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Transboundary movement of marine litter in an estuarine gradient: Evaluating sources and sinks using hydrodynamic modelling and ground truthing estimates

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ABSTRACT

Marine debris' transboundary nature and new strategies to identify sources and sinks in coastal areas were investigated along the Paranaguá estuarine gradient (southern Brazil), through integration of hydrodynamic modelling, ground truthing estimates and regressive vector analysis. The simulated release of virtual particles in different parts of the inner estuary suggests a residence time shorter than 5 days before being exported through the estuary mouth (intermediate compartment) to the open ocean. Stranded litter supported this pathway, with beaches in the internal compartment presenting proportionally more items from domestic sources, while fragmented items with unknown sources were proportionally more abundant in the oceanic beaches. Regressive vector analysis reinforced the inner estuarine origin of the stranded litter in both estuarine and oceanic beaches. These results support the applicability of simple hydrodynamic models to address marine debris' transboundary issues in the land-sea transition zone, thus supporting an ecosystem transboundary (and not territorial) management approach.

1. Introduction

Marine debris are persistent solid waste that enters the marine environment generated by land- or marine-based activities (Coe and Rogers, 1997) and it is estimated that 80% of marine debris comes from land-based activities (Windom, 1992). Marine debris can be categorized into different material classes, including cloth, rubber, paper, processed timber, glass and ceramic, metal and plastics (Cheshire et al., 2009). Several studies indicate that most marine debris (50–90%) is composed by plastics (Barnes et al., 2009; Gall and Thompson, 2015; Thompson et al., 2004) and it is estimated that between 4.8 and 12.7 metric tons of plastic debris enter the oceans annually (Jambeck et al., 2015). Since 46% of the plastic produced shows floatability in its original form (Li et al., 2016; Stevenson, 2011), they are able to disperse and generate impacts in areas distant from sources (Carson et al., 2013; Duhec et al., 2015; Maximenko et al., 2012). Marine debris pollution is thus a global problem and there is a plethora of literature describing its negative effects on biota, society and local and national economies (Coe and Rogers, 1997; GESAMP, 2015; Gregory, 2009; Jang et al., 2014; Juying et al., 2016; Mouat et al., 2010; Potts and Hastings, 2011; Thompson et al., 2009; UNEP, 2016). Despite its global ubiquity, marine debris' adverse effects are a concrete and visible problem at the local level, requiring engagement of local stakeholders to reduce its input and to remove it from the environment (Liu et al., 2013). In some cases, sinks of marine debris, *i.e.* beaches, are out of the geopolitical limits of the generator locations (Nixon and Barnea, 2010), situation where a transboundary co-operation among neighbouring municipalities, states or nations is required. There are notable efforts in monitoring regional seas (Cheshire et al., 2009; Galgani et al., 2010; Schulz et al., 2013), which support the adoption of a transboundary approach to marine debris. However, comprehension of aspects that reinforce the need of a transboundary approach (and not a territorial one) to marine debris are somehow understudied, especially at the local level. Investigating the relationship between sources and sinks, establishing the debris pathways and environmental conditions that define its trajectory are examples of gaps to be fulfilled (Ryan et al., 2009).

It is common for scientific studies to claim enforcement of annex V, from the MARPOL agreement, as a solution to prevent these “orphan” marine debris to reach seas and oceans (Duhec et al., 2015; Lane et al., 2007; UNEP, 1990). Relying exclusively on adoption of

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this agreement will only deal with ocean-based marine debris loads and some important transboundary aspects remain unmanaged. On other hand, fully adopting transboundary approaches would imply new and a frequently unknown ecosystem based co-operation efforts of international or neighbouring sub-national jurisdictions (Sandwith et al., 2001).

One effort intended to disseminate the transboundary approach is the Honolulu Strategy (NOAA and UNEP, 2011). The Honolulu Strategy emerged as a transboundary framework that deals with prevention of introduction of litter into the sea. Its three goals are focused on reducing both the amount and impacts of ocean and land-based sources of litter and diminishing accumulated marine debris in the environment. It focuses not only in shorelines but also in benthic habitats and pelagic waters (NOAA and UNEP, 2011) and thus incorporates the transboundary approach (Agardy et al., 2011). However, there is a core limitation to its full adoption, which is the lack of a widely-recognized framework that powerfully links litter to their sources (Tudor and Williams, 2004). This uncertainty undermines the recognition that marine debris may be a transboundary issue in certain regions. Consequently, marine debris may be treated as a low priority issue by decision makers, especially from locations that are sources, but not sinks. This scenario reinforces that proper establishment of the most probable origin of beached marine debris is crucial.

Marine debris monitoring programs are essential to identify sources, but they are costly (Earll et al., 2000; McIlgorm et al., 2008) and sometimes are not effective in their purpose (Tudor and Williams, 2004). Most worldwide methods used to establish an item's source fall into one of the following strategies: assigning items to a unique source (Earll et al., 2000); using indicator items (Ribic, 1998; Silva-Iñiguez and Fischer, 2003), and cross tabulating data in association with multivariate analysis or complex matrixes (Tudor et al., 2002; Tudor and Williams, 2004; Whiting, 1998). Each of these methods present limitations and the development of complimentary strategies to improve confidence on litter sources and sinks is a clear demand (Veiga et al., 2016). For instance, the usage of hydrodynamic models is an useful technique (Critchell et al., 2015; Duhec et al., 2015; Kataoka et al., 2013) that has also the potential to improve communication with society and decision makers. However, there exists a clear gap in its application in small-scale settings (Critchell et al., 2015), especially to support the transboundary management of marine litter (UNEP, 2016). Such approaches have also the potential to improve analyses about abundance and quality of marine debris in a comprehensively manner, considering local settings (Veiga et al., 2016). Marine debris' abundance is a function of proximity to urban centres (Leite et al., 2014), population behaviour (Slavin et al., 2012) and medium or large-scale oceanographic conditions (Duhec et al., 2015; Lebreton et al., 2012).

In fact, meteorological and oceanographic conditions, such as prevailing wind, tide currents and frontal systems (Liu et al., 2013; Walker et al., 2006) can be integrated under a model approach to contribute to identification of sources, pathways and sinks of litter in coastal and oceanic environments. Marine debris pathways and fates have being studied by the usage of global mapping, data from surface drifters and numerical models (Carson et al., 2013; Kataoka et al., 2013; Maes and Blanke, 2015; Maximenko et al., 2012). For instance, Kako et al. (2011) found that there exists a good reliability in forecasting amounts of marine debris that could lead to a reduced or optimized cost of cleaning. Also, crossing data obtained *in situ* with modelling has already been done on a global scale to evaluate the potential of plastic ingestion by sea turtles (Schuyler et al., 2016), estimating amount of debris in oceans (Lebreton et al., 2012) and addressing amounts of organic debris outflowing from embayment areas (Kataoka et al., 2013). However, the global scales and resolutions used in most of those models, especially applied to plastic debris movement (e.g., Lebreton et al.'s (2012) study has an average grid cell spacing of about 7 km), are not adequate enough for predicting accumulation areas at a more local scale (Critchell and Lambrechts, 2016).

Local or small scales are especially relevant in understanding the early steps of litter input into the ocean, since they represent places where most of the management measures and *in situ* marine debris' sampling take place. In this context, estuaries – in a worldwide perspective – become potentially excellent study areas to address the export and transboundary behaviour of marine litter due to the potential of marine debris generation, availability of information and sampling facilitation. In fact, estuaries and other regions where information about physical processes (winds, tidal dynamics, nearshore currents and wave patterns) is available, allows simulation of their interactions through oceanographic modelling. An example, is a study that estimated accurately the inflow of natural debris into Tokyo Bay by using simulations and results of *in situ* collection (Kataoka et al., 2013). The same logic may be applicable for other bays and estuarine regions where anthropogenic marine debris is observed. As observed by Kataoka et al. (2013), comparing results of simulations with ground truthing in such environmental setting may increase certainty about marine debris fluxes and origins in estuarine regions.

Estuarine regions and their neighbourhoods generally house high populated urban areas, harbour facilities and are an asset for leisure activities (Brown et al., 1991). In some cases, the circulation pattern of these areas is well known (Camargo and Harari, 2003). However, such data is not used for supporting management strategies, especially for the monitoring and control of marine debris (Mayerle et al., 2015). It is a fact that those environments remain understudied in relation to marine debris, especially in Latin America (Ivar do Sul and Costa, 2007). Nevertheless, some studies enlighten the dynamics of marine debris in estuaries. For instance, it is known that riverine inflows, tides, winds and currents play a significant role for litter spreading in estuarine regions (Brown et al., 1991; Browne et al., 2010; Gallagher et al., 2016). Also, salinity fronts, estuarine fronts and estuarine maximum turbidity zones influence debris distribution (Acha et al., 2003; Brown et al., 1991; Galgani et al., 2010; Largier, 1993; Possatto et al., 2015). Nevertheless, within a given estuary, differences are observed not only along the estuarine gradient (Acha et al., 2003; Possatto et al., 2015) but also between margins according to its degrees of pressure and level of urbanization (Procopiak et al., 2007; Tudor and Williams, 2001).

Some examples of those effects are the findings of Acha et al. (2003) that demonstrated Rio de la Plata salinity fronts working as a barrier to both benthic and marine debris. Similarly, but at a smaller scale, Possatto et al. (2015) observed that the estuarine maximum turbidity zones (EMTZ) potentially reduces the sediment transportation and inferred that benthic marine debris tend to accumulate in areas with low circulation and high sediment accumulation (Galgani et al., 2010). Previous studies also indicate that during high riverine flows, accumulation tend to occur seaward (Brown et al., 1991). These illustrate the varied influences of factors over marine debris distribution and exemplify that identification of sources is a less straightforward task in estuarine environments. Consequently, it reinforces those utilising complimentary methods for sourcing, which can congregate several of those aspects, *i.e.* hydrodynamic modelling, may be beneficial for advancing in the field.

The present study carried out a strategy to address the transboundary nature of marine litter in an estuarine gradient combining the results of a hydrodynamic model DELFT-3D applied to floating marine debris associated with marine debris collected *in situ*. The study was conducted in a Natural World Heritage Listed Site, Paranaguá Estuarine Complex, Brazil, and considered small temporal (days) and geographical (10s of km) scales. The study considered three steps. A simplified modelling of dispersion from probable sources was conducted to identify general marine debris movements and to identify sampling sites to characterize debris and confirm sources (ground truthing). Then, a single but synoptic *in situ* sampling was undertaken to characterize marine debris. Six sites were sampled along the estuarine gradient and most probable sources of actual items were identified (more information about each beach, is given below, in Section 3.2).