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Debris ingestion by juvenile marine turtles: An underestimated problem

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ABSTRACT

Marine turtles are an iconic group of endangered animals threatened by debris ingestion. However, key aspects related to debris ingestion are still poorly known, including its effects on mortality and the original use of the ingested debris. Therefore, we analysed the impact of debris ingestion in 265 green turtles (*Chelonia mydas*) over a large geographical area and different habitats along the Brazilian coast. We determined the death rate due to debris ingestion and quantified the amount of debris that is sufficient to cause the death of juvenile green turtles. Additionally, we investigated the original use of the ingested debris. We found that a surprisingly small amount of debris was sufficient to block the digestive tract and cause death. We suggested that debris ingestion has a high death potential that may be masked by other causes of death. An expressive part of the ingested debris come from disposable and short-lived products.

1. Introduction

The accumulation of anthropogenic debris, which is primarily plastic, in the marine environment was initially ignored or considered an isolated problem portrayed as an aesthetic concern (Derraik, 2002; Laist, 1987). However, ocean debris has become one of the most ubiquitous and long-lasting changes in natural systems (Barnes et al., 2009). Despite all of its well-recognised impacts on marine wildlife, biodiversity and human health (Gregory, 2009; Rochman et al., 2013; Teuten et al., 2009; Thompson et al., 2009a) the production of plastic and its release into the environment are intensive, continuous and rising (Cózar et al., 2014; Jambeck et al., 2015; PlasticEurope, 2012; Rochman et al., 2013; Thompson et al., 2009b). Recently was estimated that at least 5.25 trillion particles are floating at sea (Eriksen et al., 2014), and 4.8–12.7 million tons entered the ocean in 2010 alone (Jambeck et al., 2015). Currently, anthropogenic debris can be found virtually everywhere in the oceans and coastal ecosystems (Barnes et al., 2009; Ryan and Moloney, 1993; Thompson et al., 2009b), including isolated protected areas (Baztan et al., 2014; Heskett et al., 2012), due to the characteristics of plastic (e.g. durability and lightweight) and its indiscriminate use in disposable and short-lived products (Hopewell et al., 2009).

Anthropogenic debris impacts over 350 marine species (Gall and Thompson, 2015; Laist, 1997), and debris ingestion is a widespread phenomenon both geographically and taxonomically (Anastasopoulou et al., 2013; Bravo Rebolledo et al., 2013; Codina-García et al., 2013; Lusher et al., 2013; Murray and Cowie, 2011; Williams et al., 2011). Debris ingestion can lead directly to death through the blockage of the digestive tract, and it can have sublethal effects, such as a decrease in nutritional gain and exposure to the chemicals leaching from plastic (Ashton et al., 2010; Fisner et al., 2013; Gregory, 2009; Teuten et al., 2009; Yamashita et al., 2011). Marine turtles represent an iconic group of endangered marine animals that are threatened by debris ingestion. Six of the world's seven species have been reported to ingest debris (Schuyler et al., 2014). Although there is a vast body of literature on anthropogenic debris ingestion (Gregory, 2009) and debris ingestion by marine turtles is considered a global research priority (Hamann et al., 2010), the mortality caused by debris ingestion is still poorly known.

The removal of anthropogenic debris from all coastal and oceanic habitats is a nearly impossible task. The first, and more realistic, action to reduce the impact of anthropogenic debris on marine fauna is to avoid the production and entrance of debris into the ocean basins (Gregory, 2009). To do that, we must know the original use of the debris ingested by marine animals. Unfortunately, this key information is lacking in most studies of animal debris ingestion.

Debris ingestion by marine turtles has increased over time (Schuyler et al., 2014). This increase reinforces the need for information about the key aspects related to debris ingestion that are

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still poorly known, including its effects on mortality and the original use of the ingested debris. Therefore, our aims were to (i) quantify the debris ingestion by green turtles (*Chelonia mydas*) over a large geographical area and different habitats; (ii) quantify the deaths caused by debris ingestion and the amount of debris sufficient to cause death; and (iii) determine the original use of the ingested debris.

2. Methods

From 2009 to 2013, 265 dead stranded green turtles were collected along the Brazilian coast (Fig. 1). Detailed information about the study area is shown in Table 1. To evaluate the cause of death, only fresh dead animals were collected. The dead stranded turtles were found during intensive coastal monitoring conducted by TAMAR/ICMBio and CTA – Serviços em Meio Ambiente teams. The necropsies and biometry (weight and curved carapace length – CCL) were performed by trained veterinarians using standard techniques (Wyneken, 2001). To be conservative, we only assigned debris ingestion as the cause of death when the gastrointestinal tract was blocked by debris and there was no evidence of another cause of death. The cause of death was attributed to a fishery when we knew that turtles were caught by fishermen or when we found clear marks of catch equipment interaction (e.g., net wounds). The body conditions of the individuals were evaluated according to Walsh (1999). The body condition was classified as normal, underweight or emaciated by considering the characteristics of the eyes and plastron and the decrease in muscle and fat tissue in the neck and flipper area. We also calculated the body condition index (BCI $\times$ 10^5) using Fulton's index (BCI = weight/CCL^3). All animals were examined for presence of fibropapillomatosis, a debilitating

Table 1
Areas and habitats along the Brazilian coast where dead stranded green turtles were collected (N, number of individuals; CCL ± SD, mean curved carapace length ± standard deviation).

	Study area	Habitat	N	CCL ± SD (cm)
1	Sergipe coast (10°53′S, 36°50′W)	Estuarine area	22	42.6 ± 20.4
2	Linhares (19°40′S, 39°70′W)	Estuarine area	21	35.1 ± 3.5
3	Fundão and Aracruz (20°01′S, 40°09′W)	Reef	81	36.5 ± 4.6
4	Vitória (20°18′S, 40°17′W)	Reef (highly urbanised)	103	39.8 ± 7.4
5	Vila Velha (20°25′S, 40°19′W)	Reef	14	37.1 ± 5.3
6	Ubatuba (23°25′S, 45°01′W)	Reef	17	38.1 ± 5.6
7	Florianópolis (27°26′S, 48°19′W)	Reef	7	38.5 ± 3.6

disease that commonly affect green turtles (Herbst, 1994). To avoid bias we excluded all animals that were moderately or heavily affected by this disease from our body condition analysis (Work and Balazs, 1999).

We analysed the entire gastrointestinal system to retrieve debris. The anthropogenic debris found in the green turtles was washed and dried at 60 °C for 48 h. Each piece of debris was categorised according to its material (e.g., hard plastic, soft plastic, rubber, nylon and rope) and investigated to determine the original use (e.g., food related, plastic bag and fishery). All materials and original use categories were quantified by the frequency of occurrence and number of items. We also quantified the materials by their weight (0.01 g) and volume (0.1 ml; via alcohol displacement). To avoid overestimating the amount of debris ingested, only fragments longer than 0.5 cm were considered an item. We considered that debris smaller than 0.5 cm may be generated by fragmentation of larger items inside the turtle. Therefore, these items were

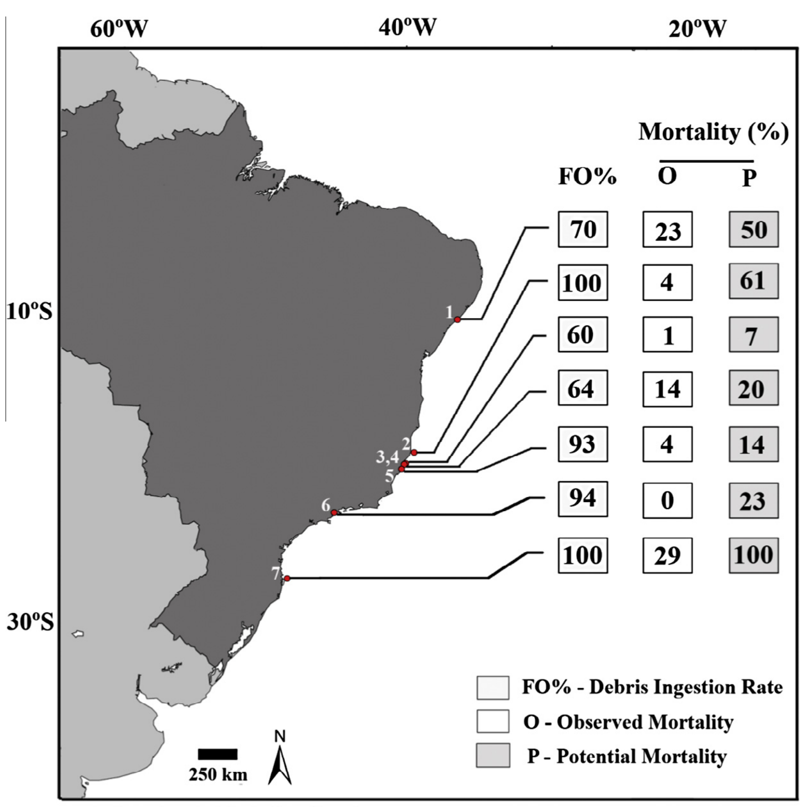

Fig. 1. Study areas along the Brazilian coast where dead stranded green turtles were collected (1 – Sergipe coast; 2 – Linhares; 3 – Fundão and Aracruz; 4 – Vitória; 5 – Vila Velha; 6 – Ubatuba; and 7 – Florianópolis. Detailed information in Table 1). Debris ingestion rate (FO%), the relative number of individuals that died due to debris ingestion (O) and the relative number of individuals that ingested debris above the critical amount (P).

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only included in the total weight and volume of the material. On the contrary, plastic pellets (raw plastic material of plastic products) were considered an individual item, independent of size.

We determined the minimum amount of ingested debris that was sufficient to cause the death of a juvenile green turtle through the blockage of the digestive tract, which we called the "critical amount". The potential mortality rate was calculated by adding the number of individuals that died due to debris ingestion to the number of individuals that died due to other causes but ingested larger amounts of debris than the critical amount. We considered only the animals of the same size-class in the potential mortality calculations to avoid bias.

We used the Mann Whitney-*U* test to evaluate the difference in BCI between turtles that died due to debris ingestion and turtles that had a normal body condition and died due to fishery interaction. We used an analysis of similarity (ANOSIM) to evaluate the differences in debris material composition between turtles that died due to debris ingestion and turtles that died due to other causes. To illustrate this relationship, we employed the Multidimensional scaling analyses (MDS). The Bray-Curtis similarity matrix was generated from the relative weight of each material for each turtle. We used the Mann Whitney-*U* test to evaluate the difference in the CCL and the weight of debris ingested between turtles that died due to debris ingestion and turtles that died due to others causes. We used the Spearman's correlation test to evaluate the relationship between the ingested debris weight and volume.

3. Results

All of the analysed turtles were juveniles, and the mean CCL of the turtles was 38.0 cm (SD: 6.6; range: 26.1–78.4 cm). Approximately 70% of the 265 turtles examined had ingested debris. The debris ingestion rate (FO%) was high in all of the areas, varying from 60% to 100% (Fig. 1). Turtles ingested a total of 8975 debris items, with a mean number of 47.5 items per turtle that ingested debris (SD: 120.1; range: 1–965 items). We found that ingested debris weight and volume were highly correlated ($r = 0.85$, $p < 0.01$); therefore, we present our data using only weight because of the high precision of this measure. These items accounted for 531.9 g, with a mean weight per turtle of 2.8 g (SD: 8.5; range: <0.1–75.2 g). It was possible to determine the cause of death of 73.3% of the individuals, and the major cause of death was associated with fishery activities (52.5%). Death caused by debris ingestion varied largely according to the area (Fig. 1), with a mean frequency of occurrence of 10.7%. Higher mortality rates from debris ingestion were observed in estuarine habitats (area 1), a highly urbanised reef (area 4) and the southernmost reef (area 7) (Fig. 1).

Death caused by debris ingestion resulted from a chronicle process. All of the individuals that died due to debris ingestion were underweight or emaciated. In addition, we found a significantly higher ($p < 0.01$) mean BCI of turtles that died due to fishery activities (10.9) compared with those that died due to debris ingestion (8.2). This difference was illustrated by the size-weight relationship shown in Fig. 2a. The analysis of the debris ingested by turtles that died due to their ingestion revealed that the critical amount of debris that was sufficient to lead a juvenile green turtle to death through the blockage of the digestive tract was very small, only 0.5 g (Appendix S1). Additionally, 47% of the turtles died due to the ingestion of less than 2.5 g of debris (Fig. 2b). When we compared the CCL ($p = 0.14$), weight ($p = 0.26$) and material composition (ANOSIM: $R = -0.03$ and $p = 0.69$; Fig. 02c) of the ingested debris between turtles that died due to debris ingestion and those that ingested debris greater than the critical amount (0.5 g) but died due to other causes, we did not find any significant differences. Therefore, we found that the potential mortality rate of debris ingestion was higher than the observed mortality rate, with mean values of 39.4% and 10.7%, respectively. The potential mortality rate varied greatly among areas, and higher rates were observed in estuarine habitats (areas 1 and 2), highly urbanised reef (area 4) and the southernmost reef (area 7) (Fig. 1).

Plastic was the major debris material and was found in 89.2% of the turtles that ingested debris. Plastic accounted for 68.6% of all of the ingested debris weight. Plastic and nylon/rope represented the main materials found in all of the areas (Fig. 2d). Natural debris, such as fragments of wood and feathers, was also found, though in small amounts (Fig. 2d). We found 163 plastic pellets distributed in 11 turtles, which represented less than 1% of the total debris weight. Most of the ingested debris originated from land-based sources, accounting for 87.8% of the total items (Fig. 3). All of the debris considered to be directly discarded into the ocean had their original use related to fishery activities. It was only possible to identify the original use of 2.8% of the land-based debris. The majority of the identified items were related to food activities (Fig. 3). Food-related debris was divided in two main classes: single-use products (plastic cups and straws) and junk food (e.g., candies and soft drink). Fragmented plastic bags were difficult to distinguish from other soft plastics. However, we found that 11.5% of the identifiable items were a very specific non-fragmented part of a plastic bag (the detachable central portion, Appendix S2). This finding suggested that plastic bags may represent a large amount of the ingested debris, primarily because most of the non-identifiable flexible plastic, which accounted for 41% of all items, were similar to plastic bags (Appendix S3).

4. Discussion

Our results showed that the impacts of anthropogenic debris on marine turtles were widespread. More importantly, we showed that a very small amount of debris was sufficient to cause the death of juvenile green turtles, particularly those that were recently recruited to the neritic zone. Additionally, we demonstrated that death caused by debris ingestion derived from a chronicle process. Together, these data suggested that the potential lethality of debris ingestion was possibly underestimated and masked by other causes of death. Plastic accounted for most of the ingested debris. We suggested that large amount of the ingested debris might come from plastic bags and food related items, based on the items that had their original use identified.

4.1. Debris ingestion and mortality

Marine debris impacts turtles in all life stages (e.g. Mrosovsky et al., 2009; Schuyler et al., 2012; Witherington et al., 2012) and its ingestion by green turtles is rising (Schuyler et al., 2014). Our results showed that the observed mortality by debris ingestion was usually low in most of the studied areas, varying from 0% to 29%, which was in accordance with the few studies that estimated the death caused by debris ingestion (approximately 4%, Schuyler et al., 2014). Fisheries are considered a major driver of population declines for many marine species (Jackson et al., 2001), especially marine turtles (Lutcavage et al., 1997), which agreed with our findings. On the contrary, we showed that the ingestion of only a small amount of debris was sufficient to lead a juvenile green turtle to death through the blockage of the digestive tract, particularly among those animals that were recently recruited to the neritic zone (CCC = 25–45 cm). An amount as small as 0.5 g blocked the digestive tract of two juvenile turtles. This amount was a quarter of the minimum amount found by Bjorndal et al. (1994). Put in perspective, this amount is approximately one-tenth of a typical plastic bag (4–5 g). Despite the current recognition of debris ingestion as an important threat to the conservation of green turtles

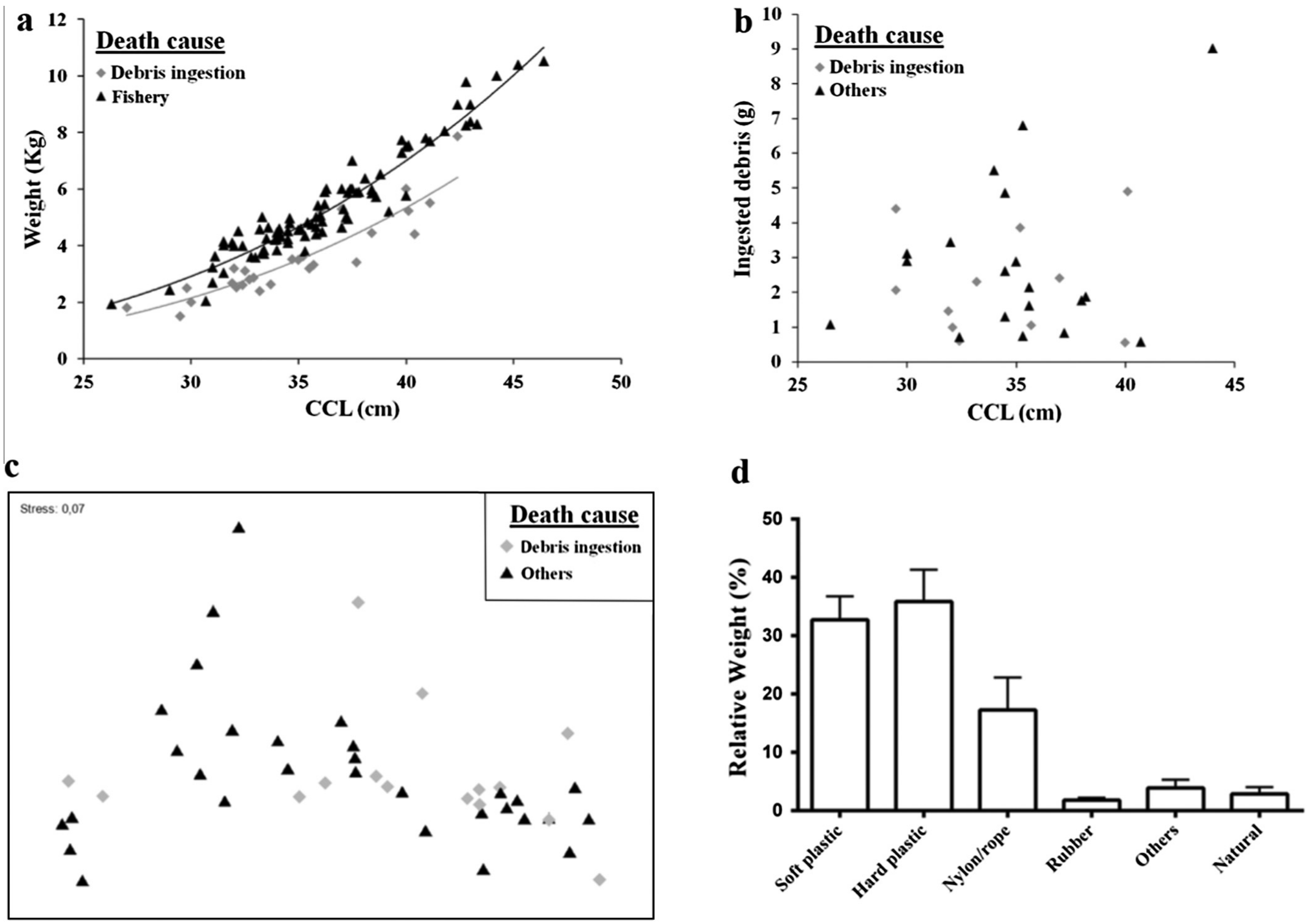

Fig. 2. (a) Size-weight relationship of green turtles with normal health conditions that died due to fishery activities (▲) and green turtles that died due to debris ingestion (◆). (b) Weight of ingested debris found in green turtles that died due to debris ingestion (◆) and in individuals that died due to other causes (▲). Only recently recruited juvenile green turtles were used, therefore, turtles larger than 45 cm CCL are not shown in this figure. We also excluded from this figure those turtles whose debris ingestion exceeds 10 g. (c) MDS analyses illustrating the differences of debris material composition between turtles that died due to debris ingestion (◆) and turtles that died due to other causes (▲). (d) Mean relative weight of debris materials ingested by green turtles from the seven collection locations along the Brazilian coast.

populations (Hamann et al., 2010), our results suggested that debris ingestion may be a larger problem. Our data supported the idea that the high impact of fishery activities on green turtles is masking the real threat imposed by debris ingestion for the following reasons: (i) interaction with fishery activities is the current main cause of green turtles death; (ii) the ingestion of debris is geographically widespread and the rate of ingestion is very high; (iii) small amounts of anthropogenic debris are sufficient to block the digestive tract causing the death of juvenile green turtles; (iv) the death caused by debris ingestion is a chronicle process, while interactions with fishery activities results in a rapid death; and (v) there was no difference between the amount and composition of debris ingested by turtles that died due to debris ingestion and those that ingested debris above the critical amount and died due to other causes, including fishery interactions. These reasons led us to estimate that the mean potential lethality of debris ingestion was higher than the observed mortality, which was approximately four times greater in our study. We believed that the underestimation of debris ingestion death potential may undermine management and conservation actions. Despite the difficulty of creating a marine protected area, it is relatively easier to protect green turtles from fishery interactions than to protect them from the impacts caused by marine debris ingestion. This difficulty is justified because the major component of marine debris is plastic, a durable material that has a high capacity for dispersion and faces increasing production and use (Cózar et al., 2014; Derraik, 2002; PlasticEurope, 2012). Therefore, the amount of plastic currently found in the marine environment will persist for many decades, at least. Additionally, cleaning up habitats is an extremely hard task because the high capacity of dispersion allows plastic debris to pollute virtually all marine habitats (Cózar et al., 2014; Eriksen et al., 2014; Lee and Sanders, 2014; Pham et al., 2014), with no respect for the boundaries of marine protected areas (Baztan et al., 2014).

Plastic debris is found in all oceans basins from pole to pole, even in the most remote islands (Barnes et al., 2009; Heskett et al., 2012). However, it shows a very patchy distribution, due to different factors, including local winds, currents, coastal geography and the distance from points of entry into the system (Barnes et al., 2009; Cózar et al., 2014; Derraik, 2002; Lebreton et al., 2012). Our results showed that turtles from estuarine areas and the southernmost area were at a higher risk than were turtles from other areas. The risk of the turtles from the southernmost reef area was most likely related to their foraging strategy. Turtles in this area consume a larger amount of pelagic diet items (e.g., ctenophore) (Reisser et al., 2013) than do turtles from the other reef areas (Ferreira, 1968; Santos et al., 2011; Sazima and Sazima, 1983), which may favour these turtles encountering floating plastics. High debris ingestion in the southernmost distributional area of green turtles was also found in other studies conducted in South America (Bugoni et al., 2001; González Carman et al., 2014). The higher occurrence of debris ingestion and the subsequent mortality

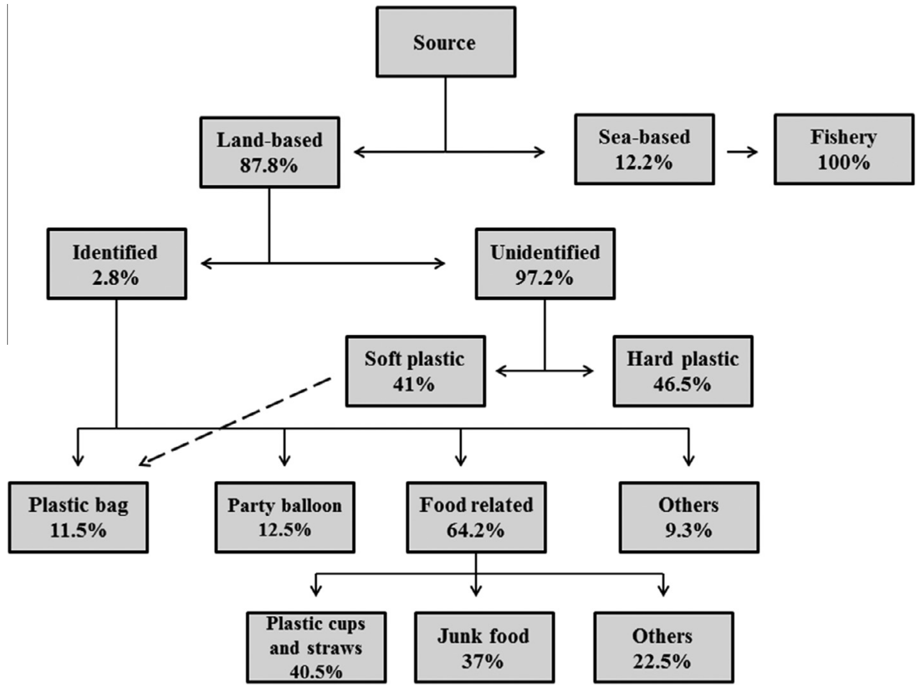

Fig. 3. Schematic figure of debris sources (land-based and sea-based) and the original use of the identified items that were ingested by green turtles. The dashed arrow indicates the probable origin of the unidentified fragments of soft plastic.

in estuarine areas most likely occurred because rivers are one of the most important entrances of debris in the oceans (Barnes et al., 2009). In this manner, animals from the estuarine areas were exposed to large amounts of debris. A similar reason applies to turtles from the highly urbanised reef area because cities are also an important source of debris; consequently, their coastal areas are important points of entry (Barnes et al., 2009; Leite et al., 2014). It is crucial to obtain knowledge about the origin of the debris that pollutes the natural environments to take effective measures and prevent the production of such debris and their entry in the natural environment.

4.2. Source and original use of the debris

Land-based plastics accounted for the majority of ingested debris, as found by most of the studies on sea turtles (Schuyler et al., 2014) and other species (Boerger et al., 2010; Codina-García et al., 2013; Ryan, 1987; Stephanis et al., 2013). However, fishery gear also had an important contribution to the ingested debris, accounting for approximately 12% of the total debris items. Therefore, fishery activities had a large impact on sea turtles both through direct death due to incidental capture and by contributing a considerable part of the ingested debris.

Information on the origin of the debris ingested by animals is very important for solving the debris ingestion problem. The land-based debris may have been deposited directly on the beaches or carried by wind and rain because their weight allows such debris to travel long distances from their source, particularly soft plastics. It was not possible to identify the majority of hard plastic fragments. However, most of them were thick and seemed to be in the environment for a long time. This debris most likely originated from the fragmentation of durable products. The evaluation of land-based debris indicated that plastic bags, single-use items (e.g., plastic cups and straws) and junk food packaging were important sources of ingested debris. The use of plastic in these products is perhaps the most unsustainable and superfluous use of plastic, which is different from the possible applications with societal benefits that some plastic products have, such as lightweight durable products and medical devices (Andrady and Neal, 2009). Plastic bags are perhaps the most iconic symbol of the unwise use of plastic. Plastic bags were considered one of the most dangerous types of plastic debris to marine fauna in the 1980s (Laist, 1987). However, the use of plastic bags is frequent in everyday life in most cities, though re-usable bags are an effective and inexpensive alternative.

4.3. Wider implications

Here, we presented data showing that the debris ingestion, a problem that is already recognised as a major threat to marine turtle conservation (Hamann et al., 2010), may be an even greater problem. Our findings serve as an alert for other marine species that are also affected by debris ingestion, such as sea birds and marine mammals. We evaluated only the direct death caused by the blockage of the digestive tract with anthropogenic debris, but the problem extends to other physical harm, such as nutrient gain reduction, which might have long-term impacts (e.g., decreases in growth rates, reductions in reproductive output and decreases in survivorship (McCauley and Bjorndal, 1999)). Additionally, individuals might be subjected to harmful chemicals that are present or absorbed by marine plastic debris, such as organic contaminants (e.g., PCBs, petroleum hydrocarbons and organochlorine pesticides), that can disrupt key physiological processes and the immune system (Fisner et al., 2013; Rochman et al., 2013; Teuten et al., 2009; Yamashita et al., 2011). The consequences of these secondary threats must be better understood.

The indiscriminate use of plastic has a direct impact on humans, not only by threatening ecologically and commercially important species but also by consuming resources. Approximately 8% of the world's oil and gas is consumed in plastic manufacturing (Hopewell et al., 2009), and solid-waste management is one of the greatest costs to cities (Hoornweng et al., 2013). Over the last 30 years, a reasonable number of studies reported the threats of the indiscriminate use of plastic to the environment and provided a number of recommendations to address this problem (González Carman et al., 2015; Jambeck et al., 2015; Laist, 1987; STAP, 2011; Thompson et al., 2009b; UNEP, 2005). Rochman et al. (2013) suggested that we already have enough reasons to classify most harmful plastic waste as hazardous, and this approach can help control plastic production and give power to environmental agencies to restore affected habitats and prevent more debris accumulation. The problem and its possible solutions are widely recognised. Our study reinforced that the plastic debris issue is a current problem, not just a future problem. All of the gathered data make it clear that our use of plastic in short-lived and disposable products is environmentally harmful. Marine debris is an important problem that has long-lasting consequences to the marine ecosystem and humans, but what is more concerning is that the marine debris problem is only the tip of a bigger problem: the increase in waste production derived from the unsustainable consumption of natural resources.

5. Conclusions

Marine debris is a major threat to marine animals (Laist, 1997), and recent studies have shown that debris ingestion by marine turtles is rising (Schuyler et al., 2014). We showed that a surprisingly small amount of debris was sufficient to block the digestive tract and cause the deaths of juvenile green turtles and that a large part of the ingested debris might come from disposable and short-lived plastic products. The threat of debris ingestion varies according to the turtles' foraging strategy and proximity to the debris entrance point in the oceans. More importantly, our data suggested that debris ingestion has a high death potential that may be masked by other causes of death. We believed that our findings are important for other marine animals, serving as an alert for marine species that are affected by debris ingestion, such as sea birds and marine mammals. The underestimation of the debris ingestion death potential may undermine the future of marine species populations, due to the rising accumulation of plastic waste in the natural environment (Thompson et al., 2009b), which may persist for centuries in coastal and oceanic habitats worldwide (Derraik, 2002; Thompson et al., 2004).

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.marpolbul.2015.02.022.

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