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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.

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 Artic 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

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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-OHRLLS, 2009). The island of Aruba is no exception to this pattern.

The island of 180 km^2 is located 24 km north of the Paraguana peninsula of Venezuela and about 72 km west of the island Curaçao (Fig. 1 a). 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 ($M_{Leeward} = 4376 \pm 1357\ m^{-2}$, $M_{Windward} = 4000 \pm 1647\ m^{-2}$, 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