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Beach debris on Aruba, Southern Caribbean: Attribution to local land-based and distal marine-based sources



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ABSTRACT

Accumulation of marine (plastic) debris from local land-based and distal marine-based sources along coastlines is a pressing modern issue. Hitherto, assessing the relative contribution of pollution sources through beach surveys is methodologically challenging. We surveyed ten beaches along the leeward and windward coastlines of Aruba (southern Caribbean) to determine differences in macro- and meso-debris densities. Differences were quantified using three metrics: 1) the gradient in macro-debris density away from the waterfront; 2) the proportion of plastic within macro-debris; 3) the meso-:macro-debris ratio. Overall 42,585 macro-debris items and 884 meso-debris items were collected. The density of near-shore macro-debris, proportion of plastic debris herein, and meso-:macro-debris ratio were highest on the windward coastline. These results suggest that southern Caribbean windward coastlines are mainly exposed to debris originating from distal marine-based sources, and leeward coastlines to local land-based sources. Our metrics clearly reflect these differences, providing novel means to survey debris source origin.

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1. Introduction

Plastic's inexpensive manufacture processes, its durability and versatility explain its status as the most used disposable material worldwide (Barnes et al., 2009; Gregory, 2009; APME, 2014). However, plastic's durability in particular creates an environmental hazard, as photo-oxidative degradation and physical abrasion mainly lead to disintegration into smaller fragments, rather than chemical transformation (Ryan et al., 2009). Hence, it is expected that all (non-incinerated) plastic hitherto introduced into the environment is still present in unmineralized form (Thompson et al., 2005). As the majority of plastic debris has buoyant properties, plastic debris is now ubiquitous in coastal and marine habitats, including areas with relatively low anthropogenic activity, such as the five major oceanic gyres and the Arctic abyssal zone (Barnes et al., 2009).

The accumulation of plastic debris in the marine environment has been acknowledged as a pressing global issue of similar importance as the loss of biodiversity, ocean acidification and climate change (Sutherland et al., 2010). Plastic is the most common material involved in encounters between marine organisms and debris, particularly leading to entanglement and ingestion (CBD-GEF, 2012; Cole et al., 2013; Schuyler et al., 2014; Gall and Thompson, 2015). These encounters affect hundreds of species, either directly or indirectly, with both non-lethal and lethal consequences (Derraik, 2002; CBD-GEF, 2012; Cole et al., 2013; Gall and Thompson, 2015). Additional environmental

impacts result from the leaching of toxic pollutants, which can enter the marine food chain and humans through consumption of seafood. Moreover, plastic debris serves as a vector facilitating the spread of exotic invasive species (Schuyler et al., 2014; Schuyler et al., 2015).

Tropical and sub-tropical islands are hotspots of biodiversity, including diverse coastal and marine ecosystems such as coral reefs, mangrove forests and seagrass beds (Nurse et al., 2001). In addition, these ecosystems often provide important services to islands' economies by stimulating fishing activities and tourism (Wilkinson and Salvat, 2012). Tropical and sub-tropical islands should also be considered as marine pollution hot-spots as their relatively vulnerable ecosystems are being severely affected by both local and foreign marine debris (Wilkinson and Salvat, 2012; UNEP-CAR/RCU, 2014). Local land-based debris originates from the activities of local populations and tourists, whereas foreign (i.e. distal) marine-based debris consists of debris originating from anthropogenic marine activities and pelagic sources. Debris is considered to have a pelagic source if it has drifted from afar, regardless of its original source (land or marine) (Gregory, 1999).

Beach surveys provide an effective tool to assess an island's exposure to marine pollution, and have been successfully applied on many tropical and sub-tropical islands in the past decades (e.g. Debrot et al., 1999, 2013; do Sul and Costa, 2007; Cheshire et al., 2009; UNEP-CAR/RCU, 2014). These studies have highlighted the environmental pressure exerted by debris may not only vary over time (Agustin et al., 2015), but also vary considerably between locations around an island. Studies

focusing on specific islands in the Caribbean and the Pacific found significant variation in both quantity and composition of debris between locations, with the most pronounced differences occurring between leeward and windward coastlines (Debrot et al., 1999, 2013; Gregory, 1999; do Sul and Costa, 2007; Ribic et al., 2012). With regard to quantity, the highest densities of debris items are found along the windward coastlines (do Sul and Costa, 2007). With regard to composition, debris on windward coastlines tends to contain a higher proportion of plastic items, of which a larger proportion falls in the smaller meso- (2–25 mm) and micro-debris (<2 mm) size classes (Corbin and Singh, 1993; Corbin et al., 1993; Debrot et al., 1999, 2013; do Sul and Costa, 2007; Ribic et al., 2012). This effect is partly due to fragmentation of plastic debris that occurs during transport, which is also reflected by plastic macro-debris (>25 mm) encountered on windward coastlines being of a more fragmented nature (Corbin and Singh, 1993; Corbin et al., 1993; Debrot et al., 1999, 2013; do Sul and Costa, 2007; Ribic et al., 2012). Meso-debris encountered on windward coastlines, however, also typically includes pellets, which are rounded, spherical, ovoidal or disc-shaped granules of virgin plastic used for the production of plastic products (Gregory, 1999). These patterns in debris quantity and debris composition suggest that windward coastlines may experience higher pressure from distal marine-based debris, whereas leeward sites may experience higher pressures from local land-based debris. Local land-based debris typically contains a larger proportion of macro-debris originating from eating, drinking and smoking activities (Debrot et al., 1999; Santos et al., 2005; do Sul and Costa, 2007; Browne et al., 2010; Ribic et al., 2012).

Until now, however, deductions of debris origin as described above have relied on visual classification of the type of debris items encountered. As a result, one type of debris is often attributed to one particular source, which may not always be accurate (Jang et al., 2014). Moreover, classification itself is especially challenging in case of fragmented debris (Debrot et al., 1999; Jang et al., 2014). It is therefore of interest to explore whether alternative metrics can be extracted from beach survey data to assess the contribution of local land-based and distal marine-based sources to debris pollution.

Based on the inherent difference between land-based and marine-based debris sources among leeward and windward coastlines, three candidate metrics can be proposed. First, one can measure how the debris density on a beach varies with distance to the waterfront. On beaches where debris is mainly of distal marine origin (as expected along windward coastlines), peak debris densities are expected to occur along the wrack-line close to the waterfront. In contrast, on beaches where debris is mainly originating from local sources on land (as expected along leeward coastlines), recreational activities are expected to create a relatively even distribution of debris. Second, on beaches where debris is mainly of marine origin, one can expect a relatively high proportion of plastic in the debris encountered. This is expected because during transport at sea, plastic's durability and buoyant properties will be better retained than other types of debris, meaning that its relative abundance will increase over time. Third, on beaches where debris is mainly of marine origin, plastic is expected to be abundant but also highly fragmented, which would be reflected by relatively high meso-:macro-debris or micro-:macro-debris ratios. The meso-:macro-debris ratio in particular may provide an accurate metric to characterize differences in source origin between leeward and windward coastlines in the absence of local sources of virgin plastics pellets (Gregory, 1999).

The aim of this study was to test whether the three proposed metrics revealed patterns of variation in macro- and meso-debris density among leeward and windward coastlines that could elucidate the importance of local and distal sources of plastic debris accumulation. More specifically, the following three main research questions were posed: 1) Is there a difference in macro-debris density between leeward and windward coastlines? If so, is this density related to the distance away from the waterfront? 2) Does the proportion of plastic debris

differ between the leeward and windward coastlines? 3) Is there a difference in the meso-:macro-debris ratio between the leeward and windward coastlines? We hypothesised that: 1) Macro-debris density is highest along the windward coastline; 2) Plastic is the most abundant material found along both coastlines, however, a higher density of plastic over non-plastic materials is expected along the windward coastline; and 3) The meso-:macro-debris ratio is highest along the windward coastline.

2. Materials and methods

2.1. Study area

The study took place in Aruba, a semi-autonomous island state that is part of the Kingdom of the Netherlands and located in the southern Caribbean. Aruba's population has grown from 62,644 in 1986 to 109,028 in 2015 (CBS Aruba, 2015b). The island has also seen a substantial increase in the number of stay over visitors from around 185,000 in 1986 to more than one million in 2015 (CBS Aruba, 2015a; Anonymous, 2015). To accommodate these tourists, long stretches of coastline have been transformed into vacation resorts and hotels. The increased development of tourism activity and demographic growth tend to put stress on coastal and marine resources, on the availability of energy, food and water resources, and it poses a challenge for proper waste management on small island developing states (UN-OHRLS, 2009). The island of Aruba is no exception to this pattern.

The island of 180 km² is located 24 km north of the Paraguaná peninsula of Venezuela and about 72 km west of the island Curaçao (Fig. 1a). At about 32 km long and 10 km wide, the population density is around 593 per square kilometre (CBS Aruba, 2014). The western and southwestern shorelines of Aruba have 11 km of white-sand beaches, whereas the northern and eastern shorelines are rocky with small sandy bays. The southern shoreline of the island constitutes a mixture of mangroves with sandy patches, urbanization and industrialization including deep-water harbours, resulting in heavy anthropogenic influence (Aruba Tourism Authority, 2015).

Aruba is exposed to the Caribbean Current, creating a leeward and a windward coastline (Fig. 1a). Once the South Equatorial Current (SEC) reaches Brazil it bifurcates whereby the north-western moving waters turn into the North Brazil Current (NBC) (Lumpkin and Johnson, 2013). After the NBC diverges, the western portion (the Guyana Current) enters the Caribbean and forms the Caribbean Current, which maintains the north-western motion (Fig. 1a; Gyory et al., 2001). Hence, Aruba's south coast is leeward of the Caribbean Current, whereas the north coast is windward of the Caribbean Current (Fig. 1).

The beach debris assessments were performed exclusively on sandy beaches. A total of ten locations were chosen along Aruba's coastlines: five on the leeward coast, approximately evenly distributed, and five on the windward coast. Locations were selected based on natural availability, feasibility and accessibility (Fig. 1b). None of the selected beaches are maintained by hotels. Due to natural availability not all beaches had the same surface area; nonetheless, overall, there was no significant difference in the extent of beach area sampled on the leeward and windward coastlines ($M_{\text{Leeward}} = 4376 \pm 1357 \text{ m}^{-2}$, $M_{\text{Windward}} = 4000 \pm 1647 \text{ m}^{-2}$, two sample t-test, $t_8 = 0.394$, $p = 0.70$ (see Appendix I for individual areas and location of surveyed beaches).

2.2. Data collection

Each location was surveyed for both macro- and meso-debris twice between February 2015 and April 2015 with 28 days between measurements on the same locations. From here, the two measurement periods will be referred to as T_1 (first round of assessments) and T_2 (second round of assessments). The selected beaches were completely surveyed and all debris encountered was collected and removed, resulting in the

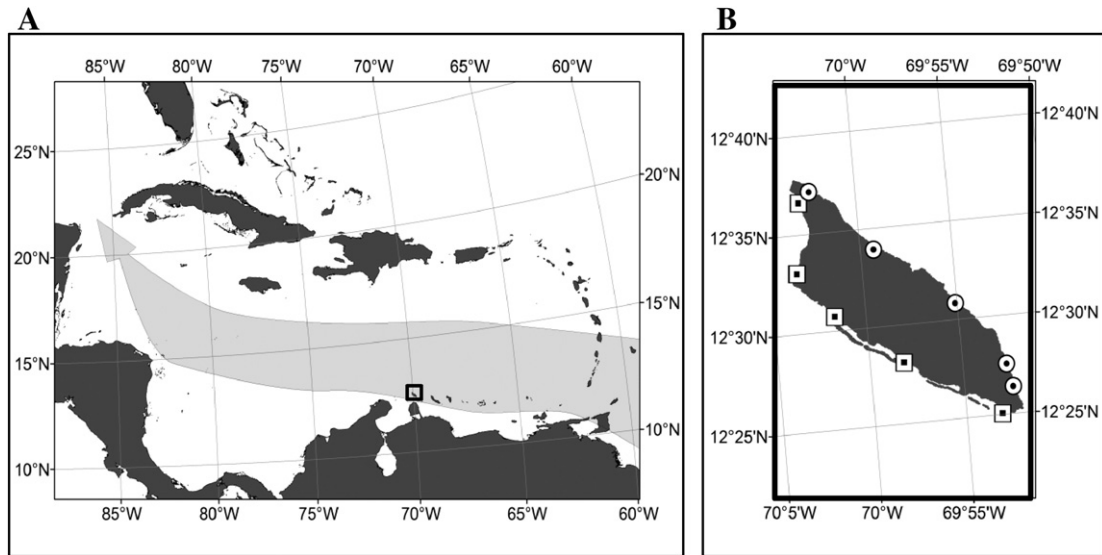


Fig. 1. a) Illustration of the north-western motion of the Caribbean Current (light grey arrow), with the position of Aruba within this current (enclosed in the square). b) Close up of Aruba with the distribution of the five surveyed sites on the leeward coast (squares) and the five surveyed sites on the windward coast (circles).

clean-up of surveyed areas. Location coordinates were recorded using GPS (Garmin eTrex 10, see Appendix I for location coordinates).

2.2.1. Macro-debris (>25 mm)

The macro-debris shoreline litter assessment used in this study was based on the standardized protocol formulated by UNEP/IOC (UN Environmental Programme/International Oceanic Commission; Cheshire et al., 2009). In addition, a modified version of NOAA's data sheet was used for site characterization and macro-debris analysis (Opfer et al., 2012). Collection and analysis consisted of the following 3 steps: 1. Beach survey and trash collection on site. Following a skirmish walking pattern with the long axis perpendicular to the water front (see Appendix II for the illustration of the followed walking pattern), all the debris items (>25 mm) encountered were collected. We kept an approximate walking speed of 1.0 km/h while scanning the ground and would stop to collect debris when encountered. 2. Sorting and counting in laboratory. Debris items were counted and classified according to type and material, plastic and non-plastic (metal, glass, rubber, processed lumber, cloth/fabric, other/unclassifiable and large debris). 3. Weighing of all debris (plastic and non-plastic) was performed after sorting in the laboratory. Macro-debris density was calculated as follows (e.g. Lippiatt et al., 2013):

$$C_M = \frac{n}{(w \cdot l)} \quad (1)$$

in which C_M is the density of macro-debris (units: # of debris/m²), n is the number of macro-debris counted, w is the width (m), and l is the length (m) of the beach sampled.

To test whether macro-debris density depended on the distance from the waterfront, debris densities were assessed in two sub-transects parallel to the water front: the first ranged between 0 and 15 m from the waterfront (from here referred to as the 0–15 m transect), the second ranged from 15 m from the waterfront until the end of the beach (from here referred to as the 15 m + transect). Division into the two sub-transects was only undertaken during T_2 (see Appendix II for the illustration of the followed walking pattern during T_2).

2.2.2. Meso-debris (2–25 mm)

The meso-debris methodology was based on the outcome of a previous review study (Hidalgo-Ruz et al., 2012), with the exception of

performing a Fourier transform infrared spectroscopy (FT-IR) to determine chemical composition. The meso-debris collection and analyses consisted of the following 5 steps: 1. Bulk sample collection on site; the sediment samples were taken from a 50 × 50 cm square along the high tide wrack-line (within the 0–15 m transect) up to a depth of approximately 8 cm, so that the sample filled a 20 l bucket. 2. Sieving in laboratory; sediments were sieved through a stainless 2 mm mesh sieve. If any macro-debris items were found, they were recorded but not counted, neither in the meso- nor in the surface macro-debris count. 3. Rinsing and drying in laboratory; the remaining debris items were then rinsed with fresh water and left to dry for 24 h in a shaded open environment. 4. Density separation in laboratory; this is a necessary step to separate sediments and organic materials from synthetic plastic debris. The entire sediment sample was immersed in sea water, mixed and shaken for 1 min and subsequently left to rest for 2 h in order to let sediments and debris settle. 5. Visual sorting and separation in laboratory; direct examination by eye and manual separation of plastic debris and other materials (e.g. organic, glass etc.). In order to increase accuracy steps 4 and 5 were repeated twice for each sediment sample.

2.3. Data analysis

The effect of time (T_1 or T_2) on debris density could have been a possible confounding factor when using each measurement as an independent observation. We observed, however, there was no effect of time on the debris density and there was no relationship between the amounts of debris collected during the first round and second round of assessments on the same locations. More specifically, the macro-debris densities obtained from the five sites at T_1 did not differ significantly from the macro-debris densities from the same sites collected at T_2 for both the leeward and windward coastlines ($M_{\text{Leeward-}T_1} = 0.18 \pm 0.01 \text{ m}^{-2}$, $M_{\text{Leeward-}T_2} = 0.22 \pm 0.04 \text{ m}^{-2}$, paired sample t-test, $t_4 = -0.87$, $p = 0.43$; $M_{\text{Windward-}T_1} = 0.98 \pm 0.23 \text{ m}^{-2}$, $M_{\text{Windward-}T_2} = 0.84 \pm 0.53 \text{ m}^{-2}$, paired sample t-test, $t_4 = 0.54$, $p = 0.62$). Similarly, the macro-debris densities obtained from each of the ten sites at T_1 (i.e. leeward and windward coastlines) did not differ significantly from the amount of macro-debris collected from the same sites at T_2 ($M_{T_1} = 0.58 \pm 0.17 \text{ m}^{-2}$, $M_{T_2} = 0.53 \pm 0.15 \text{ m}^{-2}$, paired sample t-test, $t_9 = 0.41$, $p = 0.69$). Moreover, the macro-debris densities obtained at T_1 did not significantly correlate with the macro-debris densities

obtained from the same sites at T_2 for both the leeward and windward coastlines (Spearman's rho, $r_{s\text{-Leeward}}(5) = 0.30$, $p = 0.62$; Spearman's rho, $r_{s\text{-Windward}}(5) = 0.50$, $p = 0.39$). Although not significant, the relatively higher correlation observed for the windward coastline is due to one specific beach (Dos Playa), which had a relatively low macro-debris density at T_1 and was cleaned a week before T_2 . The cleaning was organized by Parke Arikok in collaboration with TurtugAruba, in preparation for the beginning of the leatherback turtle nesting season. When removed from the analysis, a lower non-significant correlation was observed (Spearman's rho, $r_s(4) = 0.20$, $p = 0.80$). Given these observations, we assumed that measurements could be treated as independent observations in the analyses undertaken to answer the study's research questions.

For all analyses, involved variables were tested for normality with the Shapiro–Wilk test ($p > 0.05$). If the data did not obey normality ($p < 0.05$) it was attempted to achieve normality through log-transformation. Differences between groups for variables obeying normality were tested with a two sample t-test in case of homoscedastic variance between groups (tested with the Levene's test, $p > 0.05$) and with a Welch's test in case of heteroscedastic variance between groups (Levene's test, $p < 0.05$). Differences between groups for variables not obeying normality were tested with a Mann Whitney U test.

To answer the first research question, we tested whether macro-debris densities were different on the leeward and windward coastlines. In this comparison, we combined data collected at T_1 and T_2 on each coastline. Moreover, we compared the macro-debris densities found at 0–15 m and farther than 15 m from the shoreline. As noted above, this latter comparison could be made with data collected at T_2 . To answer the second research question, we tested whether the proportion of plastic in the total debris density differed between the leeward and windward coastlines. For this comparison, we again combined data collected at T_1 and T_2 . Moreover, we compared whether the density of non-plastic debris differed between the leeward and windward coastlines. To correct for overall differences in debris abundance, we used a Chi-square test. To answer the third research question, we tested whether the meso-:macro-debris ratio differed between the leeward and windward coastlines, again combining the data collected at T_1 and at T_2 . All statistical tests were performed by using IBM SPSS version 22.

3. Results

3.1. Overall description of collected debris

The two beach surveys resulted in the overall removal and collection of 42,585 items of macro-debris (243.53 kg), of which 9922 were found on the leeward coast and 32,663 on the windward coast of Aruba. The specific types of macro-debris found varied between the leeward and windward coastlines. On the leeward coastline, the majority of the macro-debris was associated with smoking, drinking and eating activities. We found in decreasing order: cigarettes (2560), beer caps (2380), plastic fragments (659), straws (605), bottle or container caps (543), and food wrappers (445) (see Appendix III for the complete list of items found on the leeward coast). In contrast, on the windward coast the majority of macro-debris consisted of plastic fragments. We found in decreasing order: plastic fragments (14,661), bottle or container caps (6285), straws (2880), plastic rope/small net pieces (1698), bags (1622), and plastic utensils (1016) (see Appendix IV for the complete list of items found on the windward coast).

3.2. Comparing macro-debris density on leeward and windward coastlines

The mean macro-debris density was significantly higher on the windward coastline (Fig. 2; $M_{\text{Leeward}} = 0.20 \pm 0.07$ debris/m², $M_{\text{Windward}} = 0.91 \pm 0.50$ debris/m², two sample t-test, $t_{12,22} = -6.06$, $p < 0.001$).

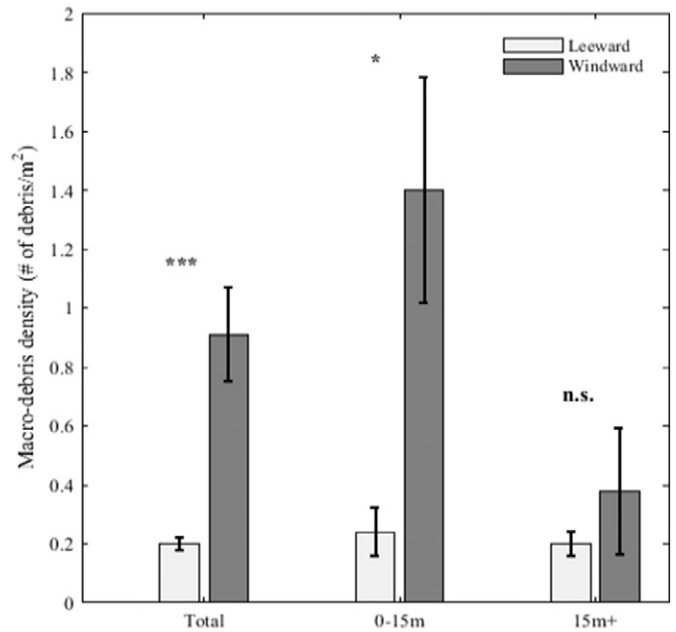


Fig. 2. Macro-debris density was significantly higher on Aruba's windward coast when compared to the macro-debris density of the leeward coast. For the area 0–15 m from the shoreline, macro-debris density was significantly higher on the windward coastline. For the area farther than 15 m from the coastlines, no significant difference in the overall mean macro-debris density was found. Asterisks (*) indicate significant differences between the leeward and windward densities. (*: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$; n.s.: $p \geq 0.05$).

The difference in macro-debris density between the leeward and windward coastlines was mainly driven by the debris found in the 0–15 m transects on the windward coast (Fig. 2). More specifically, macro-debris density was significantly higher in the 0–15 m transects of the windward coastline, but no significant difference between the leeward and windward coastlines was found on the 15 m + transects (0–15 m transects: $M_{\text{leeward}} = 0.24 \pm 0.18$ debris/m², $M_{\text{windward}} = 1.40 \pm 0.86$ debris/m², two sample t-test, $t_{4,36} = -2.97$, $p < 0.037$; 15 m + transects: $M_{\text{leeward}} = 0.20 \pm 0.09$, $M_{\text{windward}} = 0.38 \pm 0.43$ debris/m², two sample t-test, $t_{3,24} = -0.84$, $p = 0.46$).

3.3. Material abundancy: plastic vs non-plastic

On both the leeward and windward coastlines, plastic macro-debris was more abundant than all other macro-debris combined (Fig. 3a; Leeward coast: $M_{\text{Plastic-Leeward}} = 0.12 \pm 0.04$ debris/m², $M_{\text{Non-plastic-Leeward}} = 0.08 \pm 0.03$ debris/m², Mann–Whitney U test, $U = 14.50$, $p = 0.007$; Windward coast: $M_{\text{Plastic-Windward}} = 0.89 \pm 0.48$ debris/m², $M_{\text{Non-plastic-Windward}} = 0.02 \pm 0.01$ debris/m², Mann–Whitney U test, $U = 0$, $p < 0.001$). Although plastic was the most abundant material encountered on both shorelines, the proportion of plastic macro-debris on the windward coast was significantly higher than the proportion of plastic macro-debris on the leeward coast (Fig. 3a; $P_{\text{Leeward}} = 61\%$, $P_{\text{Windward}} = 98\%$, $X^2(1, N = 42,585) = 10,724.62$, $p < 0.001$).

Despite the overall number of collected macro-debris being considerably lower on the leeward coast, non-plastic macro-debris items were significantly more abundant on the leeward coast than on the windward coast (Fig. 3b; $M_{\text{Non-plastic-Leeward}} = 386.60 \pm 174.35$ debris, $M_{\text{Non-plastic-Windward}} = 71.20 \pm 56.08$ debris, two sample t-test, $t_{18} = 6.38$, $p < 0.001$). This pattern was mainly driven by the metal debris found on the leeward coast, of which the majority (94%) were beer caps (2380; Appendices C & D).

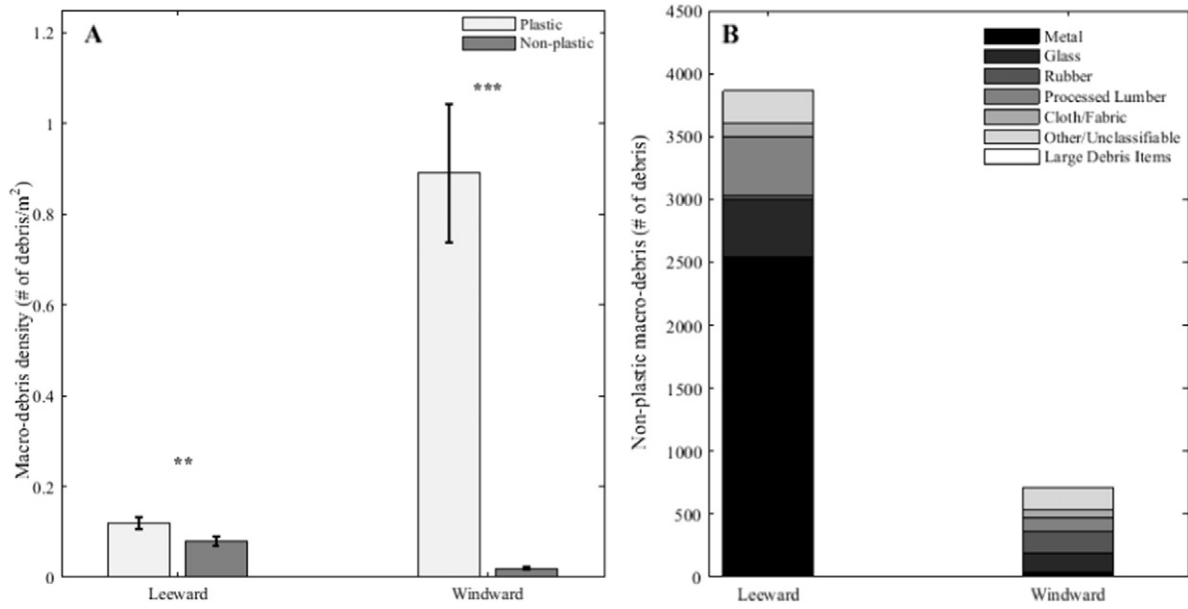


Fig. 3. a) Plastic macro-debris density was significantly higher than non-plastic macro-debris density on both the leeward and windward coasts of Aruba. In addition, a larger difference between plastic macro-debris and non-plastic macro-debris density was found on the windward coastline. b) Non-plastic macro-debris was more abundant on the leeward coast (3866 items) than on the windward coast (712 items).

3.4. Meso-debris analysis comparison of the leeward and windward coastlines

The windward coast had a density of meso-debris that was two orders of magnitude higher than the leeward one (Fig. 4a). In total 884 items of plastic meso-debris were identified: 4 items of meso-debris from the leeward coast and 880 from the windward coast (407 pellets, 471 plastic fragments and 2 rope fragments). This difference was found to be much larger than the difference in macro-debris density between the two coastlines, meaning that the meso:macro-debris ratio was significantly higher on the windward coast (Fig. 4b; $M_{Leeward} = 0.00039 \pm 0.00058$, $M_{Windward} = 0.02594 \pm 0.02051$, Mann-Whitney U test, $U = 0$, $p < 0.001$).

4. Discussion

The beach surveys performed on Aruba revealed the following patterns: 1) More macro-debris was found on the windward coast, especially closer to the shoreline; 2) Plastic was the most abundant material found on both the leeward (61%) and windward (98%) coastlines, although it comprised a larger proportion on the windward coastline; 3) the meso:macro-debris ratio was higher on the windward coastline. These results are consistent with the hypothesis that debris found on the coastlines of Aruba originates from different sources; the leeward coast having a local land-based source and the windward coast having a distal marine-based source. These findings are in line with observations from other studies comparing leeward and

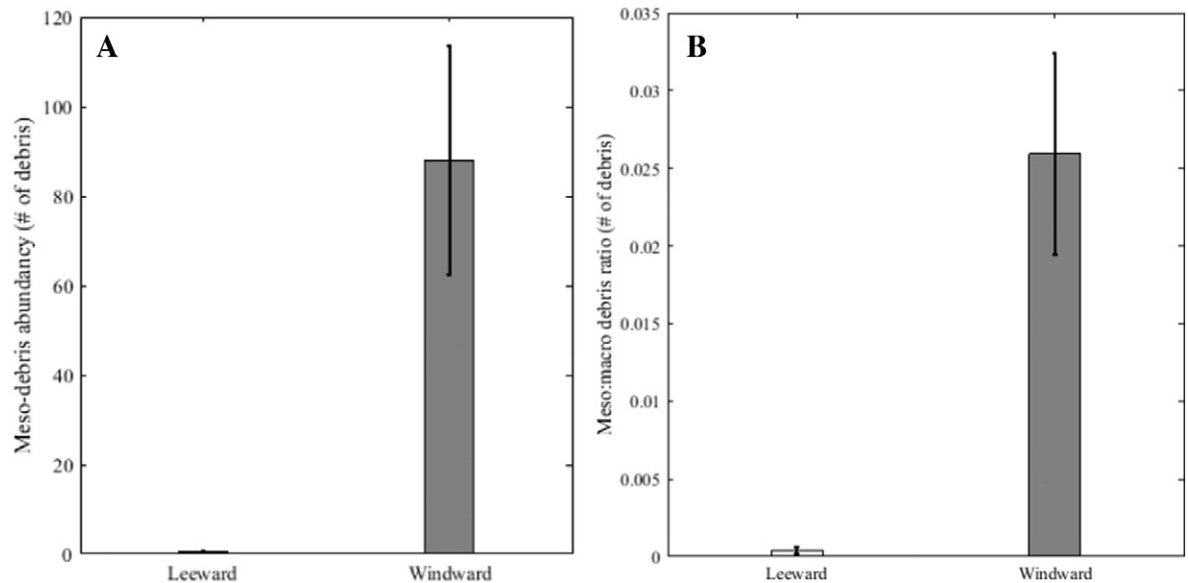


Fig. 4. a) A large difference was found in the overall mean meso-debris density, collected at T₁ and T₂ from the leeward and windward coastlines, with the highest density observed on the windward coastline. b) A significant difference was found in the meso:macro-debris ratio, with the highest ratio found on the windward coastline.

windward coastlines in the Wider Caribbean Region (WCR; Corbin and Singh, 1993; Corbin et al., 1993; Debrot et al., 1999; Gregory, 1999; do Sul and Costa, 2007; Debrot et al., 2013). The metrics used in this study (variation of debris density with distance to the waterfront, the proportion of plastic in respect to other materials and the meso-:macro-debris ratio), may provide promising means to identify the contribution of local and distal sources to marine debris deposition on coastlines.

The macro-debris of the leeward and windward coasts also differed considerably in composition; the macro-debris found on the leeward coast was predominantly related to eating, drinking and smoking activities, whereas the majority of the windward coastline's macro-debris consisted of plastic fragments. These results are also in line with the hypothesis that the debris on the leeward coastline is predominantly of local land-based origin, resulting from the accidental or deliberate inappropriate waste disposal of beachgoers (local and tourist, T. de S., personal observation) and from recreational activities. On the contrary, debris found on the windward coast is predominantly of distal marine-based origin resulting from the long permanence, buoyancy and accumulation of plastic debris in the marine environment globally. Items of meso-debris were practically absent on the leeward coastline and only resulted from the fragmentation of larger debris, whereas on the windward coastline both fragments and pellets were found, showing the importance of natural factors (as wind and oceanic currents) for the accumulation and distribution of plastic meso-debris. Previous studies have shown the ubiquity of pellets in the marine environment (Redford et al., 1997; Gregory, 1978; Mato et al., 2001; Derraik, 2002; McDermid and McMullen, 2004; Endo et al., 2005). This abundance of pellets has been attributed to spillages during transport at sea or during production on land (Gregory, 1978; Mato et al., 2001; Derraik, 2002; McDermid and McMullen, 2004; Andrady, 2011). On Aruba, local land-based sources of pellets are absent, meaning that pellets encountered likely originate from distal marine-based sources. In this study we only encountered pellets on the windward coastline. Hence, the observed distribution pattern of pellets provides further evidence that the strongest impact of distal marine-based debris sources occurs on the windward coastline.

The proportion of plastic in macro-debris found on the windward coastline of Aruba (98%) is at the upper end of debris ranges reported in the WCR, (51–73%, Ivar do Sul and Costa, 2007), leeward Bonaire (66.5%), windward Bonaire (73.4%) (Debrot et al., 2013), leeward Curacao (40%) and windward Curacao (64.2%) (Debrot et al., 1999). These studies highlight the current ubiquity and predominance of plastic among marine debris in this region. Moreover, when comparing our results to a similar study conducted on the neighbouring island of Bonaire (Debrot et al., 2013), we observe that the mean macro-debris density found on the leeward coast of Aruba is relatively high ($M_{\text{Leeward,Aruba}} = 6.8 \pm 2.5$ debris/m⁻¹, $M_{\text{Leeward,Bonaire}} = 1.6 \pm 1.5$ debris/m⁻¹). In contrast, the mean macro-debris density found on the windward coast of Aruba is relatively low ($M_{\text{Windward,Aruba}} = 29.7 \pm 18.7$ debris/m⁻¹, $M_{\text{Windward,Bonaire}} = 295.5 \pm 469.9$ debris/m⁻¹). Comparison between various studies is still difficult because of the great variability in methodologies of collection, area sampled and the use of different metrics. Moreover, studies often provide too little information to enable the calculation of alternative metrics that could facilitate cross-study comparisons.

The results presented here suggest that different influences are responsible for the macro- and meso-debris densities of the sheltered urban leeward coast (direct anthropogenic influences) and the exposed rural windward coast (natural influences). Although only items of macro-debris on the surface were collected, implying that debris collected during T₂ could have been previously buried debris, no significant difference was found between the amount of macro-debris collected during T₁ and during T₂. This observation suggests a steady accumulation of debris on the coastlines of Aruba, but a long term monitoring study would be needed to confirm this notion. Other studies have observed a similar trend of debris accumulation, although the rate of accumulation may vary over time (Garrity and Levings, 1993; Wetzel et al., 2004; Morishige et al., 2007; Ribic et al., 2012; Thiel et al., 2013). This

steady accumulation of debris implies that the leeward coast is acting as a source for debris in the marine environment, whereas the windward coast functions as a sink for debris originating from more distal sources (up to the global level). Addressing the marine debris pollution issue therefore requires both local and global action.

It is almost five decades that scientific research is reporting the ubiquity and severity of marine debris pollution and its accumulation in the marine environment, particularly of plastic debris (Kenyon and Kridler, 1969). However, despite the widespread acknowledgment of the issue, the marine debris pollution problem is still growing (Barnes et al., 2009). Debris pollution and accumulation in the marine environment, although extremely pervasive, is also one of the feasibly solvable problems currently affecting our oceans (Sheavly and Register, 2007). It is becoming evident that there is a difference in the type of pollution that affects leeward urban coastlines and windward rural coastlines. The former suffers from local land-based debris, of which the input rate is known and the potential consequences on the economy may trigger relatively quick clean-up responses. The latter, however, suffers from distal marine-based debris inducing ecological impacts that may go longer unnoticed. These differences in debris sources elucidate the importance of the adoption of both management and prevention strategies. The urgency of implementing management and prevention strategies is apparent from the increasing concentrations and ubiquity of debris reported in oceans and seas globally (Critchell et al., 2015), and the severe effects and threats this debris poses to the environment and human well-being (Hammer et al., 2012). The current polluted situation will persist for centuries (Barnes et al., 2009), but may be alleviated by more extensive coastal and ocean clean-ups, and by promoting the use of more sustainable, re-usable materials. However, these rather locally oriented alternatives alone may not be sufficient to effectively and efficiently solve the plastic marine debris issue. The problem needs to be tackled at its root as well (Wetzel et al., 2004; Santos et al., 2009), for example through diminishing mass production and consumption of disposable plastic products, halting their inappropriate disposal, and reducing the release of plastic into the natural environment.

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Appendix I. Appendix name area and coordinates of the 10 beaches assessed during this study: five located on the leeward coast and five on the windward coast of Aruba

| | Site name | Area | Coordinates |
|----------|------------------|------------|-----------------------------|
| Leeward | Arashi | 152 × 35 m | 12°36'37.93"N 70°03'12.18"W |
| | Eagle Beach | 152 × 40 m | 12°33'02.53"N 70°03'24.98"W |
| | Surfside Beach | 152 × 20 m | 12°30'43.76"N 70°01'52.70"W |
| | Mangel Halto | 110 × 40 m | 12°27'50.64"N 69°58'09.71"W |
| | Rodger's Beach | 152 × 20 m | 12°25'03.28"N 69°53'03.85"W |
| Windward | Lighthouse Dunes | 152 × 15 m | 12°37'01.13"N 70°02'43.85"W |
| | Wariruri | 87 × 37 m | 12°33'32.32"N 69°59'17.81"W |
| | Dos Playa | 102 × 37 m | 12°30'19.85"N 69°55'07.47"W |
| | Grapefield Beach | 101 × 40 m | 12°27'32.02"N 69°52'46.35"W |
| | Boca Grandi | 152 × 44 m | 12°26'22.23"N 69°52'25.99"W |

Appendix II. Appendix skirmish walking pattern followed during the collection of macro-debris

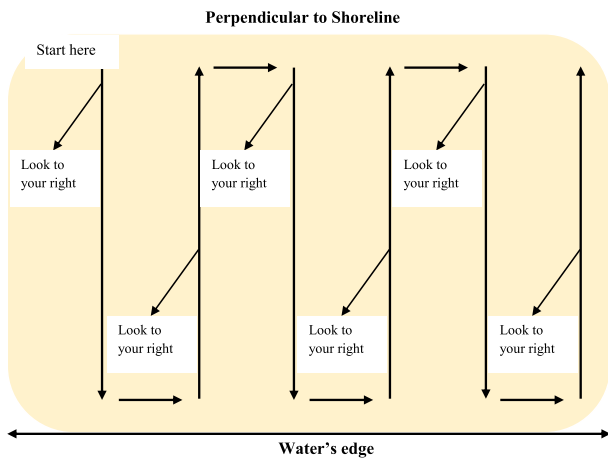


Fig. II.1. Skirmish walking pattern followed for the collection of macro-debris during T₁.

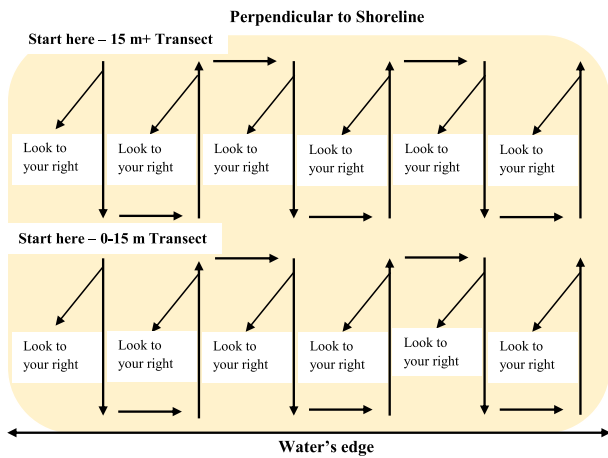


Fig. II.2. Skirmish walking pattern followed for the collection of macro-debris during T₂ in the sub-transects 0–15 m and 15 m + .

Appendix III. Appendix overall leeward coastline macro-debris data sheet, showing all the macro-debris collected after the ten assessments performed at T₁ and T₂

| Item | Material | | | Total |
|-------------------------------|----------|---------|------|-------|
| | Hard | Foam-ed | Film | |
| | Plastic | | | |
| Plastic fragments | | | | |
| Food wrappers | 176 | 3 | 266 | 445 |
| Beverage bottles | 36 | | | 36 |
| Other jugs or containers | 17 | | | 17 |
| Bottle or container caps | 543 | | | 543 |
| Cigar tips | 60 | | | 60 |
| Cigarettes | 2,560 | | | 2,560 |
| Disposable cigarette lighters | 5 | | | 8 |
| 6-pack rings | 1 | | | 1 |
| Bags | | | 168 | 168 |
| Plastic rope/small net pieces | 60 | | | 60 |
| Buoys & floats | | | | 0 |
| Fishing lures & line | 33 | | | 33 |

(continued)

| Item | Material | | Total | |
|---|--|-----------------------|------------------------|------------------------|
| | | | | |
| | Plastic | | | |
| Cups (including polystyrene/foamed plastic) | 179 | 12 | 191 | |
| Plastic utensils | 205 | 7 | 215 | |
| Straws | 605 | | 605 | |
| Balloons | | 109 | 109 | |
| Personal care products | 16 | | 16 | |
| Toys | | | | |
| Fragments | 618 | 14 | 27 | 659 |
| Other: | 279 | 12 | 40 | 331 |
| Overall | 5,399 | 43 | 610 | 6,057 |
| | Metal | | | |
| Aluminium/tin cans | 43 | | 43 | |
| Beer caps | 2,330 | | 2,380 | |
| Metal fragments | 23 | | 23 | |
| Other: | 92 | | 92 | |
| Overall | | | 2,538 | |
| | Glass | | | |
| Beverage bottles | 53 | | 53 | |
| Jars | 1 | | 1 | |
| Glass fragments | 406 | | 406 | |
| Other: | 0 | | 0 | |
| Overall | | | 460 | |
| | Rubber | | | |
| Flip-flops | 4 | | 4 | |
| Gloves | | | | |
| Tyres | | | | |
| Rubber fragments | 18 | | 18 | |
| Other: | 8 | | 8 | |
| Overall | | | 30 | |
| | Processed lumber | | | |
| Cardboard carton | 8 | | 8 | |
| Paper and cardboard | 196 | | 196 | |
| Paper bags | 6 | | 6 | |
| Tissue napkins | 214 | | 214 | |
| Lumber/building material | 22 | | 22 | |
| Other: | 21 | | 21 | |
| Overall | | | 467 | |
| | Cloth/fabric | | | |
| Clothing & shoes | 17 | | 17 | |
| Gloves (non-rubber) | 0 | | 0 | |
| Towels/rags | 5 | | 5 | |
| Rope/net pieces (non-nylon) | 62 | | 62 | |
| Fabric pieces | 30 | | 30 | |
| Other: | 0 | | 0 | |
| Overall | | | 114 | |
| | Other/unclassifiable | | | |
| Firework | 176 | | 176 | |
| Plaster | 14 | | 14 | |
| Wine cork | 16 | | 16 | |
| Condom | 6 | | 6 | |
| Hygiene pad | 15 | | 15 | |
| Battery | 4 | | 4 | |
| Stuffed animal | 1 | | 1 | |
| Razor blade | 1 | | 1 | |
| Duct tape | 3 | | 3 | |
| Baby diaper | 2 | | 2 | |
| Hand grenade Col Smoke Red L70A1 | 1 | | 1 | |
| Bullet case | 9 | | 9 | |
| Phone charger | 1 | | 1 | |
| Swimming goggles | 1 | | 1 | |
| Tampon | 2 | | 2 | |
| Overall | | | 252 | |
| | Large debris items (> 1 ft or - 0.3 m) | | | |
| Item type (vessel, net, etc.) | Status (sunken, stranded, buried) | Approximate width (m) | Approximate length (m) | Description photo ID # |
| Lumber plank | Buried | 0.15 | 3.61 | |
| Lumber plank | Buried | 0.12 | 1.16 | |
| Lumber plank | Buried | 0.12 | 1.32 | |
| Wooden pallet | Buried | 1.5 | 1.5 | |

Appendix IV. Appendix overall windward coastline macro-debris data sheet, showing all the macro-debris collected after the ten assessments performed at T₁ and T₂

| Item | Material | | | Total |
|---|----------|--------|-------|--------|
| <i>Plastic</i> | | | | |
| Plastic fragments | Hard | Foamed | Fun | |
| Food wrappers | 194 | 1 | 670 | 865 |
| Beverage bottles | 121 | | | 121 |
| Other jugs or containers | 534 | | | 534 |
| Bottle or container caps | 6,285 | | | 6,285 |
| Cigar tips | | | | 0 |
| Cigarettes | 20 | | | 20 |
| Disposable cigarette lighters | 127 | | | 127 |
| 6-pack rings | 19 | | | 19 |
| Bags | | | 1,622 | 1,622 |
| Plastic rope/small net pieces | 1,698 | | | 1,698 |
| Buoys & floats | 46 | | | 46 |
| Fishing lures & line | 74 | | | 74 |
| Cups (including polystyrene foamed plastic) | 934 | 6 | | 940 |
| Plastic utensils | 1,016 | 18 | | 1,034 |
| Straws | 2,880 | | | 2,880 |
| Balloons | | | 7 | 7 |
| Personal care products | 363 | | | 363 |
| Toys | 220 | | | 220 |
| Fragments | 12,709 | 1,951 | 1 | 14,661 |
| Other: | 400 | 33 | 1 | 434 |
| Overall | 27,640 | 2,009 | 2,301 | 31,950 |
| <i>Metal</i> | | | | |
| Aluminium/fin cans | 7 | | | 7 |
| Beer caps | 8 | | | 8 |
| Metal fragments | 10 | | | 10 |
| Other: | 18 | | | 18 |
| Overall | | | | 43 |
| <i>Glass</i> | | | | |
| Beverage bottles | 39 | | | 39 |
| Jars | 6 | | | 6 |
| Glass fragments | 94 | | | 94 |
| Other: | 3 | | | 3 |
| Overall | | | | 142 |
| <i>Rubber</i> | | | | |
| Flip-flops | 131 | | | 131 |
| Gloves | 5 | | | 5 |
| Tyres | 1 | | | 1 |
| Rubber fragments | 25 | | | 25 |
| Other: | 11 | | | 11 |
| Overall | | | | 173 |
| <i>Processed lumber</i> | | | | |
| Cardboard cartons | | | | 0 |
| Paper and cardboard | 2 | | | 2 |
| Paper bags | 1 | | | 1 |
| Tissue/napkins | 7 | | | 7 |
| Lumber/building material | 105 | | | 105 |
| Other: | 2 | | | 2 |
| Overall | | | | 117 |
| <i>Cloth/fabric</i> | | | | |
| Clothing & shoes | 46 | | | 46 |
| Gloves (non-rubber) | | | | 0 |
| Towels/rags | 3 | | | 3 |
| Rope/net pieces (non-nvlon) | 4 | | | 4 |
| Fabric pieces | 4 | | | 4 |
| Other: | | | | 0 |
| Overall | | | | 57 |
| <i>Other/unclassifiable</i> | | | | |
| Medical waste | 64 | | | 64 |
| Syringe | 80 | | | 80 |
| Brush | 2 | | | 2 |
| Bullet case | 2 | | | 2 |
| Light bulb | 9 | | | 9 |
| Led ceiling lamp | 1 | | | 1 |

(continued)

| Metal | | | | |
|--------------------------------------|-----------------------------------|-------------------|------------------------|-----------------------------------|
| Filter mask | | 1 | | 1 |
| Sawing needle | | 8 | | 8 |
| Baby diaper | | 3 | | 3 |
| Condom | | 1 | | 1 |
| Hygiene pad | | 1 | | 1 |
| Plane's seat arm rest | | 1 | | 1 |
| Overall | | | | 173 |
| Large debris items (>1 ft or ~0.3 m) | | | | |
| Item type (vessel, net, etc.) | Status (sunken, stranded, buried) | Approximate width | Approximate length (m) | Description/photo ID ³ |
| Wooden Pallet | Stranded/buried | 1.2 | Unknown | |
| Tyre | Stranded | 0.20 | 0.70 | Intact |
| Plastic bucket | Stranded | 0.35 | 0.50 | Intact |
| Plastic tube | Stranded/buried | 0.12 | 0.60 | Emerging from the sand |
| Tyre | Stranded | 0.27 | 1 | At the wreck line |
| Plastic tube | Stranded/buried | 0.027 | 1.37 | |
| Plastic box | Stranded | 0.3 | 0.5 | Broken |
| Wooden pallet | Stranded | 1.02 | 1.22 | |

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