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Accumulation of marine microplastics along a trophic gradient as determined by an agent-based model

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ABSTRACT

Microplastics are ubiquitous in the marine environment and are now consistently found in almost all marine animals. This study examines the rate of accumulation in a modelled filter feeder (mussels) both from direct uptake of microplastics and from direct uptake in addition to trophic uptake (via consuming plankton which have consumed microplastic themselves). We show that trophic uptake plays an important role in increasing plastic present in filter feeders, especially when consumption of the plastic does not reduce its overall abundance in the water column (e.g. in areas with high water flow such as estuaries). However, we also show that trophic transfer increases microplastic uptake, even if the amount of plastic is limited and depleted, as long as plankton are able to reproduce (for example, as would happen during a plankton bloom). If both plankton and plastic are limited and reduced in concentration by filter feeding, then no increase in microplastic by trophic transfer occurs, but microplastic still enters the filter feeders. The results have important implications for large filter feeders such as baleen whales, basking and whale sharks, as these animals concentrate their feeding on zooplankton blooms and as a result are likely to consume more plastic than previous studies have predicted.

1. Introduction

Plastic, especially microplastics, have become ubiquitous in the marine environment (Eriksen et al., 2014), with recent studies showing their presence in almost all marine animals including those from the deep sea (Taylor et al., 2016). Microplastic ingestion by marine organisms can cause a range of negative effects including endocrine disruption, mutagenicity and carcinogenicity (Rios et al., 2007), which can have repercussions for growth, sexual development, fecundity, morbidity and mortality (reviewed by Cole et al., 2013).

Trophic transfer of microplastics has been demonstrated in laboratory studies, from zooplankton to mysid shrimp (Setälä et al., 2014) and from mussels to crabs (Farrell and Nelson, 2013). However, little is known about the accumulation of microplastics through trophic transfer outside of laboratory studies, partially due to the difficulties of tracking microplastics and small organisms such as plankton through space and time.

In this study we present an agent-based modelling approach to investigate the role of trophic transfer of microplastics. We modelled plastic microbeads, plastic thread, zooplankton (three “species” with three different feeding preferences for microbeads and other zooplankton) and mussels as agents in the model. As much research has previously been conducted on zooplankton uptake of microbeads, we assumed in the models that microbeads could be consumed by zooplankton and mussels, whereas thread could only be consumed directly by mussels; hence comparing thread to microbead concentration in mussels allowed us to assess the effects of tropic transfer (we are subsequently aware of some research indicating thread can be consumed by zooplankton e.g. Dedman, 2014, but in the model, this was not permitted as it allows for comparisons of trophic transfer on uptake). We examined scenarios where filter feeding by mussels would: 1) not affect the concentration of microplastic and zooplankton in the water (i.e. both were highly abundant, or there was continuous movement of water); 2) not affect the concentration of zooplankton, but would reduce the abundance of microplastics (i.e. “clean” water with little microplastic, but with rapid growth in zooplankton, such as a plankton bloom) and; 3) reduce both the concentration of plastic and of zooplankton as they were consumed.

2. Methods

Agent-based models were built in R (R Core Team, 2015; see www.rickstafford.com/plastic_models.html for source code) to simulate the actions and interactions of the following six agents; mussels, selective feeding zooplankton (e.g. nauplii and cirripede nauplii), non-selective zooplankton (e.g. gastropods) and predatory feeding zooplankton (e.g.

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Table 1
Uptake probabilities (%) used for all scenarios in Models 1, 2 and 3. If random number was ≤probability when in the same grid cell (or additional 9 neighbouring grid cells for mussels) then the object would be consumed. Zooplankton feeding rate probabilities taken from Cole et al. (2013).

Scenario	Probability
Selective plankton feeding on bead	0.8
Non-selective plankton feeding on bead	0.9
Predatory plankton feeding on bead	0.8
Predatory plankton feeding on selective plankton	0.7
Predatory plankton feeding on non-selective plankton	0.7
Mussel feeding on bead	0.9
Mussel feeding on selective plankton	0.9
Mussel feeding on non-selective plankton	0.9
Mussel feeding on predatory plankton	0.9
Mussel feeding on thread	0.9

copepod, decapod and worms), and microplastic (both bead and thread) in order to assess the uptake of microplastics by mussels either directly (by examining thread uptake, which did not pass through zooplankton in the model, see introduction), or by direct and trophic transfer uptake (by examining beads, which were consumed by zooplankton as well as directly by mussels). By modelling thread and beads in this manner, it was possible to examine the differences in uptake between only direct uptake, and uptake through trophic transfer.

The model was run in a 100 × 100 grid arena and lasted 100 time-steps. Mussels were non-moving and always present (but positions of mussels were randomly generated on the grid), whereas the zooplankton and microplastic moved around and once ingested, in some simulations, were replaced by new agents in random locations (regeneration). Mussels were programmed to uptake beads, threads, and all 3 types of zooplankton, if in the same grid cell or one of the neighbouring nine grid cells to the mussel. Uptake was stochastic with a certain probability defined for likelihood of consumption if the agent to be consumed was in the specified cells. Selective and non-selective feeding zooplankton were programmed to uptake beads only, if both were in the same grid square, and predatory feeding zooplankton were programmed to uptake beads and both selective and non-selective feeding zooplankton. In all cases, uptake was not guaranteed, but stochastic and based on probability estimates of uptake of zooplankton and microplastic as defined in Cole et al. (2013), see Table 1 for the probability values used in this study.

Zooplankton, beads and threads moved by one grid square per time-step (including diagonal movement), with a heading generated from that of the heading of the previous time-step. Following directionality rules used in previous ecological ABM models (Stafford and Davies, 2005) plastic particles could adjust their bearing by up to 90° per time step and plankton by up to 45° per time step. These changes in heading were generated from random numbers drawn from a uniform distribution.

Three plastic scenarios were simulated based on the empirical data results; 1 = equal amounts of thread and beads, 2 = more thread then beads and 3 = more beads than threads. Three different ratios of plastic to zooplankton were also conducted based on the empirical data results; plastic:plankton ratio 1 = 75:25, 2 = 50:50 and 3 = 25:75. Four zooplankton community structures were used: 1 = medium to high numbers of most species, 2 = medium to high numbers of copepod and cirripede, 3 = low to medium numbers of most species, and 4 = low to

Table 2
The 36 scenarios of different plastic and plankton concentrations used in each model and the mean outputs from three replicate runs for each scenario for model 1.

Plastic thread	Plastic bead	Selective plankton	Non- selective plankton	Predatory plankton	Mussels	Plastic in mussels	Plastic thread in mussels	Plastic in selective plankton	Plastic in non-selective plankton	Plastic in predatory plankton
200	200	200	100	200	10	169	56	131	80	378
400	400	200	100	200	10	357	99	277	154	763
100	100	200	100	200	10	98	23	74	31	200
100	300	200	100	200	10	294	25	213	108	570
200	600	200	100	200	10	546	49	404	247	1145
50	150	200	100	200	10	131	9	101	61	277
300	100	200	100	200	10	81	92	65	36	192
600	200	200	100	200	10	184	169	134	79	396
150	50	200	100	200	10	39	36	45	19	101
200	200	50	50	400	10	172	48	29	27	539
400	400	50	50	400	10	358	102	55	49	1119
100	100	50	50	400	10	88	26	11	12	269
100	300	50	50	400	10	251	21	35	40	861
200	600	50	50	400	10	509	65	72	80	1645
50	150	50	50	400	10	122	20	20	20	425
300	100	50	50	400	10	83	73	9	9	271
600	200	50	50	400	10	171	143	30	30	536
150	50	50	50	400	10	42	46	6	8	132
150	150	100	100	100	10	101	40	66	81	128
400	400	100	100	100	10	263	97	194	205	331
50	50	100	100	100	10	28	14	21	33	42
100	200	100	100	100	10	129	27	86	100	159
200	600	100	100	100	10	359	54	289	301	536
25	50	100	100	100	10	32	7	21	26	47
250	100	100	100	100	10	58	59	47	49	84
600	200	100	100	100	10	116	140	90	108	167
140	50	100	100	100	10	27	43	22	44	31
200	200	50	150	200	10	150	50	32	117	345
400	400	50	150	200	10	327	111	69	232	689
100	100	50	150	200	10	72	26	19	58	171
100	300	50	150	200	10	212	22	53	188	551
200	600	50	150	200	10	421	43	90	362	1049
50	150	50	150	200	10	121	13	18	82	244
300	100	50	150	200	10	86	74	23	53	167
600	200	50	150	200	10	177	169	36	116	338
150	50	50	150	200	10	33	40	7	25	80