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Effects of industrial outfalls on tropical macrobenthic sediment communities in Reunion Island (Southwest Indian Ocean)

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Abstract

Temporal changes in the composition of soft bottom macrobenthic assemblages at Reunion Island (Southwest Indian Ocean) were studied in the context of a long-term environmental monitoring programme studying the impacts of effluents of industrial sugar cane refineries that are transferred to shallow and deep coastal environments by different pathways: surface discharge and deep underground injection. Seven stations (between 20 and 160 m depth) were surveyed between 1994 and 2003 on the industrial zone. One additional station was surveyed on a reference site. Spatio-temporal changes in the composition of macrobenthic communities were assessed using several diversity indices, ABC curves, MDS and associated ANOSIM tests and biotic indices. Among the 171 taxa recorded, polychaetes were dominant (89 species), followed by crustaceans and molluscs. The analysis of spatial changes in the composition of macrobenthos showed the existence of distinct benthic communities along the depth gradient. Temporal changes in macrobenthos composition were most prominent at the shallowest station. They mainly corresponded to the decline of several initially dominant taxa and the increase of the Eunicid polychaete *Diopatra cuprea*. This station further showed increasing macrofaunal abundance, biomass and sediment organic content over time, concomitant with decreasing sediment grain sizes. In deeper environments, temporal changes were much smaller. Macrofaunal abundance and species richness increased progressively, suggesting a moderate impact on benthic ecosystems resulting from slight enrichments due to effluents rich in organic matter. Our results highlight an original response to disturbance pattern involving opportunistic Eunicidae species (*D. cuprea*) not previously described. Moreover, they allow for the comparison of the impact on macrofauna caused by industrial effluents exported by two distinct and different pathways in a tropical coastal high-energy marine environment.
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1. Introduction

Human disturbance in marine ecosystems can be assessed directly from physical and chemical parameters (Daskalakis and O'Connor, 1995), or indirectly using communities of macrobenthic organisms that characterize the ecological quality of their habitats (Pearson and Rosenberg, 1978; Lindegarth and Hoskin, 2001; Cruz-Motta and Collins, 2004; Currie and Isaacs, 2005). Macrobenthic species are of special interest in this context because: (1) most of them are sessile or have a limited mobility (Olsgard and Gray, 1995; Rosenberg, 2001; Shin et al., 2004) and are thus directly depending on environmental conditions, and (2) they show marked responses to environmental changes depending on their species-specific sensitivity/tolerance levels (Ferraro and Cole, 1995; Paiva, 2001; Mendez, 2002; Lancellotti and Stotz, 2004). Moreover, macrobenthic community analysis provides an instantaneous both snapshot assessment of current disturbance effects, much as most chemical and physical analyses can provide, as well as an

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integrated response of the disturbance effects over the lifespan of the studied organisms. These assets have resulted in macrobenthic community analysis to become part of international standards for the assessment of marine habitat quality, such as the European Union Water Framework Directive (Borja et al., 2003; Rosenberg et al., 2004).

Spatio-temporal changes in soft bottom macrobenthic communities along gradients of organic enrichment follow the typical secondary succession model initially described by Pearson and Rosenberg (1978) and then subsequently adopted by many others (e.g., Zmarzly et al., 1994; Trueblood et al., 1994; Nilsson and Rosenberg, 2000; Rosenberg, 2001; Bolam et al., 2004). According to this model, macrobenthic species richness and abundance tend to decrease with increasing organic enrichment. However, abundance and biomass may also show marked peaks in early stages of succession due to the proliferation of opportunistic species. From a qualitative standpoint, the whole sequence of succession is characterized by the transition in the dominance from sensitive to tolerant species (Pearson and Rosenberg, 1978; Grall and Glemarec, 1997; Karlson et al., 2002). Another factor controlling the secondary succession may be the surrounding fauna recolonizing open space (Zajac et al., 1998; Snelgrove et al., 2001).

The quantitative study of macrobenthic communities results in large species/abundance tables. Numerous analytic procedures have been developed to render this information in an interpretable form, both in terms of spatio-temporal changes in community composition and in terms of habitat quality. Examples of procedures that have been used widely in assessing the effects of both natural and anthropogenic disturbances are multivariate analyses, ABC curves and biotic indices (Clarke, 1993; Dauer et al., 1993; Clarke and Warwick, 1994; Borja et al., 2000). All these approaches clearly present advantages and drawbacks. Multivariate analyses, for example, provide a better description of initial data sets but are less readily interpretable in terms of habitat quality due to the absence of a scale owing for the conversion of the obtained results in ecological quality classes. Univariate biotic indices, on the other hand, have the merit of simplicity of presentation.

Impact assessment studies based on the analysis of benthic macrofauna ideally encompass the analysis of the initial (i.e., before disturbance) composition of the studied community (Underwood, 1997). This often serves as a basis for long-term environmental monitoring programs (Ferraro et al., 1991; Morrisey et al., 1994; Ysebaert and Herman, 2002). Such information is often largely lacking for subtropical and tropical areas (Alongi, 1990; Gray, 2002) and varies with ecosystem type. Benthic communities are reasonably well known in coral reefs and mangroves (Riddle, 1988; Alongi, 1990; Warwick and Ruswahyuni, 1987; Garrigue et al., 1998; Frouin, 2000). Tidal flats and estuaries have been less studied (Dittmann and Vargas, 2001; Lindegarth and Hoskin, 2001; Mendez, 2002; De Boer and Prins, 2002), while tropical open shore habitats have been mostly studied along continental margins (Long and Poiner, 1994; Paiva, 2001; Cruz-Motta and Collins, 2004; Diaz-Castaneda and Harris, 2004; Currie and Isaacs, 2005). Very few data are available from tropical islands (Agard et al., 1993; McCarthy et al., 2000; Bailey Brock et al., 2002; Dreyer et al., 2005). This is particularly true for the islands in the Southwest Indian Ocean. Macrobenthic community compositions in open-shore soft-bottom habitats have been reported from Madagascar (Pichon, 1967; Thomassin et al., 1976), Mayotte (Gout, 1991), Seychelles (Mackie et al., 2005) and the Mozambique Channel (Makarov and Averin, 1968). From Reunion Island, the available inventories of soft-bottom benthic fauna are from coral reefs and adjacent areas only (Faure, 1982; Vadon and Guille, 1984; Saiz Salinas, 1993; Taddei and Frouin, 2005). No information is available on the composition of soft bottom non-reefal benthic communities even though anthropogenic activities and induced coastal inputs (e.g., urban wastewaters runoff, industrial sugar mill and distillery outfalls) have drastically increased during the last 20 years (SDAGE, 2001).

In this context the two main objectives of our study were (1) to provide a first contribution to the quantitative description of the composition of macrobenthic communities in the Northeast of Reunion Island, (2) to characterize the response of these communities to organic and terrigenous inputs originating from industrial sugar cane activity, which is a major source of organic wastes in Reunion Island. The results presented here are based on a study carried out off the Bois Rouge industrial complex and on an undisturbed reference site, between 1994 and 2003. Our sampling strategy consisted in repeated collections along a depth gradient and a typical Before-After-Control-Impact design (Ferraro et al., 1991; Underwood, 1996, 1997).

2. Materials and methods

2.1. Study area

A monitoring programme was set up in 1994 to investigate changes in near-shore subtidal environments related to effluents from the developing Bois Rouge industrial complex, located at the northeast coast of Reunion Island (Southwest Indian Ocean) (Fig. 1). This coast is characterized by strong hydrodynamic conditions; the swell generated by trade winds regularly affects subtidal environments down to 10 m depth (Piton and Taquet, 1992). The coast is furthermore periodically subjected to hurricanes: Three significant hurricanes took place during the study period ('Ando' in January 2001 and 'Harry' and 'Dina' in March 2002).

The Bois Rouge (BR) industrial complex encompasses a sugar mill factory, a distillery and a thermic power plant using coal and cane detritus. It presents the specificity of producing two kinds of wastes, exported to the marine environment via two distinct pathways. The first type of effluent consists of large volumes of water that contain high loads of fine terrigenous particles and ashes but relatively little organic matter. These wastes originate from the sugar mill factory (range of 0.8–1.1 tons of fine particulate dry matter

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