, green bars). For ease of illustration, data for the *presence/absence* × *precondition* × *type of SPL* interaction are presented here, and the full data set is presented in Supplementary Material (Fig. S3). Data for biodegradable-dry treatments are an order of magnitude larger than all other treatments and therefore presented as numerals (mean ± SE). Asterisks denote a significant difference between the bars/numerals connected by lines according to ANOVA (Table 2; Table S1; followed by examination of 95% confidence intervals of estimated marginal means, $p < .01$). Data are means ± SE, $n = 15$.

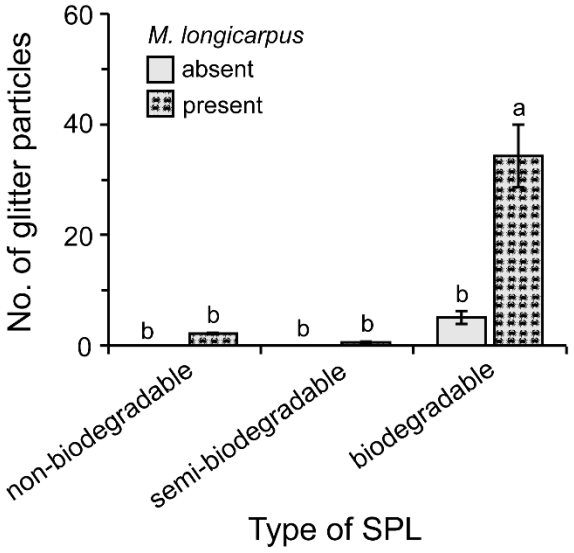


Fig. 5. The number of glitter particles found in replicate buckets housing new and preconditioned non-biodegradable, semi-biodegradable, and biodegradable soft plastic lures (SPL) in the absence and presence of soldier crabs, *Mictyris longicarpus*, in a laboratory experiment for 48 h. For ease of illustration, data for the *presence/absence* × *type of SPL* interaction are presented here, and the full data set is presented in Supplementary Material (Fig. S4). No glitter particles were found in buckets housing *M. longicarpus* without SPLs. Bars that have a common letter are not significantly different according to ANOVA (Table 2, *presence/absence* × *type of SPL* interaction, $p < .05$) followed by examination of 95% confidence intervals of estimated marginal means ($p < .01$). Data are means ± SE, $n = 15$.

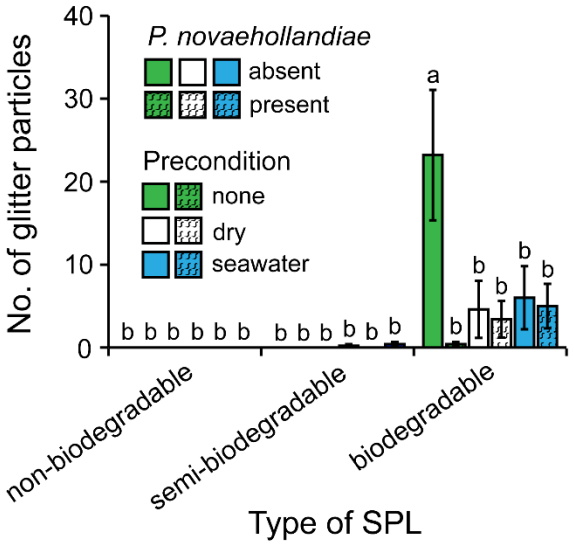


Fig. 6. The number of glitter particles found in replicate buckets housing new and preconditioned non-biodegradable, semi-biodegradable, and biodegradable soft plastic lures (SPL) in the absence and presence of green paddle worms, *Phyllodoce novaehollandiae*, in a laboratory experiment for 48 h. SPLs were preconditioned in seawater for 7 days (seawater, blue bars), held out of water for 7 days (dry, white bars), or were not conditioned (none, green bars). No glitter particles were found in buckets housing *P. novaehollandiae* without SPLs (not displayed). Bars that have a common letter are not significantly different according to ANOVA (Table 2, *presence/absence* × *type of SPL* × *precondition* interaction, $p < .05$) followed by examination of 95% confidence intervals of estimated marginal means ($p < .01$). Data are means ± SE, $n = 5$.

Tables

Table 1. Outcome of ANOVA analysis examining the effects of the type of material (type) and physicochemical conditions (treatment) on the change in wet weight of soft plastic lures (SPL) and organic matter measured at 24 h, 7 days, and 14 days (time) in a laboratory experiment. df, degrees of freedom; MS, mean square. Significant factors are in bold ($p < .05$).

Source	df	MS	F	*p*
type	**3**	**2.25E4**	**5.77**	**<.002**
treatment	**2**	**1.67E4**	**31.69**	**<.001**
time	**2**	**6.76E3**	**435.43**	**<.001**
type × treatment	**6**	**7.46E3**	**6.82**	**<.001**
type × time	**6**	**3.88E3**	**250.14**	**<.001**
treatment × time	**4**	**500.19**	**32.23**	**<.001**
type × treatment × day	**12**	**1.07E3**	**68.95**	**<.001**
replicate (type × treatment)	**72**	**26.07**	**1.68**	**<.006**
residual	251	15.52		

Table 2. Outcomes of ANOVA analyses examining the effects of material preconditioning (condition), type of material (type), and presence/absence of two marine invertebrates (presence), *Mictyris longicarpus* or *Phyllodoce novaehollandiae*, on the change in wet weight (ΔWW) of soft plastic lures (SPLs) after 6, 24, and 48 h and the number of glitter particles present after 48 h, in laboratory experiments. df, degrees of freedom; MS, mean square; Significant factors are in bold ($p < .05$).

Species	Parameter	Source	df	MS	F	*p*
M. longicarpus	ΔWW	**presence**	**1**	**128.26**	**10.40**	**.002**
		condition	**2**	**5.36E4**	**30.86**	**<.001**
		type	**2**	**5.86E4**	**43.87**	**<.001**
		time	**2**	**1.46E3**	**2.35E3**	**<.001**
		presence × condition	**2**	**36.39**	**3.53**	**.035**
		presence × type	**2**	**49.14**	**4.40**	**.015**
		presence × time	**2**	**2.81**	**4.51**	**.013**
		condition × type	**4**	**5.18E4**	**29.81**	**<.001**
		condition × time	**4**	**1.73E3**	**2.77E3**	**<.001**
		type × time	**4**	**1.33E3**	**2.13E3**	**<.001**
		presence × condition × type	**4**	**24.17**	**2.44**	**.019**
		presence × condition × time	4	0.91	1.47	.216
		presence × type × time	**4**	**1.73**	**2.77**	**.027**
		condition × type × time	**8**	**1.73E3**	**2.78E3**	**<.001**
		presence × condition × type × time	8	0.56	0.91	.517
		replicate (presence × condition × type)	**72**	**9.59**	**15.42**	**<.001**
		residual	144	0.62		
	glitter	**presence**	**1**	**2.33E3**	**26.95**	**<.001**
		condition	2	44.04	0.51	.611
		type	**2**	**3.74E3**	**43.21**	**<.001**
		condition × presence	2	86.98	1.01	.371
		type × presence	**2**	**2.04E3**	**23.53**	**<.001**
		condition × type	4	35.51	0.41	.807
		condition × type × presence	4	74.59	0.86	.494
		residual	72	86.50		
P. novaehollandiae	ΔWW	presence	1	32.49	2.75	.090
		condition	**2**	**5.90E4**	**26.44**	**<.001**
		type	**2**	**6.37E4**	**38.80**	**<.001**
		time	**2**	**1.95E3**	**1.05E3**	**<.001**
		presence × condition	**2**	**40.63**	**3.33**	**.038**
		presence × type	**2**	**39.30**	**3.27**	**.044**
		presence × time	2	0.28	0.15	.868
		condition × type	**4**	**5.68E4**	**25.74**	**<.001**
		condition × time	**4**	**2.22E3**	**1.19E3**	**<.001**
		type × time	**4**	**1.63E3**	**874.20**	**<.001**
		presence × condition × type	**4**	**40.83**	**3.33**	**<.003**
		presence × condition × time	4	0.55	0.29	.883
		presence × type × time	4	0.36	0.19	.941
		condition × type × time	**8**	**2.19E3**	**1.18E3**	**<.001**
		presence × condition × type × time	8	0.62	0.33	.955
		replicate (presence × condition × type)	**72**	**12.22**	**6.56**	**<.001**
		residual	144	1.86		
	glitter	**presence**	**1**	**165.38**	**5.95**	**.009**
		condition	2	55.03	1.98	.130
		type	**2**	**497.10**	**17.87**	**<.001**
		condition × presence	**2**	**134.48**	**4.84**	**<.004**
		type × presence	**2**	**177.88**	**6.40**	**<.001**
		condition × type	4	58.18	2.09	.078
		condition × type × presence	**4**	**129.03**	**4.64**	**.002**
		residual	72	27.81		

Supplementary Material for

Switching to bioplastics may exacerbate ingestion of lost and discarded fishing gear by marine invertebrates

Sandra Powell [1], Benjamin Mos [1,2]

[1] Moreton Bay Research Station (MBRS), School of the Environment, The University of Queensland, 37 Fraser Street, Dunwich, Minjerribah, QLD 4183, Australia

[2] Centre for Marine Science (CMS), The University of Queensland, Brisbane, QLD, 4072, Australia

Corresponding Author: Benjamin Mos

Postal Address: Moreton Bay Research Station (MBRS), The University of Queensland, 37 Fraser Street, Dunwich, QLD 4183, Australia

Email: b.mos@uq.edu.au

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Figures S1 to S4

Table S1

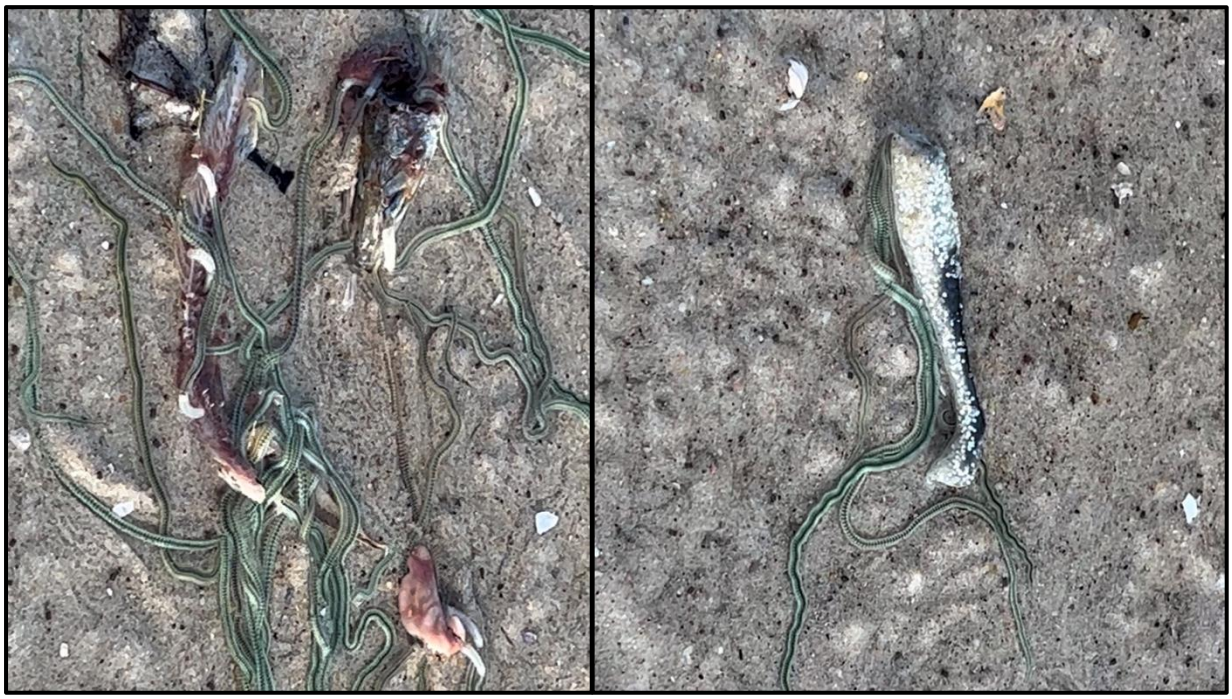

Fig. S1. *Phyllodoce novaehollandiae* feeding on pieces of fish, *Sardinops sagax* (organic matter) (left) and a biodegradable soft plastic lure (SPL) (right) *in situ* at low tide at Bradbury's Beach, North Stradbroke Island, Queensland, Australia during a pilot study (June, 2023).

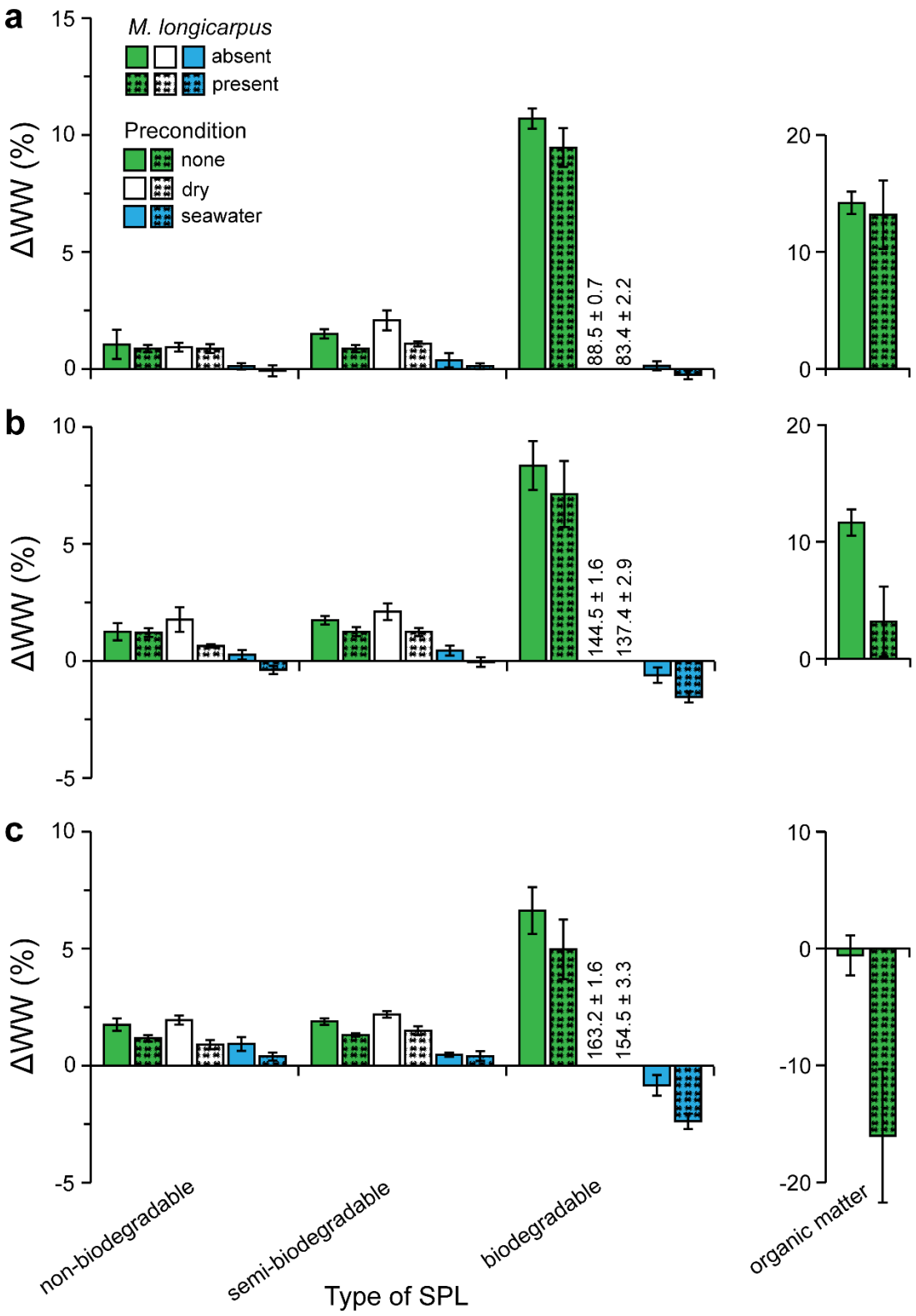

Fig. S2. Change in the wet weight (ΔWW) of new and preconditioned non-biodegradable, semi-biodegradable, and biodegradable soft plastic lures (SPL) and similar sized pieces of fish, *Sardinops sagax* (organic matter) in the presence and absence of soldier crabs, *Mictyris longicarpus*, in a

laboratory experiment. **a**) 6 h. **b**) 24 h. **c**) 48 h. SPLs were preconditioned in seawater for 7 days (seawater, blue bars), held out of water for 7 days (dry, white bars), or were not conditioned (none, green bars). Values for biodegradable-dry treatments are presented as numerals (mean ± SE). Data are means ± SE, $n = 5$.

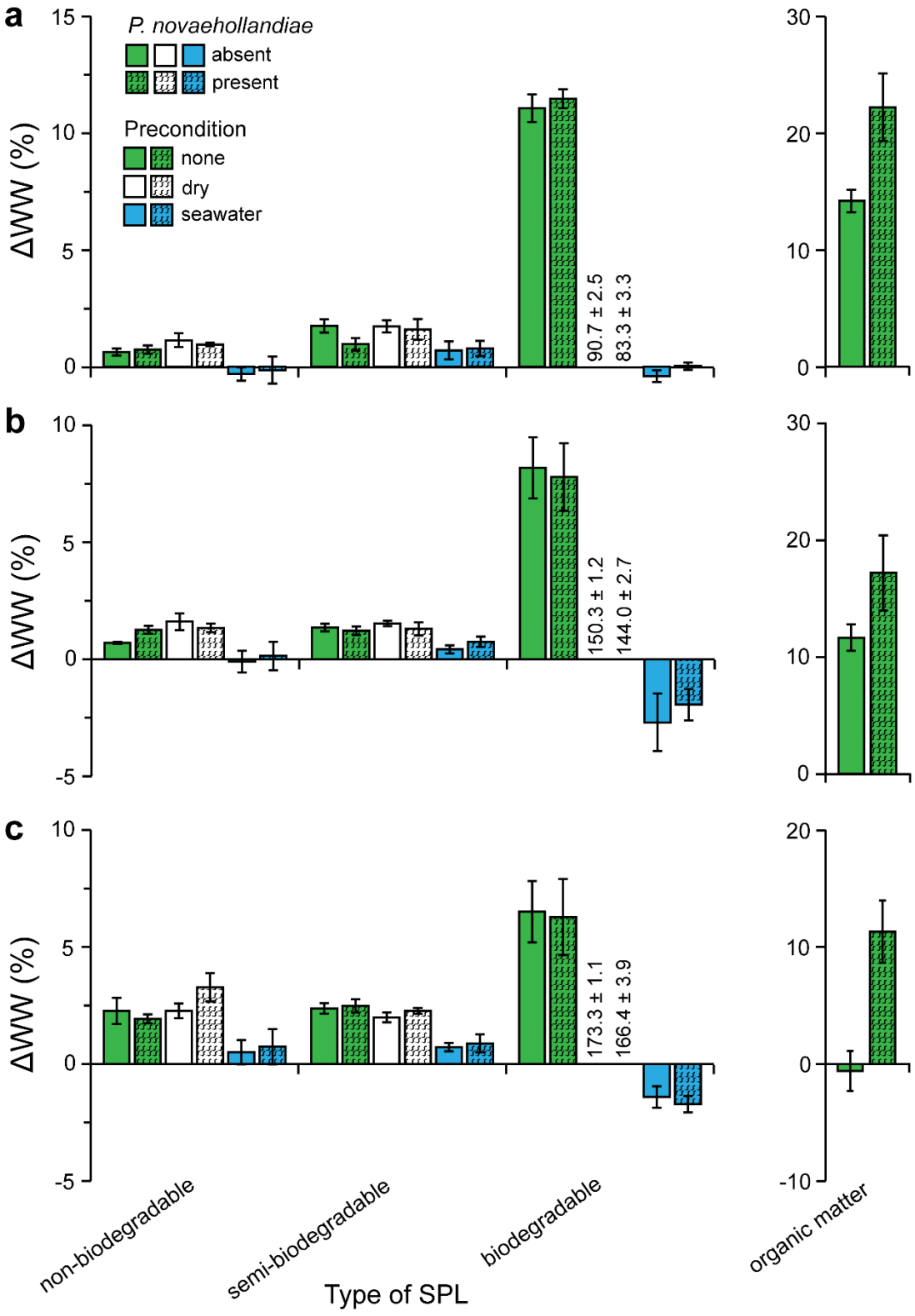

Fig. S3. Change in the wet weight (ΔWW) of new and preconditioned non-biodegradable, semi-biodegradable, and biodegradable soft plastic lures (SPL) and similar sized pieces of fish, *Sardinops sagax* (organic matter) in the presence and absence of green paddle worms, *Phyllodoce novaehollandiae*, in a laboratory experiment. **a**) 6 h. **b**) 24 h. **c**) 48 h. SPLs were preconditioned in

seawater for 7 days (seawater, blue bars), held out of water for 7 days (dry, white bars), or were not conditioned (none, green bars). Data for biodegradable-dry treatments are presented as numerals (mean ± SE). Data are means ± SE, $n = 5$.

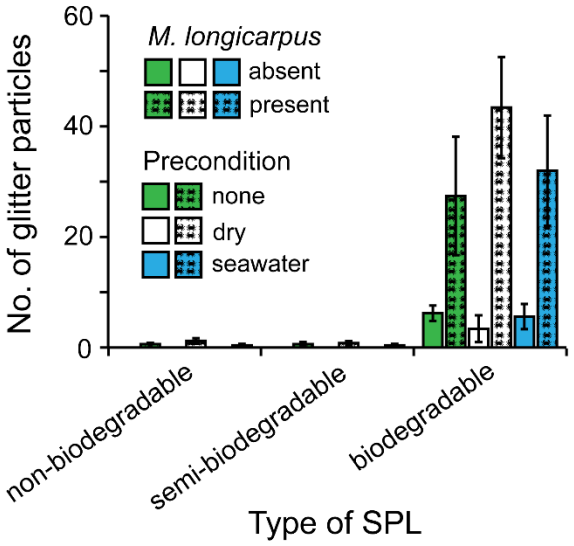

Fig. S4. The number of glitter particles found in replicate buckets housing new and preconditioned non-biodegradable, semi-biodegradable, and biodegradable soft plastic lures (SPL) in the absence and presence of soldier crabs, *Mictyris longicarpus*, in a laboratory experiment for 48 h. SPLs were preconditioned in seawater for 7 days (seawater, blue bars), held out of water for 7 days (dry, white bars), or were not conditioned (none, green bars). No glitter was found in buckets housing *P. novaehollandiae* without SPLs (not displayed). Data are means ± SE, $n = 5$.

Table S1. Outcomes of ANOVA analyses comparing changes in the wet weight (WW) of pieces of fish, *Sardinops sagax* (organic matter) in the presence and absence of two marine invertebrates (presence), *Mictyris longicarpus* or *Phyllodoce novaehollandiae*, after 6, 24, and 48 h in laboratory experiments. df, degrees of freedom; MS, mean square; Significant factors are in bold ($p < .05$).

Species	Source	df	MS	F	*p*	post hoc
M. longicarpus	initial WW	1	348.22	4.35	.073	*interaction*
	time	**2**	**1.28E3**	**81.94**	**<.001**	6, 24 h: present = absent
	presence	**1**	**459.54**	**5.36**	**.049**	48 h: present < absent
	time × presence	**2**	**130.26**	**8.32**	**<.004**	*interaction*
	replicate (presence)	**7**	**80.11**	**5.11**	**<.004**	absent: 6 = 24 > 48 h
	residual	16	15.67			present: 6 > 24 > 48 h
P. novaehollandiae	**initial WW**	**1**	**519.28**	**9.86**	**.016**	*interaction*
	time	**2**	**434.97**	**73.04**	**<.001**	6, 24 h: present = absent
	presence	1	178.38	2.56	.114	48 h: present > absent
	time × presence	**2**	**25.56**	**4.29**	**.034**	*interaction*
	replicate (presence)	**7**	**52.69**	**8.85**	**<.001**	absent: 6 > 24 = 48 h
	residual	16	5.96			present: 6 = 24 > 48 h