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Spatial variation of plastic debris on important turtle nesting beaches of the remote Chagos Archipelago, Indian Ocean

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ABSTRACT

We report Anthropogenic Marine Debris (AMD) in Chagos Archipelago in the Indian Ocean, globally amongst the most isolated island groups. AMD on 14 island beaches in five atolls were surveyed in 2019 using two techniques: Marine Debris Tracker (MDT) along littoral vegetation and photoquadrats in open beach. Over 60 % of AMD in both beach zones was composed of plastics, especially bottles and fragments (mean = 44.9 %, 27.2 %, range = 16.5–73.2 %, 4.8–55.9 % respectively in vegetation; mean = 28.7 %, 31.5 %, range = 17.7–40.7 %, 11.6–60.0 % respectively in open beach). The density of plastic debris in littoral vegetation (MDT data: 1995 bottles, 3328 fragments per 100 m^2) was 10-fold greater than in open beach (photoquadrat data: 184 bottles, 106 fragments per 100 m^2). Significant latitudinal variation in vegetation AMD occurred (8-fold greater in southern atolls, $p = 0.006$). AMD varied within island zones: most debris observed on oceanside beaches (oceanside vs lagoon, $W = 365$, $p < 0.001$; ocean vs island tip, $W = 107$, $p = 0.034$). Standardisation of surveys using the open-source MDT App is recommended. Debris accumulation hotspots overlapped with sea turtle nesting habitat, guiding future beach clean-up prioritisation.

1. Introduction

Anthropogenic marine debris (AMD) is accumulating along coasts across the world, and whilst AMD includes metal and lumber, plastic represents 75 % of all AMD (Pieper et al., 2019). Approximately 4.8–12.7 million metric tons of plastic waste entered the world's ocean in 2010, predicted to increase by an order of magnitude by 2025 (Jambeck, 2015), with 4 million metric tons of accumulated microplastics estimated on the oceans' surface by 2050 (Lebreton et al., 2019). The longevity of plastics in the natural environment, including mass produced single-use plastics and poorly discarded multi-use plastics, makes them extremely damaging to coastal and marine ecosystems; and, even after breaking down, plastic fragments persist in aquatic environments for decades (Andrady, 2015; Lebreton et al., 2019; Napper and Thompson, 2020).

Between 2.8 and 18.6 % of coastal plastic emissions are dispersed via river transport, with an estimated 1.2–2.4 million metric tons arriving in the ocean every year from the global riverine system (Lebreton et al., 2017). The exponential increase in ocean plastic pollution has led to accumulation of AMD at 'sink' sites (Borrelle et al., 2020) in remote areas, for example the Great Pacific Garbage Patch is estimated to contain 4–16 times more AMD than previously recorded (Lebreton et al., 2018). There is mounting evidence that all levels of the marine ecosystem are negatively impacted by AMD. Impacts include physical accumulation on coastlines (Laist, 1997; Fazey and Ryan, 2016), increased transport of biofouling organisms (Lavers and Bond, 2017), and increasing rates of coral diseases (Lamb et al., 2018). Coastal ecosystem health may also be affected. For example structurally complex biota such as sponges or corals are smothered by plastic (Smith and Edgar, 2014) and marine vertebrates ingest or are entangled in plastic

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(Kühn and van Franeker, 2020; Browne et al., 2015; Rochman et al., 2016). Once onshore, plastic debris can cause entanglement and obstructions for beach fauna such as hermit crabs (Lavers et al., 2020) and nesting or hatchling sea turtles (Aguilera et al., 2018; Nelms et al., 2016; Martin et al., 2019).

The biological impacts of AMD are widely recognised; records of species impacted by AMD have increased by 50 % in two decades (Gall and Thompson, 2015). Entanglement or ingestion have been recorded in 914 marine species including 41 % of tubenose seabirds (Kühn and van Franeker, 2020), and 65 % of 494 examined fish species, including 67 % of 391 commercial fish species (Markic et al., 2020). Microplastics have been detected at tissue level in zebrafish *Danio rerio* (De Sales-Ribeiro et al., 2020) and in neonate sea turtle tissue (Rice et al., 2021). Population-scale impacts of plastic ingestion have been observed when malnutrition, starvation and ill-health negatively impact survival and reproductive success (Kühn et al., 2015; Lavers et al., 2014). Scavenging behaviour, an adaptive foraging strategy in most marine ecosystems, increases the likelihood of plastic ingestion and is a key explanation for widespread plastic ingestion by marine animals (Andrades et al., 2019). Sea turtles exhibit a diet preference for plastic debris which resembles principal dietary items, such as plastic bags that represent jellyfish for leatherback turtles (*Dermochelys coriacea*), although ingestion may also be due to indirect consumption through trophic transfer (Orós et al., 2021; Duncan et al., 2019). Ultimately, flexible plastic is the main cause of debris-related death in marine megafauna due to gastric obstruction with plastic bags, packaging, balloons and discarded fishing gear being disproportionately lethal compared to other AMD (Roman et al., 2021; Bond et al., 2021).

Marine-based sources of debris, such as fishing gear, can be the largest contributor to coastal debris accumulation (Lavers and Bond, 2017) on oceanic islands and undeveloped continental beaches (Burt et al., 2020), with an estimated loss in 2017 of 5.7 % of all fishing nets and 29 % of all lines worldwide (Richardson et al., 2019). Broader impacts of abandoned, lost or otherwise discarded fishing gear (ALDFG) include entanglement and associated injuries. For example, all sea turtle species have been associated with gear entanglement (Kühn and van Franeker, 2020), which is known to cause skin infections, septic infections and leg amputations (Kühn et al., 2015). ALDFG can also create complications for foraging and breathing processes (Wabnitz and Nichols, 2010) by restricting the passage of food (Udyawer et al., 2013), or impairing jaw movement and gill ventilation (Sazima et al., 2002). Ghost fishing is a direct consequence of ALDFG, where the discarded or lost gear continues to fish marine organisms (Gilman et al., 2016; Beneli et al., 2020), impacting megafauna and smaller species. For example, crabs and octopuses become trapped in derelict fishing traps, that subsequently cause death through stress, injuries or starvation (Antonelis et al., 2011; Cho, 2011; Stelfox et al., 2016, 2019).

Remote islands have become significant sinks for global waste (Lavers and Bond, 2017), and such an area was chosen as the subject of this study. The Chagos Archipelago in the equatorial Indian Ocean forms one of the world's most isolated regions and has been protected as a Very Large Marine Protected Area (VLMPA; an area exceeding 100,000 km^2) and as an IUCN management category 1a strict nature reserve (Day et al., 2019) by the British Indian Ocean Territory (BIOT) since 2010, with no permitted fishing. At the same time, the legality of this MPA has been challenged (Appleby, 2015; United Nations, 2019). The MPA is recognised as an important site for conservation and includes a range of habitats with deep oceanic areas surrounding the shallow reef environments and reef islands (Sheppard et al., 2012). The Chagos Archipelago provides beaches for increasing numbers of regionally significant nesting populations of hawksbill (*Eretmochelys imbricata*) and green turtles (*Chelonia mydas*) (Mortimer et al., 2020). It is thus important to understand the full extent of the AMD problem across different habitats for turtles as they are particularly vulnerable to both entanglement and ingestion (Duncan et al., 2019; Clukey et al., 2017). Considering the importance of the Archipelago as a nesting refuge for green turtles from across the Western Indian Ocean (Hays et al., 2014, 2020), coastal accumulation of high quantities of AMD could have implications on sea turtle nesting and hatchling emergence success.

The direct and indirect effects of AMD on marine wildlife, even in isolated areas of ecological importance, underpin the importance of understanding the scale and spatial variation of the AMD problem facing turtle nesting sites (Nelms et al., 2016). Greater understanding will facilitate coastal conservation efforts and beach clean-up strategies. This study aims to (a) trial two standard AMD sampling methods in a remote island context; (b) categorise AMD on nesting beaches of the Chagos Archipelago; and (c) assess spatial variation in AMD accumulation. Consequent understanding of AMD and its variation across the Chagos Archipelago will inform beach management approaches to mitigate the impact of AMD on wildlife, particularly sea turtles.

2. Materials and methods

2.1. Study sites

Five islanded atolls and several submarine banks and atolls form the Chagos Archipelago in the equatorial Indian Ocean (Fig. 1). Diego Garcia (DG) is the only inhabited atoll with a semi-enclosed shallow lagoon, accounting for > 50 % of land area with 72 km coastline. The Great Chagos Bank (GCB) is the largest living coral atoll structure worldwide with eight islands forming 33 km of coastline along its rim. In contrast, the Egmont Islands (EI) form the smallest atoll with five to eight dynamic islands forming 23 km of coastline around a semi-enclosed shallow lagoon. Peros Banhos (PB) and the Salomon islands (SI) are large, well-formed circular atolls with shallow lagoons in the north: PB has 36 islands with 81 km of coastline, whereas SI has 11 islands and 26 km of coastline (Mortimer et al., 2020). Of these atolls, one island was surveyed from DG, one from GCB, four from EI, five from PB and three from SI.

All surveys took place above the strand line (representing the most recent High Water Level (HWL) mark) on sandy beaches that are used by hawksbill and green turtles as nesting sites (Mortimer et al., 2020) and included three island zones (oceanside beaches on the outside of atolls, lagoon-side beaches and island tips, defined as the end of the island where the lagoon and ocean-side beaches converge, forming a spit). Surveys were limited to ocean-side beach zones on Diego Garcia (nesting does not occur lagoon-side or on island tips) and Nelson's Island (classified as a table reef without lagoon on the submerged Great Chagos Bank, Goldberg, 2016). To assess effect of relative beach location on AMD accumulation, sampling included (where present) beaches on each side of atoll islands. The category of each survey location (oceanside, lagoon-side, island tip) was confirmed by plotting coordinates on Google Earth (version 7.3.3.7786).

2.2. Data collection techniques

Photoquadrat sampling took place between the vegetation line, found above the high tide mark where frequent tidal movement cannot disturb vegetation growth, and the strandline, on sandy beaches of 12 islands (SI Table 1). Four or five 100 m^2 plots (10 m × 10 m or equivalent surface area depending on available beach width) were set out on available nesting beach area and equally distributed around each island coastline where possible. For each plot, corner coordinates, date, time and recorder were noted. 20 photoquadrats were taken per plot by throwing a 50 × 50 cm quadrat as randomly as possible within the plot and taking a photo facing straight down ensuring the quadrat frame was within each photo. The sampling method required the quadrat to lie flat onto the sand, so it was not possible to sample beyond the vegetation line, where quadrats would become entangled.

Transect sampling took place at nine islands (SI Table 1) for 1 m either side of the vegetation line using a citizen science open source app, the Marine Debris Tracker (MDT) App (NOAA, 2010) allowing for

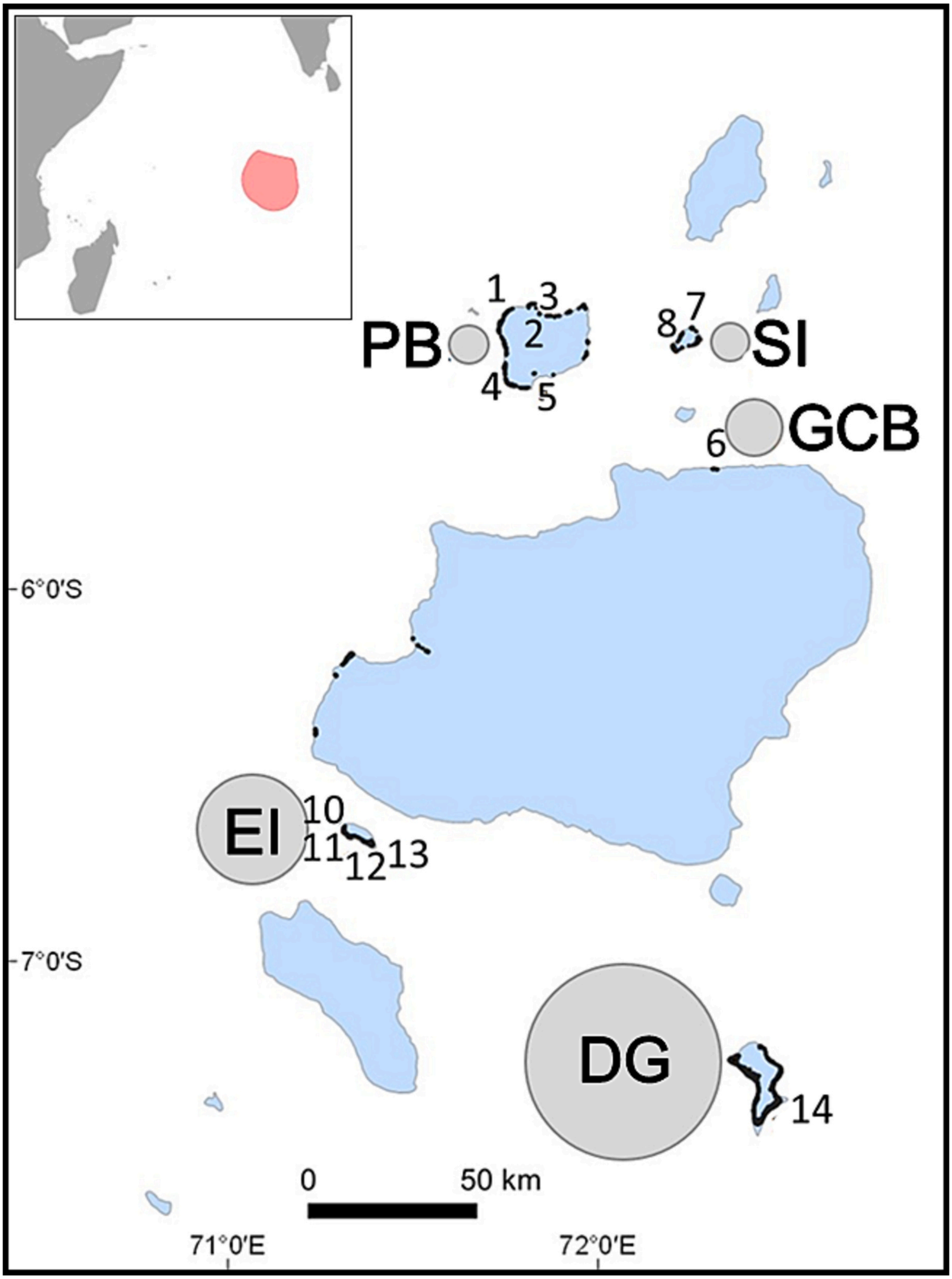

Fig. 1. Debris accumulation was significantly greater in the southern atolls of Chagos Archipelago where > 80 % was recorded in Diego Garcia (DG) and Egmont Islands (EI). Lower accumulations were found on smaller islands in the Great Chagos Bank (GCB), Peros Banhos (PB) and Salomon Islands (SI). Inset: Chagos Archipelago MPA (red shading) within the Western Indian Ocean. AMD % distribution per atoll indicated by grey circles using Marine Debris Tracker App data. Black lines indicate land, blue shading indicates waters shallower than 100 m. Numbers indicate surveyed beaches: 1. Moresby, 2. Parasol, 3. Île Longue, 4. Île Coin, 5. Île Vache Marine, 6. Nelson's Island, 7. Mapou, 8. Île Passe, 9. Boddam, 10. Île Des Rats, 11. Île Sipaille, 12. Île Lubine, 13. Île Sudest, 14. Diego Garcia. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Map adapted from Hays et al., 2020.

georeferenced and categorised debris item logging in situ. The survey area was a 2 × 100 m belt transect. Three transects were recorded on each island, separated by a minimum of 100 m. One individual per survey logged the AMD present on the site, assisted by others who pointed out the debris. AMD were counted if visible to those collecting the data, so excludes microplastic or buried AMD. For each item logged, the MDT App recorded GPS location, material/origin (plastic, metal, glass, paper and lumber, cloth, fishing gear, rubber, mixed or other) and category (e.g., bottle, bag, buoy; SI Table 2). Material was defined using categories set by the National Oceanic and Atmospheric Administration (NOAA).

Each MDT transect survey took 20–40 min (depending on quantity of items) whilst each photoquadrat plot took about 30 min to layout and record. MDT App data were not collected on some islands due to technical difficulties with remote use of the App.

2.3. Statistical analyses

Photoquadrat images, based on a technique developed in the Philippines (Panes, H. and Patel, S., pers. comm.), were analysed individually to assess the quantity, type and percent cover of debris. We used ImageJ (Rueden et al., 2017) to analyse and extract metrics for AMD recorded in photoquadrats. We categorised items by material/origin (paper, plastic, glass, metal, rubber, cloth, fishing gear, mixed, other or unknown) and colour and further allocated each item to a list of 26 items, using NOAA categories provided in the MDT app (SI Table 2). We then calculated the surface area of each item of debris by multiplying the item's length and width, which were measured using ImageJ calibrated with the known length of the photoquadrat. AMD cover data were nonparametric. Variations between atolls and islands were analysed using a Wilcoxon Rank sum test with Bonferroni correction.

MDT App data were downloaded from the App into a .csv file. Frequency of occurrence and density of AMD were compared using photoquadrat and MDT App datasets between atolls, islands and beach zone (oceanside, lagoon-side, island tip) using Kruskal-Wallis chi-squared analysis. All statistical analyses were conducted using R version 4.0.3 (R Core Team, 2020).

3. Results

AMD accumulation on turtle nesting beaches was recorded along the littoral vegetation on nine islands and in open beach areas on 12 islands across the five islanded atolls of the Chagos Archipelago between March–June 2019 (SI Table 1). Using the MDT App, we recorded 15,960 pieces of AMD along the vegetation line with over 80 % in southern atolls (50.8 % in DG, 30.6 % in EG) compared with northern atolls (7.6 % in GCB, 5.9 % in PB and 5 % on SI) (Fig. 1). Debris accumulation in open beach areas was much lower with 604 items recorded ($n = 860$ quadrats; 43 plots) using photoquadrats. Debris accumulation along the littoral vegetation was significantly greater in southern atolls (DG and EI) than in the north (PB and SI) (MDT: $t = -3.152$, df = 15.3, p-value = 0.006) whilst higher debris accumulation occurred in open beaches in

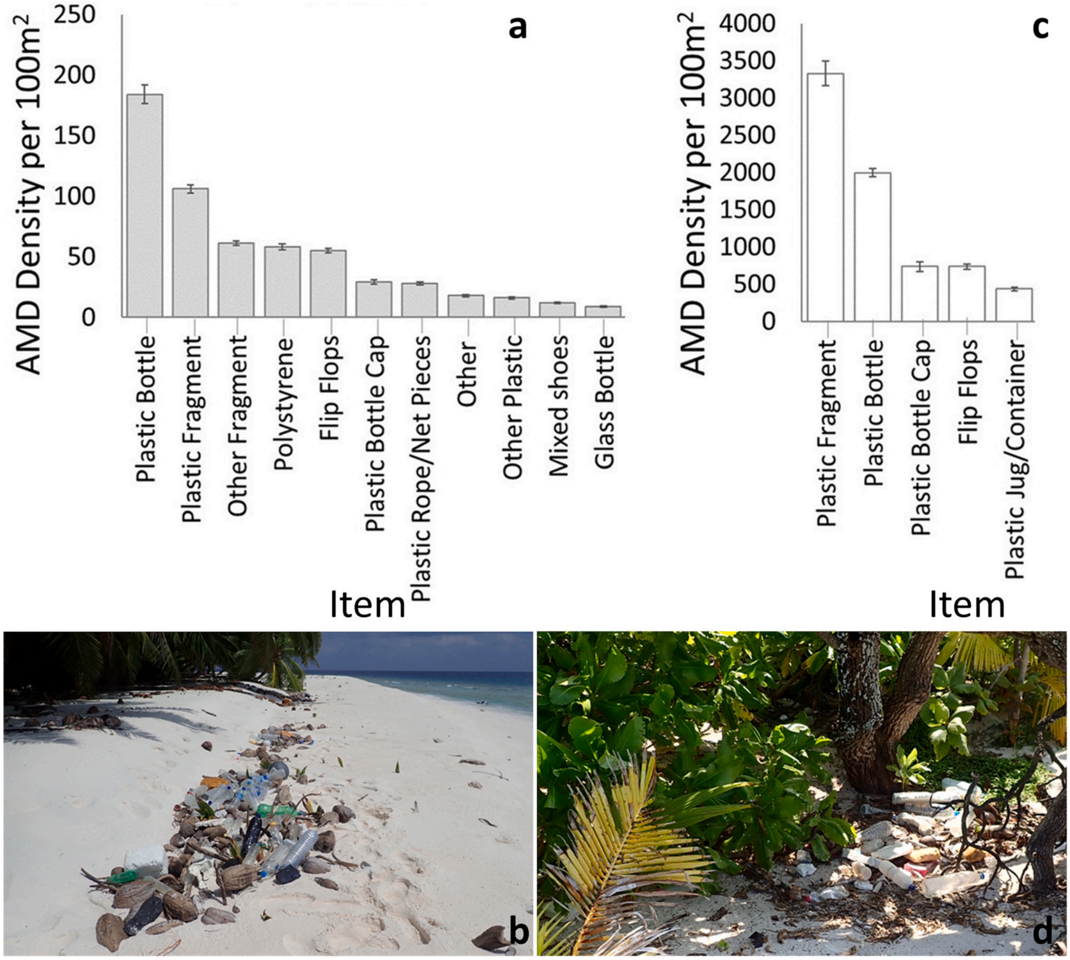

Fig. 2. Plastic items (especially bottles and fragments) dominated marine debris on sandy beaches above the strandline on all atolls of the Chagos Archipelago. (a–b) A ten-fold lower debris density was recorded in open beach areas (184 bottles, 106 fragments per 100 m^2, $n = 860$ photoquadrats, 43 plots, 12 islands) compared with (c–d) debris along littoral vegetation (3328 fragments, 1995 bottles per 100 m^2 with Marine Debris Tracker App, $n = 27$ transects, 9 islands). Categories representing < 0.5 % AMD excluded (see SI Table 2). Note variation in the y-axis scale. Error bars indicate standard deviations.

the northern atolls of PB and SI (photoquadrat: $t = 6.485$, df = 424.5, p-value < 0.001).

3.1. Material and item type

Plastics dominated the marine debris above the strand line in terms of density, regardless of sampling technique (Fig. 2). Significant variation in density of item categories occurred in both beach zones (Open Beach photoquadrats: Kruskal-Wallis, H(34) = 1426.9, $p < 0.001$; Littoral vegetation MDT: H(27) = 102,220, p < 0.001). Plastic fragments (42 % of total AMD) and plastic bottles (30 % of total AMD) were the most frequently occurring item types along the vegetation line and in open sand respectively. On every atoll, the most frequently occurring AMD material type was plastic (Fig. 3), dominated by plastic bottles and plastic fragments (mean MDT = 44.9 %, range = 16.5–73.2 %, sd = 20.8 %, mean photoquadrat = 28.7 %, range = 17.7–40.7 %, sd = 9.3 % and mean MDT = 27.2 %, range = 4.8–55.9 %, sd = 16.9 %, mean photoquadrat = 31.5 %, range = 11.6–60.0 %, sd = 19.2 % respectively).

Plastic debris recorded by photoquadrats on open sand varied significantly from other debris types on four atolls: SI (H(8) = 122.73, $p < 0.001$), PB (H(8) = 323.63, p < 0.001), GCB (H (8) = 85.84, p < 0.001) and EI (H(8) = 295.2, p < 0.001) but not for DG (f = 1.486, $p = 0.169$). Likewise, plastic debris recorded by the MDT App along the vegetation line varied significantly with the other items on four atolls: SI (Wilcoxon Rank Sum Test, W = 1282, $p = 0.001$), PB (Wilcoxon Rank Sum Test, W = 26,200, p < 0.001), GCB (Wilcoxon Rank Sum Test, W = 5700, p < 0.001) and EI (Wilcoxon Rank Sum Test, W = 53,700, p = 0.001), but not for the largest island DG where plastic and fishing gear accounted for almost 20 % of marine debris.

3.2. AMD variation across island zones (oceanside, island tip, lagoon-side)

Plastic was the most dominant material type collected across all three of the zones regardless of collection technique: plastic bottles and plastic fragments were the dominant item along the vegetation line (Fig. 4). After plastic, rubber (13 % of AMD) and fishing gear (9 % of AMD) were the next most frequently occurring debris. Plastic represented 78 % of debris on the oceanside beaches (in open sand and along vegetation line), followed by rubber (10 % photoquadrat, 7 % MDT App). Plastic and rubber abundance varied significantly (photoquadrat: Wilcoxon Rank Sum Test, W = 378, $p < 0.001$, MDT App: Wilcoxon Rank Sum Test, W = 81, $p < 0.001$). At island tips, plastic contributed to 67 % of AMD on open beach (photoquadrats) and 77 % along vegetation lines (MDT App) respectively. Finally, plastic also represented the dominant material type on the lagoon-side beaches at 59 % for both data collection methods. Rubber was the second most frequently occurring debris type and varied significantly from plastic (photoquadrats: 13 %, Wilcoxon Rank Sum Test, W = 378, p < 0.001; MDT App: 7 %, Wilcoxon Rank Sum Test, W = 161.5, p < 0.001).

Marine debris distribution varied by survey type, i.e., debris accumulation varied between the vegetation line and open sand. Along the vegetation line 84 % of AMD (MDT App) occurred on oceanside beaches, whilst only 7 % and 9 % occurred on the tip and lagoon-side respectively. In contrast, on open sand, 48.5 % of all AMD recorded by photoquadrats was located on lagoon-side beaches, whilst 29 % and 22.5 % were found on the oceanside and island tip respectively.

Plastic bottles, followed by plastic fragments, were the dominant item types for all zones and both methods, except for ocean-side beaches (MDT App) where plastic fragments dominated. Variation between plastic bottles and fragments was statistically significant on lagoon-side beaches (Wilcoxon Rank Sum Test, W = 362, $p < 0.001$; W = 1475, p < 0.001) and oceanside beaches (Wilcoxon Rank Sum Test, W = 77.5, p < 0.001; W = 6761, p < 0.001) for the photoquadrat and MDT App data respectively. Significant variation between plastic bottle and plastic fragment contribution occurred at island tips for MDT App (Wilcoxon Rank Sum Test, W = 64,888, $p < 0.001$) but not photoquadrat data (W = 168, $p = 0.373$).

3.3. AMD cover

AMD percent cover on open sand varied significantly between atolls (Fig. 5a; H (4) = 119.46, $p < 0.001$). AMD cover did not vary significantly between the most northerly atolls (PB and SI; w = 164, $p > 0.05$) where AMD covered > 3 % of the beach surface. Median AMD cover was lowest at the southerly atolls, in particular DG which varied significantly from all atolls (PB: Wilcoxon Rank Sum Test, w = 5, $p < 0.001$; SI: Wilcoxon Rank Sum Test, w = 1, p < 0.001; GCB: Wilcoxon Rank Sum Test, w = 319, $p = 0.004$; EI: Wilcoxon Rank Sum Test, w = 13, p < 0.001). The southern atoll of EI was also significantly different from all other atolls (PB: Wilcoxon Rank Sum Test, w = 13, $p = 0.006$; SI: w = 34, p < 0.001; GCB: w = 33, p < 0.001).

Significant intra-atoll variation in percent cover AMD was evident on atolls where multiple islands were surveyed (Fig. 5b; Kruskal-Wallis, H (11) = 180.78, p < 0.001). The highest median percent cover occurred on three islands (Ile Passe and Boddam in SI, Ile Coin in PB) but variation was not significantly different. It was not possible to analyse percent cover of AMD along the vegetation line using MDT App data.

4. Discussion

High rates of AMD accumulation were recorded at every sandy beach surveyed across four uninhabited and one inhabited atolls of the Chagos Archipelago, an isolated island group and one of the world's largest no-take MPAs (Hays et al., 2020). Plastics were by far the dominant debris, in particular bottles and fragments, representing > 70 % of AMD. Our finding that plastic was the most frequently occurring debris material is consistent with debris accumulation recorded at beaches in densely populated regions such as India (Daniel et al., 2020) and China (Pervez et al., 2020), as well as isolated islands and regions, such as the Galapagos (Jones et al., 2021), the Pitcairn Islands (one of the world's largest MPAs and comparable to the Chagos Archipelago; Ryan and Schofield, 2020) and the Arctic (Bergmann et al., 2017a). Small island states accumulate large quantities of the world's ocean plastics, with similar proportions of plastics in AMD reported elsewhere in the Western Indian Ocean where densities of 0.44 kg per m^2 of coastline have been removed (Aldabra Atoll; Burt et al., 2020). Our study contributes to the under-researched literature base of plastic pollution in remote locations with low accessibility, increasing the understanding of the large scale of debris accumulation on islands that are not generating plastic at a local level.

We found that plastic bottles and plastic fragments were consistently the most abundant AMD above the strandline reflecting results from other remote rural beaches (Gómez et al., 2020; Yin et al., 2020). AMD density varied significantly between open sand and vegetation, and was ten-fold higher in beach vegetation, indicating that debris was likely to accumulate and remain long-term once it crossed the vegetation line. The littoral vegetation found across the archipelago, specifically on sea turtle nesting beaches, consists of a range of shrubs and trees such as scaevola (*Scaevola taccada*), bay cedar (*Suriana maritima*), beach heliotrope (*Argusia argentea*) and coconut palm (*Cocos nucifera*), that vary in height and shrub density (Esteban et al., 2016). Complex beach morphologies have caused high AMD accumulation rates (Viehman et al., 2011). This could explain why these low-lying, sandy, coral reef atoll islands accumulated high densities of AMD if the littoral vegetation adjacent to sea turtle nesting sites has a greater propensity to amass debris. The greatest proportion of debris accumulation also occurred on sandy, uninhabited island beaches in the Caribbean (Schmuck et al., 2017).

Our findings that AMD tended to be found on oceanside coastlines were not unexpected; oceanside beaches are more exposed to the open ocean, which is the proximal source of the AMD. Buoyant AMD is highly

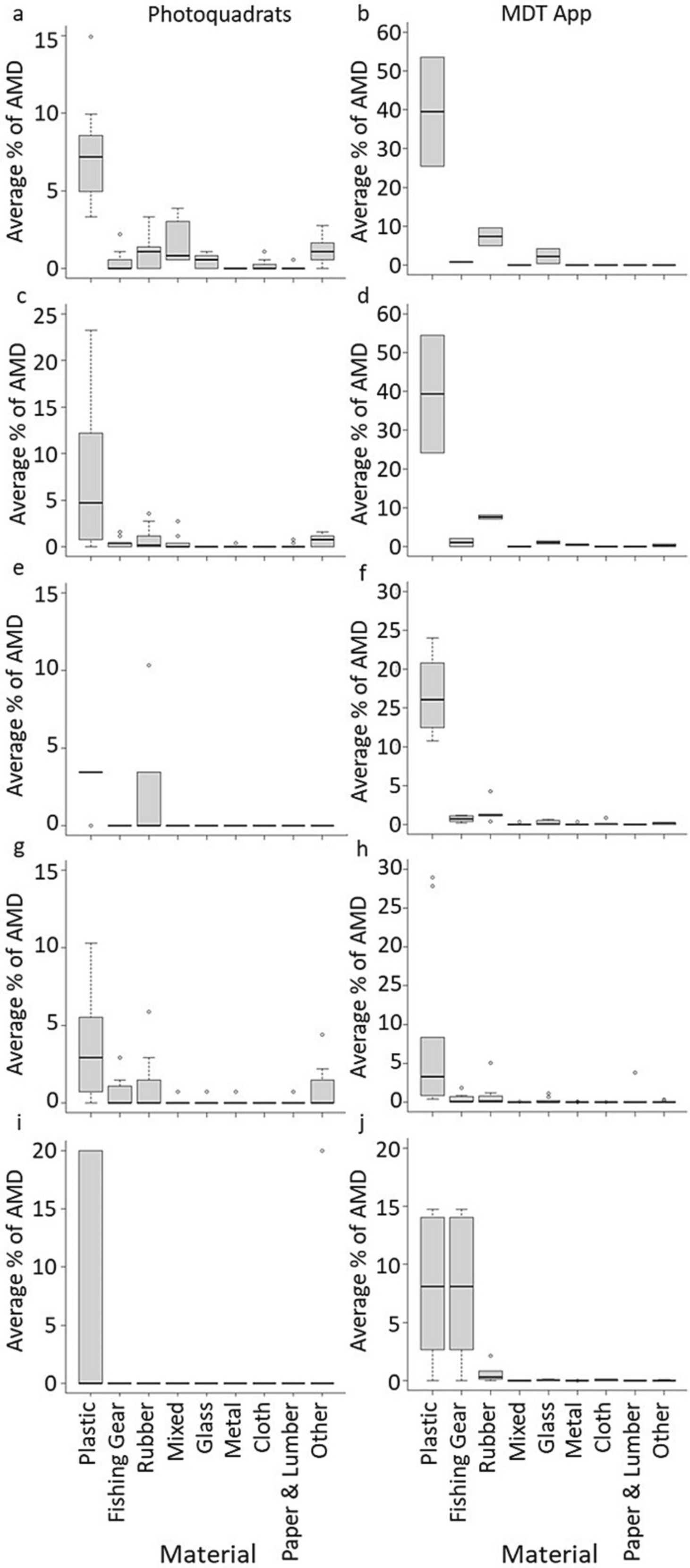

Fig. 3. Regardless of beach zone and sampling technique, plastic was the dominant debris type recorded on all atolls of the Chagos Archipelago (left: photoquadrats in open beach; right: Marine Debris Tracker along littoral vegetation). Atolls grouped from north to south: (a–b) Salomon Islands, (c–d) Peros Banhos, (e–f) Great Chagos Bank, (g–h) Egmont Islands, (i–j) Diego Garcia. Note variation in the y-axis scales. Bold horizontal lines indicate median, boxes delineate the upper and lower quartiles and whiskers define the data's range. Outliers are plotted as separate points.

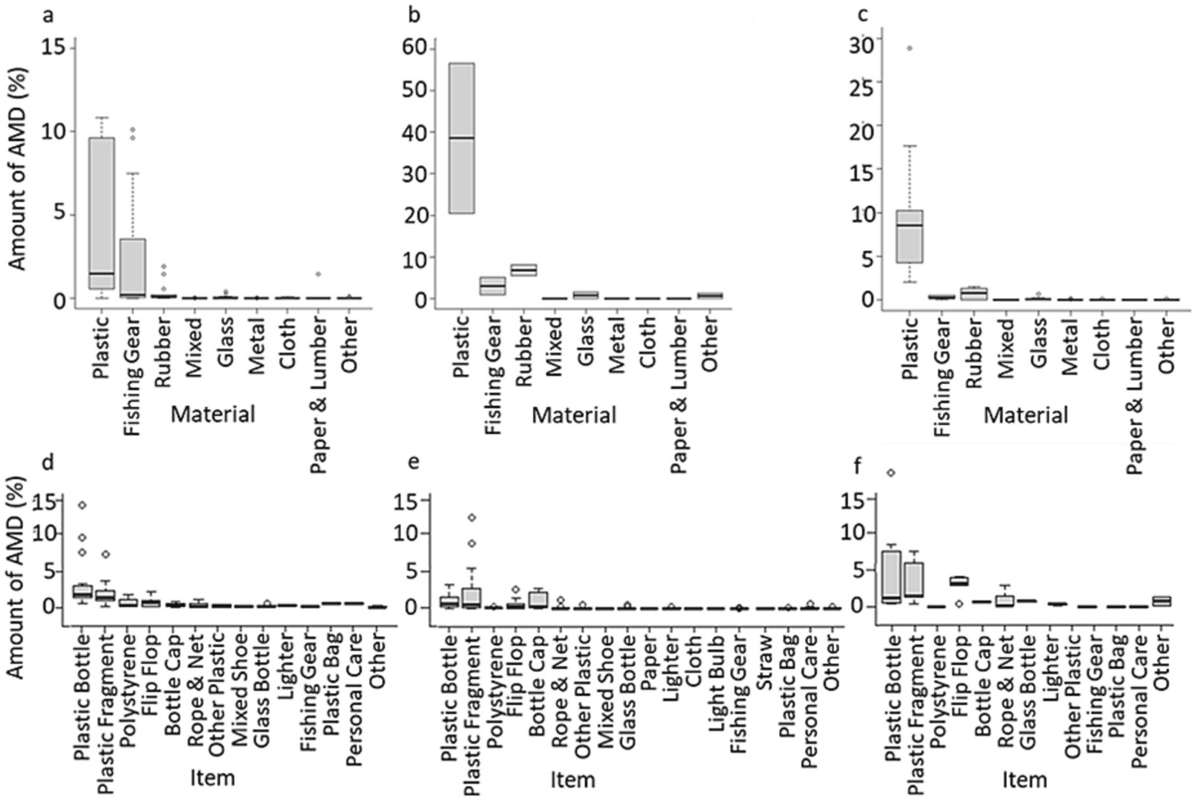

Fig. 4. Plastics dominated debris along the littoral vegetation in each island zone (a) oceanside, (b) island tip and (c) lagoon-side. Variation in types of plastic items occurred between zones: (d) plastic fragments were dominant on oceanside, (e, f) plastic bottles and fragments were common on island tips and lagoon-side respectively. Mean amount of AMD per category reported. Categories < 1 % AMD excluded (see SI Table 2 for complete list). Note variation in the y-axis scales. Bold horizontal lines indicate median, boxes delineate the upper and lower quartiles and whiskers define the data range. Outliers are plotted as separate points. Source: Marine Debris Tracker data.

likely to accumulate in one of the five garbage patches in the world's subtropical oceans (van Sebille, 2015), within an ocean gyre. The closest ocean garbage patch to Chagos Archipelago is within the Agulhas current (van Sebille, 2015) in the Southern Indian Ocean (SIO). Wind and ocean currents are key drivers of debris accumulation (Blickley et al., 2016), with buoyant debris in the SIO extremely sensitive to these transport mechanisms, making dispersal of debris away from this garbage patch more likely. The garbage patch in the SIO is highly dispersive as strong easterly trade winds cause accumulation towards the western side of the basin, closer to the Chagos Archipelago within the Western Indian Ocean (van der Mheen et al., 2019). It is difficult to predict debris accumulation north of 10°S (latitudinal extent of the Chagos Archipelago) as wind (as well as current) at these latitudes vary markedly with season and reverse direction with monsoons, swinging from westerly in January, to south-easterly in June, and then to weak westerly in November (Schott et al., 2009). Future research could investigate the relationship between global garbage patches and the potential for one to develop in the equatorial Indian Ocean, and would involve monitoring across the entire oceanic region, including land masses therein.

The oceanside beaches of the Chagos Archipelago could be acting as a sink for AMD, similar to the Galapagos beaches exposed to the Humboldt current where macroplastic abundance was more than five-fold higher between the vegetation line and water line (Jones et al., 2021) and on windward beaches of the Bahamas facing the Atlantic Ocean (Ambrose et al., 2019). Conversely, on open sandy beaches away from the vegetation line almost half of AMD was recorded on the lagoon-side using photoquadrats. This is likely due to higher accumulation rates on leeward facing or sheltered beaches where disturbance is lower (Schmuck et al., 2017). After AMD enter the lagoon, there is often less chance of removal back to sea (Willoughby et al., 1997). This pattern of accumulation may explain the variation in AMD accumulation between northern and southern atolls. Beach debris abundance on open sand was higher in the northern atolls, possibly due to increased shelter provided by their well-formed circular shape and distinct shallow lagoons (Goldberg, 2016). Another explanation for lower abundance on open sand in the southern atolls may be that the beaches in the southern atolls are more easily or frequently accessed as Diego Garcia is the only inhabited atoll and Egmont Island is the closest. Easily accessed beaches often have lower debris abundance due to increased targeting for beach cleans (Schmuck et al., 2017), which indicates that Diego Garcia may have lower rates of AMD due to a higher frequency of beach cleans.

In contrast to coastal debris accumulation, oceanic macroplastic densities can be comparatively low, for example onshore versus offshore of the Pitcairn Islands in the South Pacific (Ryan and Schofield, 2020). Very few studies have considered AMD accumulation on shorelines versus AMD remaining in the ocean. Oceanic AMD is comparatively difficult to quantify though it heavily impacts a range of foraging marine taxa (including different life stages), especially sea turtles, seabirds, cetaceans and carnivorous fish species (Markic et al., 2020). The impact of AMD on these marine megafauna could vary depending on whether that exposure is oceanic- or coastal-based, presenting important future research considerations to inform AMD clean-up policy and management. For example, determination of location of exposure to AMD could inform targeted clean-up action on land or at sea, a critical consideration when beach clean-ups are more time- and cost-efficient than some of the emerging ocean clean-up technologies (Cordier and Uehara, 2019).

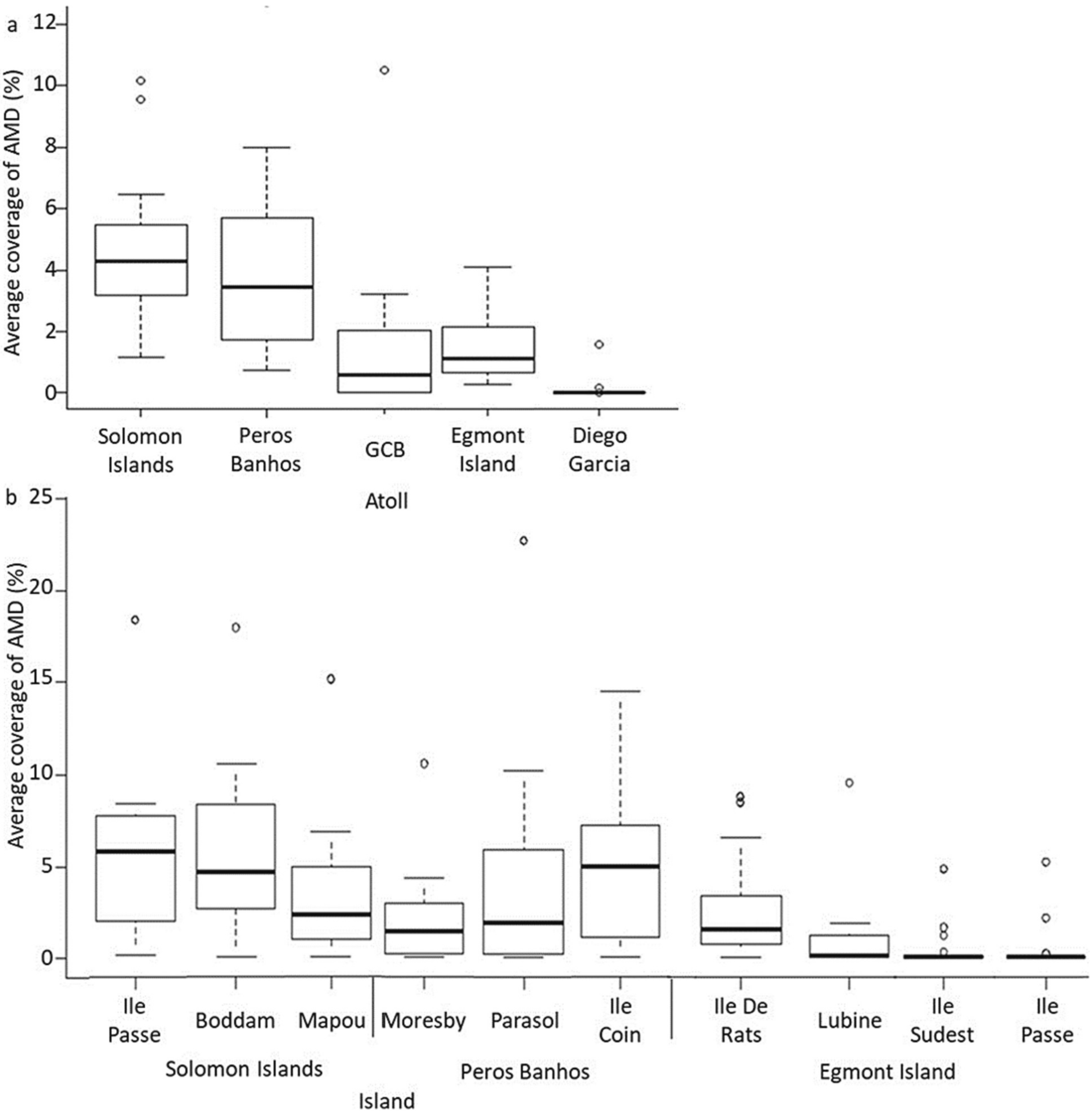

Fig. 5. (a) Debris accumulation on open sand varied between northern and southern atolls of the Chagos Archipelago ($p < 0.001$). (b) Intra-atoll variation occurred between the three atolls where multiple islands were surveyed (left to right: three islands on Salomon and Peros Banhos atolls, four islands on Egmont atoll). Note variation in the y-axis scales. Box plots display the upper and lower quartiles and the median value. Outliers are plotted as separate points.
Source: Photoquadrat data.

4.1. Beach debris monitoring recommendations

Assessments of beach debris composition, accumulation rates, trends over time and effectiveness of beach management systems are difficult to investigate (Cheshire et al., 2009). Many methods of beach debris surveys use volunteers, who record the AMD present and flux (or accumulation) rate of marine debris over a specific time period (e.g., since the last clean-up) following best-practice guidelines and litter-identification guides (Nelms et al., 2017; Ocean Conservancy, 2021). Whilst this approach could be beneficial for the sole inhabited island of Diego Garcia, the heavy reliance on citizen science makes it impracticable for > 55 uninhabited islands across four atolls as data from those sites depend on irregular, infrequent and short visits from scientists or MPA managers. Therefore, any monitoring systems must be focused on time efficiency and ease of remote data collection, hence our testing of the use of photoquadrats and the MDT App (using pre-defined categories of debris).

Our findings provide useful information about the value of photoquadrat and MDT App survey techniques, although constrained by the lack of comparable methods due to the tailoring of data collection for the site, similar to many other survey frameworks around the world (Cheshire et al., 2009). One key benefit of the MDT App was that the survey allowed a better representation of marine debris occurring across the turtle nesting zone that extends from HWL to several metres beyond the vegetation line (Esteban et al., 2016). It was not physically possible to survey the vegetation line (or further inland) using the photoquadrat technique. However, it is worth considering that the MDT App was not always reliable as remote technical problems occurred, and the MDT App could not be used to measure size of debris so that data metrics (e.g., surface area covered by AMD) were not always comparable with those from some other beaches in the region (e.g., Heo et al., 2013). Despite these caveats, we recommend continued use of the MDT App in future monitoring of AMD to increase understanding of accumulation rates and trends in abundance and composition in the Chagos Archipelago. It is suggested to prioritize monitoring on beaches with high density of hawksbill and green turtle nesting activities, especially Diego Garcia, Peros Banhos and Egmont atolls (Mortimer et al., 2020).

It is important to note that without future repeats of data collection, this study does not record the rate of accumulation, but rather aggregates accumulation since the last beach clean. Beach cleans only take place on Diego Garcia, at one controlled site on Egmont Island, and occasional unrecorded clean-ups by the small number of visiting yachts and researchers, meaning that at most sites debris has been accumulating over a long period of time. Long-term monitoring would enable investigation and comparison of accumulation rates from different sites globally. It is currently difficult to compare sites directly as AMD can be recorded by weight (e.g., Burt et al., 2020), by surface cover (this study), or by counts of items (e.g., Pieper et al., 2019; this study). Reporting of AMD abundance using comparable freely available techniques (such as MDT App) will allow an objective assessment of how debris levels vary across the world in response to potential drivers, such as ocean currents, sources of the debris and beach cleaning.

4.2. Beach debris management considerations

Our study highlighted that high proportions of marine debris accumulated along the vegetation line of oceanside and island tips where the majority of turtle nesting activity takes place in the Chagos Archipelago (Mortimer et al., 2020). High abundance of AMD in critical turtle nesting habitats will likely lead to an increase in deleterious effects arising from AMD, like entrapment, injury and ingestion (Nelms et al., 2016). However, our data collection took place over a short duration of four months and is insufficient to assess seasonal variation or long-term trends in AMD accumulation linked to turtle activity. Long-term monitoring of AMD accumulation on a selection of beaches is important for evaluation of the seasonal or annual variations impacting beach morpho-dynamics and integrity and can then be compared with nesting seasonality of sea turtles to inform effective beach management and targeted beach cleans.

BIOT Administration holds environmental management responsibility for the shorelines of the BIOT MPA. For effective beach debris management to occur, it is important to gain an understanding of the processes responsible for debris generation (sources, inputs, nature of debris) (Cheshire et al., 2009). This first step is relatively straightforward in the remote islands of the Chagos Archipelago where all islands are uninhabited so that all debris is de facto AMD. On Diego Garcia, waste management is strictly regulated with no observations of island-generated debris on the beaches (Esteban, N., pers. comm.). AMD waste management therefore should consider environmental and economic costs and benefits of management strategies for Diego Garcia and remote islands.

On Diego Garcia, an effective ‘Adopt a Beach’ campaign commenced in 2019 with a prioritisation of beaches with highest density of hawksbill and green turtle nesting activities (BIOT, 2018). A standardised beach clean *Code of Conduct* was issued to clean-up teams that included recommendations that clean-ups took place during low tide neap tides (to maximise clean-up effort), using existing access paths to the beach (to avoid damage to littoral vegetation) and using re-useable and biodegradable hessian clean-up bags. Furthermore, guidance was provided about how to react if turtles are observed, which is important as hawksbill turtles nest during daytime in Chagos Archipelago (Mortimer et al., 2020). For the remote and uninhabited islands, where economic costs of clean-ups are much higher, careful prioritisation of environmental benefits of clean-ups are necessary. Successful strategies to reduce economic costs and enhance environmental benefits have included prioritisation of limited beach clean-up and disposal resources (e.g., Eastern Mediterranean, Portman and Brennan, 2017) by targeted removal of plastic items and fragments due to their prevalence and risks to wildlife (Lavers et al., 2014, 2020; Lavers and Bond, 2017) from entanglement, ingestion, as well as re-suspension and further breakdown of plastics.

The Chagos Archipelago beaches are categorised by intact vegetation that provides shade and nesting habitat for wildlife (Esteban et al., 2016). The impact of AMD on nesting turtles, especially in areas of likely high accumulation, such as the littoral vegetation line, includes obstruction or entanglement (Ware and Fuentes, 2020) of both adult and juvenile sea turtles, which can decrease fitness and survival rates (Martin et al., 2019). Beach AMD can also increase hermit crab entrapment in debris such as plastic bottles (Lavers et al., 2020). The Midway Atoll is a comparative example of AMD accumulation on remote islands, where AMD ingestion rates in immature and adult seabirds has been increasing since the 1980's and affects 11 out of 16 locally-breeding species (Rapp et al., 2017), due to ingestion of nesting materials and foraging respectively. We therefore recommend careful selection of beach clean-up locations in AMD hotspot locations (identified by this study) with consideration for priority beaches for wildlife such as sea turtle, sea bird and crab populations (Carr et al., 2021; Laidre, 2017; Mortimer et al., 2020).

5. Conclusions

The present study describes marine debris accumulation dominated by plastics on the Chagos Archipelago island beaches, adding to the established fact that AMD is a plastic problem (Jones et al., 2021; Bergmann et al., 2017b; Gómez et al., 2020; Yin et al., 2020). This study sheds light on the understudied topic of accumulation of AMD on small, isolated island regions. Not only does this study recommend a suitable and freely-available method for the assessment of AMD in remote island contexts (MDT App), but our data suggest that AMD accumulation hotspots overlap with critical turtle nesting habitat (Mortimer et al., 2020). This emphasises the priority for targeted clean-ups that reduce risks for wildlife that AMD accumulation poses, including on uninhabited islands, even though clean-ups are a costly endeavour, especially when not generated by that country or territory (Burt et al., 2020). Future studies are recommended to investigate the seasonal and long-term impacts of Indian Ocean weather and ocean currents on AMD accumulation to inform future management and beach clean efforts, as well as efforts into identifying sources of AMD that accumulate in the Chagos Archipelago. Addressing the AMD that are already in circulation and accumulating within the world's marine environments is often overlooked within policy and practice (Williams and Rangel-Buitrago, 2019).

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CRediT authorship contribution statement

NE conceived the study with HK and RJ. NE, NAB, RJ, HK, J-OL, EL, FL and HM conducted the fieldwork. VH led the data analysis with support from NE. VH and NE led the writing with contributions from all authors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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