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A modeling approach for reposition dynamics of litter composition in coastal areas of the city of Santos, Sao Paulo, Brazil

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ABSTRACT

Given the complexity of the dynamics in litter reposition, our objective was modeling the possible main and interaction effects of tidal oscillations, seasons of the year and the moon phases over the solid waste in Santos beaches. A total of 80 collections were carried out using quadrat sampling, from which we classified, counted and weighed all residue items. We fitted mixed Hurdle models to the output datasets and performed hypotheses tests based on this framework. We found plastic to be the most abundant residue in all seasons, moon phases and tides, followed by Styrofoam and wood. Our models suggest the strongest effect was due to seasonal variations, which, in turn, may be related to different human activities. Although the dynamics of different components showed independency of all interaction structures, plastics depended on the interaction of tide and season, whose impact over estuarine life and ecosystem services shall be further investigated.

1. Introduction

The solid residue composition in the marine environment has drawn attention in the past decade, due to its clear damaging effects over human health, species diversity and habitat quality as well as due to economic and aesthetic losses (Abu-Hilal and Al-Najjar, 2004; Krelling et al., 2017; Rech et al., 2016). The most common litter found by researchers is plastic and plastic-based materials (Cordeiro and Costa, 2010; Fazey and Ryan, 2016; Schulz et al., 2015), which led to further studies focusing the spatial and temporal distribution of this type of residue (Cannas et al., 2017; Doyle et al., 2011; Syakti et al., 2017).

Although plastics are expected to be the greatest contributors in debris composition (see Derraik, 2002 and Ivar do Sul and Costa, 2007 for comprehensive reviews on this issue), other types of solid waste may endanger estuarine life as well. Galgani et al. (2014) pointed out that different types of macrolitter (e.g., fishing gear) may compromise the life cycles of marine vertebrates. In addition, Oigman-Pszczol and Creed (2007) found paper residue to be the main source of anthropic litter in coastal areas of Búzios (State of Rio de Janeiro, Brazil), to which they attributed to effects of tourism and recreation during holidays and peak seasons.

The hypothesis of season effects over the reposition dynamics of litter in coastal and estuarine areas has been of concern in rather recent studies. Golik and Gertner (1992) suggested that tourism intensity and winter storms are important factors in controlling the residuals in Israeli beaches. According to Rech et al. (2014), seasonal differences in beach debris abundances and composition are to be expected due to rainfall variation and human activities. The above-ground washes during rainy seasons carry different debris types that commonly end up at the sea shore through river loading (Jayasiri et al., 2013).

In addition, the composition and overall amount of solid waste are expected to increase with anthropogenic disturbance, i.e., in populous areas, where a greater number of human activities takes place, then greater is the quantity of litter and more diverse is its composition. Terzi and Seyhan (2017) verified that beach littering, originated from improperly stored or discarded terrestrial solid, waste was carried to the shore by the surrounding rivers. Accordingly, Cannas et al. (2017) found both, qualitative and quantitative, differences in plastic litter sediments across coastal areas in the south of Tuscany, which they related to the dynamics of floods. Simeonova et al. (2017) found a substantial increase in littering during the summer when compared to other seasons, which they attributed to recreational activities and to the increase of the touristic flux. Furthermore, human activities are responsible for qualitative differences found in the debris neighboring harbors in Northern Ireland (Williams et al., 2017).

Conjointly with seasons, tidal fluctuation is commonly assumed to

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influence the abundance in numbers or in weight of litter in the shore. Since the early work of Caulton and Mocogni (1987), there has been little effort to more directly evaluate the effect of tides over solid residue in the coast, nonetheless. Storrier et al. (2007) argue that marine currents, climatic conditions and tidal patterns are the strongest factors influencing the solid waste dynamics on the beaches of Firth of Forth (Scotland). They state that detailed climatic data are important descriptors and provide the basis for predicting the most probable locations of litter accumulation and that storm conditions combined with tidal cycles are the most likely explanation for the periodic increase in the debris abundance of beaches, due to the transport of offshore littering.

Even though the city of Santos (State of Sao Paulo, Brazil) harbors the largest marine port in South America and its considerably urbanization and industrialization, most studies evaluating beach quality and coastal pollution in Brazil were conducted in the Northern region (Ivar do Sul and Costa, 2007). Thus, we aimed at evaluating the possible effects of season, moon phases and tidal status over the dynamics solid waste in Santos beaches as well as at evaluating the composition of the litter. We tested the following hypotheses regarding the overall quantity of solid waste: (i) increase during spring and summer, due to both tourism and rain intensities; (ii) decrease during the first and third quarters, since the tidal ranges are smaller; (iii) increase after high tides that potentially carry debris further onto the beach; (iv) interaction effects among or between effects (i)–(iii).

2. Methods

2.1. Study site

The city of Santos (23°57′52″S 46°20′0″W) is a Brazilian municipality of strategic importance, since it holds the largest marine port in South America, located at the coast of the State of Sao Paulo. According to IBGE (2010), the estimated population in Santos was 417,983 habitants. The regional climate is Tropical rainforest (Af, Köepen classification), with average precipitation of at least 60 mm during the driest month, typical high temperature of coastal zones (below 300 m of altitude). There are not hoar-frosts/rime and the soil is hydric (Alvares et al., 2013). In addition, the region is subjected to seasonal wave incidence across the coastline. During the summer (December to February), hot wind blows from east; whilst, during the winter, winds from south and southeast are amplified by cold fronts. The Bay of Santos is oriented to South-Southwest, thus it does not receive waves from east, partially receives waves from southeast and is completely exposed to south and southwest waves. Furthermore, due to its geographical localization, the Bay of Santos receives mostly low waves from east and southeast during the summer and, during the winter, the highest waves were observed from south and southwest (Magini et al., 2007).

There are seven river canals across the city, which are the natural boundaries for different neighborhoods, each with its own namesake beach (Magini et al., 2007). The field study was conducted in two contiguous sand beaches, located at the central area of the city of Santos, a zone of hydrodynamic stability with regards to wind speed, marine currents and tidal cycles (Carminatto et al., 2017) — namely, Boqueirão and Embaré (Fig. 1). The former is 920 m long and the latter is considerably shorter (730 m), whilst both are considered of dissipative-type, due to their sub-horizontal declivity, homogenous and thin sand granulation (Souza, 2012). For statistical purposes, the amount of litter in both beaches was pooled, thus there was not a comparison between beaches in our analyses.

2.2. Sampling processes

The period over which we collected the samples was comprised between October 2015 (spring) and July 2016 (winter). We considered all four seasons of the year (spring — from September 21st to December 20th; summer — from December 21st to March 20th; fall — from March 21st to June 20th; winter — from June 21st to September 20th) aiming at evaluating possible effects over the quantity of solid wastes, according to weather regime and tourism intensity. Within each season, we conducted 20 samples, totaling 80 collections.

In each week, we selected a day for conducting the collections, based on the Tidal Tables of The Brazilian Navy, such that two samples were performed within the period of the low tide and two samples of the high tide. According to this information, we placed the sampling units ($2 \times 2\,\mathrm{m}^2$ PVC quadrats) 1 h before the predicted maximum or minimum of a particular tide and all recently trapped (i.e., not already buried) material within a quadrat was collected in plastic bags and taken for identification.

The number of sampling units varied in each collection, according to a randomly selected spacing between two sampling units. The first quadrat in each beach was placed at the seawalls (in canal 3, which is the west boundary of Embaré Beach, and in canal 4, the boundary between Embaré and Boqueirão beaches). Then, we generated a uniformly (1200) distributed integer, representing the number of steps, parallel to the sea line, separating the quadrats.

The total solid waste material in the pooled sample quadrats for each one of the 80 collections was transported to the Santa Cecilia University Coastal Management Laboratory (Laboratório de Gestão Costeira da Universidade de Santa Cecília — LABOMAC), where it was categorized, counted and weighted, thus comprising the dependent variables in this study. Please note that henceforth the term "weight" refers exclusively to the total weight of each type of litter in each collection and not to individual weight of a single piece or shred. The categories for the waste materials and their respective descriptions are available in Box 1.

For all samples, we annotated the moon phase. Thus, the moon effects considered in our models were "syzygy" (sum of the observations during the new and full moons) and "quadrature" (sum of the observations during the first and third quarters).

2.3. Data analysis

Since our data was comprised of two multivariate datasets (available for download from Cordeiro et al., 2017), we proceeded with separate analyses — one for the weights (continuous) and another for the counts (discrete). In both cases, we treated the response variates as independent of one another, because a simple exploratory correlation analysis pointed to rather low correlations between all pairs of variables (Fig. 2). Note that we used a Pearson correlation for the weights and Kendall correlation for the counts, following the recommendations of Zar (2010) with regards to their use for continuous responses and categorical data with ties, respectively.

Due to the presence of many, exclusively random zeros and the failure of simpler statistical models, we decided using, for each of the response variables, a mixed hurdle model, i.e., a combination of two separate generalized linear models (McCullagh and Nelder, 1989; Yee, 2015; Zeileis et al., 2008) whose general formula is given by

$$g_j(\mathrm{E}Y_i) = \left\{ \begin{matrix} \eta_{0i}(\boldsymbol{X}_0, \boldsymbol{\beta}_0) & for \quad Y_i = 0 \\ \eta_{1i}(\boldsymbol{X}_1, \boldsymbol{\beta}_1) & for \quad Y_i = 0 \end{matrix} \right\}, \tag{1}$$

where Y_i is the $i-$ th (with $i = 1, 2, \ldots, 80$) response variate; $\eta_j(\cdot)$ (with $j = 0, 1$) is the linear predictor containing the covariable matrix $\boldsymbol{X}_j$ and its respective parameter vector $\boldsymbol{\beta}_j$; $g_j(\cdot)$ (with $j = 0, 1$), is the link function between the $j-$ th predictor and the expectancy of the corresponding response variate. Hence, we had eight models, four for the continuous responses and four for the discrete data, for all of which we used maximum likelihood estimation methods.

For each the four continuous response variables (the weights of hard plastics (HP), soft plastics (SP), Styrofoam (S) and of wood (W) — see Box 1), we used a special case of Eq. (1), i.e., an univariate, mixed