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1 **Source, Sea and Sink - a holistic approach to understanding plastic pollution in the**
2 **Southern Caribbean**

3

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16

17

18 **Abstract**

19 Marine plastics are considered to be a major threat to the sustainable use of marine and coastal
20 resources of the Caribbean, on which the region relies heavily for tourism and fishing. To date,
21 little work has quantified plastics within the Caribbean marine environment or examined their
22 potential sources. This study aimed to address this by holistically integrating marine (surface
23 water, subsurface water and sediment) and terrestrial sampling and Lagrangian particle
24 tracking to examine the potential origins, flows and quantities of plastics within the Southern
25 Caribbean. Terrestrial litter and the microplastics identified in marine samples may arise from
26 the maritime and tourism industries, both of which are major contributors to the economies of
27 the Caribbean region. The San Blas islands, Panama had the highest abundance of microplastics
28 at a depth of 25m, and significantly greater quantities in surface water than recorded in the
29 other countries. Modelling indicated the microplastics likely arose from mainland Panama,
30 which has some of the highest levels of mismanaged waste. Antigua had among the lowest
31 quantities of terrestrial and marine plastics, yet the greatest diversity of polymers. Modelling
32 indicated the majority of the microplastics in Antigua coastal surface were likely to have
33 originated from the wider North Atlantic Ocean. Ocean currents influence the movements of
34 plastics and thus the relative contributions arising from local and distant sources which become
35 distributed within a country's territorial water. These transboundary movements can undermine
36 local or national legislation aimed at reducing plastic pollution. While this study presents a
37 snapshot of plastic pollution, it contributes towards the void of knowledge regarding marine

38 plastic pollution in the Caribbean Sea and highlights the need for international and
39 interdisciplinary collaborative research and solutions to plastic pollution.

40

41 **Keywords:**

42 Microplastic; waste management; modelling; litter; plastic; policy

43

44 **1. Introduction**

45 There are substantial and increasing quantities of plastic pollution in the environment and the
46 flux of plastics entering the oceans, primarily from land-based sources, is expected to continue
47 to rise over the next decade (Geyer et al., 2017, Lebreton and Andrady, 2019). Owing to their
48 durability, plastics can accumulate in the environment and their persistence has been reported
49 over geological timescales (Ostle et al., 2019, Brandon et al., 2019, Courtene-Jones et al.,
50 2020).

51 It is evidenced that plastics detrimentally impact marine life and ecological processes (Bucci
52 et al., 2020, Galloway et al., 2017). In addition plastic pollution can adversely affect economy
53 and society through impacts on food security (Barboza et al., 2018), human wellbeing
54 (Beaumont et al., 2019, Wyles et al., 2016) and coastal economic activity (Rangel-Buitrago et
55 al., 2018, Garces-Ordonez et al., 2020a, Ambrose et al., 2019), and as such plastics have been
56 acknowledged as a pressing global issue (Sutherland et al., 2010, Rockström et al., 2009).

57 The tropics and the islands lying within this region are hotspots of biodiversity both above and
58 below the water (Myers et al., 2000). These areas provide a wealth of ecosystem services, such
59 as provision of food and generate income through tourism (Wilkinson and Salvat, 2012).
60 Located within the tropics, the Caribbean region is a group of states and territories lying in or
61 bordering the Caribbean Sea, and has a population of ~44.4 million (The World Bank, 2019).
62 Only a small proportion (8.7%) of the total region is dry land with an extensive marine territory.
63 The lack of physical land space poses a pressing challenge for island nations around the world,
64 in that they have a finite and often very limited amount of space for their primary form of waste
65 management, which is typically sanitary landfill.

66 Few Caribbean countries have a comprehensive solid waste management framework and it is
67 estimated that 54% of waste is disposed of in sanitary landfills, with much of the rest being
68 dumped illegally or entering the marine environment (Diez et al., 2019, Riquelme et al., 2016,
69 UNEP, 2018b, Phillips and Thorne, 2013). In 2018, it was estimated that the Caribbean and
70 Latin America region comprised 11% of global waste production and less than 5% of that waste
71 was being recycled. It has also been estimated that roughly 12% of the waste stream in the
72 region is plastic (Kaza et al., 2018).

73 The accumulation of plastics in the marine environment is considered to be one of the most
74 serious threats to sustainable use of the marine and coastal resources of the Caribbean (UNEP,
75 2014) and has ramifications on tourism on which the region relies heavily upon and which
76 contributes ~14% of the regions gross domestic product (World Travel and Tourism Council,
77 2020, Ambrose et al., 2019). It has also been suggested that island nations, such as those in the

78 Caribbean will be disproportionately affected by increasing plastic pollution, due to their
79 ocean-dependent economies and their still developing and vulnerable waste management
80 infrastructure (Diez et al., 2019).

81 To date evidence of the spatial abundance of plastic within the marine environment of the
82 Wider Caribbean Region is sparse (Kutralam-Muniasamy et al., 2020, Correa-Herrera et al.,
83 2017, Botero et al., 2020, Kikaki et al., 2020). The distribution of plastic within ocean waters
84 is influenced by their point of entry and the subsequent complex physical, chemical and
85 biological interactions within the environment. Reports indicate the long-range movement of
86 plastics between geographic regions (Ambrose et al., 2019, van Sebille et al., 2020), which
87 may undermine local or national policies aimed at reducing plastic pollution.

88 The present study integrates marine plastic pollution research with modelling approaches,
89 terrestrial litter assessments and regional policy; a holistic approach which has been largely
90 lacking to date. The specific aims of this study were to spatially quantify the composition of
91 (micro)plastics within different environmental compartments (the sea surface, subsurface water
92 and subtidal sediments) in the Southern Caribbean region and consider the potential geographic
93 origins of these particles. Terrestrial litter composition as well as Lagrangian particle tracking
94 studies enabled further assessment of potential plastic pollution sources and the flow of plastic
95 waste into the marine environment.

96
97

98 **2. Methods**

99 **2.1. Sample collection**

100 To study the distribution of microplastics within the Caribbean, sampling was performed from
101 the sailing vessel TravelEdge as part of the ‘Round the World’ voyage organised by
102 eXXpedition. Three transects involving sampling of surface water, subsurface water and
103 subtidal sediment within the wider Caribbean region took place between 24th November - 20th
104 December 2019 with scheduled stops along the route in Antigua, Bonaire, Aruba and the San
105 Blas Islands before its final docking in Colón, Panama (Figure 1 and SI Table S1-S3).

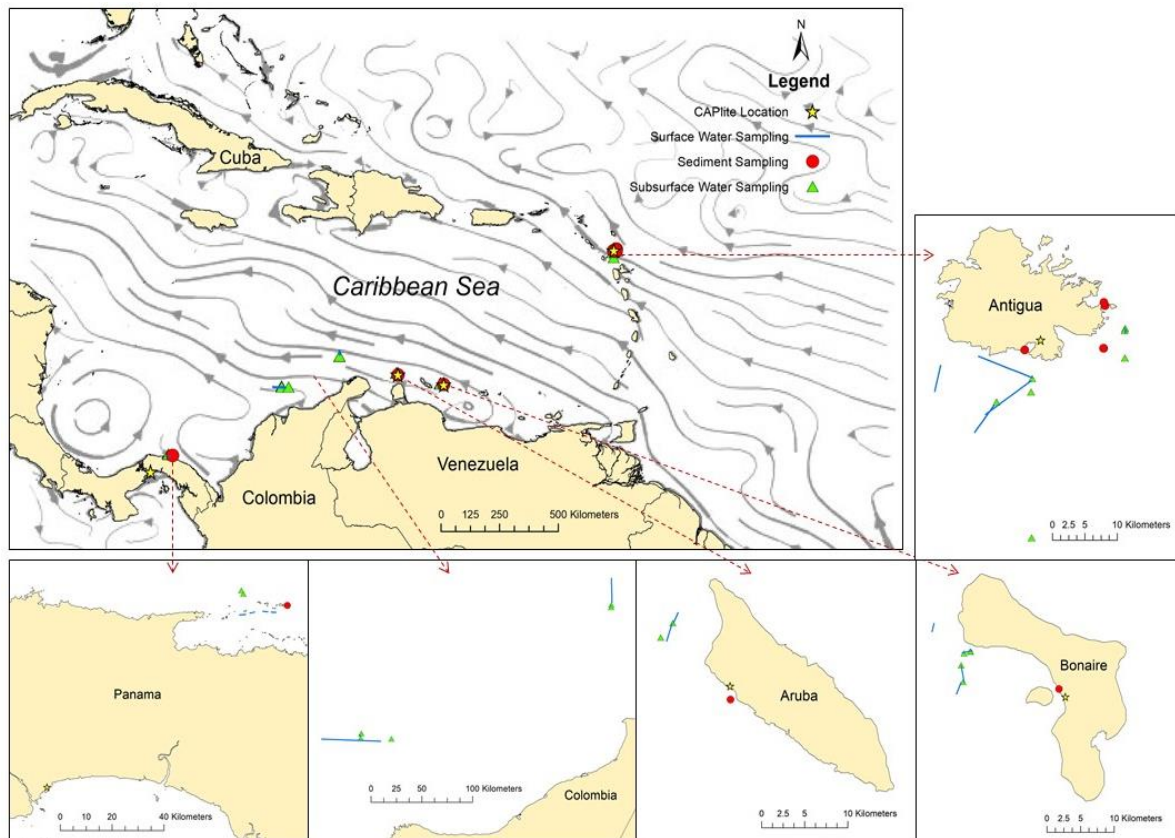


Figure 1. The location of land (yellow stars) and marine sampling locations (surface water: blue tracks; subsurface water: green triangles and sediments: red points) within the Caribbean region. The prevailing surface currents and their direction are indicated (grey arrows). Note the scale bars differ in each panel.

106

107 2.1.1. Surface water sampling

108 Samples (n = 19) were collected using an aluminium manta trawl (rectangular mouth, inner
 109 dimensions: 13.6 cm height x 64.4 cm wide) which had a 1.5 m long net with a detachable cod-
 110 end (30 x 10 cm) both made from 335 μm polyamide mesh. The manta trawl was towed along
 111 the sea-air interface using the spinnaker pole to position the towline outside of the wake of the
 112 vessel. For each 30 minute trawl the start and end GPS locations and times were recorded and
 113 were used to calculate the distance travelled (as in Jones-Williams et al., 2020; Law et al.,
 114 2014). The volume of water sampled through the trawl was subsequently estimated by
 115 multiplying the distance travelled by half of the net aperture (0.04 m^2): this assumes a laminar
 116 flow through the cod end of the net and that 50% of the net aperture was submerged as in other
 117 studies (Schonlau et al., 2020). The water volume was used to quantify the abundance of
 118 microplastics in surface waters

119 Sampling only occurred in Beaufort Sea state ≤ 2 , and for all trawls environmental data
 120 including the sea state, wind speed and direction were also recorded. Once the manta trawl was
 121 recovered on board, the cod-end was removed. This was carefully inverted over three stacked
 122 sieves, of mesh sizes 4.75 mm, 1mm, and 0.335 mm. A gentle flow of filtered seawater (50
 123 μm , see section 2.1.4) was used to facilitate the transfer of the contents of the cod-end into the
 124 sieves, and the cod-end was inspected thoroughly to ensure no microplastics remained on the

125 net. Any natural debris, e.g. *Sargassum* sp. contained within the sieves were individually
126 picked up with forceps and rinsed thoroughly with filtered seawater over the sieve and
127 examined to ensure there were no microplastics adhered. Once cleaned, the natural debris was
128 discarded. For the size fractions 4.75mm and 1mm from each trawl, all putative plastics were
129 transferred into glass vials, separated by size, and for the 0.335mm all material on the sieve
130 was transferred. Samples were stored in the dark at ambient temperatures.

131

132 **2.1.2. Subsurface water sampling**

133 A 5 litre OSIL NISKIN bottle, made of dark grey PVC, was used to collect bulk subsurface
134 water samples, with three replicates collected at each sampling location ($n = 9$). The bottle was
135 deployed open, from the spinnaker pole using a blue polypropylene rope. It was deployed to a
136 depth of 25m, and a brass messenger weight was used to trigger and close the caps of the bottle
137 before it was recovered to the surface. NIKSIN bottles were only deployed in Beaufort Sea
138 state ≤ 2 . During sampling, the vessel was held stationary. The GPS location and time of
139 deployment was recorded as was environmental data on the wind speed and direction. Once
140 on-board, the NISKIN bottle was filtered below deck through a 20 μm cellulose filter paper (\O
141 70mm) using a stainless-steel hand vacuum filtration system. A clear-silicon tube was used to
142 deliver the water from the NISKIN bottle into the filter funnel. Once the entire 5 L volume of
143 water had been filtered, the filter paper was immediately placed into a petri dish and sealed for
144 further analysis at the University of Plymouth. This entire process was repeated for each of the
145 triplicate samples, using a separate filter paper for each NISKIN bottle deployment.

146

147 **2.1.3. Sediment sampling**

148 Sediment samples were collected while the vessel was on anchor in natural or engineered
149 marinas/anchorages. A 0.045m² OSIL stainless steel van Veen grab was utilised, with five
150 replicates taken at each location ($n = 6$) within the Caribbean. At one location only 4 replicates
151 were obtained due to the seabed substrate. The grab was thoroughly washed with ambient
152 seawater between each deployment. Sediment from the centre of the grab, not in contact with
153 the sides was transferred to a transparent polypropylene 110 ml container using stainless steel
154 spoons, which were also washed thoroughly in ambient seawater prior to, and between each
155 sample being taken. The lids were immediately replaced on sample containers and the sediment
156 was frozen at -20 °C.

157

158 **2.2. Contamination controls**

159 Measures were taken to reduce contamination during sample collection and analysis. Sieves,
160 used to sort the manta trawl samples, were backwashed thoroughly with the deck hose fitted
161 with a 50 μm aperture stainless steel mesh screen, prior to receiving each sample. Fibres were
162 not included in manta trawl data; however, pieces of monofilament line were considered.
163 During water filtration from the NISKIN bottles the funnel was kept covered with aluminium
164 foil, apart from a small gap where the tube delivering water into the funnel was placed. Petri
165 dishes remained closed apart from briefly to transfer the filter paper, whereupon they were

166 closed and sealed immediately. Atmospheric controls were implemented during filtration,
167 which involved placing a damped filter paper (11µm aperture, Ø 90mm) in an uncovered petri
168 dish adjacent to filtration, to sample any airborne microplastics which may be deposited into
169 our samples. A separate atmospheric control was used for each individual NISKIN bottle. For
170 each polymer identified, the count on the atmospheric controls were subtracted from the raw
171 count from each sample to obtain a blank-corrected count. Samples of all putative contaminants
172 (manta trawl net, NISKIN bottle, lines and ropes, boat hull and deck paints etc) were collected
173 and spectroscopically analysed concurrently with samples. Sample counts were adjusted where
174 necessary, for any particles with colours and polymer types matching the contaminants.
175 Laboratory procedural blanks for the sediment extractions (section 2.3.1) were carried out, and
176 polymer-corrections implemented where necessary.

177

178 **2.3. Laboratory methods**

179 Analysis was performed in a positive pressure microplastics laboratory (air filtered to 0.5µm)
180 at the University of Plymouth. Personnel inside the laboratory were kept to a minimum and all
181 wore natural fibre clothing under a cotton laboratory coat and specific laboratory shoes.
182 Subsurface water filters and manta trawl samples were examined thoroughly under a Lumos
183 dissecting microscope.

184

185 ***2.3.1. Extracting microplastics from sediment***

186 Sediment samples were transferred to separate glass dishes and were dried for 10 days at 50°C.
187 During drying the glass dishes were loosely covered with aluminium foil to prevent
188 contamination but to allow moisture to escape. The samples were weighed to 2 d.p. prior to
189 and after being dried. To isolate microplastics from dry sediment a modified version of the oil
190 extraction protocol (Crichton et al., 2017) was used. Briefly, 20 g dry sediment was added to a
191 50 ml centrifuge tube, to this 25 ml of water and 1.5 ml of rapeseed oil was added. The content
192 of the tube was shaken vigorously for 5 minutes and was then centrifuged at 5000 rpm, for 5
193 minutes, with a brake speed of 5. The oil and aqueous layers were filtered under vacuum
194 filtration through cellulose filter paper with 20µm aperture. The protocol was repeated to
195 analyse each sediment sample in its entirety.

196

197 ***2.3.2. Identification of microplastics***

198 Microplastics were classified based on their morphology as either i) fragment, ii) films, iii)
199 monofilament line, iv) foam, v) pellets or vi) fibres (only counted for subsurface bulk sampling)
200 (Hidalgo-Ruz et al., 2012). Sizes of plastics obtained in the manta trawls were categorised
201 according to the sieve size fractions, while microplastics in subsurface water and sediment
202 samples were measured using the ocular scale of the Lumos dissecting microscope, and then
203 assigned to the same size classes used for surface sampling.

204 Microplastics (1mm and 4.75mm size fractions) collected during the manta trawls were
205 identified using a PerkinElmer Spectrum Two attenuated total reflectance Fourier Transform

206 infrared (ATR-FTIR) spectrometer. Each spectrum was the average of four co-added scans in
207 the range 400-6000cm⁻¹ wavenumbers, with a background scan performed prior to each sample.
208 The spectral resolution was 0.5cm⁻¹. Data were compared against the inbuilt PerkinElmer
209 ‘Polymer’ spectral library to facilitate sample identification. Microplastics sampled by manta
210 trawl which were retained on the 0.335mm sieve, along with those sampled from subsurface
211 water and sediments were analysed with a Bruker Vertex 70 µFTIR coupled with a Bruker
212 Hyperion 1000 microscope in transmission mode. Each spectrum and background scan were
213 the average of 32 co-added scans in the wavenumbers 600 – 4000cm⁻¹. Microplastics were
214 analysed on a diamond compression cell (Specac DC2; 2mm diameter). Spectra were visualised
215 in the complimentary OPUS v7.5 software, manually inspected and compared against the
216 ‘BPAD’ and ‘synthetic fibres’ spectral libraries.

217

218 **2.4. Statistical analysis**

219 Pearson correlations were applied to determine any influence of environmental variables on
220 the concentration of microplastics within each environmental compartment (surface water,
221 subsurface water and sediment). A Kruskal-Wallis analysis of variance followed by Dunn’s
222 post hoc test (Dinno, 2017) was used to examine statistical differences in the abundance of
223 surface water microplastics between countries. Permutational multivariate analysis of variance
224 (PERMANOVA) were used to test the null hypothesis that there was no significant difference
225 in polymer composition according to environmental/sampling factors or between countries.
226 Pearson correlation test was used to examine the relationship between factors and in this case
227 wind speed and sea state were correlated and wind speed was subsequently omitted. Surface
228 water and subsurface water were considered separately, due to low replication PERMANOVA
229 could not be applied to sediment. For surface water the factors were transect, country, water
230 volume sampled and sea state. For subsurface water the factors were transect, country and sea
231 state. The polymer composition analysis was based on a Bray-Curtis dissimilarity matrix. The
232 statistical significance of the variance components were tested using 9999 permutations and
233 the null hypothesis was rejected when the significance level (p) was <0.05. Statistical analyses
234 were performed in R v1.3.1093 (R Core Team, 2019) using the packages *vegan* (Oksanen et
235 al., 2019), *dplyr* (Wickham et al., 2020) and *dunn.test* (Dinno, 2017). Unless otherwise stated,
236 the standard deviation of the mean has been reported when ± is given.

237

238 **2.5. Land-based surveys**

239 A condensed version of the Circularity Assessment Protocol (CAP), which was developed by
240 the Circularity Informatics Lab at the University of Georgia (UGA), was performed in Antigua,
241 Bonaire, Aruba and Panama in November and December 2019. In this case, one portion of the
242 CAP was used to collect localised data that serves as a baseline for characterizing the leakage
243 of plastic and other materials in a community. Further details on the CAP can be found at
244 circularityinformatics.org.

245 Three principal transects and three backup transects were randomly selected (within restraining
246 parameters) by the UGA team for each location. Site selection criteria was as follows; i) the

247 selected site was accessible from the marina. As such, the data does not characterise the
248 community as a whole, but provides information about the neighbourhood in the immediate
249 vicinity of the marina. ii) The population density of study sites, which was extracted from
250 LandScanTM (<https://landscan.ornl.gov/>), was limited to the most densely populated 5th of the
251 community area. Coverage of the most densely populated areas of each community was
252 dependent upon the distribution of the population.

253 From the most densely populated areas, three circular areas 1km in diameter were randomly
254 generated for field sampling. Within each field sampling sites, teams aimed to conduct a
255 minimum of three 1m x 100 transects, totalling 9 transect per community, using the Marine
256 Debris Tracker app to record data. However, due to unforeseen circumstances, some sites
257 collected more or less than three transects of data, and therefore sample sizes vary.

258 Within the transects the teams documented every visible item of litter, locations of stores,
259 vendors and restaurants, locations of schools, parks, and religious centres, formal and informal
260 waste management infrastructure, waste piles, and storm water infrastructure. The team logged
261 the litter items based on the item names and associated material categories in the Marine Debris
262 Tracker app (e.g. a “Plastic Food Wrapper” in the “Food Plastic” material category, see full list
263 in SI Table 4). All of the data was stored in the open source and freely available Marine Debris
264 Tracker database (debristracker.org) and analysed post-expedition by the UGA team.

265

266 **2.6. Lagrangian particle tracking**

267 To identify the potential origins of the plastics retrieved in the surface water trawls a hindcast
268 2D Lagrangian modelling approach was used. Velocity fields for the period 01/09/2019
269 00:00:00 to 01/01/2020 00:00:00 were provided by the GOFS 3.1: 41-layer Hybrid Coordinate
270 Ocean Model (HYCOM) + Navy Coupled Ocean Data Assimilation (NCODA) based ocean
271 prediction system output, obtained from the HYCOM OpenData server
272 (hycom.org/dataserver/). This ocean model provides 3 hourly surface velocities on a global
273 grid (80S to 90N) with a grid scale of 0.08° longitude by 0.08° latitude. Particles were released
274 from each of the 19 sampling locations at the given time of sampling (see table SI Table 1) and
275 were backtracked for 60 days using the Lagrangian ocean analysis framework, Parcels (v2.0:
276 (Delandmeter and van Sebille, 2019)). Particles were advected using a 4th order Runge-Kutta
277 advection scheme and stochastic diffusivity was implemented using a scaled random walk.
278 Multiple particles were released from each site so that variation in dispersal resulting from the
279 diffusive component of the model could be explored. In post-processing, each model run was
280 standardised so that simulation duration was based on time rather than date. To determine
281 whether a particle was backtracked to land, and the timescale of this, a global land mask
282 function was used in Python 3.8 (Karin, 2020). When a particle reached land, the town and
283 country of the particle location was obtained in Python using ‘Openstreetmaps’ API, the
284 duration taken for the particle to back-track to land and the Euclidean distance travelled by the
285 particle are recorded.

286

287 **3. Results**

288 **3.1. Plastics in surface waters**

289 Plastics were identified in every manta trawl conducted except two; one of which was located
 290 in Antiguan water and one was off the coast of Colombia. The frequency of plastics differed
 291 between trawls and countries (Figure 2). The greatest quantity of plastics (486 pieces equating
 292 to 5.09/m³) was located around the San Blas islands, Panama. When grouping trawl data by
 293 country, the water sampled around Panama had significantly more microplastics than Antigua
 294 ($p = 0.031$), Bonaire ($p = 0.039$) or Colombia ($p = 0.007$), however it is noted that trawls around
 295 Panama occurred in sea states of '0', while sea states of 1 and 2 were recorded for other
 296 sampling locations (Figure 2). Sea state was the only environmental variable found to have a
 297 significant negative relationship with the quantities of microplastics detected (Pearson's p , $r =$
 298 -0.5 , $p = 0.04$).

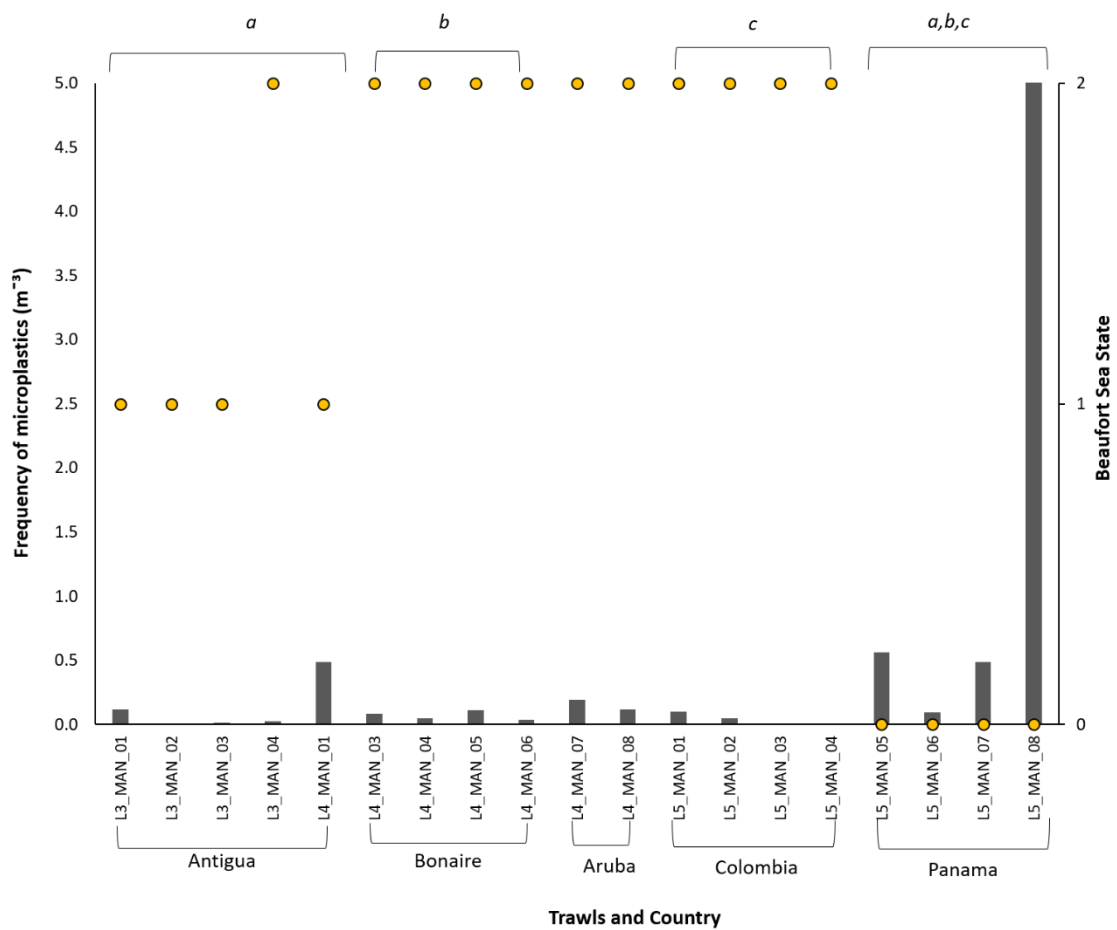


Figure 2. The frequency of all size classes of plastic per m³ identified in surface water for each manta trawls and grouped by country. Letters denote statistically significant differences ($p < 0.05$) between country groups. Yellow circles show the Beaufort sea state (shown on the secondary axis) in which trawls were performed.

299

300 A total of 18 polymers (including two co-polymers) were identified in Caribbean Sea surface
 301 water (Figure 3). PERMANOVA analysis indicated that the composition of polymers differed
 302 significantly ($F_{\text{model}} = 1.698$, $p = 0.027$) between countries. For example, paint flakes,

303 polyamide (PA) and polyethylene (PE) were found in all countries, however the prevalence of
 304 PE was lower in Antigua (only in 1 out of 5 trawls) than in other countries where PE was
 305 consistently recorded. Polypropylene (PP) was present in all country's waters apart from Aruba.
 306 Other polymer types had more localised occurrence, for example polyester was identified
 307 around Antigua and Panama only, polycarbonate only around Antigua, and acrylonitrile was
 308 only identified in the most western of our survey sites, around Colombia and Panama.

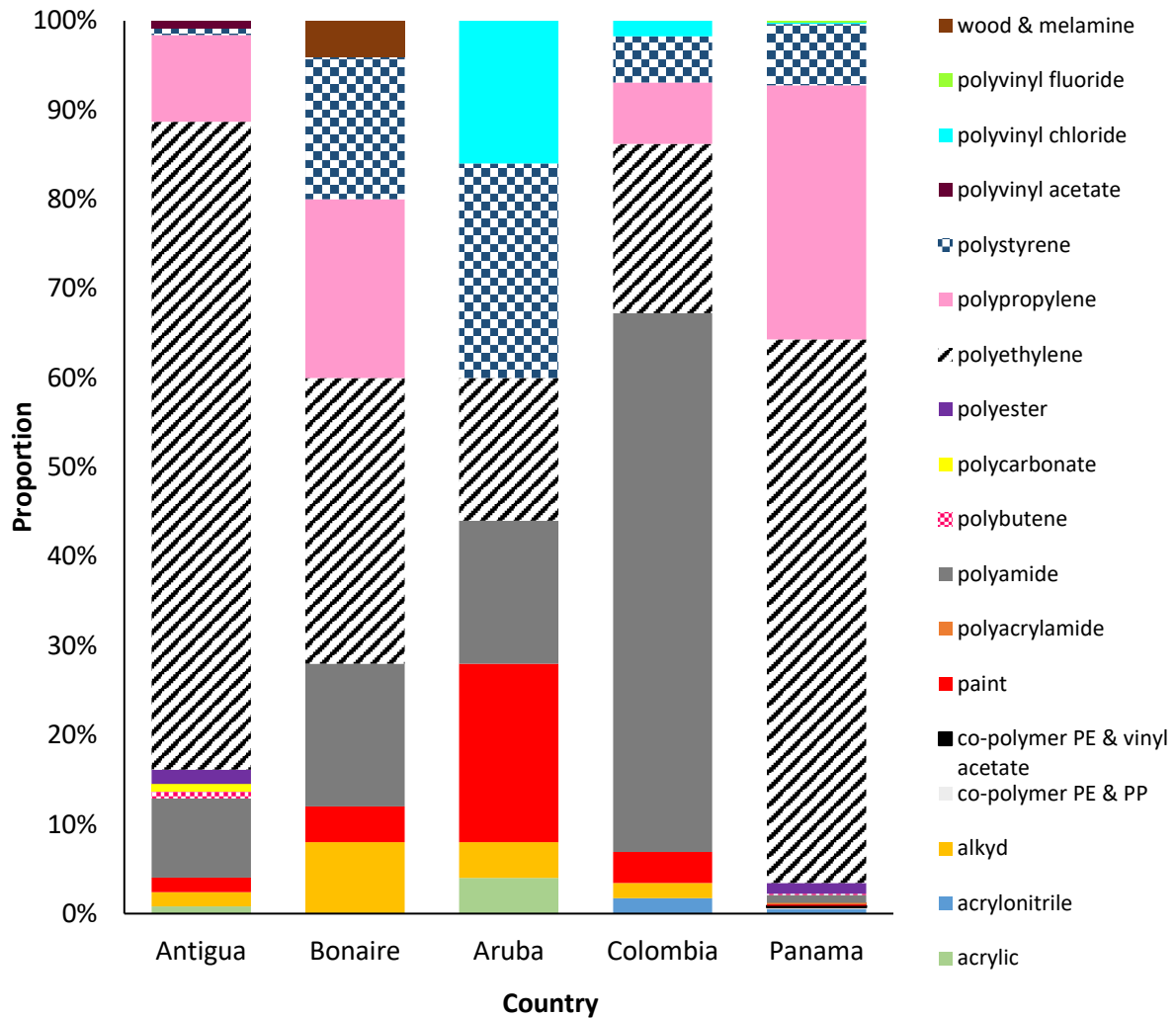


Figure 3. Polymer types (percentage of the total) identified in surface waters of the different countries sampled.

309

310 Fragments were the most abundant morphology (SI Figure 1), accounting for between 40 -
 311 100% of the plastic pieces within each trawl sample. Plastic pellets were documented only in
 312 two samples, one from Antigua (0.014 pellets/m³) and one from Panama (0.774 pellets/m³).
 313 Foam (expanded PS) was present in at least one sample from each country's waters in
 314 concentrations ranging between 0.003-0.889/m³ recorded in Antigua and Panama respectively.
 315 Large plastics pieces (> 4.75mm) were infrequently recorded and were only present in three
 316 trawls (SI Figure 2), with the most numerically dominant size of plastics was the fraction 1mm

317 – 4.74mm in size, and the most frequently identified within trawls (present in 16 of the 19
318 samples) was the size category 0.335-0.99 mm.

319

320 **3.2. Microplastics in subsurface waters**

321 Microplastic data were polymer-corrected based on counts and composition recorded in the
322 atmospheric controls and putative contaminants sampled from the yacht. The majority of the
323 particles isolated were fibrous (n = 91; 85%) with the remaining items categorised as fragments
324 (n = 16, 15%). Of the fibres, the majority were cellulosic in their origin (n= 77, 85% of fibres;
325 SI figure 3) with the remaining synthetic items (n= 14, 15% of fibres) comprised of acrylic,
326 polyester, polyamide and polypropylene. In addition, fragments (n =16) identified as paint,
327 PVC, PA, polyester were also identified. Deployments from Panama contained the greatest
328 quantities of synthetic polymers (av. 0.53/L \equiv 533/m³), while Bonaire had the lowest (av.
329 0.067/L \equiv 67/m³). Correlation analysis indicated that there was no significant relationship
330 between wind speed or sea state and the quantity of particles.

331 The diversity of polymers identified in subsurface water was much lower than in surface water.
332 In addition to cellulosic fibres, which were coloured implying they were likely
333 regenerated/processed, a total of 6 synthetic polymers were isolated from the subsurface
334 samples (Figure 4). PERMANOVA analysis indicated that the composition of polymer types
335 differed significantly ($F_{\text{model}} = 2.29$, $p = 0.035$) between countries. PP was only identified in
336 Antiguan waters and in contrast to surface water and sediment samples, polyethylene was not
337 identified in subsurface water samples.

338 On average, synthetic particles were smaller ($0.867\text{mm} \pm 1.050$) in their size than cellulosic
339 particles ($1.089\text{mm} \pm 0.719$) (SI Figure 4). Across all of the countries, the quantities of
340 synthetic microplastics were two orders of magnitude greater in subsurface water samples (33
341 MP/m^3) than in surface waters ($0.40 \pm 1.21 \text{MP/m}^3$).

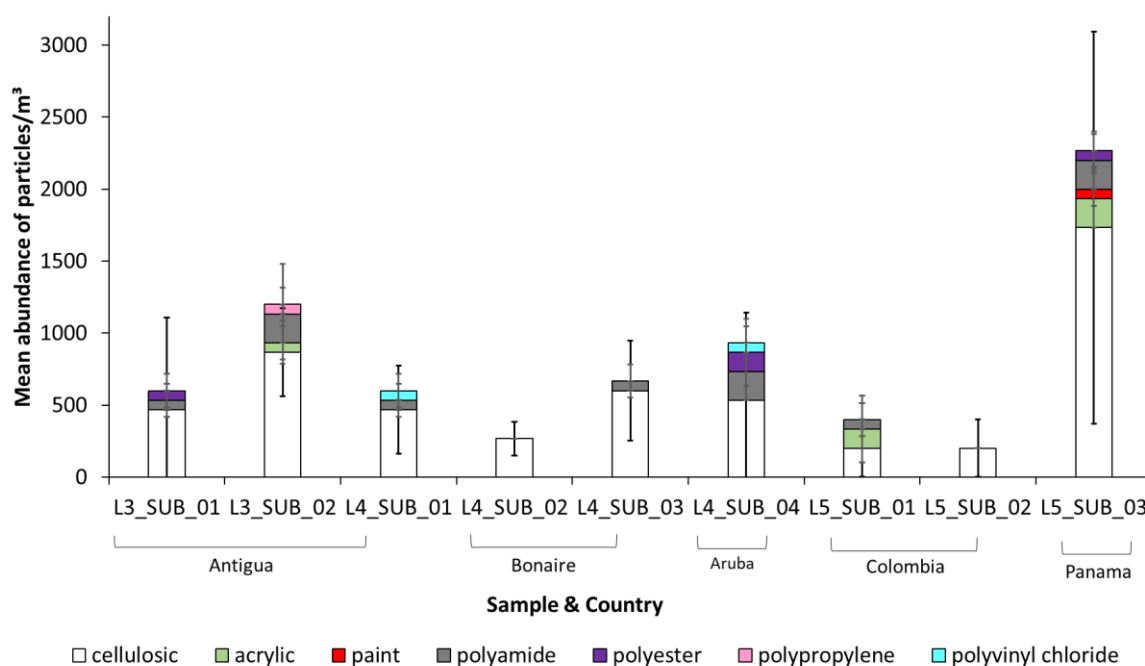


Figure 4. The mean abundance ($n=3$) of polymers per m^3 sampled from a depth of 25 m at each site and country. Error bars denote standard deviation.

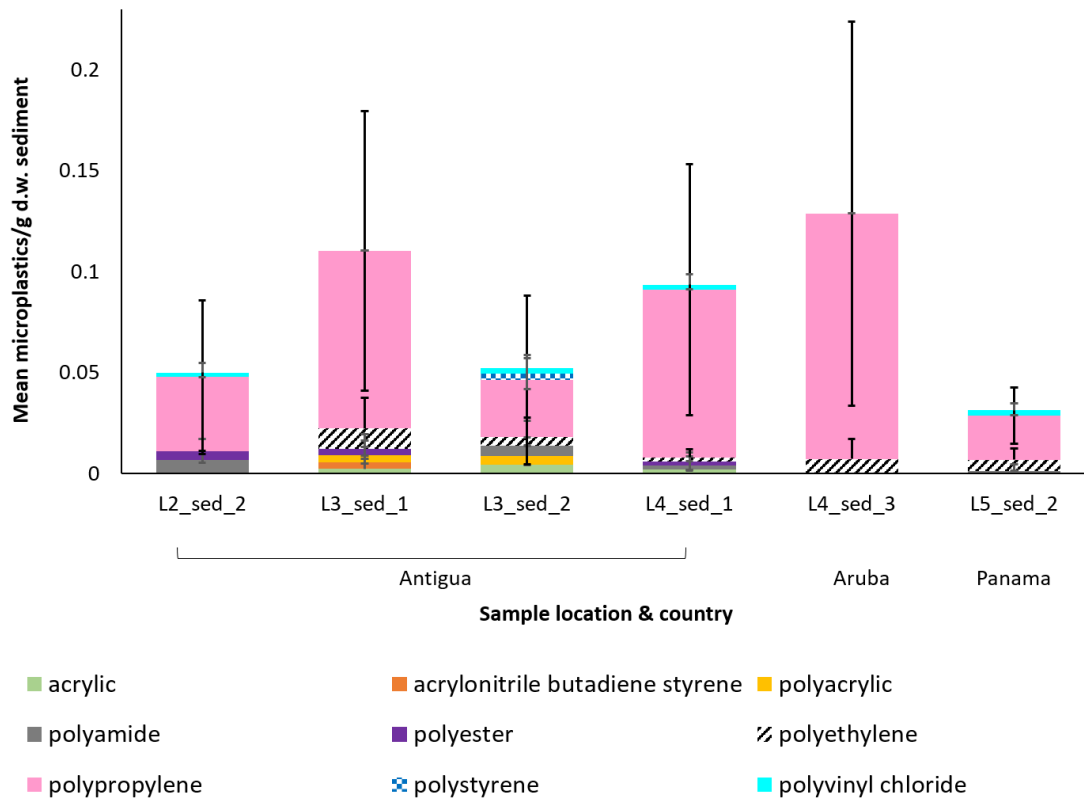
342

343 3.3. Microplastics in sediment

344 Five replicate samples were obtained for each location, apart from L4_sed_3 where four
 345 replicates were collected due to seabed substrate. Overall, the greatest abundance of
 346 microplastics was recorded in the sample from Aruba (0.13 ± 0.10 MP/g), and the lowest
 347 reported in Panama (0.03 ± 0.003 MP/g). Analysis indicated there was no correlation between
 348 environmental variables (sea state or water depth) on the quantity of microplastics in sediments.
 349 A total of 9 polymers were identified; polypropylene was identified in the highest abundance
 350 in all samples (Figure 5). While the polymer composition could not be statistically tested
 351 between locations due to sample sizes, the greatest diversity of polymers was observed in the
 352 samples collected from Antigua. Acrylic, acrylonitrile butadiene styrene, polyacrylic and
 353 polystyrene were unique to sediments collected from Antigua (Figure 5).

354 Fragments were the most abundant morphology isolated from samples collected around
 355 Antigua (52-93%) and Panama (73%) (SI Figure 5), while in Aruba monofilament line
 356 composed of polypropylene accounted for 60% of the microplastics. Plastics ranged in size

357 between 0.08-14.0 mm, however the majority (59%) were between 0.335-0.999 mm in size (SI
 358 Figure 6).



359

360 *Figure 5. The mean polymer composition/g dry weight sediment. Error bars show standard deviation.*

361

362 3.4. Land-based surveys and overview of local policy

363 The litter data collected via the Marine Debris Tracker app as part of the land-based survey
 364 methodology yielded information regarding the composition of waste that ends up in the
 365 environment in the immediate vicinity of the marinas along the eXXpedition route. Overall,
 366 cigarettes were the most numerous litter item in every country except for Antigua, where hard
 367 plastic fragments dominated. Hard plastic fragments and plastic food wrappers were among the
 368 most commonly identified litter items in every country surveyed (Table 1), and all countries
 369 surveyed except Panama had plastic fragments (of a range of morphologies) within their top
 370 two litter categories. The litter found in the surveys also appear to be linked to plastic consumer
 371 goods, which are largely lightweight packaging that is optimal for import and on which island
 372 nations rely heavily. Detailed country specific data are available in SI Figures 7 – 10.

373

374 3.4.1. Antigua

375 Six 100m litter transects were conducted in Antigua. Sheetlike plastic fragments were the most
 376 numerous litter item documented, and fragments in general constituted the most abundant litter
 377 category recorded (37% of items), followed by food plastics. Of the countries sampled, Antigua
 378 was the only one that had plastic rope among its top litter items (Table 1 and SI Figure 7).

379 Antigua was also the only country where tobacco products (encompassing cigarettes,
380 packaging and lighters) constituted less than 20% of the litter in terms of categories - all other
381 countries had tobacco products as their most frequent category identified (Figure 6).

382 Antigua and Barbuda have a relatively low percentage of mismanaged waste (3.2%) and per
383 capita waste generation rate (0.90 kg/person/day) (IDB, 2020). It has been estimated that
384 Antigua and Barbuda's waste collection services serve 98.61% of the population and therefore
385 there are very low estimates of waste leakage (3.2%) (Luken, 2017). Antigua and Barbuda also
386 instituted a National Plastic Bag Ban in 2016 and a ban on Expanded Polystyrene in 2017 (SI
387 Table 5).

388

389 **3.4.2. Aruba**

390 Two 100m litter transects were conducted in Aruba, which differed greatly in the number of
391 litter items, and therefore may not present representative data for the area. The data from Aruba
392 were unique in that there was a high prevalence of glass fragments, which originally
393 represented the top litter item documented. Upon further investigation, it appeared that the
394 fragments were localised and were likely from a broken glass bottle. Cigarettes were the most
395 frequently encountered litter item, with hard plastic fragments the next most documented.

396 Compared to other Caribbean countries, Aruba has a mid - high percentage of mismanaged
397 waste (21.6%) and a higher than average per capita waste generation rate (2.91 kg/person/day)
398 (IDB, 2020). It is estimated that 12.4% of the waste stream in Aruba is composed of plastic. In
399 2016, Aruba, along with Bonaire and Curacao, convened and established the Caribbean Waste
400 Collective with the goal of increasing inter-island cooperation to stimulate a new economy that
401 views waste as a valuable and profitable item, which has also included increased Recycling
402 infrastructure and industry (Luken, 2017).

403

404 **3.4.3. Bonaire**

405 Three 100m litter transects were conducted in Bonaire. The top three most prevalent litter
406 categories were closely balanced between tobacco products, plastic fragments, and food plastic.
407 As for the individual items, cigarettes dominated the composition by a large margin. There was
408 a high prevalence of fragments among the top items, including both hard and sheetlike plastic
409 fragments. Bonaire was the only country where bottle caps were listed among the top five litter
410 items (Table 1).

411 Bonaire's Department of Space and Development proposed legislation in 2018 that would ban
412 certain types of single-use plastic, which is currently awaiting approval and the State Secretary
413 of the Netherlands has expressed support in improving waste management infrastructure and
414 policy in Bonaire in the coming years (Davies, 2020).

415

416 **3.4.4. Panama**

417 Six 100m litter transects were conducted in Panama. The litter transects were conducted on the
 418 Pacific coast while the marine samples were collected on the Caribbean coast of Panama. The
 419 most abundant category of litter was tobacco products (encompassing cigarettes and associated
 420 packaging and lighters) and the count of tobacco products was higher in Panama than in any
 421 other country (Figure 6). Cigarettes were the dominant litter item documented by a relatively
 422 high margin (by 63 items, SI Figure 8). Like in the other countries surveyed, there was a high
 423 prevalence of plastic fragments, including both hard plastic fragments and threadlike
 424 fragments; the latter of which could suggest association fishing or with fabric/clothing. Food
 425 plastic was the third most prevalent category documented.

426 Of the four countries sampled, Panama has the highest estimated mismanaged waste (44.3%),
 427 but a comparatively low to average per capita waste generation rate (1.03 kg/person/day) and
 428 percentage of plastic in the waste stream (12%) (IDB, 2020). Panama is also unique among the
 429 countries sampled in that it has government support for the informal recycling sector, as well
 430 as the Pepsico sponsored ‘Recycling with Purpose (PepsiCo, 2019)’ program which could also
 431 explain why larger and more readily recycled plastic items were not found among the litter
 432 items in Panama. For example, only 1 PET bottle was documented among the 285 litter items
 433 in Panama. In 2018, Panama also became the first Central American country to implement a
 434 plastic bag ban (Karasik et al., 2020) and in 2020 a second ban for single use articles (including
 435 cotton swabs, straws, plastic cutlery and food containers) was approved by the government
 436 (República de Panamá, 2020).

437

Table 1. The top 5 numerically abundant litter items and the average density of all litter recorded within each country sampled.

Country (# of transects)	Top 5 Most Abundant Litter Items	Average Litter Density
Panama (n=6)	1) Cigarettes, 2) Plastic food wrapper (multilayer), 3) Hard plastic fragments, 4) Threadlike plastic fragments, 5) Other paper	0.475 items/m ²
Bonaire (n=3)	1) Cigarettes, 2) Hard plastic fragments, 3) Plastic food wrapper (multilayer), 4) Plastic bottle cap, 5) Sheetlike plastic fragments	0.7133 items/m ²
Aruba (n=2)	1) Cigarettes, 2) Hard plastic fragments, 3) Paper, 4) Plastic food wrapper (multilayer), 5) Foam or plastic cups/lids	2.520 items/m ²
Antigua (n=6)	1) Sheetlike plastic fragments, 2) Other paper, 3) Plastic food wrapper (multilayer), 4) Hard plastic fragments, 5) Plastic rope	0.536 items/m ²

438

439

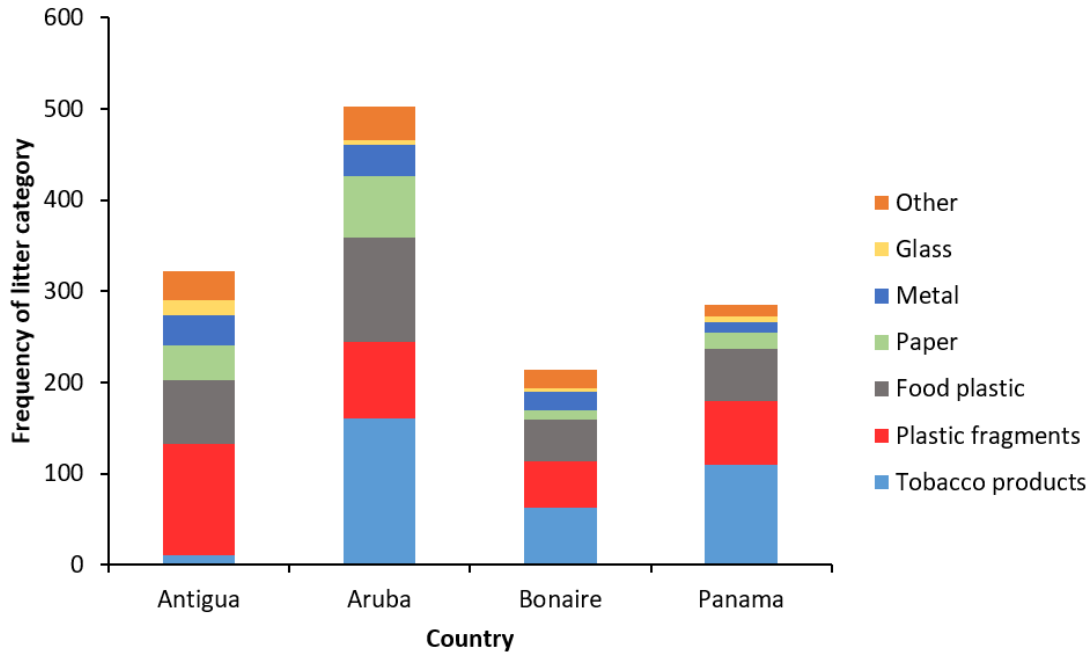


Figure 6. The frequency of litter categories recorded within each country sampled

440

441 **3.5. Lagrangian particle tracking: the potential geographic sources of marine**
 442 **microplastics**

443 The majority of simulated particles (80%) were back-tracked to land within the 60-day model
 444 simulation (SI Table 6). On average, it took particles 11 ± 12.98 SD days to reach land. For the
 445 Antiguan samples, 66% of particles backtracked did not reach land within the 60-day
 446 simulation. Those that did reach land in ≤ 1.2 days, suggesting some short term self-seeding of
 447 marine litter to Antiguan waters, however the model suggests that the majority of plastics
 448 sampled in this area have travelled from the East, i.e. the Atlantic Ocean (Figure 7).

449 All particles released at the Bonaire sampling sites were backtracked to land within 6 days and
 450 all were traced back to Bonaire itself (Figure 7). A similar occurrence was observed in particles
 451 released from the Aruba sites, with 85% of particles being backtracked to the Aruban shoreline
 452 in < 1 day (Figure 7). The potential source of the remaining 15% of particles was found to be
 453 the Federal Dependencies of Venezuela, with particles traveling a distance of $439\text{km} \pm 4\text{km}$
 454 over $33\text{days} \pm 1.77\text{days}$. Venezuela was also predicted to be a predominant potential source
 455 location for the plastic collected off the coast of Colombia with 40% of all particles being
 456 tracked to the Falcón region. Most other particles seeded in Colombian waters could be traced
 457 back to Colombia, with La Guajira being a considerable potential source location.

458 Finally, the model predicted the majority of the litter in the water around the San Blas islands
 459 to come from mainland Panama, with 72.5% of particles being traced back to the Comarca
 460 Guna Yala region. Of the remaining particles, 10% were each traced back to the Chocó and
 461 Córdoba regions of Colombia respectively, and 7.5% did not reach land with the 60-day model
 462 simulation.

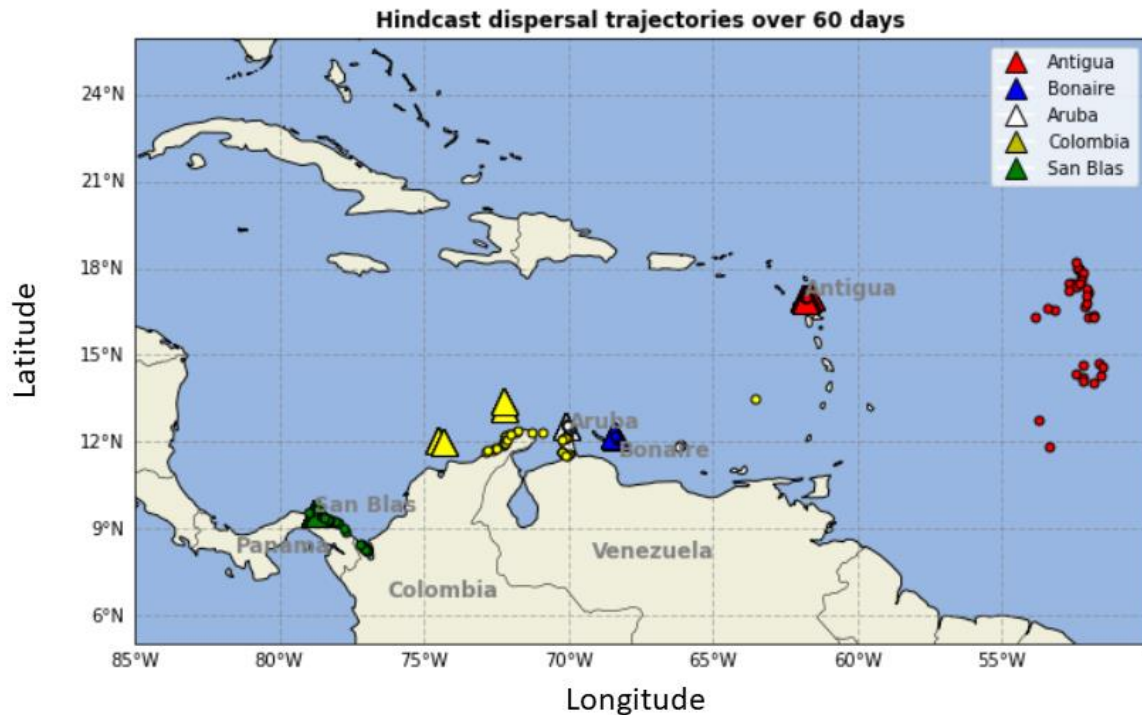


Figure 7. Dispersal of microplastics (circular points) from the sampling locations (triangular points) over a 60-day hindcast simulation. Colours refer to the country where sampling was conducted.

463

464

465 **4. Discussion**

466 This study provides baseline data on the abundance of (micro)plastics within different
 467 environmental compartments in the Southern Caribbean region and examines their potential
 468 origins through land-based assessments and Lagrangian modelling approaches; an
 469 interdisciplinary approach absent from plastic pollution research. Evidence of the abundance
 470 of plastics within the Caribbean's marine environment are lacking, and to this end the data
 471 presented give a holistic approach to examine the potential origins, flows and quantities of
 472 plastics within the Southern Caribbean.

473 Previous research has documented macro and microplastics in beach sediments (Bosker et al.,
 474 2018, Mazariegos-Ortiz et al., 2020, de Scisciolo et al., 2016, Delvalle de Borrero et al., 2020)
 475 from the Caribbean region, yet few have assessed those in the marine ecosystem (Kutralam-
 476 Muniyasamy et al., 2020). In this study, the quantities of microplastics varied considerably
 477 between different environmental compartments and locations, i.e. individual samples within
 478 countries and between countries. For example, while different sampling methods were utilised
 479 between surface and subsurface sampling which may result in differences in the quantities of
 480 microplastics collected, particularly fibres; on average the abundance of synthetic plastics were
 481 two orders of magnitude greater within water collected at 25m than in surface waters. This
 482 finding is contrary to observation from the upper North Atlantic gyre where particle count
 483 decreased with depth (Reisser et al., 2015). Additionally variation was noted between
 484 sediments and surface waters. Panama had the lowest concentrations of microplastics in

485 sediment samples, while the highest quantities of surface water plastics. Conversely sediment
486 from Aruba had the highest microplastics load while the lowest surface water concentrations.
487 These findings warrant further work to examine plastic pollution over larger spatial scales
488 within territorial water and elucidate any localised influences on the sinking of plastic particles.

489 Of the regions studied, the San Blas islands, Panama had the highest abundance of microplastics
490 present at a water depth of 25m (0.89 MP/L) and significantly greater quantities in surface
491 water (average 1.56 ± 2.36 SD. MP/m³) than recorded in the other countries sampled. It is
492 important to note that the lightest wind and lowest sea state was recorded during these sample
493 collections. A statistically significant negative relationship was identified between sea state
494 and the concentration of microplastics in surface waters, which may explain the patterns we
495 observed. Larger waves (indicative of sea state) and higher wind speeds will increase surface
496 water mixing and redistribute plastics into the ocean interior (Kukulka et al., 2012). Further
497 sampling campaigns undertaken within the Southern Caribbean would be beneficial to
498 establish whether there are differences in the quantities of plastic between countries or whether
499 this is an artefact of environmental conditions.

500 Linking environmental data with Lagrangian particle modelling, a technique which has been
501 widely utilised to inform on the likely sources and transport of marine plastic pollution
502 (Lebreton and Borrero, 2013, Hardesty et al., 2017, Kaandorp et al., 2020), attempts to indicate
503 potential origins for the marine plastics identified within this study. The majority of the plastics
504 collected within this study from the water around Bonaire, Aruba, Colombia and Panama were
505 tracked back to the country itself, suggesting leakages of plastic waste from land or the
506 mobilisation of beached debris from their shorelines. In 2020, daily waste generation rates per
507 capita were estimated to range between 0.76 – 2.91 kg/person/day for Aruba, Colombia and
508 Panama (data not available for Bonaire) which are slightly higher than the 0.99 kg/person/day
509 average for the Latin America and Caribbean region. Annual quantities of mismanaged waste
510 was estimated at 21.6%, 6% and 44.3% for each country respectively (IDB, 2020), and
511 indicates waste leakages, of which plastic is a major component (IDB, 2020). Research
512 conducted along the Caribbean coast of Colombia support this. The majority of beaches studied
513 along northern Colombia were classified as ‘high’ or ‘very high’ in terms of their microplastic
514 pollution (Rangel-Buitrago et al., 2021), with the greatest accumulations and leakages of
515 plastics linked to river discharge (Rangel-Buitrago et al., 2021), local currents (Rangel-
516 Buitrago et al., 2019), increased tourism and poor waste management (Garces-Ordonez et al.,
517 2020b, Garces-Ordonez et al., 2020a).

518 Particle modelling revealed a different pattern for Antigua compared to the other countries.
519 While a small proportion of the particles were traced back to Antigua itself, the majority of the
520 trajectories indicate transport from the wider North Atlantic Ocean, suggesting distant sources
521 and to a slightly lesser extent local sources, contribute to the plastics found in Antigua’s coastal
522 marine environment. Antigua had among the lowest terrestrial litter density, relatively low
523 waste generation rates compared to other Caribbean countries (3.2%) (IDB, 2020) and some of
524 the lowest quantities of surface water microplastics yet a high diversity of polymers were
525 recorded. Integrating these datasets further supports that plastics located around Antigua may

526 have been transported via Atlantic Ocean currents and from leakages from the North Atlantic
527 sub-tropical gyre, as also evidenced for other eastern Caribbean countries (Ambrose et al.,
528 2019, Davranche et al., 2020).

529 Plastic pellets were identified in surface water samples collected around Antigua (0.01
530 pellets/m³) and Panama (0.77 pellets/m³). Pellets collected around Antigua appeared
531 discoloured inferring prolonged environmental weathering and long-range transport.
532 Conversely the majority of the pellets around Panama had little evidence of degradation (e.g.
533 pristine white colour) suggesting localised sources, such as the plastic production facilities
534 located in the industrialised Cartagena region of Colombia. Other studies have evidenced
535 relatively high densities of new white pellets beached in Cartagena (Acosta-Coley et al., 2019a,
536 Acosta-Coley et al., 2019b) and found greater quantities of pellets present along the Caribbean
537 coast of Panama than the Pacific coast (Delvalle de Borrero et al., 2020) suggesting their
538 transport in north-westerly currents from Colombia to Panama, and corroborating our model
539 predictions.

540 The high proportions of fragmented plastic identified in both the land and marine samples
541 suggests degradation through environmental exposure and/or ocean transport. This is supported
542 by the particle modelling which indicates that for all countries sampled a combination of local
543 (i.e. the country itself) and more distant sources contribute towards the environmental plastics
544 identified. It is important to note that the model does not consider the remobilisation and
545 redistribution of beached plastics which could have originated from elsewhere, processes
546 which may also cause fragmentation. Quantities of plastic debris and the factors influencing its
547 distribution can vary even over small geographic areas largely associated with prevailing wind
548 and ocean circulation (Ambrose et al., 2019). For example, greater quantities of beached litter
549 have been recorded on windward coastlines than on leeward facing coastlines (de Scisciolo et
550 al., 2016). As such, our results may be somewhat localised to the sample points studied and
551 may not be representative of the country as a whole. The findings do however highlight the
552 transboundary movements of plastics between Caribbean countries which may undermine local
553 policies to tackle plastic pollution.

554 Furthermore, challenges can be presented when trying to tackle plastic pollution associated
555 with and arising from industries on which nations depend upon heavily, such as tourism. With
556 an estimated 31.5 million tourists in 2019 (Caribbean Tourism Organisation, 2020), travel and
557 tourism contributed an estimated \$59 billion to the economy of the Caribbean region,
558 representing nearly 14% of the region's GDP (World Travel and Tourism Council, 2020).
559 However, tourism in the Caribbean has significant impacts on waste management practices in
560 the region, and globally studies have suggested that solid waste generation in the tourism sector
561 can put significant stress on municipal solid waste management systems and in some cases can
562 account for higher per capita waste generation than other industries or residential areas (Bashir
563 and Goswami, 2016, Saito, 2013, Mateu-Sbert et al., 2013). Many of the polymers identified
564 in the water and sediment samples, e.g. fragments and films of PE and PP, and PS fragments
565 and foams, have applications within consumer products such as food and beverage packaging.
566 Food packaging items were routinely found during terrestrial surveys, which when coupled

567 with pressures on waste management infrastructure within the Caribbean region may result in
568 leakage into the marine environment.

569 Paint particles were identified in the water of all regions sampled, which could have been shed
570 from the hulls of vessels while in transit (Dibke et al., 2021), or when carrying out maintenance
571 (Muller-Karanassos et al., 2019, Turner, 2010). The paint fragments were distinct in their
572 colour and FTIR spectra to any of the paints used on S.V. TravelEdge precluding their source
573 as contamination. Further, rope debris was identified within the most common street litter items
574 in Antigua. Ropes are commonly made of polyester, polypropylene and polyamide, and all
575 three polymers were found within sediment and water column samples suggesting they may
576 have arisen from the maritime sector. In particular PP dominated the polymer composition
577 across all the sediment samples collected, despite its inherent density being less than seawater,
578 meaning it will naturally float (Andrady, 2011). The Caribbean is a renowned destination for
579 nautical tourism with >30 million passengers arriving by cruise ships (Caribbean Tourism
580 Organisation, 2020) and >130,000 by yacht/leisure craft (Zappino, 2005, Phillips, 2014), which
581 may play a role in the origin of these particles.

582 As highlighted in this study, combining terrestrial litter data with marine sampling is
583 advantageous to consider the potential flows of plastic pollution. The portion of the Circularity
584 Assessment Protocol utilised was an abridged version of the full methodology, and limitations
585 arise from the relatively small number of transects conducted meaning data are not fully
586 representative of the geographic areas as a whole. However, based on other studies and
587 complimentary data, such as waste generation rates and waste management infrastructure the
588 findings presented are in accord with expected patterns in the region. Litter estimates recorded
589 during land-transect are similar to those documented in the Caribbean previously, which are
590 higher than the global average of 573 items/km (Diez et al., 2019).

591 Litter data can also be used to evaluate plastic reduction interventions. Over 20 Caribbean
592 countries already have some form of national plastic policy in place (Karasik et al., 2020) (see
593 SI Table 5), the majority of which are plastic bag bans, and another 8 countries are currently in
594 discussion to develop such policies. Antigua, Aruba, and Panama all have existing plastic bag
595 bans in place. Interestingly, no plastic bags were documented among terrestrial litter in Aruba
596 or Bonaire, only 1 was recorded in Panama and 4 were documented in Antigua. In contrast,
597 prior to the plastic bag ban in Antigua and Barbuda in 2016, it was reported that plastic bags
598 from supermarkets accounted for 90% of plastic litter found in the environment (UNEP,
599 2018a). In 2005, it was estimated that Aruba used 30 million single-use carry-out bags per year,
600 most of which would have ended up in the environment or in landfill (UNEP, 2018a).

601 While plastic bags are the dominant item of focus for policy in the Caribbean, expanded
602 polystyrene items are the second most common for national bans, one such country being
603 Antigua. Only four whole foam plastic items were documented in terrestrial surveys in Antigua
604 and Bonaire respectively, five in Panama, and 27 in Aruba. However, polystyrene fragments
605 were found among the microplastic from surface water sampling, particularly in the waters
606 around the San Blas archipelago, Panama suggesting that perhaps they are originating from
607 elsewhere.

608 While this data may suggest that the enforcement of policies in the region is translating to
609 certain items ending up in the environment less frequently, it is important to note that the
610 Caribbean provides a case study on the importance of multinational efforts to prevent plastic
611 pollution on a holistic level. As seen in the modelling and environmental data, there is potential
612 for marine litter in the Caribbean to move through the prevailing ocean currents and to become
613 highly fragmented over time before beaching. This means that policy in one location may not
614 translate to less litter on their own coastline, and waste leakage can end up on other country's
615 shorelines because of ocean currents. This further amplifies the importance of regional
616 partnerships such as the Caribbean Waste Collective, the Trash Free Waters International
617 Partnership, and the Caribbean Regional Action Plan for Marine Litter.

618 Throughout the Caribbean, marine litter and plastic pollution have increasingly become the
619 focus of research, policy, and conservation efforts. It is clear that there are strategies in place
620 to take action on this issue in the Caribbean, but also that the Caribbean is particularly
621 vulnerable to the impacts of plastic pollution due to its high percentage of landfilling and open
622 dumping, low percentage of recycling, finite and in some cases shrinking land area, physical
623 location for oceanic transport of litter, its import of consumer goods and economic reliance on
624 ocean-related activities such as fishing and tourism (Clayton et al., 2020, Diez et al., 2019,
625 IDB, 2020). While nearly all Caribbean nations have taken steps towards implementing plastic
626 policies, few have implemented comprehensive solid waste management plans, which would
627 also serve a critical role to capture and contain waste and prevent it from entering the
628 environment (Riquelme et al., 2016). There is no one solution for eliminating plastic pollution,
629 interventions should be implemented in an integrated and complementary way. Research such
630 as this can help to identify which interventions may be interlinked, resulting in the most
631 significant impact.

632

633 **5. Conclusion**

634 It is clear that plastic pollution is an international challenge that demands interdisciplinary
635 research and solutions. While this study provides a snapshot of data from a limited number of
636 samples and countries in the Southern Caribbean region, collecting information in a holistic
637 manner is critical to inform the most effective and integrated solutions to plastic pollution. The
638 findings from this study illustrate that we can begin to better understand the multifaceted issue
639 of plastic pollution if studies combine land-based data, ocean-based data, and physical
640 modelling.

641

642

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649

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