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Microplastic retention by marine vegetated canopies: Simulations with seagrass meadows in a hydraulic flume☆

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ABSTRACT

Marine canopies formed by seagrass and other coastal vegetated ecosystems could act as sinks of microplastics for being efficient particle traps. Here we investigated for the first time the occurrence of microplastic retention by marine canopies in a hydraulic flume under unidirectional flow velocities from 2 to 30 cm s^{-1}. We used as model canopy-forming species the seagrass *Zostera marina* with four canopy shoot density (0, 50, 100, 200 shoots m^{-2}), and we used as microplastic particles industrial pristine pellets with specific densities from 0.90 to 1.34 g cm^{-3} (polypropylene PP; polystyrene PS; polyamide 6 PA; and polyethylene terephthalate PET). Overall, microplastics particles transported with the flow were retained in the seagrass canopies but not in bare sand. While seagrass canopies retained floating microplastics (PP) only at low velocities (<12 cm s^{-1}) due to a barrier created by the canopy touching the water surface, the retention of sinking particles (PS, PA, PET) occurred across a wider range of flow velocities. Our simulations revealed that less dense sinking particles (PS) might escape from the canopy at high velocities, while denser sinking particles can be trapped in scouring areas created by erosive processes around the eelgrass shoots. Our results show that marine canopies might act as potential barriers or sinks for microplastics at certain bio-physical conditions, with the probability of retention generally increasing with the seagrass shoot density and polymer specific density and decreasing with the flow velocity. We conclude that seagrass meadows, and other aquatic canopy-forming ecosystems, should be prioritized habitats in assessment of microplastic exposure and impact on coastal areas since they may accumulate high concentration of microplastic particles that could affect associated fauna.

1. Introduction

Plastic has become ubiquitous in the oceans worldwide, with microplastics, i.e. plastic particles smaller than 5 mm, probably being the most abundant plastic debris in the oceans (Barnes et al., 2009; Cole et al., 2011). Microplastics are released into the marine environment as primary microplastics, such as industrial pellets and microbeads, or they are formed as a result of the breaking down of larger pieces into smaller ones, so called secondary microplastics (Barnes et al., 2009). Microplastics are of significant environmental concern because their small size makes them accessible to a wide range of organisms through filtration or ingestion, thus possibly threatening wildlife (Cole et al., 2011; Wright et al., 2013). In addition, microplastics contain chemical additives and can also adsorb hydrophobic waterborne pollutants enhancing their negative effects in the environment (Cole et al., 2011). The increasing concentration of microplastics into the oceanic and coastal areas demands investigating the factors that drive their transport and deposition across marine environments, particularly in key habitats for marine wildlife (Vetger et al., 2014).

Marine and coastal vegetated ecosystems that form underwater or temporarily flooded canopies, such as seagrass meadows, macroalgae beds, mangrove forests or saltmarshes, are key habitats for marine megafauna (Sievers et al., 2019) and for a wide variety of juvenile fish and invertebrates (Lefcheck et al., 2019). These ecosystems are also well-known for their ability to promote the deposition of suspended particles within their canopies, including sediments (Gacia et al., 1999), phytoplankton (Agawin and Duarte

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2002) or zooplankton eggs (Scheef and Marcus 2010), through attenuation of the currents and wave energy (Infantes et al., 2012) and stabilisation of the sediment from resuspension (Terrados and Duarte 2000). The role of marine canopies in particle trapping suggests that these ecosystems could also retain microplastics, especially those with negative buoyancy, becoming accumulation areas for microplastic. The investigation of the role of marine canopies in the retention of microplastics is very recent, and the few available studies show that mangroves (Garcés-Ordóñez et al., 2019; Zhou et al., 2020), seagrass meadows (Goss et al., 2018; Huang et al., 2019; Cozzolino et al., 2020; Jones et al., 2020), salt-marshes (Cozzolino et al., 2020; Wu et al., 2020), and canopy-forming macroalgae (Cozzolino et al., 2020) could act as filters to microplastics at variable degrees. These studies were field-based and aimed to report environmental concentration of microplastics in the marine canopies, without investigating the drivers of such accumulation. Since this is a novel research field, there are still many questions to be answered, such as “which are the bio-physical factors (e.g. canopy structure, hydrodynamics, plastic types) that underlie their microplastic retention capacity?”. Understanding these factors will enable us to identify microplastics accumulation areas that should be included in plastic debris assessments.

Microplastics are diverse in terms of the polymer they are made of, their shape and size. These factors influence their transport and distribution in the marine environments and, along with hydrodynamical conditions, may determine whether they are retained in a specific area or not (Chubarenko et al., 2016; Zhang 2017). The capacity of coastal vegetated ecosystems to filter and retain small particles (e.g. seeds and sediments) depends also on the physical properties of the particles and hydrodynamic factors, such as current velocity and wave action, but also on the canopy properties, such as height and shoot density (De Boer, 2007; Hendriks et al., 2008; Wilkie et al., 2012; Pereda-Briones et al., 2018; Meysick et al., 2019). We therefore hypothesise that the potential capacity of marine canopies to retain microplastics may depend on a combination of bio-physical factors including the physical properties of the particles (polymer density), the meadow properties (shoot density), and the local hydrodynamic conditions (flow velocity). Experimental manipulations of these factors in hydraulic flumes arise as an appropriate tool to identify the drivers that control the microplastic trapping within canopies of coastal vegetated ecosystems, as previously done regarding their capacity to trap natural particles (e.g. Hendriks et al., 2008; Hendriks et al., 2010; Pereda-Briones et al., 2018; Meysick et al., 2019). This approach can guide more efficiently future research to reveal the role of marine canopies in the microplastic retention and to identify microplastic accumulations in coastal areas.

Here we investigated the probability of occurrence of microplastic retention in marine canopies with controlled bio-physical conditions in a hydraulic flume, using the seagrass *Zostera marina* as model vegetation and industrial pristine pellets of known polymer composition and specific density as microplastic particles. *Zostera marina* was selected for representing the morphology of most seagrass species and for being widely distributed. Plastic pellets were selected for being particles of known specific density and for being a common type of marine litter, particularly in the proximity of plastic manufacturing plants, cargo loading docks, and shipping lanes of raw plastic materials (Norén 2007; Karlsson et al., 2018) but also far from them in remote areas (McDermid and McMullen 2004; Moore 2008). We simulated the capacity of eelgrass canopies with varying shoot densities (0, 50, 100, and 200 shoots m^{-2}) under a range of unidirectional flow velocities (2–30 cm s^{-1}) to retain pellets with different polymer densities (0.90–1.34 g cm^{-3}). Our aim was to identify i) which type of microplastics (polymer type) are more prone to get trapped in seagrass meadows, ii) which seagrass density is more prone to trap microplastics, and under iii) which hydrodynamical conditions (flow velocity) the trapping is more likely to occur. The study design did not attempt to investigate the mechanisms underlaying the retention of microplastics in the canopies, yet some general behaviours were observed and discussed. These simulations will allow us to understand the role of canopy shoot density, velocity and particle density in the capacity of seagrass to act as a barrier or sink to microplastics.

2. Materials and methods

2.1. Microplastics particles and plant material

Primary microplastic particles were used in the form of industrial pristine pellets, i.e. millimetre-sized particles with relatively uniform dimensions within the pellet’s batch, used as feedstock within the plastic industry. Industrial pellets were selected among the variety of microplastic shapes (i.e. fragments, fibres, films) for presenting uniform size and composition and for being of environmental significance as plastic debris (e.g. McDermid and McMullen 2004; Moore 2008). Four types of pellets were used with specific densities from 0.90 to 1.34 cm g^{-3} (Table 1; Fig. 1). Polypropylene (PP), Polystyrene (PS) and Polyethylene terephthalate (PET) pellets were purchased from the supplier CARAT GmbH, Buchold, Germany, with reference numbers CRT200.00, CRT300.00, and CRT401.00, respectively, and producer’s names PP030 GP/3, Styron 637 and NEOPET 80, respectively. Polyamide 6 (PA) was purchased from a Chinese supplier (anonymous, via Alibaba) and detailed information is not available for the product, except for the specific density (Table 1). The maximum length of individual plastic pellets was determined with a digital calliper (±0.01 mm) and their weight in a precision balance (±0.01 mg) (n = 10, Table 1, Supplementary Material S1). The settling velocity of the particles was estimated in a 1-m sedimentation column using a hand chronometer to measure the falling time. The settling velocity was calculated by dividing the distance fallen by the falling time (n = 10, Table 1, Supplementary Material S1).

Eelgrass (*Zostera marina*) shoots were collected in August 2019 from a shallow meadow (~1 m depth) in the Gullmars Fjord (west

Table 1
Physical properties of the industrial pristine pellets used in the simulations: polymer composition and class, buoyancy in seawater, specific density, maximum length (size range between brackets), weight, and settling velocity. Data for maximum length, weight, and settling velocity are given as mean ± SD (n = 10 individual pellets). Specific density and size range were given by the manufacturer. NA, not available.

Polymer	Class	Buoyancy	Density (g cm^{-3})	Maximum length (mm)	Weight (mg)	Settling velocity (cm s^{-1})
Polypropylene (PP)	Homopolymer, general purpose grade	Positive	0.90	4.07 ± 0.18 (2–5)	28.5 ± 4.9	not sinking
Polystyrene (PS)	General purpose grade	Negative	1.05	3.59 ± 0.12 (2–4)	19.6 ± 2.6	2.6 ± 0.1
Polyamide 6 (PA)	NA	Negative	1.14	2.27 ± 0.18 (NA)	9.2 ± 1.3	6.6 ± 0.2
Polyethylene terephthalate (PET)	Crystalline copolymer	Negative	1.34	2.79 ± 0.21 (2–3.15)	16.0 ± 1.8	10.4 ± 0.2

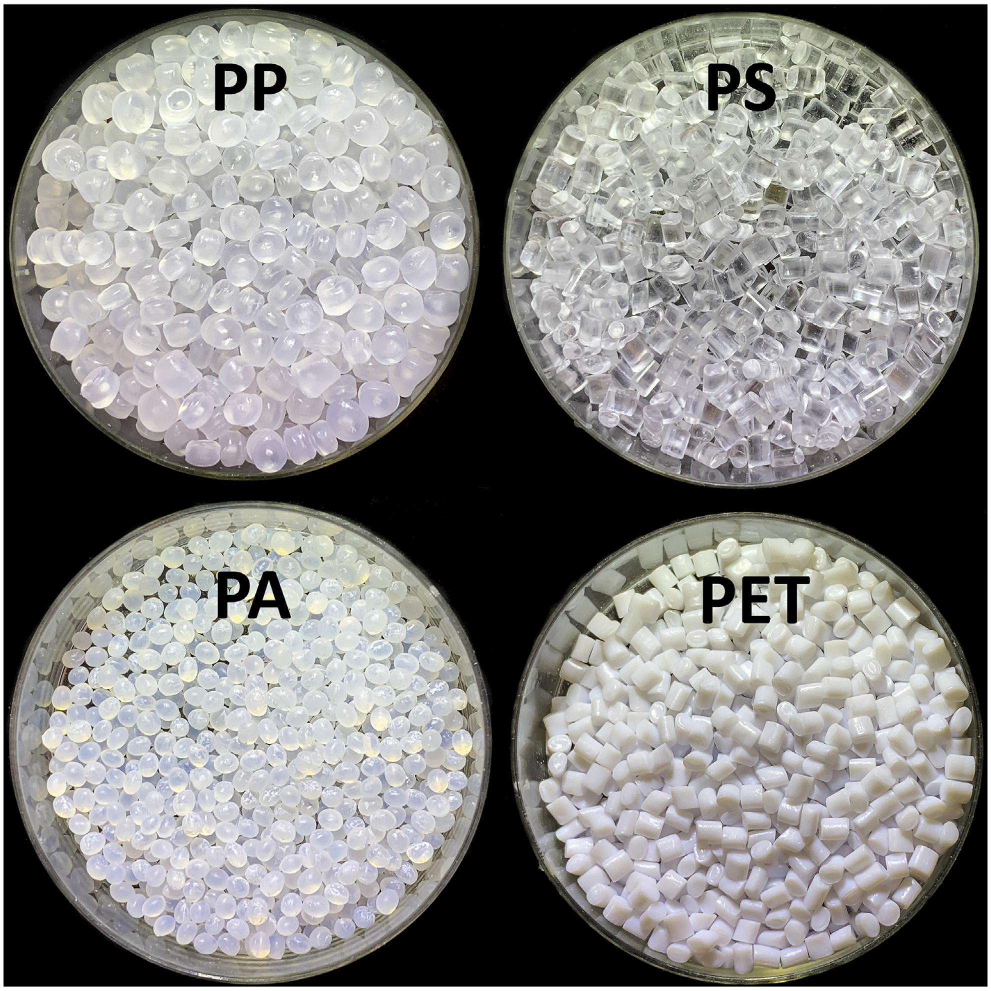

Fig. 1. Macroscopic view of the industrial pristine pellets used in the simulations. Pellet types: PP, polypropylene; PS, polystyrene; PA, polyamide 6; PET, polyethylene terephthalate. Diameter of Petri dish (6 cm) used for scale.

coast of Sweden), next to Kristineberg Marine Research Centre, University of Gothenburg (58.25° N, 11.45° W). Plants were immediately transported to the laboratory where they were kept in tanks with flow-through seawater (24.6 PSU, 18.8 °C) from the fjord. Eelgrass plants had 5.2 ± 1.0 leaves shoot^{-1} with a shoot length of 45.3 ± 7.3 cm, shoot width of 3.8 ± 0.5 mm and shoot total area of 59.9 ± 18.2 cm^2 (shoot length and width refer to the maximum length and width of the individual leaves within a shoot; data given as mean ± standard deviation, n = 20, Supplementary Material S1).

2.2. Hydraulic flume set-up and trapping simulation trials

Microplastics trapping by eelgrass canopies was simulated using a hydraulic flume located at Kristineberg Marine Research Station. The flume is 8 m long, 0.5 m wide, and 0.5 m deep, with a 2-m box located in the middle of the flume to be used as test section. Unidirectional flow was generated by using a propeller driven by an electrical motor (for more technical details, see Pereda-Briones et al., 2018). The box of the flume test section was filled with natural fine sand (previously sieved through 2 mm) collected at the same location as the eelgrass, and the flume was filled up to 0.15 m with seawater from the fjord (24.6 PSU, 18.8 °C). Flow velocities were measured with an acoustic Doppler velocimeter (Nortek, Vectrino), before the test section at the middle of the water column (7.5 cm from the bottom; i.e. at the point where the sinking particles were released; Fig. 2), using a sampling rate of 25 Hz for 3 min. The obtained velocities were used with the purpose of comparing the velocity treatments, and not as the absolute velocities experienced by the particles when being transported or retained across the test section. Flow velocity is expected to vary vertically in the water column and in the presence of a canopy (e.g. Pereda-Briones et al., 2018; Meysick et al., 2019).

Simulation trials were conducted under 4 type of canopies by manipulating the shoot density of the seagrass meadows (0, 50, 100, and 200 shoots m^{-2}), with 0 shoots m^{-2} being bare sand. The selected shoot densities are within the rage of eelgrass meadows in the Swedish region (20–500 shoots m^{-2}; Boström et al., 2014). Each meadow was built along the first 1-m within the box of the flume by placing eelgrass shoots by hand, one by one, into the sand. The sand surface was flattened at the beginning of each treatment, whereafter it was allowed to be naturally modified by the increasing unidirectional flow from one velocity level to the next one. The microplastics retention capacity for each shoot density treatment was determined under twelve current velocities (2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 24, and 30 cm s^{-1}), a range which is naturally found in eelgrass meadows of the area. Each simulation ('polymer type' x 'flow velocity' x 'shoot density') was run 10 times, accounting for 1920 trials in total. Flow was initialized for 2 min prior to each trial to establish constant flow conditions in the flume.

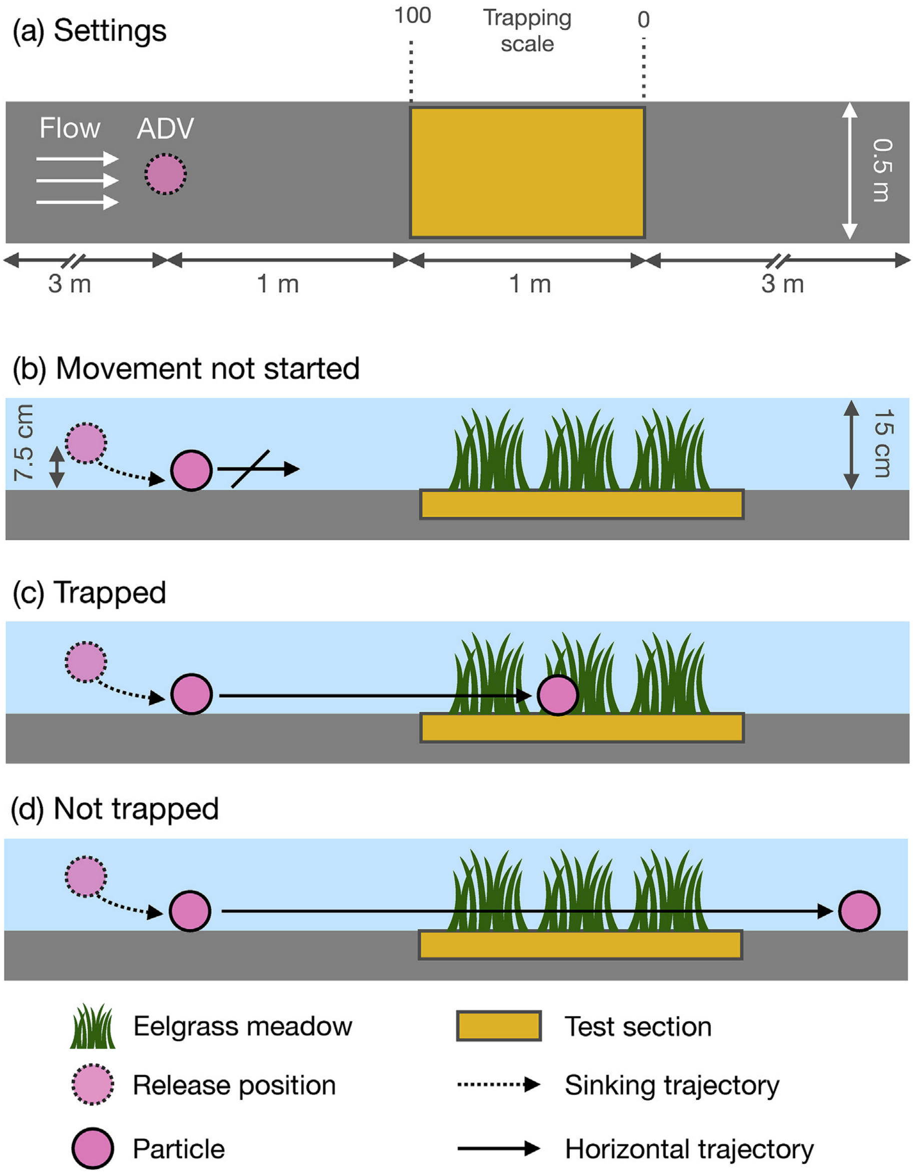

Fig. 2. Diagram (not at scale) showing (a) top view of the hydraulic flume with the point of the particle release and velocity measurements (ADV), and the three behavioural categories of particles defined for the simulation trials: (b) movement not started (when the flow velocity was not high enough to start the movement of the plastic pellet), (c) trapped (when the pellet got trapped for more than 1 min in the test section after having initiated the movement), (d) not trapped (when the pellet passed the test section after having initiated the movement). For all pellets that initiated the movement and entered into the test section (b and c), a continuous linear scale was used to quantify the trapping, with a value of 100 being trapped at the beginning of the section, 50 being trapped in the middle, and 0 not being trapped (i.e. passed through the test section). Diagram depicts only sinking particles, yet it applies also to floating particles (with release position and trajectory on the water surface).

Then, the pellets were individually released with a tweezers, 1 m upstream the test section: on top of the water surface for the floating pellet (PP) or in the middle of the water column (i.e. at 7.5 cm depth) for the sinking pellets (PS, PA, PET). After being released, sinking particles always reached the bottom before the start of the test section. The positions in the water column at which the particles were released were selected according to their natural transport pathway observed in preliminary tests: particles less dense than water (PP) floated at the water surface, and particles denser than water (PS, PA, PET) sank into the water column. Replicated pellets were released along the central width of the flume, to avoid particles to repeat the same trajectory across the test section. If the particle started the movement, it was allowed to pass through the 1-m test section (meadow or bare sand), or until it got trapped in the substrate for at least 1 min (monitored with a manual chronometer, ± 0.01 s). If trapped, the distance at which a particle was trapped in the test section (if that was the case) was measured from the beginning of the test section with a metric tape (±1 cm). The 1-min criterion for the definition of the retention was based on preliminary trials in which we observed that this time duration did not normally imply a resuspension of the particles. The behaviour of the particle in each simulation trial was described in two ways: (1) in a 0–100 linear scale based on the distance at which it was trapped, with a value of 100 being trapped at the beginning of the section, 50 being trapped in the middle, and 0 not being trapped (i.e. passed the test section) (Fig. 2a), and, (2) as a categorical variable with three levels: movement not started, trapped, and not trapped (Fig. 2b–d). The category “movement not started” refers to the behaviour in which the particle, after having been released, did not initiate the movement because the flow velocity was not high enough. The water of the flume was disposed at the end of all the simulations, after been filtered through a 2-mm mesh to avoid any potential release of the plastic pellets from the facility.

2.3. Data analysis

The particle retention was expressed in two ways: i) as the percentage of simulations in which the particles did not initiated the movement, were trapped, or were not trapped; and ii) as the mean and its standard error (SE) of the trapping in the 0–100 scale for the replicated trials run under each treatment (‘polymer type’ x ‘flow velocity’ x ‘shoot density’), after excluding those that did not initiate the movement.

To investigate the probability of occurrence of microplastic retention under the different controlled levels of the factors, we used a multinomial logistic regression, since our data meet the criteria of the response (nominal with more than 2 levels) and predictor variables for that statistical test. The multinomial logistic regression was used to fit the response variable (particle behaviour) expressed as a categorical variable (3 levels: movement not started, trapped, and not trapped), using as predictor variables: the flow velocity (continuous), the shoot density (categorical, with 4 levels: 0, 50, 100, 200 shoots m^{-2}), and the polymer type (categorical, with 4 levels: PP, PS, PA, PET). To directly respond to our research question, the model was built as an additive model (i.e. without interactions; model formula: particle behaviour ~ polymer type + shoot density + flow velocity) and we focused on the model coefficients, which correspond to the comparison of the probabilities, in log odds, of the pellets to be trapped vs not to be trapped. Briefly explained, the log odds represent the natural logarithm of the ratio between the probability of being trapped (*P trapped*) and the probability of not being trapped (*P not trapped*). Positive log odds mean that probability of being trapped is higher than that of not being trapped (*P trapped* > *P not trapped*), while negative odds mean the opposite (*P trapped* < *P not trapped*). The p-values (two-tailed) of the model coefficients were calculated using Wald test (z) and used to assess the significance of the predictor variables. The model was then used to obtain predicted probabilities for each behaviour category (movement not started, trapped, and not trapped) associated to the variation of the predictor variables, in order to depict and further understand the model outputs. The significance level was $p < 0.05$ for all tests. Data analysis was done with the R programming language R 3.6.1 (R Core Team, 2019). The “multinom” function from the “nnet” package (Venables and Ripley 2002) was used for the multinomial logistic model. Raw data and full data analysis report, including the full model output, are given in Supplementary Material S1 and S2, respectively.

3. Results

The flow velocity at which the movement of the pellets started varied according to their density (given in brackets): PP (0.90 g cm^{-3}) started moving at the water surface already at the lowest velocity tested (2 cm s^{-1}), while PS (1.05 g cm^{-3}), PA (1.14 g cm^{-3}), and PET (1.34 g cm^{-3}) started rolling constantly on the bottom at 8, 10, and 18 cm s^{-1}, respectively. These velocity thresholds mirrored the settling velocity of the pellets (Table 1). The number of simulations in which pellets were trapped, in relation to those that were not trapped, increased with the shoot density (Fig. 3a) and, generally, with polymer density (Fig. 3b), but not with flow velocity (Fig. 3c).

Particle trapping within the canopies differed among pellet types (Fig. 4). PP pellets, being floating particles (density 0.90 g cm^{-3}), only got trapped in the presence of eelgrass and at low velocities (<12 cm s^{-1}), when the leaves were touching the water surface, thus creating an obstacle for the particles that travelled along the water surface (Figs. 4a, Fig. 5a–b). This superficial trapping was more obvious at the two highest eelgrass shoot densities (Fig. 4a). PS pellets got trapped on the seagrass meadows but not on the bare sediment when exposed to velocities from ~8 cm s^{-1} to 16 cm s^{-1}, while at velocities above 16 cm s^{-1}, PS pellets travelled through the meadows without being trapped

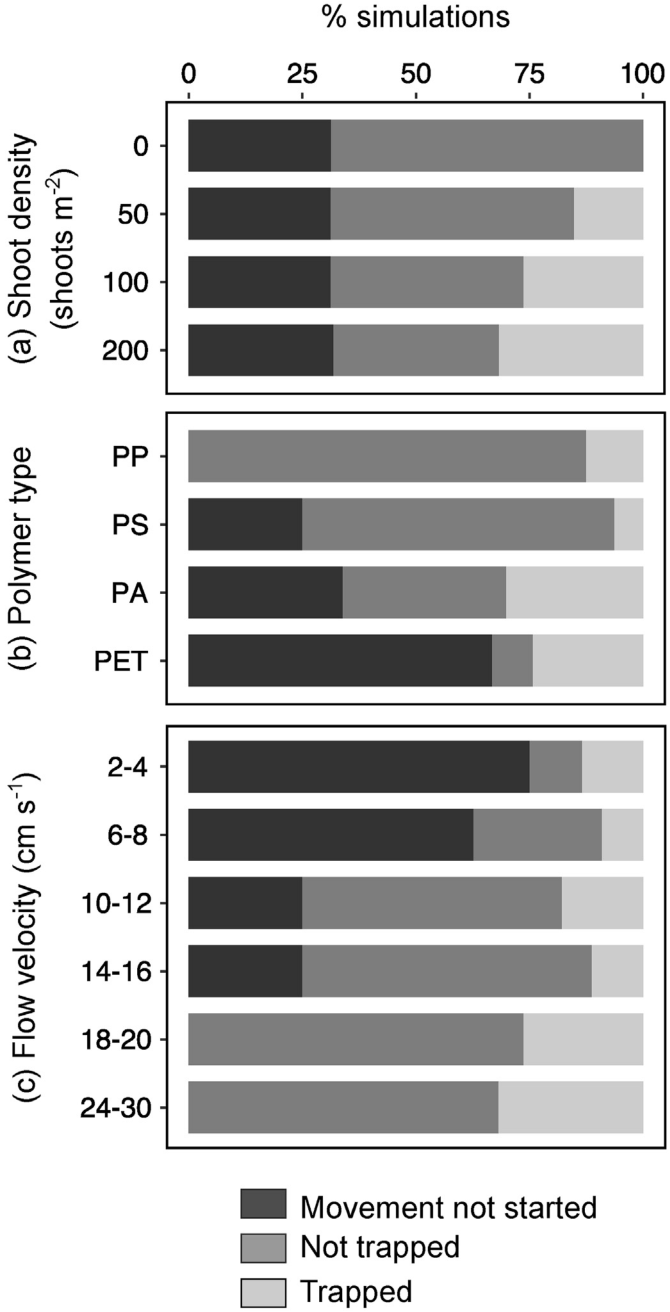

Fig. 3. Percentage of simulations in which the plastic particles did not start movement, were trapped, or were not trapped, when grouping all trials by each factor: seagrass shoot density (a), polymer type (b), and flow velocity (c). Polymer type levels (density in brackets): polypropylene, PP (0.90 g cm^{-3}); polystyrene, PS (1.05 g cm^{-3}); polyamide 6, PA (1.14 g cm^{-3}); and, polyethylene terephthalate, PET (1.34 g cm^{-3}). In (c) data were grouped every two consecutive flow velocity levels for visualisation purposes only. N = 480 for each polymer and seagrass density level, and N = 320 for each velocity range.

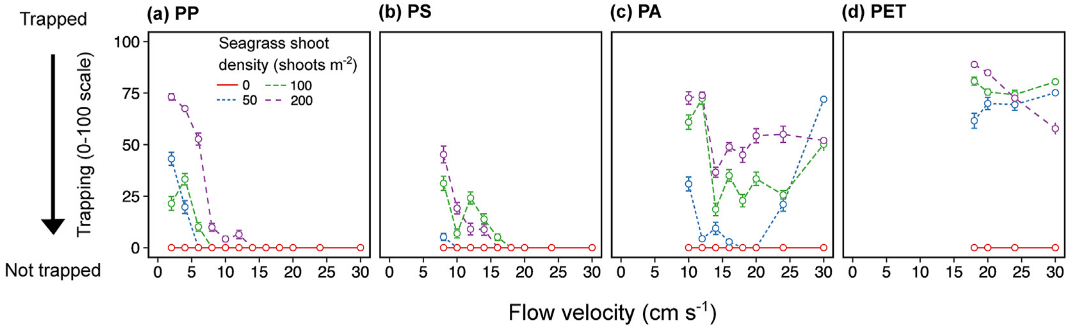

Fig. 4. Trapping of microplastic particles consisting of pellets of polypropylene, PP (a), polystyrene, PS (b), polyamide, PA (c), and polyethylene terephthalate, PET (d) on eelgrass meadows with four shoot densities (0, 50, 100, and 200 shoot m^{-2}) at flow velocities from 2 to 30 cm s^{-1}. Trapping is expressed in a scale from 0 to 100: 0 being not trapped (the particle passed through the test section) and 100 being trapped at the start of the test section. Absence of points at low velocities means that the particle did not start the movement after having been released.

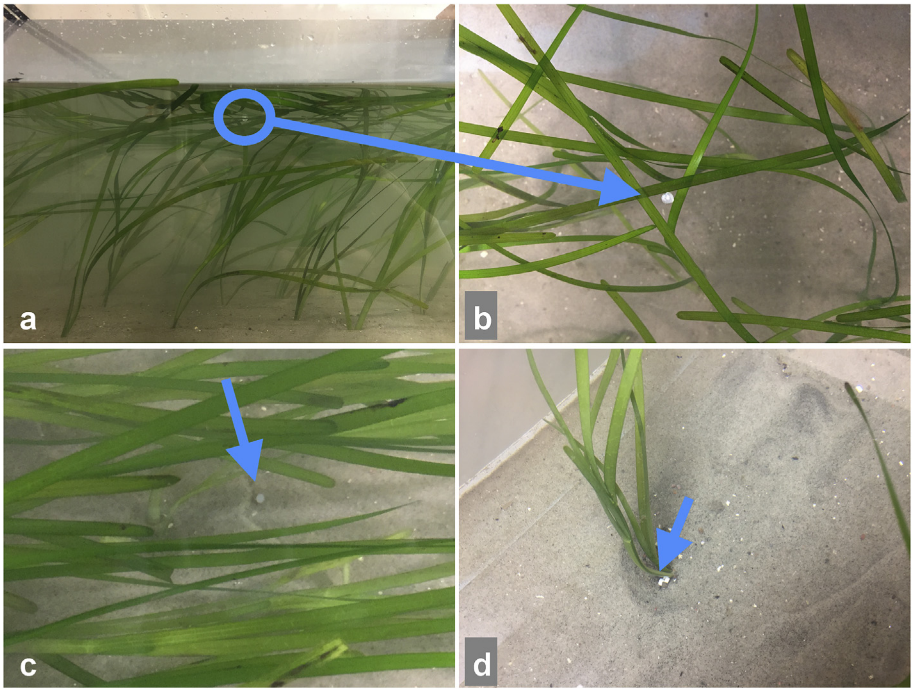

Fig. 5. Examples of microplastic retention by eelgrass meadows during the simulations in the hydraulic flume: retention at the surface of the water column for floating polypropylene (PP) pellets at low velocities (a: lateral view, b top view), and retention in the scouring areas created within the meadow at high velocities for polyamide 6 (PA) and polyethylene terephthalate (PET) pellets (c and d top views).

(Fig. 4b). PA and PET pellets behaved similarly (Fig. 4c and d). After their movement started, the particles got trapped in the canopies, especially in the denser one, but not in the absence of seagrass. The only exception was for PA particles, that were not trapped in the canopy with the lowest shoot density at 18–20 cm s^{-1} (Fig. 4c). At the highest velocities tested (24–30 cm s^{-1}), and opposite to PS particles, which were flushed away at those velocities, the particles of PA and PET were trapped in the scouring areas in the sediment created by erosive processes around the eelgrass shoots due to the high velocity (Fig. 5c–d).

Based on the coefficients of the multinomial logistic regression (Table 2), the three predictors (shoot density, polymer type, and flow velocity) significantly explained the trapping of the particles. The probability of being trapped slightly decreased with flow velocity (the log odds of the trapped vs not trapped categories of the multinomial regression were decreased by 0.148 with a unit increase in flow, Fig. 6). Regarding the polymer type, PP and PS showed similar probability of being trapped (the increase in the log odds of PS in comparison to PP was not significant, Table 2, Fig. 6a–b). However, this probability was highly increased for PA (3.4-fold increase in the log odds) and PET (7.6-fold increase in the log odds) (Table 2, Fig. 6c–d). The eelgrass shoot density was also a significant predictor of the trapping probability, although the greatest difference was between sand and presence of eelgrass (note the similarity of the coefficients in Table 2 for the three categories with seagrasses, Fig. 6).

4. Discussion

We investigated for the first time the occurrence of microplastic retention by marine canopies under experimental conditions, using eelgrass (*Zostera marina*) as model species and pristine plastic pellets as microplastic particles. Overall, our simulations showed that, at certain bio-physical conditions, marine canopies can act as

Table 2
Model coefficients obtained from multinomial logistic regression, with particle behaviour as response variable (3 levels: movement not started, trapped, and not trapped) and the following predictor variables (model formula: particle behaviour ~ polymer type + shoot density + flow velocity): polymer type (PP, polypropylene; PS, polystyrene; PA, polyamide 6; PET, polyethylene terephthalate), seagrass shoot density (0, 50, 100 and 200 shoots m^{-2}), and flow velocity (cm s^{-1}). Table shows the log odds, i.e. the natural logarithm of the ratio between the probability of being trapped (*P trapped*) and the probability of not being trapped (*P not trapped*).

Coefficients	Ln (*P trapped*/*P not trapped*)	z and p-value (comparison to intercept)
Intercept (PP, Seagrass = 0, Flow velocity = 0)	−85.310 ± 0.171	−500.17, $p < 0.001$
Polystyrene (PS)	0.037 ± 0.269	0.14, $p = 0.705$
Polyamides (PA)	3.428 ± 0.287	11.93, $p < 0.001$
Polyethylene terephthalate (PET)	7.633 ± 0.650	11.75, $p < 0.001$
Seagrass 50	83.796 ± 0.180	465.15, $p < 0.001$
Seagrass 100	85.429 ± 0.146	584.49, $p < 0.001$
Seagrass 200	86.073 ± 0.149	579.85, $p < 0.001$
Flow velocity	−0.148 ± 0.018	−8.39, $p < 0.001$

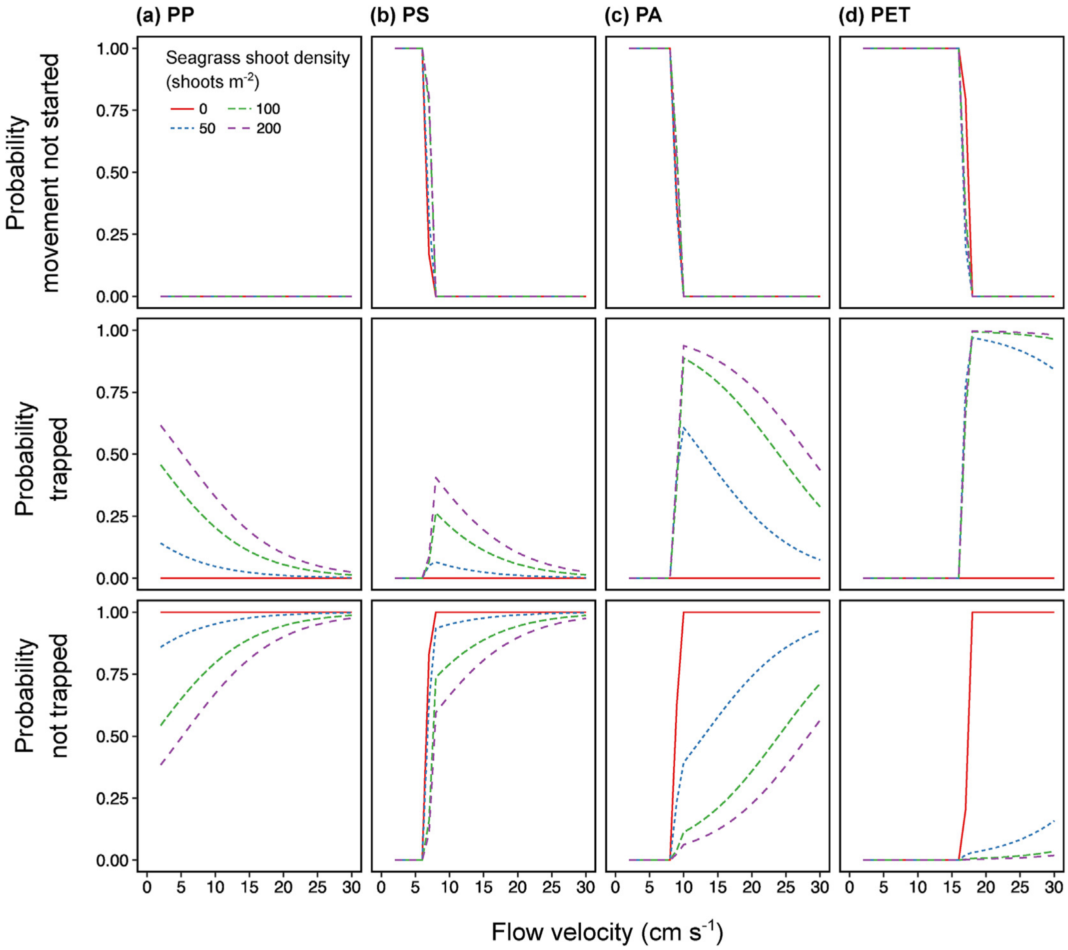

Fig. 6. Variation of the predicted probabilities for the three behaviours (movement not started, trapped and not trapped) of the pellet types a) polypropylene, PP, b) polystyrene, PS, c) polyamide, PA and d) polyethylene terephthalate, PET, with seagrass shoot density and flow velocity.

barriers or sinks for microplastics. The probability of microplastic retention generally increased with the canopy shoot density and specific density of the particles, and decreased with flow velocity, yet with a high variability among pellet types. Our findings will help set new experimental scenarios to further investigate the biophysical conditions and mechanisms that promote the microplastic retention in marine or aquatic canopies, in order to better understand the patterns of accumulation of microplastics on coastal areas.

Our results showed that pellets made of dense polymers, such as PA and PET, were more prone to be trapped by the eelgrass meadows, once the movement of the particles started. While seagrass canopies trapped floating microplastics only at low velocities (<12 cm s^{-1}) due to a barrier created by the top part of the canopy touching the water surface, the retention of sinking particles occurred across a wider range of flow velocities. After having initiated their movement, sinking microplastics accumulated in the seagrass canopies but not in bare sand. However, at high velocities, less dense particles, such as PS, might escape from the canopy while denser ones (PA and PET) can be trapped within the meadow or in scouring areas created by erosive processes around the eelgrass shoots. The accumulation of high-density microplastics in the benthic environment has already been observed when comparing sea surface water and beach sediment (Morét-Ferguson et al., 2010). Under experimental conditions, we demonstrated that floating microplastics can be trapped at low velocities by marine vegetated canopies, at least during a short period of time (1 min). This barrier could occur naturally in seagrass meadows, or other aquatic canopy-forming ecosystems, when growing in shallow areas or during low tide for intertidal meadows, acting as accumulation zones for microplastic particles. Yet, retained particles could be flushed away by changes in the water flow or even the wind in the natural environment. Our study, by using the time duration for retention of 1 min, aimed to understand the effect of the different drivers in the retention probability, so we are aware that the results do not encompass the full complexity of particle retention in nature. Therefore, the retention capacity of both floating and sinking particles should be further explored over more complex environmental conditions, for instance by incorporating changes in current direction, to test if microplastics can be resuspended or redirected after being initially trapped.

This study identified some of the drivers of microplastic trapping in marine canopies under controlled laboratory conditions. We demonstrated that the three factors, namely polymer type, flow velocity, and shoot density, explained the probability of microplastics to be retained in marine vegetated canopies, at least for particles in the upper size range of microplastics (i.e. 2-5 mm). Our simulations may eventually help us to identify areas of high microplastic accumulation or predict the behaviour or microplastic particles in coastal or other aquatic environments such as rivers and lakes. The retention of microplastics across different hydrodynamic regimes has not yet been addressed in field studies. The available field studies show that microplastics accumulate to varying degree in areas dominated by seagrass meadows (Goss et al., 2018; Huang et al., 2019; Cozzolino et al., 2020; Jones et al., 2020) and other coastal ecosystems such as mangroves (Garcés-Ordóñez et al., 2019; Zhou et al., 2020) and saltmarshes (Cozzolino et al., 2020; Wu et al., 2020). In the case of saltmarshes, Wu et al., (2020) suggested that calm waters during neap tides could explain the higher abundance of sediment microplastics in comparison to more turbulent waters during spring tides. Based also on other studies showing the role of flow velocity on the capacity of seagrasses to trap other types of particles, such as seeds and propagules (e.g. Pereda et al., 2018; Meysick et al., 2019) or fine sediments (e.g. Wilkie et al., 2012; Santos et al., 2019), hydrodynamics seem to be a key driver to identify microplastics accumulation areas within coastal vegetated ecosystems. Regarding the effect of the meadow properties, our study revealed that even sparse meadows can act as microplastic sinks and that trapping increased with the shoot density, yet not in a linear proportion. Moreover, our results may underestimate the trapping capacity of meadows, since we only tested the effect of the eelgrass canopy, while other organisms usually present on the meadow, such as bivalves or epiphytes, might increase the bottom complexity increasing the particle trapping. Available literature on the effect of canopy complexity in microplastic trapping is scarce and variable. While Zhou et al. (2020) showed that the density and height of mangrove trees were positively related to the microplastic abundance, Helcoski et al. (2020) showed that microplastic abundance in wetlands is negatively related to vegetation cover and stem density. For other type of particles, such as seagrass seeds and seedlings, the trapping capacity was enhanced by dense canopies of seagrasses (Pereda et al., 2018; Meysick et al., 2019).

We observed during the trials that the seagrass canopy can enhance the retention of microplastics in the sediment through a variety of mechanisms: a) pellet particles slowed down inside the seagrass meadow, which can be explained by the well-known effect of seagrass canopies in reducing flow velocity by increasing the shear stress (e.g. Infantes et al., 2012); b) pellets were retained in scouring areas created around the seagrass shoots at high velocities, as previously shown for seeds (Meysick et al., 2019); c) pellets hit the seagrasses, which acted as blockage preventing the particle from moving forward thus being retained in front of the shoots, as previously shown for seeds (Meysick et al., 2019); d) pellets that had been retained were rarely resuspended (at least for 1 min), while particles were sometimes resuspended in the bare sand treatment in less than 1 min; avoidance of resuspension is a mechanism previously reported for sediments (e.g. Terrados and Duarte 2000) and copepod eggs (Scheef and Marcus, 2010); e) for floating particles, the blockage of the seagrass leaves touching the surface (Fig. 5). Other potential mechanisms that could potentiate the retention and accumulation of microplastics in marine canopies are: a) through bioturbation, as shown for copepod eggs (Scheef and Marcus, 2010); b) through binding onto seagrass leaf surfaces by physical adherence, in particular to exopolymeric substances excreted by epiphytes (Agawin and Duarte 2002; Hendriks et al., 2008); c) through ingestion by protozoa residing on the surface, as demonstrated for 1–15 μm particles of phytoplankton and beads (Agawin and Duarte 2002); and, d) through loss of momentum and increased path length derived from the collisions with leaves (Hendriks et al., 2008). Further studies should aim at investigating quantitatively these direct and indirect mechanisms and other potential ones (e.g. entanglement of fibres) for a better understanding of the role of marine vegetated canopies in microplastic trapping.

The retention of microplastics in aquatic canopies may have negative environmental consequences, such as accidental ingestion by wildlife and by acting as vectors for other contaminants. Thus, investigating the likely negative impact of such accumulated microplastics on aquatic canopies and on biota associated with, or food webs supported by those habitats, should be of high priority (Bonanno and Orlando-Bonaca, 2020). Given the infancy of this field, further research is needed to improve our understanding about the bio-physical interaction of microplastics and marine canopies. In our study, plastic pellets were selected for the trials for being particles of known specific density and uniform size. Despite not being among the most common type of microplastics found in coastal areas, their environmental concentration is of significance, particularly in the proximity of manufacturing plants, cargo loading docks and shipping lanes of raw plastic materials (Norén 2007; Karlsson et al., 2018), but also far from them in remote areas (McDermid and McMullen 2004; Moore 2008). For instance, preproduction pellets comprised 11% by abundance of the microplastics collected along 9 remote beaches in the Hawaiian Archipelago (McDermid and McMullen 2004). Further research should investigate the hydrodynamical behaviour of other microplastic shapes, especially those that are getting increasingly common in coastal areas (e.g. films, fibres, fragments), and sizes, since their transport and retention may differ from the ones showed here for millimetre-sized pellets. Size is likely an important factor to investigate further because it varies in a wide range (from nano to mega) and it determines, along with particle's specific density, the transport pathway of the plastics, as well as the travel distance, the trajectory and the residence time (Zhang 2017). In addition, our study included four levels of seagrass shoot density and 12 levels of unidirectional flow, yet aquatic canopies occur in a wide diversity of forms (e.g. short vs tall canopies, branches vs non-branched) and under complex hydrodynamic regimes, including the effect of waves or bi-directional tidal currents for marine vegetation. The drivers of the microplastic retention in marine vegetated canopies should be also investigated at the leaf level, since recent studies found that seagrass leaves and macroalgae can act as an important sink for microplastics, particularly fibres (Gutow et al., 2016, Goss et al., 2018; Cozzolino et al., 2020; Seng et al., 2020). We encourage further studies to test this by performing field assessments of microplastic in seagrass meadows, and other marine vegetated canopies, with focus on the drivers for the microplastic trapping and the impacts on the associated fauna.

We demonstrated under experimental conditions that marine canopies, such as seagrass meadows, may act as barriers or sinks of microplastics. Based on these results, we predict that natural seagrass meadows exposed to anthropogenic activities might contain high levels of microplastics, yet the prediction capacity of our study needs refinement since other bio-physical factors not addressed here may be relevant to consider. Similar results could be applied to other aquatic canopies, such as riverine underwater vegetation, yet differences between the density of freshwater and seawater might affect the buoyancy of microplastics with particle's specific density near the values of the water density (Zhang 2017). We conclude that marine and freshwater canopies should be prioritized habitats in assessment of microplastic accumulation in coastal areas or riverine ecosystems.

CRediT author statement

Carmen B. de los Santos: Conceptualization, Methodology, Investigation, Formal Analysis, Data curation, Visualisation, Writing - Original draft preparation, Project administration, Funding Acquisition. **Anna-Sara Krång**: Conceptualization, Methodology, Resources, Writing- Reviewing and Editing. **Eduardo Infantes**: Conceptualization, Methodology, Resources, Writing- Reviewing and Editing, Funding Acquisition.

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.

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Appendix A. Supplementary data

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