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Long-term decline of brown algal assemblages from southern Brazil under the influence of a nuclear power plant

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ABSTRACT

We investigated long-term trends in brown macroalgal assemblages inhabiting shallow subtidal rocky bottoms under the influence of thermal effluent discharge from the Brazilian nuclear power plant (BNPP). Three operational periods based on the units of the BNPP were analysed: T0 = pre-operational, between the years 1980 and 1983; T1 = operational period of unit 1, between 1988 and 1999; and T2 = operational period of units 1 and 2, between 2005 and 2012. Using generalized linear mixed models (GLMMs), we found significant declines in the numbers of genera and species over time. More than half of the species of brown macroalgae disappeared during T2. In addition, the numbers of macroalgal genera and species were inversely related to the local surface seawater temperatures. Multivariate analyses revealed a clear separation between the years of T2 and those of T0, indicating long-term changes in the community assemblages. Among the most common species in the area, the frequencies of *Canistrocarpus cervicornis, Dictyopteris delicatula*, *Hincksia mitchelliae*, *Sargassum* spp. and *Sphacelaria tribuloides* decreased during T2, while *Padina gymnospora* maintained rather high yearly frequencies during T2 (> 40%). Our data suggest that seawater temperatures consistently higher than 30 °C together with peaks higher than 35 °C may have triggered the decline in the brown algae on rocky bottoms under the influence of the BNPP discharge. These results from southern Brazil are consistent with studies from other locations that ascribe changes in seaweed diversity to increasing seawater temperatures, highlighting the sensitivity of brown macroalgae to thermal stress and demonstrating their effectiveness as an ecological indicator for monitoring the effects of nuclear power plant effluents on coastal environments.

1. Introduction

Sea temperature may be the most important driver of the distribution of marine organisms, setting spatial and temporal limits on species occurrence (Eggert, 2012; Harley et al., 2006; Lüning, 1990). Temperature variations influence the physiological processes, performance and survival of marine organisms, as well as the structure of benthic communities (Ferreira et al., 2014; Komatsu et al., 2014; Morelissen and Harley, 2007; Pedersen et al., 2008; Southward et al., 1995; Teixeira et al., 2009). Thus, sea temperature changes may influence patterns of global marine biodiversity (Tittensor et al., 2010).

Variability in the structure of benthic communities has been the subject of many investigations concerning climatic changes (Kordas et al., 2011; Wernberg et al., 2011). The local loss of even one species due to climatic change is recognized to have important consequences for communities and ecosystems (Harley et al., 2006). For example, after the anomalous warming of the sea surface temperature by 2–4 °C along the coast of Australia for more than ten weeks, the abundance of habitat-forming seaweeds decreased, leading to an impoverished community structure with significantly different patterns in the diversity of seaweeds, sessile invertebrates and demersal fishes (Wernberg et al., 2013).

Anthropogenic impacts, such as those from power plant activities, may also induce thermal stress in marine biota (Arieli et al., 2011; Jokiel and Coles, 1974; Schiel et al., 2004; Steinbeck et al., 2005; Suresh et al., 1993; Teixeira et al., 2009; Thorhaug et al., 1973;

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Vilanova et al., 2004). A drastic reduction in the number of benthic species followed by an expansion of tolerant species is a typical scenario in areas experiencing thermal impacts (Bamber and Spencer, 1984; Kim et al., 1998; Krishnakumar et al., 1991; Mayer-Pinto et al., 2012; Northeast Utilities Service Company, 1987). In particular, decreased macroalgal diversity in assemblages exposed to thermal pollution has been recorded at different locations (Devinny, 1980; Kim et al., 1992; Schiel et al., 2004; Schneider, 1981; Snoeijs and Prentice, 1989; Széchy and Nassar, 2005; Verlaque et al., 1981). The decline in macroalgal richness is related to temperatures in the thermal plume that are higher than the tolerance limits of the species. The upper temperatures for survival are reported to be 33–35 °C for several tropical and temperate species (Lüning, 1990). Subtidal macroalgae potentially face local extinction if seawater temperatures exceed 30–33 °C (Pakker et al., 1995). In the case of brown macroalgae (Phaeophyceae), which are mainly perennial species, negative responses to temperatures higher than the ambient seawater temperature regime have been noted by multiple studies (Eggert, 2012; Keser et al., 2005). For example, Tsuchiya et al. (2012) studied the photosynthetic characteristics of five *Sargassum* species from Kagoshima, Japan, where the average ambient summer temperature is 29 °C, and observed that the relative electron transport rate of photosystem II was augmented by increasing temperatures. The rate increased between 28 and 30 °C but decreased at temperatures above 32 °C, impairing the performance of these species.

Brown macroalgae have been identified as suitable indicator species for monitoring programmes (Coleman et al., 2008). Nonetheless, detecting the effects of anthropogenic disturbance on the structure of benthic communities is an enormous challenge. Species distributions are intrinsically variable over time because of the effects of short-term noise and the variability between consecutive samples, which may result in misleading interpretations of hypothesis tests (Gotelli et al., 2010; Underwood, 1992). Consequently, long-term investigations are indispensable for environmental monitoring (Hewitt and Thrush, 2007; Litzow et al., 2016; Steinbeck et al., 2005).

The Brazilian nuclear power plant (BNPP) on the southern coast of Rio de Janeiro State is the only Brazilian industrial corporation that generates electric energy from nuclear fission. The BNPP began commercial activity in 1985 and since 2001 has had two operational units. Previous data have indicated that the thermal effluent from the BNPP, which is directly released into the coastal seawater, affects the benthic compartment up to 100 m from the discharge site, but these effects could reach 600 m depending on the operational activities of the BNPP. This effluent disturbs the benthic community in three different ways: by increasing the sea temperature (creating a thermal plume), increasing the local current velocity and increasing the chlorine levels (Mayer-Pinto et al., 2012; Vilanova et al., 2004). Although short-term spatial-temporal disturbances of thermal effluents have been documented at multiple locations worldwide, there have been very few long-term investigations of the ecological consequences of environmental warming, particularly on the South Atlantic coast (Bartsch et al., 2012). In this context, we have assembled a unique dataset of brown macroalgal species composition covering a temporal scale of more than three decades. To address the effects of long-term discharge of nuclear power plant effluent on macroalgal assemblages, we related changes in the numbers and frequencies of species and genera of brown macroalgae to increased seawater temperature.

2. Materials and methods

2.1. Study area

The BNPP, located at Itaorna Beach (23°07′S and 44°28′W) in Ilha Grande Bay on the southern coast of Rio de Janeiro State (Fig. 1), currently has two ^{235}U pressurized water reactors, unit 1 and unit 2, which began commercial operation in 1985 and 2000 and produce 640 and 1350 MW of electrical energy, respectively (Mayer-Pinto et al., 2012). Seawater from Itaorna Beach is used in their cooling systems, and the heated effluents from units 1 and 2 are discharged together in the inner section of Piraquara de Fora Cove, with average fluxes of approximately 40 $m^3 s^{-1}$ and 80 $m^3 s^{-1}$, respectively (Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis, 2007), creating a thermal plume. This thermal plume, which can reach distances of 3 km from the discharge site, spreads along the entire cove in varying directions and distances depending on the operational capacity of the units and on the oceanographic and meteorological conditions, such as tides and winds (Lucca et al., 2005). The surface

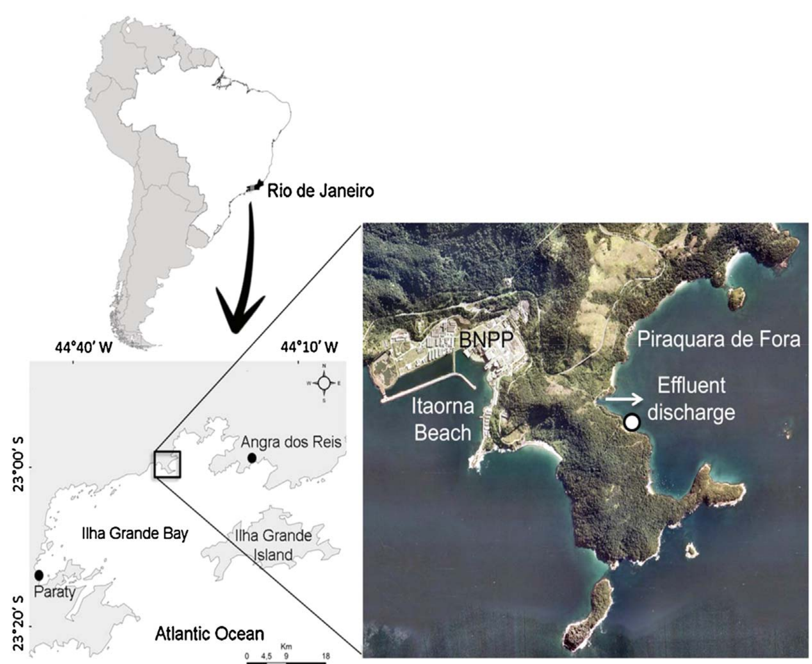

Fig. 1. Location of the Brazilian nuclear power plant (BNPP), its effluent discharge site in Piraquara de Fora Cove (white arrow) and the permanent site (white circle) used for monitoring the brown macroalgal assemblages and surface seawater temperatures. The satellite image is presented at a scale of 1:30000. Image from Fundação Instituto Brasileiro de Geografia e Estatística (2017).