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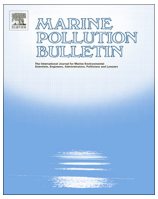

Coastal urbanization leads to remarkable seaweed species loss and community shifts along the SW Atlantic

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ABSTRACT

Coastal urbanization is rapidly expanding worldwide while its impacts on seaweed communities remain poorly understood. We assessed the impact of urbanization along an extensive latitudinal gradient encompassing three phycogeographical regions in the SW Atlantic. Human population density, number of dwellings, and terrestrial vegetation cover were determined for each survey area and correlated with diversity indices calculated from seaweed percent cover data. Urban areas had significantly lower calcareous algal cover (−38%), and there was significantly less carbonate in the sediment off urban areas than off reference areas. Seaweed richness averaged 26% less in urban areas than in areas with higher vegetation cover. We observed a remarkable decline in Phaeophyceae and a substantial increase of Chlorophyta in urban areas across a wide latitudinal gradient. Our data show that coastal urbanization is causing substantial loss of seaweed biodiversity in the SW Atlantic, and is considerably changing seaweed assemblages.

1. Introduction

Coastal urbanization is rapidly advancing on a global scale, although relatively pristine areas still remain in South America. Terrestrial vegetation cover is being cleared and replaced with impervious surfaces, such as tarmac and concrete (Yuan and Bauer, 2007); in combination with human population growth this is increasing the run-off of contaminated waters into coastal seas (Marsalek et al., 1999; Bay et al., 2003). Almost 60% of the human population now lives within 100 km of the coasts, adversely affecting the oceans' productive coastal margins (Vitousek et al., 1997; Lotze et al., 2006; Worm et al., 2006; Halpern et al., 2008) and reducing the health of marine coastal ecosystems (Halpern et al., 2012). Marine biodiversity losses and community shifts are among the effects of coastal pollution. Such effects on seaweed communities have been documented worldwide; however, most studies have been designed to detect local impacts (i.e. Terlizzi et al., 2002; Oliveira and Qi, 2003; Liu et al., 2007; Martins et al., 2012). Assessments of the impact of urbanization on seaweed communities at continental scale, and encompassing regions with different phycogeographical characteristics, are lacking.

Seaweeds are important coastal primary producers. Together with seagrasses they underpin many of the goods and services provided by costal environments (Beaumont et al., 2007; Harley et al., 2012), providing habitat, nursery and food for marine fauna (Grall et al., 2006), removal of organic and inorganic pollutants from seawater (Wang and Zhao, 2007) and sequestering carbon (Koch et al., 2013). Furthermore, seaweed provides food for humans and has a variety of biotechnological applications in medicine, the food industry, agriculture, cosmetics and animal food (Zemke-White and Ohno, 1999). Calcareous algae, such as *Halimeda* and Corallinaceae provide essential ecological services in the marine environment, particularly in coral reef ecosystems where they play an important role in the carbon and carbonate budgets (Littler and Littler, 1988; Sinutok et al., 2012). However, calcareous algae and phaeophyceae species are very sensitive to pollution, while other seaweed groups, such as chlorophyta benefit from it (e.g. Bjork et al., 1995; Liu et al., 2009; Teichberg et al., 2010; Scherner et al., 2012a). Phaeophyceae species are known to have their reproduction and physiology negatively affected by urban pollution (Kevekordes, 2001; Scherner et al., 2012a), and calcareous algae

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may experience the negative effects of excess nutrients (Bjork et al., 1995), leading to declines in calcium carbonate productivity (Hallock and Schlager, 1986). The distinct responses of different phyla, functional groups, genera and species to coastal urbanization may cause substantial seaweed communities shifts, from perennial to ephemeral species' dominated systems, and a consequent decline in biodiversity.

The Brazilian coast is almost 8000 km long with a diverse set of oceanographic and ecological conditions (Floeter et al., 2006). The coast is divided into three major Phycogeographical Regions (PRs); the warm temperate province, the transition zone, and the tropical province (Horta et al., 2001). These PRs present differences in the seaweed flora that are thought to be mainly due to differences in substratum availability and seawater temperature. These different biogeographic conditions and the rapid coastal urbanization process observed along the coast makes it a natural laboratory to study the effects of urbanization on different seaweed communities, considering that effects may vary according to the environmental factors controlling the distribution of seaweed species, component of each PR. Against this background, we assessed the effects of coastal urbanization on different seaweed communities in the south-western Atlantic. We expect that intensive urbanization causes substantial seaweed species declines within all PRs, particularly among phaeophyceae and calcareous algae, and declines in carbonate in the sediment due to lower calcium carbonate productivity. It should reflect the lower water quality in urban areas, as assessed here by chlorophyll *a* concentrations. We tested the hypotheses that intensive coastal urbanization leads to: 1. lower water quality; 2. seaweed diversity declines; 3. declines of calcareous algae richness and cover; 4. lower carbonate in the sediment; 5. changes in seaweed species and phyla composition and percent cover within PRs.

2. Materials and methods

2.1. Study area

The occurrence of reefs is widespread along the coast occurring at least on a third of the coastline with coral reefs predominating in the north (0°52′N–19°S) and rocky reefs in the south (20–28°) (Floeter et al., 2006). The seawater temperature increases towards the north with average surface temperatures of 24 °C off São Paulo and Espírito Santo in the southeast region, and 28 °C off the coast of Pernambuco in the northeast (Fig. 1). The coast of Espírito Santo is influenced by low temperature, nutrient-rich upwelled water derived from an upwelling zone.

Most of the seventeen Brazilian coastal states have their capitals near the coast. Even when the capital is not located on the coast, large cities have grown, such as the Baixada Santista metropolitan area, on the coast of São Paulo with a population of 1.7 million. In Espírito Santo the coastal urban sprawl around Vitória also has 1.7 million people whereas in the north-eastern state of Pernambuco, Recife and neighboring cities have 3.7 million people (IBGE, 2010). In addition, there are medium sized coastal cities with relatively high numbers of dwellings, which increase in population density due to tourism in the holidays and summer months.

The Archipelago of Fernando de Noronha, (3°54′S–32°25′W), lies 360 km offshore and comprises 21 islands, covering 26 km^2. Average seawater surface temperature is around 28 °C yearly. The archipelago has 3500 inhabitants all concentrated on the main island. Since 1988, 2/3 of its terrestrial territory is protected as a National Park and the remaining territory is populated with restrictions as an Environmental Protection Area. Thus, urbanization on the archipelago is very low, especially along the coast.

2.2. Sampling design

Sampling design was planned to represent areas under high and low urban pressure. The coasts of the states of São Paulo, Espírito Santo and Pernambuco, and the archipelago of Fernando de Noronha, were surveyed, representing the warm temperate, the transition zone, and the tropical PRs, in the last case including the main land and an oceanic island, respectively (Fig. 1). Surveys were performed once at each sampling area during the summers of 2011 and 2012. A total of 25 areas were selected along the Brazilian coast and in the archipelago of Fernando de Noronha. The areas were selected based primarily on aspects that determine urban centres. The main parameters used to determine urban areas were: human population density, number of dwellings and vegetation index (Normalized Difference Vegetation Index – NDVI). Population and dwellings data were obtained from the 2010 census of the Brazilian Institute of Geography and Statistics (IBGE, 2010). To have an accurate picture of the sampling areas individually, a circumference of 2 km radius was generated from each sampling area using GIS techniques, and the urbanization parameters mentioned above were acquired only for the areas within the generated perimeters. Urban areas were considered those with number of dwellings and population above 7000 within the 2 km perimeters. Areas presenting values below those were considered areas under low urban pressure, and here they will be designated as reference areas. Additionally, sampling area selection criteria considered the homogeneity of environmental factors among areas, such as vertical inclination of substrata and salinity variations, avoiding estuaries and mangrove areas.

Seven areas were selected along the warm temperate province among which three were located in urban centres and four in reference areas. Along the transition zone nine areas were chosen of which four were located in urban centres and five in reference areas. Finally, nine areas were selected in the tropical province, three urban areas located in the continent and another six reference areas of which three were in the continent and the other half in the archipelago of Fernando de Noronha. Table 1 presents a summary of urban parameters of study areas.

Seaweed assemblages were quantitatively assessed on the lower intertidal zone, during low spring tides, using photoquadrats (625 cm^2). This allowed standardization and sampling on the richest intertidal zone. In each area three sub areas 50 m apart were sampled and considered as triplicates. A thirty meter transect was positioned parallel to the shore and thirty photographs were taken in each sub area, one every meter, along the transect. Photographs were taken with a digital camera Canon G12 (Canon, Japan). A qualitative survey was carried out to identify the taxa present in each area and give taxonomic support to the photographical analysis. Seaweed were identified at the most detailed taxonomic level that could be achieved; some algae were grouped in the morpho-functional categories of Steneck and Dethier (1994). Nomenclature followed Wynne (2011).

Sediment samples were collected from the lower intertidal zone of the nearest available sandy substrata using a tubular core (8 cm diameter and 3.5 cm height). Three replicates were collected – approximately 30 m apart from each other.

2.3. Terrestrial vegetation cover

Normalized Difference Vegetation Index (NDVI) values were calculated using Resource-Sat-1 images with sensor LISS3 spanning the periods from 2011 to 2012 for the continent, and CBERS images from the CCD camera from 2007 for the archipelago of Fernando de Noronha. The images were rectified to the UTM projection system and were georeferenced onto a Brazilian Institute of Geography and Statistics (IBGE) base map.

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