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Through bleaching and tsunami: Coral reef recovery in the Maldives

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ABSTRACT

Coral reefs are degrading worldwide, but little information exists on their previous conditions for most regions of the world. Since 1989, we have been studying the Maldives, collecting data before, during and after the bleaching and mass mortality event of 1998. As early as 1999, many newly settled colonies were recorded. Recruits shifted from a dominance of massive and encrusting corals in the early stages of recolonisation towards a dominance of *Acropora* and *Pocillopora* by 2009. Coral cover, which dropped to less than 10% after the bleaching, returned to pre-bleaching values of around 50% by 2013. The 2004 tsunami had comparatively little effect. In 2014, the coral community was similar to that existing before the bleaching. According to descriptors and metrics adopted, recovery of Maldivian coral reefs took between 6 and 15 years, or may even be considered unachieved, as there are species that had not come back yet.

1. Introduction

Global climate change, with consequent seawater warming, sea level rise and ocean acidification, is causing coral reef degradation worldwide (Knowlton and Jackson, 2008; Lasagna et al., 2014). Extreme climatic anomalies related to global warming, in particular, have triggered extensive bleaching and mass mortality events across most tropical regions (Baker et al., 2008). In association with local natural (storms, cyclones, tsunamis, crown-of-thorns starfish outbreaks, etc.) and anthropogenic (tourism, fishing, coral mining, anchoring, pollution, etc.) disturbances, climate change is at the origin of the so-called 'coral reef crisis' (Bellwood et al., 2004; Brown et al., 2013; Ban et al., 2014). Under projections of global climate change and local stressors, significant alterations in the ecology, structure and function of coral reefs are expected (Rogers et al., 2015). Recovery of degraded coral reef ecosystems may prove difficult (Graham et al., 2011) and their decline under climate change has been predicted (Descombes et al., 2015).

Recent global analyses indicate that about 75% of world coral reefs are severely threatened by global and local pressures of anthropogenic origin, and, given the present escalation of human impacts, it is estimated that 90% of them will be at risk by 2050 (Wilkinson, 2008; Burke et al., 2011). Coral reefs survived Quaternary climatic oscillations (Pandolfi and Jackson, 2006), but the recent increase in scale and frequency of disturbances may lead to 'phase shifts', i.e., changes in community structure and composition (Dudgeon et al., 2010; Montefalcone et al., 2011; Mumby et al., 2013).

Estimating magnitude, patterns and trajectories of change is necessary to evaluate the possibility of recovery of coral reefs, but requires information on previous conditions of coral-reef communities (Bruno and Selig, 2007). Unfortunately, this kind of historical data are extremely rare for most regions of the world ocean. Best known examples come from the Wider Caribbean and the Great Barrier Reef, worldwide international initiatives (such as Reef Check) being more recent (Hughes et al., 2010). Little information is available for Indian Ocean coral reefs (Ateweberhan et al., 2011).

The rise in sea-surface temperature linked to the 1997–1998 El Niño event caused massive bleaching and coral mortality throughout the Indian Ocean (Plass-Johnson et al., 2015). The Maldives has been among the most affected countries, with 60–100% coral mortality reported, depending on species and locality (Bianchi et al., 2003). This was not the first bleaching event in the Maldives (Edwards et al., 2001), but has probably been the most severe.

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We have been studying the coral reefs of the Maldives for the last 25 years. Early studies consisted of snapshot assessments in Ari (Morri et al., 1995), Felidhoo (Bianchi et al., 1997) and North Malé Atolls (Morri et al., 2010), but since 1997 we conducted research with yearly scientific cruises (Bianchi et al., 1998, 2009). Thus, we had the opportunity to collect data on the state of coral reefs before, during and after the mass mortality event of May 1998 (Bianchi et al., 2003). The first results of this monitoring activity indicated that recolonisation already started in 1999, with many newly settled colonies recorded (Bianchi et al., 2006). Six years after the 1998 mass mortality, tabular *Acropora* corals were again abundant and large (Lasagna et al., 2010a). This notwithstanding, the recovery of the coral community as a whole appeared slow, suggesting there was an ongoing risk of degradation of these reefs (Lasagna et al., 2008, 2010b). Recovery was still in progress when the Sumatra–Andaman tsunami of December 2004 hit the Maldivian atolls, potentially causing further damage to the reef (Gischler and Kikinger, 2006).

This paper aims at describing the recovery trajectory of Maldivian coral reefs to 2014, taking into consideration multiple descriptors: (1) composition of coral reef communities; (2) coral recruitment; (3) hard coral cover, considering also historical data; (4) reef rugosity, at two different spatial scales; (5) coral ecosystem functioning, in terms of constructional capacity and trophic structure.

2. Methods

2.1. Study area and field activity planning

The Maldives, comprised of 27 atolls and ca. 1120 islands, form the central part of the Chagos-Maldives-Laccadive ridge in the central Indian Ocean, stretching in a north–south direction from about 7°07′ N to 0°40′ S in latitude and 72°33′ E to 73°45′ E in longitude (Risk and Sluka, 2000; Gischler et al., 2014). The climate in the Maldives is monsoon-dominated, with a wet summer monsoon (April to November) due to winds blowing to the northeast and a dry winter monsoon (December to March) with winds blowing westward. Such a wind regime controls the formation of the typical Maldivian reefs called faros (Kench et al., 2006). Although the earliest field investigations on the Maldivian coral reefs date back to the turn of the 20th century (Gardiner, 1901–1905; Agassiz, 1903), thorough studies on coral communities started with the *Xarifa* expedition in the late 1950s (Wallace and Zahir, 2007 and references therein). Recent reference for the ecology of Maldivian coral reefs is provided by Andréfouët (2012).

Our scientific cruises took place annually (except in 2011) in April, on board of the M/y *Eagle Ray*, *Maavahi*, *Conte Max*, or *Duca di York*. The cruises visited eight atolls: Ari, Felidhoo, Huvadhoo, North Malé, Rasdhoo, South Malé, Thoddoo, Vattaru. Due to weather conditions and logistic constraints or other opportunities, the actual route of the cruises differed from year to year. Every year, 8 sites, chosen randomly, were surveyed along the route of the cruise: 4 ocean reef sites (ocean-facing sides of faros situated on the atoll rim) and 4 lagoon reef sites (lagoon faros or lagoon-facing sides of the atoll rim) (Lasagna et al., 2010b). Sites were located on the British Admiralty Chart No 1013 and their position recorded using a GPS. It happened that some sites were revisited years apart. All data were collected by scuba diving, using different protocols according to the specific survey done.

2.2. Data collection and management

2.2.1. Coral reef communities

The composition of reef communities was described using 23 benthic categories (Morri et al., 2010): 20 'lumped' levels of classification of sessile organisms, combining taxa with growth-forms, and 3 non biotic physiognomic attributes (Table 1). For each of these benthic categories, the percent substratum cover was estimated in three depth zones: outer flat (4–6 m), upper slope (10–12 m), and intermediate slope (16–18 m). Three replicated 20 m long point intercept transects (Bianchi et al., 2004) were laid parallel to the reef edge from an arbitrarily selected starting point in three depth zones and two reef types (ocean and lagoon). In total, 1224 transects (17 years × 2 reef types × 4 sites × 3 depth zones × 3 replicates) were employed.

The matrix containing percent cover data of the 23 benthic categories in the 1224 transects was submitted to Correspondence Analysis (CA), after arcsine $\sqrt{(x/100)}$ transformation (Legendre and Legendre, 1998). Significance of the axes ($p < 0.05$) was evaluated through Lebart's tables (Lebart, 1975).

2.2.2. Coral recruitment

Commencing 1999, hard coral recruitment was quantified by counting small corals with approximately circular outlines in 12 replicated quadrats of 0.25 m^2, randomly placed in the same sites and the same depth zones as the community transects described in Section 2.2.1 above. Coral colonies smaller than 5 cm in diameter were called 'recruits', whereas the term 'juveniles' was used for colonies ranging between 5 and 15 cm (Cardini et al., 2012). Both recruits and juveniles were divided into three categories: *Acropora*, *Pocillopora*, others (Bianchi et al., 2003, 2006). The total number of quadrats surveyed was 4320 (15 years × 2 reef types × 4 sites × 3 depth zones × 12 replicates).

Recruit density (number·m^{-2}) data were subjected to 4-way analysis of variance (Underwood, 1996), with reef types as fixed factor with 2 levels (ocean and lagoon), years as fixed factor orthogonal to reef types with 15 levels (from 1999 to 2014, except 2011), depth zones as fixed factor orthogonal to years and with 3 levels (4–6 m; 10–12 m; 16–18 m), sites as random factor nested within depth zones and years with 4 levels, and quadrats as replicates ($n = 4$). Temporal autocorrelation was avoided by randomly

Table 1
List of benthic categories (together with their codes as used in Fig. 3) chosen to describe reef communities during our yearly cruises in the Maldives.

Benthic categories	Codes
BIOTIC	
Acropora branching	CAB
Acropora digitate	CAD
Acropora tabular	CAT
Coral branching	CB
Coral foliose	CF
Coral massive	CM
Coral encrusting	CE
Tubastrea micranthus	CT
Heliopora coerulea	H
Millepora	M
Corallimorpharians	CMR
Palythoa	P
Soft corals (alcyonarians) zooxanthellate	SZ
Soft corals azooxanthellate	SA
Whip- and wire-corals (to include the gorgonian *Junceella* and the anthipatarians *Cirripathes* and *Stichopathes*)	W
Sea fans (gorgonians and anthipatarians with planar or bushy colonies)	V
Algae (including *Tydemania expeditionis* and *Halimeda*)	A
Sponges	SP
Clams (*Tridacna*)	TR
Tunicates	TU
NON-BIOTIC	
Dead coral/coral rock	RK
Coral rubble	R
Sand	S