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Mangrove forests as traps for marine litter☆

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ABSTRACT

To verify weather mangroves act as sinks for marine litter, we surveyed through visual census 20 forests along the Red Sea and the Arabian Gulf, both in inhabited and remote locations. Anthropogenic debris items were counted and classified along transects, and the influence of main drivers of distribution were considered (i.e. land-based and ocean-based sources, density of the forest and properties of the object). We confirmed that distance to major maritime traffic routes significantly affects the density of anthropogenic debris in Red Sea mangrove forests, while this was independent of land-based activities. This suggests ocean-based activities combined with surface currents as major drivers of litter in this basin. Additionally, litter was more abundant where the mangrove density was higher, and object distribution through the mangrove stand often depended on their shape and dimension. We particularly show that pneumatophores act as a sieve retaining large plastic objects, leading to higher plastic mass estimates in mangroves compared to those of beaches previously surveyed in the Red Sea.

1. Introduction

The global load of marine floating plastic litter in surface waters is far smaller than expected based on the loads of mismanaged plastic entering the marine environment (Cozar et al., 2014; Eriksen et al., 2014; Jambeck et al., 2015; Van Sebille et al., 2015). This finding has, therefore, driven attention to the need for identification of the marine sinks holding the missing plastic. Although recent studies, focusing on larger plastic fractions, have revised upwards the load of floating plastic contained in the open ocean (Lebreton et al., 2018), the "missing plastic" (Cozar et al., 2014) remains a large fraction of the expected load, so identifying the marine sinks holding it remains an urgent matter to assess risks and impacts and plan interventions to manage this modern problem.

Shore deposition has been identified as a major sink of marine plastic pollution, together with other sink processes including nanofragmentation (Gigault et al., 2016), sedimentation (Van Cauwenberghe et al., 2015), and ingestion (Ryan, 2016) or, more generally, interaction with marine biota (Watts et al., 2014). Plastic was found washed ashore already in the early 1970s, when the realization that marine plastic pollution was a problem was emerging (Gregory, 1977), and surveys confirm that even the shores of the remotest beaches accumulate significant plastic loads (Lavers and Bond, 2017). However, while shore deposition is often associated with beach litter only (Browne et al., 2011), coastal environments other than sandy shores can also accumulate plastic debris (Thiel et al., 2013).

Mangrove forests cover about 132,000 Km^2 along subtropical and tropical shores (Hamilton and Casey, 2016). Mangrove trees occupy the intertidal fringe and develop a partially emerged root system, pneumatophores and prop roots, forming an effective filter that attenuates wave energy and turbulence (Horstman et al., 2014; Norris et al., 2017) and may possibly trap objects transported by currents, like floating plastic objects. However, the role of mangrove pneumatophores or prop roots as traps for litter reaching the system from the open sea has not been tested. Indeed, only a handful of studies have reported plastic pollution in mangroves, mostly focusing on microplastic in mangrove sediments (Barasarathi et al., 2011; Lima et al., 2014; Mohamed Nor and Obbard, 2014; Lourenço et al., 2017; Naji et al., 2017) so that information on macroplastics, the component possibly trapped by the filter of pneumatophores and that also has a higher contribution in terms of mass, is scarce. Ivar do Sul et al. (2014) reported tracked drifting plastic items released in a mangrove forest, showing different retention capacities dependent on the hydrodynamic of the object (e.g. plastic bags were more easily retained

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than plastic bottles). However, while that experiment demonstrated differential interactions between mangrove stands and different types of plastic debris, thereby providing indications of what plastic debris might be found in mangrove forests, it considered only plastic released inside the forest itself, and did not report loads of plastic litter trapped from the open sea. Similarly, Cordeiro and Costa (2010) sampled litter from estuarine mangroves, where litter came mainly from land and riverine sources.

The key role of mangroves as providers of important ecosystem services, including carbon sequestration (McLeod et al., 2011; Almahasheer et al., 2017), coastal protection and habitat for marine life (Spalding et al., 2010; Duarte et al., 2013), requires efficient management of the threats affecting these ecosystems, including marine plastic pollution. Plastic trapped by mangrove pneumatophores and prop roots may constitute a physical impediment affecting both the tree itself and the associated fauna, by preventing gas exchange and releasing harmful chemicals absorbed by or industrially added to plastic materials (Cole et al., 2011). Yet, the role of mangrove forests as traps for marine plastics remain largely unexplored.

Here we test the hypothesis that the pneumatophore array of mangrove forests represents an effective filter for macroplastics reaching the mangrove from the adjacent open water. We also examine the role of possible drivers and sources of marine and, in general, anthropogenic litter in affecting the distribution of debris in the studied mangrove forests. We did so by conducting visual census surveys in Saudi Arabian mangrove forests located in mainly remote or uninhabited areas where plastic has clearly a marine origin in both the Red Sea and the Arabian Gulf. Saudi Arabian mangroves extend for almost the entire length of national coasts (excluding the northernmost areas, north of 28°N) covering 48.42 m^2 and 10.36 km^2 on the Red Sea and Arabian Gulf Saudi shores, respectively (Almahasheer et al., 2016a; Almahasheer, 2018). Particularly, Red Sea mangroves are fringe forests that develop along the coast, but not inland due to lack of permanent estuaries in the catchment area of the basin and narrow tidal ranges, and therefore are less developed than forests in other tropical areas (Mandura et al., 1987). Red Sea and Arabian Gulf stands are dominated by *Avicenna marina* which forms extensive forests, while *Rhizophora mucronata* is scattered and limited to few areas in the southern Red Sea and in the Western Arabian gulf (Almahasheer et al., 2016a). For this reason, we focused on surveying *A. marina* forests. *Avicenna marina* aerial roots have pneumatophores, vertical finger-like structures rising about 30–40 cm from the sediment and conforming a filter, which can potentially interfere with floating plastic items. Indeed, similarly to what has been observed for the open ocean, unexpectedly low concentration of plastics in surface waters were also observed in Saudi Arabian basins, the Red Sea (Martí et al., 2017) and the Arabian Gulf (Castillo et al., 2016; Abayomi et al., 2017), despite management of plastic litter in the region lagging behind best standards (Demirbas et al., 2016). This observation and the extension of Arabian mangrove forests make the region a good case study to test whether mangroves constitute a sink for marine plastic pollution.

2. Materials and methods

Visual census surveys were conducted in 16 mangrove forests on the Saudi coast of the Red Sea and 4 in the Arabian Gulf (Fig. 1). Five of the 20 surveyed forests were situated along a city shore, one in Yanbu and 4 in the Arabian Gulf, another 2 are only 2 km away from a coastal inhabited center, and the remaining 13 are located at $\geq$ 7 km from a coastal town or city, with 7 of those located on uninhabited offshore islands (Table 1). Selected mangrove forests were monospecies stands of *A. marina*, with trees ranging from approximately 1.5 m up to 4 m in height (Khan and Kumar, 2009; Almahasheer et al., 2016b), except for one young forest 9 km from Yanbu (24.193 N 37.948 E) where trees were <1 m in height.

In each mangrove stand, hereafter also referred as "station", we counted anthropogenic debris in 4–10 transects, except for one forest (25.54 N 36.85 E) where we completed only one transect due

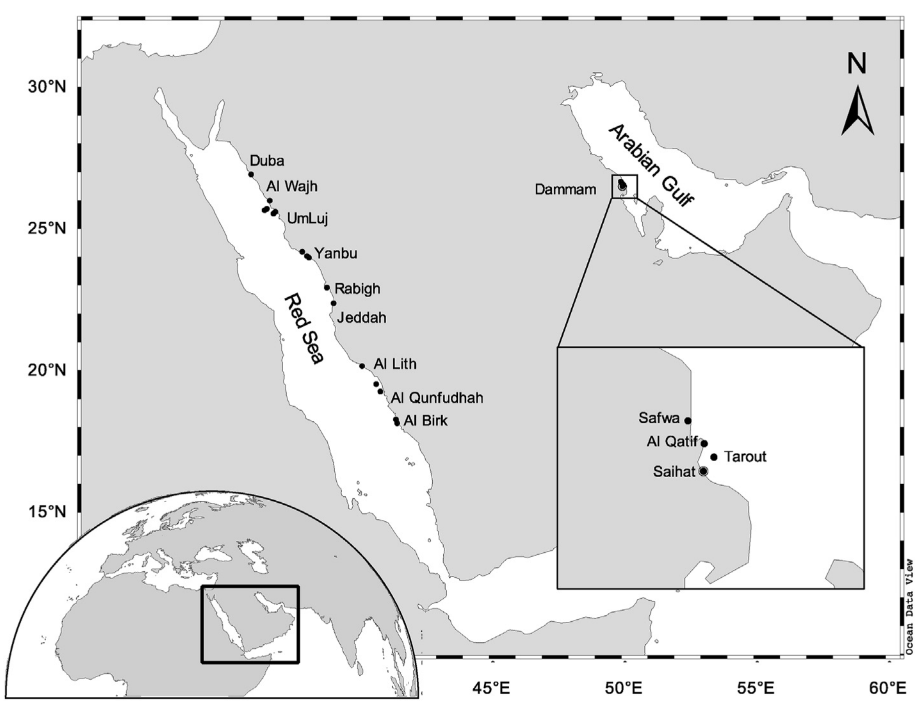

Fig. 1. Geographic location of the study area (Arabian Peninsula) and stations where mangrove litter was surveyed (black dots). Closest towns and cities are reported.

Table 1
Coordinates of surveyed mangrove forests, distance to closest town or city and to closest high-intensity maritime traffic area (>1000 routes km^{-2} year^{-1}). Indicated population estimates are retrieved from http://worldpopulationreview.com/ and http://www.citypopulation.de/. Maritime traffic intensity estimates are obtained for the year 2017 from www.marinetraffic.com.

Latitude (°N)	Longitude (°E)	Location	Closest town or city	Population of town or city	Distance to town or city (km)	Distance to high-intense maritime traffic area (km)
Red Sea						
26.917	36.01	Onshore	Duba	22,000	50	35
25.993	36.708	Onshore	Al Wajh	26,636	35	60
25.702	36.599	Offshore	Al Wajh	26,636	60	35
25.655	36.512	Offshore	Al Wajh	26,636	64	25
25.607	36.918	Offshore	Umluj	33,874	68	50
25.538	36.849	Offshore	Umluj	33,874	69	60
24.193	37.948	Onshore	Yanbu	200,161	9	12
24.037	38.118	Onshore	Yanbu	200,161	2	4
23.983	38.191	Onshore	Yanbu	200,161	0	3
22.935	38.880	Onshore	Rabigh	41,759	25	7
22.381	39.132	Onshore	Thuwal	<20,000	7	9
20.162	40.207	Onshore	Al Lith	72,000	2	75
19.532	40.743	Offshore	Al Qunfudhah	24,512	54	102
19.271	40.896	Offshore	Al Qunfudhah	24,512	23	103
18.151	41.533	Offshore	Al Birk	<20,000	7	111
18.286	41.483	Onshore	Al Birk	<20,000	9	109
Arabian Gulf						
26.663	49.990	Onshore	Safwa	45,876	0	17
26.591	50.046	Onshore	Al Qatif	98,259	0	12
26.549	50.080	Onshore	Tarout	85,371	0	8
26.504	50.044	Onshore	Saihat	66,702	0	10

to logistic constraints. A total of 76 transects were surveyed in the Red Sea and 20 in the Arabian Gulf, covering an area of 5737 m^2 and 549 m^2, respectively. Transects were randomly laid parallel to the coastline or the main direction of the mangrove stand. They were mainly placed at the seaward fringe of the forest (N = 61, 48 in the Red Sea and 13 in the Arabian Gulf). If accessibility allowed, transects were also surveyed inside the stand (N = 35, 28 in the Red Sea and 7 in the Arabian Gulf), at > 10 m from the seaward fringe. This information (position of the transect) was recorded and GPS points taken. Distance of each transect to the seaward fringe was measured on satellite images in Google Maps as the minimum linear distance between the transect starting geographic coordinate and the edge of the trees. Because transects were mainly positioned at or close to the seaward fringe, water level was >10 cm in the majority of the surveyed areas. However, in few cases, particularly when transects were close to the beach behind the mangrove, the surveyed area was dry. If this was the case, only anthropogenic debris found where pneumatophores and trees grow were recorded, while we ignored items exclusively on the sand, considered as litter that has overpassed the mangrove forest and stranded on the beach instead. Distance of each transect to the beach behind the mangroves was measured in Google Maps as the minimum linear distance between the transect starting point and the littoral. Similarly, we measured distance of each transect to the shore on the main land and to the nearest coastal town or city (>10,000 inhabitants), the latter as the linear distance between the transect starting point and the closest point of the town or city center (i.e. the area of the city with the highest building density). We also measured the minimum linear distance of each transect to areas of high intensity maritime traffic. We considered as high intensity traffic areas those traversed by > 1000 routes km^{-2} y^{-1}, including all vessels types (e.g. fishing, recreational and commercial vessels) and dimensions, from small boats (<10 m in length) to big vessels (>60,000 Gross Tonnage). This information was retrieved from https://www.marinetraffic.com for the year 2017.

Density of trees in each transect was recorded as either "high" (tree coverage >75%) or "low" (≤50%). Low tree density was reported for 61 transects (47 in the Red Sea and 14 in the Arabian Gulf), and high density for 35 (29 in the Red Sea and 6 in the Arabian Gulf).

Transect length ranged between 4 m and 60 m, dependent on litter density: shorter lengths for highly dense areas and longer length where items were sparsely scattered, following the same principle used for beach litter visual census in the Red Sea (Martin et al., 2018) and other beach litter surveys (Andrades et al., 2016), since the precision of density estimates is dependent on the total number of items censused. Width ranged from 2 m to 8 m depending on the accessibility of the site: when tree density and practicability of the stand allowed it, larger widths were preferred. A measuring tape was used to determine the length of the transect and the width at the starting point. From the starting point on, width was visually established and maintained constant for the whole length of the transect. The transect length was always greater than the width. Plastic items and any anthropogenic debris >2.5 cm were counted along the transect and recorded per type. Items were counted also if underwater or below plant debris, to the best of our capacity. Objects were classified in types. Correspondence of the types used in this study and unified litter types proposed by UNEP/IOC guidelines (Cheshire et al., 2009) is reported in Table S1, in order to allow comparisons with other studies using the same classification (e.g. Williams et al., 2016; Campbell et al., 2017). We did not weigh all recorded items due to logistics constraints. In total, we weighed 268 plastic objects belonging to 16 types (drink bottles, plastic bags, ropes, food wraps, oil containers, polystyrene, small containers, carboys, big containers, buoys, nets, fishing lines, fragments, bottle caps, detergent bottles and footwear, Table 2). We randomly selected, within each object type, a number of objects to be weighed. The number of randomly-selected objects of each type varied depending on bulkiness (we sampled fewer objects of bulky types, e.g. big containers and carboys) and frequency (we weighed more samples of frequently encountered objects). At 10 of the 20 stations (6 in The Red Sea and 4 in the Arabian Gulf, N = 53 transects), we also recorded where the object was observed, either among mangrove pneumatophores and seedlings in the area surrounding the trees or trapped in the tree branches and trunk, in order to determine if the properties of the object (i.e. shape, material and dimension) influence its distribution in the forest. To this end, plastic items were combined in categories based on the above

Table 2
Weights (min, max, average ± SE and median values) of collected samples belonging to 16 plastic objects types.

Object type	N of weighed objects	Min weight (g)	Max weight (g)	Average weight ± SE (g)	Median weight (g)
Fragments	12	0.06	0.7	0.4 ± 0.06	0.35
Fishing Lines	4	0.02	4.9	1.8 ± 1.2	1.19
Food Wraps	21	0.2	6.6	1.9 ± 0.4	1.29
Bottle caps	31	1	7.5	2.3 ± 0.3	1.62
Ropes	52	0.02	110.3	7.1 ± 2.3	1.36
Polystyrene	16	0.2	32.5	8.6 ± 2.2	5.69
Plastic Bags	13	2.5	26.4	11.2 ± 1.7	10.41
Buoys	8	6.1	20	13.2 ± 1.7	12.78
Small containers	29	3.4	121.7	15.8 ± 4.0	10.23
Drink Bottles	37	9.2	70	23 ± 2.1	17.55
Nets	7	2.4	112	37.6 ± 17.0	10.26
Detergent bottles	5	40.2	69.9	58.8 ± 5.5	63
Oil containers	9	40.7	287.5	75 ± 26.8	42.3
Footwear	11	40.5	357.1	185.7 ± 34.9	204
Carboys	7	88.1	842	301.1 ± 130.6	102
Big containers	6	130	3200	898.1 ± 467.2	498

cited properties (Table 3), and their frequencies in the two forest compartments (i.e. pneumatophores and seedlings or tree branches and trunk) were compared using a Chi-square test. We excluded from this analysis non-plastic object types due to their low abundance and high variability (e.g. aluminum objects include cans, foils, bowls) and less represented plastic objects types with a relative abundance <2%, unless with properties very similar to more represented objects (e.g. fishing lines were merged with nets and ropes). We also measured the distance between pneumatophores in 5 of the studied mangroves as a measure of their capacity to retain floating debris of various characteristic size.

To test which variables are significant drivers of litter distribution in the studied mangroves, we used a generalized additive model (GAM). The GAM was preferred to a generalized linear model to explore non-parametric relationships between litter density and other variables. Particularly, we tested if litter density in each transect depends on:

a. Distance to the nearest coastal city, proxy of land-based sources of litter discarded directly from the coast;
b. Distance to the main shore, proxy of all land-based sources of litter, including those transported in the marine environment from the inner land;
c. Distance to high intensity maritime traffic areas, proxy of ocean-based sources of litter;
d. Distance to the seaward fringe, proxy of the ability of tides and currents in transporting marine litter through the stand.
e. Distance to the beach behind the mangroves, proxy of land litter, which is either litter never dispersed in the marine environment (reaching the mangrove forest for a direct human intervention or transported by winds) or marine litter first stranded on shore and then washed again ashore;
f. Tree density categories (low and high), proxy of density of obstacles to litter redistribution.

Table 3
Description of plastic objects categories based on their properties (i.e. shape, material and dimension).

Category	Description
PET bottles	Bottles for drinks normally in Polyethylene Terephthalate (PET) of a capacity ≤ 2.5 L
Other bottles	Bottles in plastic material other than PET normally used for solvents, engine oil, cleaners ≤ 2.5 L
Carboys	Containers for liquids of a capacity ≥ 2.5 L
Films	Plastic bags, tarpaulin bags, food wraps and any thin, flexible and sheet-like plastic excluding synthetic fabrics
Ropes, Lines and Nets	Thin and flexible plastic made out of threads
Big containers	Boxes, crates, baskets and buckets
Small containers	Cups, bowls, pots and jars
Polystyrene	Fragments of polystyrene material

All variables are continuous, except for the last, which is categorical. The GAM was first applied to data collected from the Red Sea using all listed variables. Successively, we repeated the GAM excluding non-significant variables to obtain a more robust model. Since the categorical variable was significant, we used a non-parametrical test (the Mann-Whitney U test) to compare mean litter densities in transects with "low" and "high" tree density. We did not apply the GAM to data collected from the Arabian Gulf because of the limited number of transects available there and the fact that the sampled forests in this basin were all located on a city shore, so they did not allow to test for the distance from urban centers. Hence, merging of the Arabian Gulf with Red Sea data in the GAM analyses could have biased or confounded the results. We did not apply the GAM on data from the Arabian Gulf separately because the sampled population (number of transects) was too limited to obtain a robust integrated model.

Last, to further determine whether mangroves are to be considered sinks for plastic, we compared results from mangrove surveys along the Arabian coast of the Red Sea with beach litter visual census previously conducted in the same area (Martin et al., 2018). Surveys conducted in this study and Martin et al. (2018) study applied comparable approaches, by recording anthropogenic debris >2.5 cm in replicate transects of variable lengths, depending on litter density, placed parallel to the coastline. Since we observed larger items in the mangroves compared to beaches, we did not only compare litter densities, but also the weight distribution of items belonging to the main plastic types. To do this comparison we used a Pareto distribution, built as a relationship between the median weight of each plastic type (W) at the x-axis and the probability that an item, with a random weight w, weighs as much or more as W (y-axis). The median weight was obtained, as explained above, by weighing representative samples of the 16 most frequent plastic types. The probability was calculated as:

$$prob\ (w \geq W) = \frac{N_{(w \geq W)}}{N_t}$$

Where $N_{(w>W)}$ indicates the sum of recorded items belonging to types with a median weight ≥ W and N_t the total number of items belonging to the 16 weighed types. A Pareto distribution was fitted for litter in each of the two studied habitats, mangrove and beach litter. Because the two distributions seemed to diverge for $W \geq 50$ g, we calculated the proportion (±CI) of items belonging to types with a $W \geq 50$ g and compared them with an inference for two proportions with independent samples. As a further comparative measurement, the weighted-mean mass of the items in Red Sea mangroves and beaches was calculated as the sum of the product of the median weight of each type and its relative frequency. All statistical analyses were computed in R Studio 1.1.383. All data are reported as mean ± SE. Statistical tests are considered significant if p-value <0.05.

3. Results

The distance between mangrove pneumatophores in 5 mangroves ranged from 0 to 13 cm (N = 55, average 4.5 ± 0.4 cm). A total of 1254 litter items were recorded in the Red Sea, resulting in a density of 0.66 ± 0.18 items m^{-2} (mean ± SE) among transects. Litter densities in the surveyed stations ranged from 0.02 ± 0.01 items m^{-2} in a newly planted mangrove forest with sparse trees 9 km away from Yanbu city to 3.7 ± 1.8 items m^{-2} in a 30 years old natural forest on the Yanbu city shoreline (Fig. 2a; Fig. 3a, b, c). A total of 450 litter items were recorded in the Arabian Gulf, yielding an average of 1.21 ± 0.53 items m^{-2} across transects. We recorded litter densities ranging from 0.22 ± 0.06 items m^{-2} in Safwa to 3.0 ± 2.0 items m^{-2} on Tarout island (Fig. 2b; Fig. 3d, e, f).

The dominant litter type was plastic material on both coasts (Table 4). Main items found in Red Sea mangroves were plastic bottles (23.5% ± 4.8 of items), followed by plastic bags and oil containers, while in the Arabian Gulf forests the most abundant litter were ropes (29.4% ± 13.5%), followed again by plastic bags and food wraps (Table 4). Anthropogenic material of ocean-based origin (i.e. ropes, nets, lines, buoys, oil containers, polystyrene and polystyrene boxes), accounted for 19 ± 2.3% and 41.4 ± 11.35% along the Red Sea and Arabian Gulf Saudi mangroves, respectively.

The GAM for Red Sea transects, testing all drivers considered together, showed that litter density is significantly affected by distance to high intensity maritime traffic areas (p-value < 0.01), distance to the beach behind the mangroves (p-value < 0.001) and by the density of the forest (p-value < 0.01). The GAM including only the significant variables explains 32.2% of the variability and confirms that those 3 variables had statistically significant effects (Table S2). Particularly, the relationship between litter density and distance to high intensity maritime traffic areas is not linear: it is negative in the first 15 km and positive from 15 to 70 Km (Fig. S1). Instead, distance to the beach behind the mangroves has a linear effect on litter density: the closer the transect to the beach, the higher the density (Fig. S1). Besides, transects with high tree densities tended to show higher litter density (N = 29, 1.09 ± 0.42 items m^{-2}) than transects with low tree density (N = 47, 0.4 ± 0.13 items m^{-2}, Mann-Whitney U test, W = 2613.5, p-value < 0.01).

The frequency and distribution of plastic objects differed, based on the mangrove compartment considered and the object properties. Plastic films were more likely to be found associated to pneumatophores and seedlings, while ropes, more easily entangled in the tree branches and trunk, were more abundant in areas near mangrove trunks (Fig. S2a, Chi-square test, $X^2 = 95.02$, df = 7, p-value < 2.2 e^{-16}), a result that is confirmed even when Red Sea and Arabian Gulf transects are considered separately (Table 5). Indeed, given the high variability of objects recorded in the two areas (Table 4), we computed a Chi-square test for each basin. The three tests also confirmed that carboys and non-PET bottles are slightly

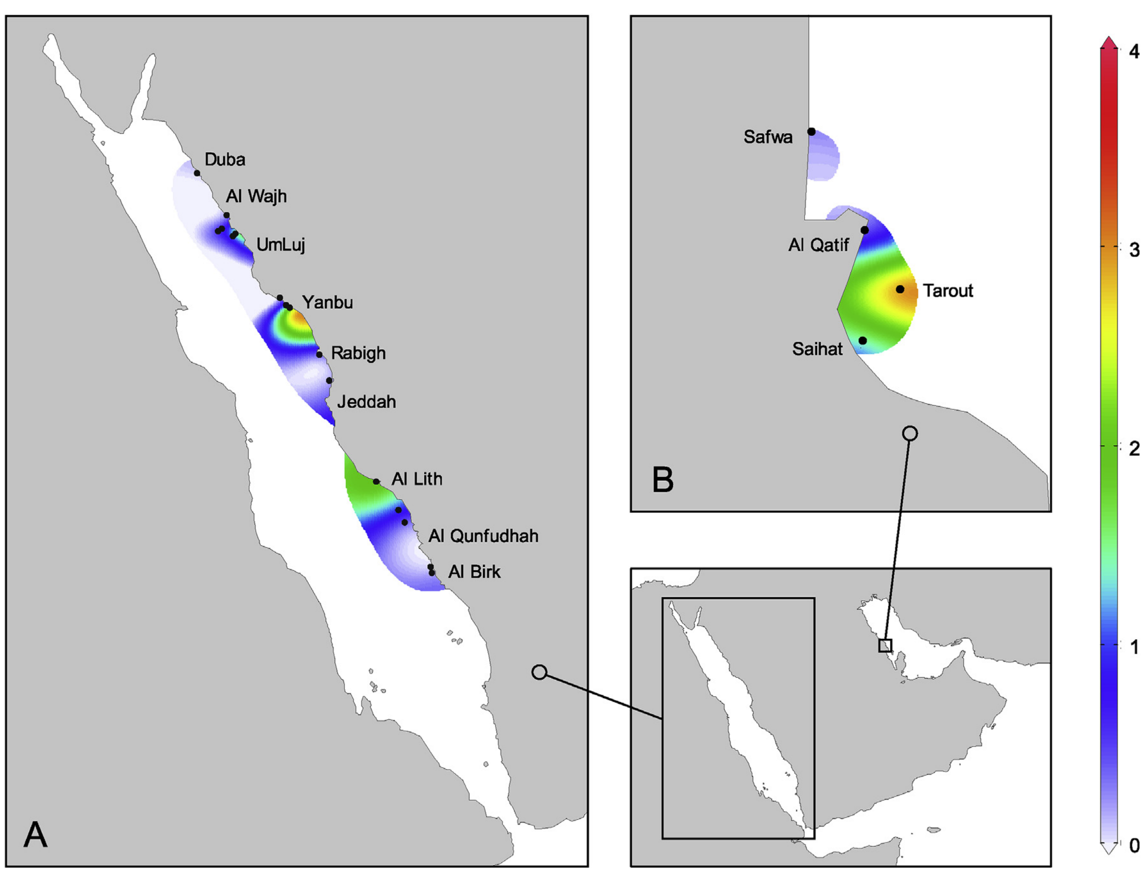

Fig. 2. Density of litter expressed in items*m^{-2} for transects in Red Sea (a) and Arabian Gulf (b) mangrove stands, marked with a black dot.

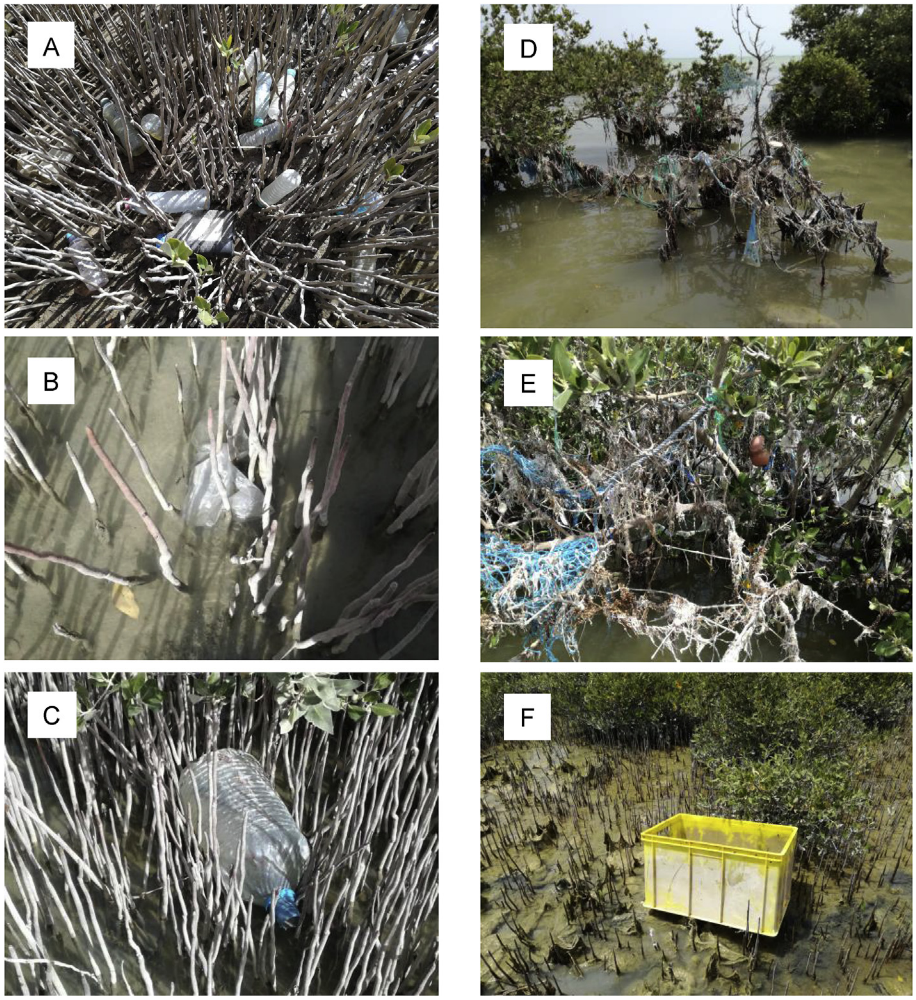

Fig. 3. Pictures of litter in the two most polluted mangrove forests of this study, one in the Red Sea on Yanbu shoreline (23.983 N 38.191 E; a, b, c) and one in the Arabian Gulf on Tarout island (26.549 N 50.080 E; d, e, f). Pictures show objects of various types: bottles (a), an oil container (a), plastic bags (b, d), a carboy (c), ropes and nets (d, e), a buoy (e) and a box (f).

more frequent in pneumatophores and seedlings, while small containers are mainly trapped in trunks and branches (Table 5, Fig. S2b – c; p-values < 5 e¯6). These observations are illustrated by images (Fig. 3), where an oil container, a bag and a carboy are shown trapped in pneumatophores (Fig. 3a, b and c respectively), while ropes are entangled on the branches of a mangrove tree (Fig. 3d).

The comparison between the two Pareto distributions for plastic objects in Red Sea mangroves and beaches respectively shows a significantly steeper decline in abundance with object size for Red Sea beaches compared to Red Sea mangroves (Fig. 4). Particularly, large items, > 50 g in individual weight, were twice as abundant (9.3% ± 1.8% of all items, N = 1018) in mangroves compared to beaches (5.85 ± 1.2 of all items, N = 1553), with these proportions differing significantly ($Z = 3.32$, $p < 0.001$), indicating that mangrove habitats were richer in large-sized litter items compared to beaches. Moreover, we obtained a weighted-mean (±SE) mass of items over two-fold greater for mangrove plastic litter (60.12 ± 9.67 g) compared to Red Sea beach plastic litter (23.97 ± 2.03 g, Mann Whitney test, $W = 7120$, p-value = 0.04).

4. Discussion

The results presented confirm that mangrove forests act as traps for marine litter. Previous surveys on Saudi Arabian Red Sea shores conducted on beaches using the same methodology estimated a litter density of 0.63 ± 0.1 items m^{-2} (Martin et al., 2018) dominated by plastic bottles, similar with our findings in mangrove forests for the same region. Instead, the higher density of litter in mangrove stands of the Arabian Gulf is most probably due to the close vicinity of the 4 surveyed areas to highly traversed maritime routes in the Arabian Gulf. Indeed, although we could not apply a GAM to Arabian Gulf mangroves, the significant influence of distance to high intensity maritime traffic areas demonstrated for the Red Sea suggests that this could also be a main driver of litter distribution in Arabian Gulf stands. This hypothesis is further supported by the higher proportion of ocean-based related litter found in the Arabian Gulf, where high intensity maritime traffic areas are close, compared to the Red Sea, where distances to this source were variable. Further surveys are therefore needed for the Arabian Gulf, particularly in offshore forests, to evaluate this hypothesis and obtain a better estimate of mangrove litter in this basin. However, this could be challenging since the coast of the Arabian Gulf is highly developed and natural or remote stands not directly impacted by anthropogenic activities are scarce (Almahasheer, 2018).

In the Red Sea, the maritime traffic seems to be a direct source of litter in a short range (<15 Km), where, as expected, the closer the

Table 4
Mean contribution (±SE) of each object type to anthropogenic debris found in Red Sea and Arabian Gulf mangroves. All plastic objects types with a relative proportion <0.4% were merged in "Others, plastic items", while "Others, non-plastic items" includes those items that are of composite materials and cannot be univocally included in one object type.

Red Sea (N = 1254)		Arabian Gulf (N = 450)	
Object type	Mean Proportion ± SE (%)	Object type	Mean Proportion ± SE (%)
Plastic	**92.2 ± 1.4**	**Plastic**	**95.5 ± 2.5**
Drink Bottles	23.5 ± 4.8	Ropes	29.4 ± 13.5
Plastic Bags	14.7 ± 3.1	Plastic Bags	15.0 ± 2.9
Oil Containers	6.9 ± 2.2	Food wraps	7 ± 4.5
Food Wraps	5.7 ± 2.1	Drink Bottles	6.9 ± 2
Carboys	5.3 ± 1.6	Polystyrene	4.7 ± 3.4
Tarpaulin Bags	5.3 ± 4.1	Buoys	3.1 ± 2.1
Small Containers	4.6 ± 1.2	Plastic Bags Pieces	3.7 ± 1.6
Ropes	4.1 ± 1.2	Small Containers	2.6 ± 1.0
Polystyrene	4.1 ± 1.3	Nets	2.1 ± 1.0
Boxes	3.9 ± 1.2	Tarpaulin Bags	1.6 ± 0.7
Polystyrene Boxes	1.6 ± 0.6	Lines	1.5 ± 0.5
Fragments	1.3 ± 0.6	Boxes	1.0 ± 0.5
Buoys	1.2 ± 0.6	Fragments	1.0 ± 0.6
Detergent Bottles	0.8 ± 0.5	Cloth	0.7 ± 0.4
Lines	0.7 ± 0.3	Others, plastic items	14.2 ± 4.8
Bottle Caps	0.5 ± 0.2		
Footwear	0.4 ± 0.2		
Nets	0.4 ± 0.3		
Others, plastic items	6.1 ± 1.5		
Wood	**3.2 ± 1.2**	**Aluminium**	**2.5 ± 1.7**
Aluminium	**3.1 ± 0.8**	**Glass**	**1.4 ± 1.4**
Glass	**0.5 ± 0.3**	**Cardboard**	**0.6 ± 0.6**
Cardboard	**0.02 ± 0.02**	**Wood**	**0.5 ± 0.5**
Others, non-plastic items	**0.9 ± 0.5**		

Table 5
Abundance (N) of total plastic objects in each of 8 categories (defined in Table 2) in 6 mangrove forests in the Red Sea and 4 in the Arabian Gulf and relative frequency of total plastic objects ("All") and of objects from each category in two mangroves compartments (pneumatophores and seedlings or trunks and branches) for each of the two basins. When relative frequency of a category in one of the two mangroves compartments (observed frequency) is higher than the relative frequency of total objects in that compartment (expected frequency), objects of that category are more likely to be found in that compartment and *viceversa*.

Categories	Red Sea			Arabian Gulf		
	N	Relative frequency in pneumatophores and seedlings	Relative frequency in trunks and branches	N	Relative frequency in pneumatophores and seedlings	Relative frequency in trunks and branches
All	495	0.4	0.6	394	0.13	0.87
PET bottles	114	0.28	0.72	24	0.42	0.58
Other bottles	37	0.54	0.46	6	0.17	0.83
Carboys	37	0.54	0.46	2	0.5	0.5
Films	185	0.5	05	128	0.24	0.76
Ropes, lines, nets	68	0.24	0.76	204	0.02	0.98
Big containers	23	0.13	0.87	4	0.5	0.5
Small containers	10	0.3	0.7	9	0.1	0.9
Polystyrene	21	0.52	0.48	17	0.12	0.88

distance of the stand to a highly traversed maritime route, the strongest the impact of this source on litter densities. However, the unexpected result for distances >15 Km suggests the concomitant role of currents in delivering litter of ocean-based origin in the mangrove forest. Indeed, the GAM showed that distance to high intensity maritime traffic areas has its strongest influence on litter distribution in mangroves when routes are at approximately 70 Km from the stand. The horizontal surface water circulation in the Red Sea is mainly characterized by mesoscale currents, alternant cyclonic and anticyclonic eddies with an approximate dimension of 50–130 Km (Zhan et al., 2014), potentially justifying how litter originated from ocean-based activity accumulates in mangrove forests at 70 Km of distance.

Land-based sources instead had no significant influence on litter distribution in the Red Sea, although the most polluted mangrove stand was the only one located on the shore of a town. This result reflects the low development of the Red Sea coast, where cities and towns are scarce and the coastal population accounts for only approximately 6 million people, 2.8 million of them living in one city, Jeddah (data obtained from http://worldpopulationreview.com/ and http://www.citypopulation.de/). Moreover, the Red Sea catchment area lacks permanent rivers, which are responsible for major emissions of litter in the marine environment from inland elsewhere (Lebreton et al., 2017). Differently, maritime traffic is uniformly developed in all the basin, particularly in the central axis, which is one of the most trafficked routes worldwide (Tournadre, 2014). Therefore, it is no surprise that our analysis demonstrated ocean-based sources to be more important than land-based sources as drivers of litter distributions in mangrove stands of the Red Sea. This hypothesis is also confirmed in previous beach litter surveys conducted in the Red Sea, where passenger and cargo ships were identified as major sources of anthropogenic debris (Abu-Hilal and Al-Najjar, 2004).

The finding that ocean-based activities are major drivers of litter in the Red Sea also helps explain why litter density estimated for mangrove forests of the Red Sea are lower than those of stands in

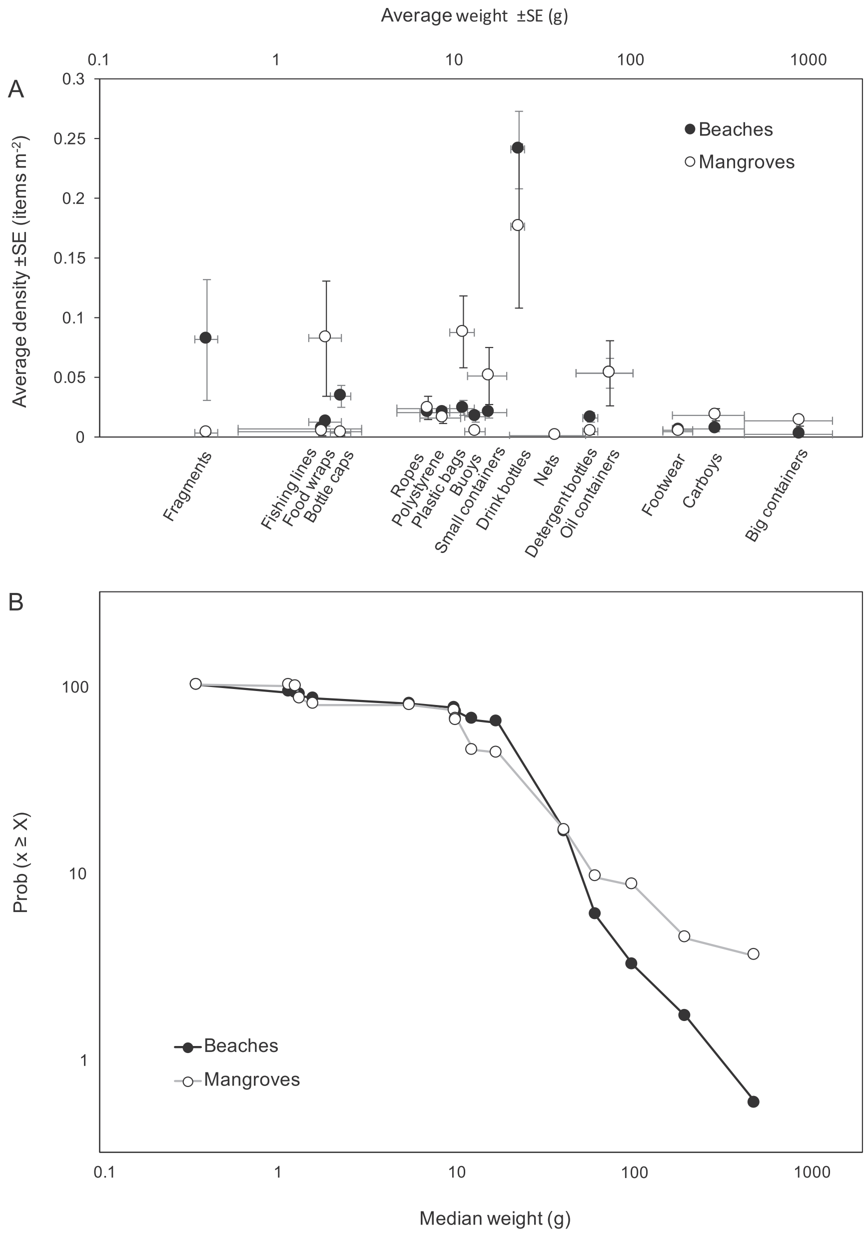

Fig. 4. Distribution of plastic objects in the 16 most frequent types, ordered per weight, found on beaches (data from Martin et al., 2018, in black, N = 1553) and mangroves (in white, N = 1018) in the Red Sea. (a) Average weight and density (±SE) of objects belonging to the 16 most frequent types. (b) Pareto distribution of plastic objects of the 16 most frequent types found in beaches (black dots and black line) and mangroves (white dots and grey line).

Papua New Guinea (1.2 ± 0.3 to 78.3 ± 15.1 litter items m^{-2}, Smith, 2012) or Brazil (1.33 items m^{-2}, Cordeiro and Costa, 2010), which were located closer to inhabited areas and where land-based activities were recognized as major sources of anthropogenic debris. While litter densities reported in Cordeiro and Costa (2010), although generally higher, are still within the range of those of the most polluted mangroves in our study, Smith (2012) reported litter densities up to two orders of magnitude higher in Papua New Guinea mangroves. These findings might be related to the fact that Papua New Guinea is located close to those countries releasing the highest loads of land-based plastic waste in the marine environment (Jambeck et al., 2015).

Although land-based activities are not significant drivers of litter in Red Sea mangroves, distance from the back of the beach is. This suggests that mangroves are likely to trap litter before it is dispersed in the marine environment or, if litter from the marine environment can reach the beach, it hardly will be washed again ashore in presence of a mangrove forest. Generally, litter stranded on a beach is transported back to the marine environment by winds and once in the water by currents. However, in presence of a mangrove stand, litter is blocked before it can reach the water. Therefore, mangroves appear to be efficient barriers against redistribution of litter in the marine environment by wind and wave action.

The category “film” (including plastic bags, tarpaulin bags and food wraps as reported in Table 3) was the most frequent in Red Sea mangroves (Table 5, Fig. S2). Similarly, Cordeiro and Costa (2010) identified plastic bags and food wraps as major contributors of plastic pollution in mangroves. Indeed, plastic bags were identified as the objects more easily retained in a mangrove forest in the experimental release study by Ivar do Sul et al. (2014), which explains the high abundance of these items in our study and supposedly in Cordeiro and Costa (2010) study. In Red Sea mangroves, litter density recorded in transects with high tree density was almost three times higher than that in transects with low tree density, suggesting that dense mangrove stands have a higher retention capacity, as also proposed by Ivar do Sul et al. (2014). Among the few debris items counted in waters where pneumatophores and seedlings rise, the main contributors were again films and they were proportionally more frequent than near tree trunks and branches. Aerial roots form a less intricate structure than the branch network, and therefore many object types are less trapped in pneumatophores; however, films, which are flexible and have a high surface to volume ratio, can easily wrap around any interface. Moreover, films tend to sink (Ivar do Sul et al., 2014), while floating objects like bottles could more easily escape the system of seedling transported by currents or changing tide. Tides have been proposed to be an important factor influencing the interaction of debris with mangroves (Ivar do Sul et al., 2014). Tidal ranges in the Red Sea are smaller, average ~0.5 m (Aramco, 2018), than those in the Arabian Gulf, > 1 m (Reynolds, 1993), which may also contribute to the lower loads of marine litter in Red Sea, compared to Arabian Gulf mangroves. In our study, carboys were more frequent near roots and seedlings, probably because they are transported close to the mangroves during high tide and then retained during low tide by pneumatophores. However, because of their big size, they cannot penetrate the dense network of tree trunks and branches. Small containers instead, are not easily found in the water surrounding the mangroves, because either they are not retained by aerial roots, which are widely spaced (up to 13 cm), and get dispersed again in the marine environment, or they penetrate through the branching structure and are then trapped further inside the mangrove forest. Ivar do Sul et al. (2014) findings corroborate this hypothesis when observing that margarine tubs, also small containers, were not retrieved in the delimited studied area at the end of the experiment.

While the density of anthropogenic debris retained in mangrove stands is similar to that estimated for beach litter in the Red Sea, we demonstrated that in mangroves there is a higher frequency of large-sized objects, which, given the above results and conclusions, could be due to the presence of the pneumatophores acting as a filter in mangrove forests. Moreover, on sandy shores, larger plastic items are more easily dispersed away by strong winds, while, as pointed out earlier, the mangrove forest itself constitutes a barrier against litter dispersion by winds, further explaining the higher frequency of large plastic objects in mangroves compared to beaches. The difference in frequency of large objects among the two environments might be also due to higher plastic fragmentation rates on beaches due to stronger winds and exposure to sunlight than in mangrove stands. However, although fragments were indeed more frequent on beaches than in mangroves, their abundance did not explain the difference in large items frequency between the two environments (Fig. 4). For all these reasons, we conclude that a higher mass of plastic is trapped in mangroves compared to sandy shores.

In summary, our results support the hypothesis that mangroves act as sinks for marine plastic litter as well as a barrier for anthropogenic debris before they are dispersed in the marine environment. Our findings support previous suggestions that mangroves retain floating debris based on their properties and that pneumatophores act as a filter, preventing objects of big size, advected into the mangroves by tidal currents and waves, to be again dispersed in the marine environment. These results, for mangrove stands in the arid Arabian Peninsula, should provide impetus to examine the role of mangroves elsewhere, particularly in the wet tropics where mangrove forests are extensive and highly developed. Most importantly, this study is a further demonstration of the urgency to reduce plastic consumption and dispersion in the environment given its ability to reach even remote environments and, once there, settle for long times.

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2019.01.067.

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