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Fringing reefs exposed to different levels of eutrophication and sedimentation can support similar benthic communities

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ABSTRACT

Benthic communities are sensitive to anthropogenic disturbances which can result in changes in species assemblages. A spatio-temporal survey of environmental parameters was conducted over an 18-month period on four different fringing reefs of Moorea, French Polynesia, with unusual *vs.* frequent human pressures. This survey included assessment of biological, chemical, and physical parameters. First, the results showed a surprising lack of a seasonal trend, which was likely obscured by short-term variability in lagoons. More frequent sampling periods would likely improve the evaluation of a seasonal effect on biological and ecological processes. Second, the three reef habitats studied that were dominated by corals were highly stable, despite displaying antagonistic environmental conditions through eutrophication and sedimentation gradients, whereas the reef dominated by macroalgae was relatively unstable. Altogether, our data challenge the paradigm of labelling environmental parameters such as turbidity, sedimentation, and nutrient-richness as stress indicators.

1. Introduction

Over the last three decades, coral reef ecosystems have been dramatically threatened by a complex combination of stressors. Many of these stressors are increasing in frequency and severity over global and/or local scales (Hughes et al., 2003; Pandolfi et al., 2003), with consequences for coral reef marine communities. Coral reef lagoons, like many coastal waters, are also highly exposed to anthropogenic disturbances, which increase with population expansion. Pollution-based threats to coral reefs, especially in fringing reefs directly exposed to human activities, include: sedimentation, eutrophication, and herbicide/pesticide pollution (Wilkinson and Hodgson, 1999; Wilkinson, 2004). Eutrophication and sedimentation (e.g., range values reviewed in Cooper et al., 2009; Fabricius, 2005) due to runoff from land have been described as having a range of negative consequences for corals such as smothering, decreased recruitment due to unsuitable substrata (Loya, 1976; Loya et al., 2004; McCulloch et al., 2003), reduction of metabolic and tissue growth rates, and modification of trophic structure (Fabricius, 2005; Lapointe, 1997), potentially leading to coral mortality or maintenance failure (Anthony et al., 2008; Fabricius, 2005). Eutrophication has also been shown to modify phytoplankton community structure leading to dystrophic crisis (Margalef, 1978). Recent work (Weber et al., 2012) suggests that organic enrichment of sediments could accelerate microbial processes (e.g., respiration, desulfurylation) responsible for coral tissue degradation. All these disturbed conditions can trigger phase-shifts from coral-dominated to macroalgae-dominated communities (McManus and Polsenberg, 2004; Norström et al., 2009).

While most reefs in French Polynesia are relatively undisturbed by humans, some of them are exposed to pressure from growing human populations (census of Statistical Institute of French Polynesia). This is the case around Moorea, the second most populated island in French Polynesia, where coastal development, tourism, fishing, pollution from sewage, and runoff from the land have increased over the last decades (Chin et al., 2011). Monitoring is necessary to assess health status of, determine reliable health indicators for, and detect changes in community structure of coral reefs. Long-term monitoring of coral and fish communities, with annual or seasonal frequency has been in place for many years in French Polynesia (Chin et al., 2011) at a large scale (e.g., "Polynesia Mana" project ran by the CRIOBE research staff in 14 Polynesian islands, http://observatoire.criobe.pf/CRIOBEData/), and small scale

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(e.g., "Tiahura Outer Reef Sector" project led since 1971 on the north coast of Moorea by CRIOBE, http://observatoire.criobe.pf/CRIOBEData/ or the "Long Term Ecological Research" conducted by the University of California at Santa Barbara and Berkeley GUMP station in Moorea; http://mcr.lternet.edu/data/). Environmental parameters (temperature, pH, dissolved oxygen, salinity, sea level and wave activity) are also recorded on the outer slope of Tiahura. However, little is known about the dynamics of physical, chemical and biological parameters along gradients of anthropogenic pressure or their respective impacts on major benthic groups.

"Bio-indicators" of water quality (e.g., sedimentation rate, coral cover, nutrient levels, chemical pollution) have been employed to monitor coral reefs with contrasting environmental conditions, where contrasted benthic communities were expected, on a small scale (e.g., island scale; Cooper et al., 2009; Fabricius et al., 2004, 2012; Meng et al., 2008). Following this model, a spatio-temporal survey of environmental parameters was initiated bi-monthly for 18 months, on different coastal locations around Moorea Island chosen for their relative anthropogenic pressure exposure (i.e. low *vs*. high human influence). This study provides a baseline for the physical, biological, and chemical characteristics of four lagoon locations in Moorea, similar to baselines established in other regions of French Polynesia (Charpy et al., 2012; Dufour et al., 2001,1999; Fournier et al., 2012; Thomas et al., 2010). Over all, analysis of data collected in this study highlighted unexpectedly that some parameters, classically considered to be "bio-indicators", were not always effective predictors of benthic community structure.

2. Materials and methods

2.1. Site locations

The study was conducted in the Moorea lagoon, in the Society Archipelago, French Polynesia (17°30′9S, 149°50′9W). Moorea's climate is characterised by two seasons: the dry season, from May to October and the wet season from November to April. Four inshore fringing reef locations (1–2 m deep) spread over different coasts were selected for their contrasting environmental conditions and exposure to human pressure (Fig. 1). Two locations were exposed to anthropogenic influence: (1) Maharepa (Ma) is exposed to touristic impacts (e.g., hotel facilities, nautical activities) and is located close to a river mouth which subjects it to terrestrial runoff, and (2) Vaiare (Va) is in the direct vicinity of the ferry wharf (~10 ferry passes day^{-1}). Conversely, the two others locations, Teavaro (Te) and Linareva (Li), were more isolated from human activities.

2.2. Studied parameters

To investigate the environmental temporal variability (location × seasonality), monitoring was conducted bimonthly from February 2011 to August 2012, providing a total of 10 campaigns including two wet seasons (i.e. 2011: WS11 and 2012: WS12) and two dry seasons (i.e. 2011: DS11 and 2012: DS12). Biological, chemical, and physical parameters were assessed and chose for their current status of bio-indicator.

2.3. Biological parameters

2.3.1. Phytoplankton

Chlorophyll *a* (chl *a*) concentration was determined in three seawater replicates, as a proxy for phytoplankton, characterised here in two size fractions, pico- (<2 μm) and nano-microplankton (>2 μm). In order to minimise phytoplankton fluctuation due to diurnal variation, water sampling was conducted between 8 and 10 am. Water samples (500 mL) were filtered by serial filtration on Millipore filters (2 μm pore size and 25 mm in diameter) and GF/F (0.7 μm pore size and 25 mm in diameter). Chl *a* from phytoplankton cells was extracted with 96% (5 mL) ethanol for 5 h in the dark at 4 °C, using a procedure described in Wasmund et al. (2006) and fluorometrically measured on a TD 700 fluorometer (Turner Designs) calibrated with a pure chl *a* standard (Sigma).

2.3.2. Benthic communities

Benthic communities were characterised using the line intercept transect method. Six 20-m transects were conducted parallel to the coast at each location. Major benthic groups were identified every 40 cm, resulting in 300 point observations per location. Observations were assigned to one of six benthic groups: (1) coral (CORAL), (2) macroalgae (MALG), (3) turf (TURF), (4) sand (SAND), (5) rubble (RUB) and (6) crustose coralline algae on rocks (R/CCA). Hard corals were identified at the genus level in order to compare generic frequencies and occurrence among locations, with the rationale that sensitivity to environmental conditions is influenced by genus. The percentage cover of each benthic group was estimated using the ratio of the sum of points in which a particular group occurred relative to the total points observed across all transects (i.e. 300). Additionally, composition of coral communities was estimated using the ratio of the sum of points in which a particular coral genus of hard coral occurred relative to the total points where corals were recorded in the transect.

2.4. Chemical parameters

2.4.1. Nutrients

In order to minimise nutrient fluctuation due to diurnal variation, water sampling was conducted between 8 and 10 am. Ammonium (NH_4^+) and soluble reactive phosphate (PO_4^{2-}) were analysed within a day of sampling. Ammonium (NH_4^+) concentrations were fluorometrically determined in three unfiltered 40-ml replicates using the o-phthaldialdehyde (OPA) method described in Holmes et al. (1999) on a trilogy fluorometer (Turner Designs). The OPA reagent was immediately added to samples after collection in order to avoid the loss of NH_4^+ due to its high instability.

Unfiltered seawater samples were immediately poisoned with mercuric chloride ($HgCl_2$: 20 μL of solution concentrated at 35 mg mL^{-1}) to prevent the proliferation of micro-organisms while in storage (as per Kattner, 1999) prior to measurement of the inorganic nutrients phosphate (PO_4^{2-}), nitrate (NO_3^-), nitrite (NO_2^-), and silicate (Si–OH_4). Evaluation of the soluble reactive phosphate (PO_4^{2-}) concentration was done in five unfiltered 20-mL replicates with a Shimadzu UV-mini 1240 spectrophotometer (cell length: 10 cm), using the molybdenum blue reaction method (Murphy and Riley, 1962). The other nutrients were analysed by colorimetry using a Technicon Autoanalyzer III system at the IRD Nouméa centre Centre in New Caledonia.

2.4.2. Pesticides and hydrocarbons

The presence of chlordecone, multiresidue pesticides, and polycyclic aromatic hydrocarbons in sediments was tested by Hill Laboratories (Hamilton, New Zealand; http://www.hill-laboratories.com/page/pageid/2145880586). Sediment was collected, lyophilised, and 100 g samples were analysed.

2.5. Physical parameters

2.5.1. Temperature

Seawater temperature measurements were performed every 5 min for the duration of the study. Three permanent data loggers were used at around a 0.5–1.5 m depth at each of the four sites

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