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Small-scale temporal and spatial variability in the abundance of plastic pellets on sandy beaches: Methodological considerations for estimating the input of microplastics

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ABSTRACT

Microplastics such as pellets have been reported for many years on sandy beaches around the globe. Nevertheless, high variability is observed in their estimates and distribution patterns across the beach environment are still to be unravelled. Here, we investigate the small-scale temporal and spatial variability in the abundance of pellets in the intertidal zone of a sandy beach and evaluate factors that can increase the variability in data sets. The abundance of pellets was estimated during twelve consecutive tidal cycles, identifying the position of the high tide between cycles and sampling drift-lines across the intertidal zone. We demonstrate that beach dynamic processes such as the overlap of strandlines and artefacts of the methods can increase the small-scale variability. The results obtained are discussed in terms of the methodological considerations needed to understand the distribution of pellets in the beach environment, with special implications for studies focused on patterns of input.

1. Introduction

Coastal environments are likely to accumulate much of the solid waste released by modern industrial and urban society to the oceans. Globally, millions of tons of plastic are produced every year and it is estimated that 10 to 20 million tonnes find their way into the world's oceans each year, costing an estimated US$13 billion per year in environmental damage to marine ecosystems (UNEP, 2014a). The industrial society chooses to take advantage of the light weight and durability of plastic and as a result it is found in nearly all modern products (Andrady and Neal, 2009). Nevertheless, these advantages also make plastic a serious environmental and health threat, as its widespread distribution and persistence in the ocean are favoured (Thompson et al., 2005; Oehlmann et al., 2009; Talsness et al., 2009; Rochman et al., 2013).

Among the wide spectrum of plastic debris, concern is growing over the threats posed by particles with an upper size limit of 5 mm in diameter, known as microplastics (Cole et al., 2011; UNEP, 2014b). Microplastics can originate from the fragmentation of discarded items or can be the industrial raw material for plastic products, such as virgin pellets, nibs or "mermaids' tears", which are categorized as the primary forms of microplastics (Cole et al., 2011). The sources of pellets found in the marine environment can be both marine and land-based and include losses during handling, transfer, transportation (Turner and Holmes, 2011) and possibly at port terminals (Manzano, 2009). Once lost, pellets and other microplastics reach coastal areas where tidal movements and alongshore drift currents carry these particles to the shoreline of habitats such as sandy beaches (e.g. Shiber, 1982; Moore et al., 2001; Kusui and Noda, 2003; Abu-Hilal and Al-Najjar, 2004; Ivar do Sul et al., 2009; Martins and Sobral, 2011; Liebezeit and Dubaish, 2012; Turra et al., 2014).

The loss of pellets represents a high cost to the environment and to industry, thus global efforts are in place to reduce losses along the production chain, such as 'Operation Clean Sweep' (OCS) created in the U.S. in 1992 and adopted in many countries (www.opcleansweep.org) and, the 'Declaration of the Global Plastics Associations for Solutions on Marine Litter' signed in 2011 (www.marinedebrissolutions.com/Declaration). Therefore, the need to understand patterns of distribution of plastic pellets and other microplastics across the beach profile is already established in the scientific community and industrial sector. Nevertheless, studies designed to evaluate the abundance and distribution of pellets and other microplastics on sandy beaches have been conducted in different tidal zones, using different sampling methods (see Hidalgo-Ruz et al., 2012), and usually not considering any possible artefacts caused by small-scale temporal and spatial variability associated with beach dynamics.

Plastics arriving on beaches are firstly deposited in the intertidal zone, commonly on drift or strandlines (Thornton and Jackson, 1998),

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defined as the marking left by the high water of tidal action, and typically composed of debris left after a high tide (although additional lines may be produced due to oscillation during the descending tide, see Fig. S1). The distribution of pellets and other microplastics is not uniform across the beach profile (Heo et al., 2013), neither along the beach, nor with depth (Turra et al., 2014). In the across-shore direction, pellets are limited to the surface of the sediment in the upper beach intertidal zone, but are concentrated on the upper backshore where they can be found down to 2 m depth (Turra et al., 2014). Thus, the intertidal zone acts as a zone of transference of pellets from the sea to the backshore, and potentially to the dunes, where they accumulate. As a consequence, depending on the beach height and depth of the sediment sampled, different estimates of microplastic distribution and abundance can be obtained. Estimates using surface sediment samples taken from the intertidal zone would, therefore, be more appropriate to evaluate the input or load of microplastics to the beach system (i.e. the amount of litter arriving on a beach; Escardó-Boomsma et al. (1995)), while those taken from the backshore and dunes, and preferentially considering the depth distribution of these particles, would be meaningful to evaluate their standing-stock (i.e. the amount of accumulated plastics in the habitat). Such clear distinction is an important point for the design of sampling strategies, comparisons among beaches and the proper interpretation of data in time series. Although such rationale is already incorporated into protocols and studies for the evaluation of macro debris on beaches (e.g. Cheshire et al., 2009; Ribic et al., 2010), it is usually not evident in studies on microplastics (but see Claessens et al., 2011).

Early surveys assessing meso-debris (2–20 mm fragments) loads (i.e. accumulation) demonstrated the importance of integrating estimates across the beach profile, sampling the surface sediment from transects running from the most recent high tide line up the beach to the storm strandline (Ryan and Moloney, 1990). In the intertidal zone, some studies evaluating the abundance and distribution of pellets were conducted using across-shore transects to integrate estimates across the beach profile, although the specific tidal zone varied or was not stated (Khordagui and Abuhilal, 1994; Abu-Hilal and Al-Najjar, 2009). Nevertheless, many studies on micro and macroplastics still use strandline areas to evaluate the abundance of debris (see Barnes et al., 2009) and again, the drift line considered, varied among studies (e.g. Browne et al., 2011; Martins and Sobral, 2011; Hidalgo-Ruz and Thiel, 2013; Dekiff et al., 2014) or was not stated (e.g. Ivar do Sul et al., 2009; Costa et al., 2010). Also, studies that have compared the abundance of microplastics among beaches, using samples from the intertidal zone, have either only sampled once per beach (Ivar do Sul et al., 2009; Martins and Sobral, 2011; Hidalgo-Ruz and Thiel, 2013) or repeated the sampling at each beach with largely spaced intervals (i.e. several months between samplings) (Khordagui and Abuhilal, 1994; Abu-Hilal and Al-Najjar, 2009). However, usually small-scale spatial and temporal variability is not considered. Moreover, sampling to compare abundance among beaches are usually not done contemporaneously, but samples for comparison have been taken from the different study beaches within a time window of several months (Khordagui and Abuhilal, 1994; Abu-Hilal and Al-Najjar, 2009; Ivar do Sul et al., 2009; Hidalgo-Ruz and Thiel, 2013). Only one study specified that the last high tide mark was used and also, that samples were taken at five beaches during equinoctial spring tides of a specific month (Martins and Sobral, 2011), thus controlling for any eventual consequences of not taking samples at the same time.

While studies have demonstrated that debris-stranding patterns are influenced by factors such as wave action (Thornton and Jackson, 1998), wind-driven water currents (Moore et al., 2001; Edyvane et al., 2004) and the direction of the prevalent wind (Browne et al., 2010), many other intrinsic factors may influence patterns of distribution on sandy beaches. These may be related to 1) the quantities of plastics commercialized in the nearby areas and local rain patterns, which may vary through the year or between years and influence the input of plastic debris into the marine system and onto sandy beaches; 2) the direction and morphology of the beach; and 3) barometric pressure, the cycle of the moon and the tidal stage, which together will influence tidal height. Moreover, the intertidal zone of sandy beaches is very dynamic and the distribution of the drift lines and the height of the shore reached by each high tide may vary on a daily or even on a tidal cycle basis. These variations are influenced by a combination of intrinsic factors affecting beach dynamics, such as the local tidal type (i.e. diurnal, semi-diurnal or mixed), the tidal stage (i.e. ebbing or flooding), height oscillations during descending tides, changes in wave action and wind forces (see Jackson et al., 2002; Ryan et al., 2009). Due to these factors, drift lines in the intertidal zone may or may not suffer an overlapping effect during subsequent tidal cycles and long-term debris may also be accumulated on storm strandlines in the backshore, thus potentially causing significant noise in estimates of microplastics based on point samples.

Hence, gathering knowledge about the influence of these factors is of central importance to the development of sampling methods and non-confounded sampling designs, with sufficient replication on appropriate temporal and spatial scales, to adequately quantify trends (Ryan et al., 2009) in terms of the input and accumulation of microplastics on sandy beaches. Nevertheless, factors such as the cycle of the moon, tidal stage and, especially, the history of the strandline are not usually considered in studies evaluating the distribution of microplastics in the intertidal zone of sandy beaches. These factors may increase temporal and spatial variability in the data, directly influence estimates of pellet abundance in the beach environment and possibly explain part of the high variability observed on estimates of micro-plastics distribution in data sets around the world (Gregory, 1978; Khordagui and Abuhilal, 1994; Abu-Hilal and Al-Najjar, 2009; Kershaw and Leslie, 2012; Dekiff et al., 2014).

The aim of this study was to investigate the small-scale temporal and spatial variability in the abundance of pellets in the intertidal area of a sandy beach and evaluate factors that can increase the variability in data sets from that coastal area. To achieve this aim, we estimated the abundance of pellets in drift lines during consecutive tidal cycles to test the specific hypotheses that the abundance of pellets sampled from drift lines would vary according to the tidal cycle and the sampling day (temporal scale; hypothesis 1) and that the number of pellets would be different among drift lines across shore (spatial scale; hypothesis 2). The underlying assumption of this study is that calculations of the abundance of plastic pellets in the intertidal of sandy beaches are highly influenced by environmental processes at a very small spatial and temporal scale and thus may not allow accurate and comparable estimates among areas and between studies without a strict sampling design.

2. Methods

2.1. Study area and sampling design

The study was conducted during 2010 at Pontal do Sul, a sandy beach located close to the mouth of the Paranaguá estuary, Paraná State, southern Brazil (Fig. 1). The selected study site was located in front of the Center for Marine Studies (Federal University of Paraná). Site selection was based on the abundance of natural debris, which was used as marker/indicator of the drift line position as well as the proximity to the Port of Paranaguá (located about 20 km inland), a possible source of pellets to the sampling area. The sampling strategy consisted of limiting the spatial scale (i.e. variability) and intensifying and refining the temporal and micro-spatial scale, considering a location with semi-diurnal tidal cycles, with diurnal inequality, during 12 subsequent tidal cycles.

Sampling started on the full moon on 30th January 2010 and finished in the waning moon on 4th February 2010. Tidal range during this period varied between 0.1–1.6 m (1st day) to 0.5–1.4 m (6th day) (Diretoria de Hidrografia e Navegação, 2010 — at Barra de Paranaguá, Canal Sueste, Estado do Paraná). Prior to the sampling, there were 22 days of constant rain with stronger peaks on the 8th and 23rd