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# The current status of coral reefs and their vulnerability to climate change and multiple human stresses in the Comoros Archipelago, Western Indian Ocean

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ABSTRACT

Coral bleaching and various human stressors have degraded the coral reefs of the Comoros Archipelago in the past 40 years and rising atmospheric $CO_2$ levels are predicted to further impact marine habitats. The condition of reefs in the Comoros is poorly known; using SCUBA based methods we surveyed reef condition and resilience to bleaching at sites in Grande Comore and Mohéli in 2010 and 2016. The condition of reefs was highly variable, with a range in live coral cover between 6% and 60% and target fishery species biomass between 20 and 500 kg per ha. The vulnerability assessment of reefs to future coral bleaching and their exposure to fishing, soil erosion and river pollution in Mohéli Marine Park found that offshore sites around the islets south of the island were least likely to be impacted by these negative pressures. The high variability in both reef condition and vulnerability across reefs in the Park lends itself to spatially explicit conservation actions. However, it is noteworthy that climate impacts to date appear moderate and that local human pressures are not having a major impact on components of reef health and recovery, suggesting these reefs are relatively resilient to the current anthropogenic stresses that they are experiencing.

RÉSUMÉ

Le blanchiment du corail et les diverses pressions humaines ont dégradé les récifs coralliens de l'archipel des Comores au cours des 40 dernières années et il est prévu que l'augmentation de la concentration de $CO_2$ dans l'atmosphère va nuire davantage aux habitats marins. La condition des récifs aux Comores est peu connue; à l'aide de méthodes SCUBA, nous avons suivi la condition des récifs et leur résilience au blanchiment du corail dans des sites en Grande Comore et Mohéli en 2010 et 2016. La condition des récifs était très variable, avec une gamme de couverture de corail entre 6% et 60% et une biomasse des poisson-cibles à la pêche entre 20-500 kg per ha. L'évaluation de la vulnérabilité de récifs au blanchiment du corail et leur exposition à la pêche, à l'érosion des sols et à la pollution fluviale dans le Parc National de Mohéli, a trouvé que les sites au large, près des îlots au Sud de l'île, étaient le moins susceptibles d'être affectés par ces pressions négatives. La grande variabilité dans les conditions des récifs et leur vulnérabilité aux pressions anthropogéniques, se prêtent à des mesures de conservation spatialement explicites. Cependant, nous avons trouvé que les impacts climatiques sont modérés et que les pressions humaines locales n'affectent pas beaucoup les processus critiques à la santé des récifs et à leur reprise des stress aigus, ce qui suggère que ces récifs sont résilients aux stress anthropogéniques auxquels ils sont soumis.

## 1. Introduction

Mass coral bleaching and mortality have impacted coral reefs in nearly every part of the world including many sites in the western Indian Ocean (WIO), especially during the extreme El-Niño Southern-Oscillation (ENSO) events in 1997–1998 and 2015–2016 (Wilkinson, 2008; Ateweberhan et al., 2011; Heron et al., 2016; Obura et al., 2017a). The Northern Mozambique Channel (NMC), which comprises northern Madagascar, northern Mozambique, southern Tanzania and the Comoros is an area of global biodiversity importance (Obura, 2012)

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but is also threatened by climate and local human pressures (Obura et al., 2012, 2015; McClanahan et al., 2014). Further, the coastal peoples of these countries are intimately dependent on marine resources and habitats for their livelihoods (Obura et al., 2017b).

The islands of the Comoros Archipelago are geologically recent, formed by volcanic hotspot activity which began approximately 10 million years ago (Audru et al., 2010). These four islands covering 2,230 km$^2$, have a combined coastline of 340 km which is largely fringed by coral reefs. The Republic of Comoros (excluding Mayotte, which is a *département* of France) support a population of ~700,000 with an annual growth rate of ~3%. The islands have one of the lowest human development index (HDI) in the WIO and economic development is low (UNDP, 2013; Obura et al., 2017b). Grande Comore with the capital city Moroni has the largest population (300,000), whereas an estimated 45,000 people live on Mohéli, making it the least densely populated island in the archipelago. Direct and indirect human pressures on reefs in Comoros include fishing, pollution and sewage from towns, sand mining, and soil erosion as a result of deforestation and agriculture (Freed and Granek, 2014; Audru et al., 2010).

Future management of coral reefs requires a better understanding of climate vulnerability to develop appropriate strategies that will help to address both human and climate impacts on marine and coastal resources and local communities (Maynard et al., 2010; Anthony et al., 2015). A vulnerability analysis of a threat to a coral reef requires knowledge of the reef's exposure to the threat, the sensitivity of the reef and its ability to recover from acute stress (Cinner et al., 2012; Harris et al., 2017). The most important factors for triggering coral bleaching are temperature and light (Coles and Jokiel, 1978). Physical factors that reduce coral's exposure to temperature and light during a bleaching event include depth, shade from sunlight, high wave exposure and cool upwelling (West and Salm, 2003; Obura, 2005). The reef's sensitivity to bleaching is determined by the composition of the coral community, with certain genera (*Acropora*, *Monitpora*, *Seriatopora*, *Pocillopora* and branching *Porites*) being consistently more sensitive to bleaching than others (Loya et al., 2001; McClanahan et al., 2007). Factors important for reef recovery include low algal competition with corals, high abundance of herbivorous and detritivorous fishes, high coral recruitment and suitable substrate for new coral growth (Obura, 2005; Hughes et al., 2007; McClanahan et al., 2012; Bellwood et al., 2014). Local human impacts can reduce reef recovery potential (Fabricius, 2005; Mumby et al., 2006) hence local stressors of pollution, fishing and coastal erosion are considered alongside the climate vulnerability assessment.

The Worldwide Fund for Nature (WWF) have spearheaded the 'Climate Adaptation Methodology for Protected Areas' (CAMPA) approach in protected areas around the world (Belokurov et al., 2016). In this study the climate vulnerability of reefs in the Parc National de Mohéli (PNM) was investigated and represents the second application of this method in an MPA in the NMC, after the assessment carried out by Gough (2012) in Nosy Hara, Madagascar. We quantify the condition of the reefs in Grande Comore and Mohéli in 2010 and 2016, calculate the vulnerability to climate change and human stressors in Mohéli and compare these reefs with other countries in the WIO.

## 2. Methods

### 2.1. Sites and survey periods

In 2010 six sites were surveyed in Grande Comore and 4 sites in Mohéli and in 2016 only Mohéli was visited, where data were collected from 10 sites (Table S1) (Fig. 1). Most sites were ~10 m on reef slopes, with the exception of Ferenga (18 m), Nioumachoua (5 m) and Nioumachoua Flat (1 m). In Grande Comore the only reef geomorphology (sensu Andréfouët et al., 2006) is Ocean-Exposed Fringing-Reefs (OEFR), with coral communities on underlying basalt bed-rock or narrow reef platforms along the coastline of this young volcanic island. In Mohéli the reef structures surrounding the island are more developed, with several reef geomorphologies (Table S1) and reef-associated habitats, such as seagrass beds and mangroves. Offshore from the central part of PNM a shallow (< 50 m) plateau extends beyond the main island to 10 km offshore, on which are several small uninhabited islands (islets). Three reef morphologies were observed at sites in Mohéli including Ocean-Exposed Fringing Reef (OEFR), Intra-Seas Fringing Reef (ISFR) and a Coastal Patch Reef (CPR) at Sambia.

### 2.2. Survey methods

Data were collected on the coral, fish, algae and benthic structure of the reef. Benthic cover was recorded using photo-quadrats. In 2010 photo-quadrats were recorded from a height of ~70 cm from the substrate, in clusters of 5–6 adjacent to transects with 20–24 photos per site. In 2016 fifteen 1 m$^2$ quadrats were photographed. Cover was analysed with Coral Point Count with Excel extensions (CPCe) (Kohler and Gill, 2006) using a grid of 25 points per image. Major benthic categories included: hard coral, soft coral, recently killed coral, sponge, macroalgae, turf algae, bare substrate and loose sediment and in 2016 the frond length of turf and macroalgae was measured.

Fish were counted in five 50 × 5 m (250 m$^2$) belt transects per site (Samoilys and Carlos, 2000). In 2016 all species from 11 important reef fish families were included: *Acanthuridae*, *Chaetodontidae*, *Ephippidae*, *Epinephelidae*, *Haemulidae*, *Kyphosidae*, *Lethrinidae*, *Lutjanidae*, *Pomacanthidae*, *Scarinae* (*Labridae*), *Siganidae* (Supplementary Table S2). In 2010 species from 8 families were counted, excluding *Ephippidae*, *Haemulidae* and *Kyphosidae*. Each fish (> 5 cm TL) was identified to species and assigned to trophic groups (Green and Bellwood, 2009; Obura et al., 2011) with its total length estimated to the nearest 5 cm. The fish observer also recorded the presence of each unique species seen from 19 families during a 75-minute search period around the site (Obura et al., 2011). The approximate area of reef searched at each site during this period was ~7000 m$^2$ (350 m × 20 m).

Adult coral colonies (> 10 cm) were assessed in belt transects, whereas juvenile colonies (< 10 cm) were assessed in quadrats (Obura and Grimsditch, 2009). In 2010 belt transects varied in size (1 m wide and 11 to 25 m long) and juvenile corals were sampled in 1 m$^2$ quadrats placed within the belts (2–5 per site). In 2016 five 1 m × 10 m belt transects were sampled per site, with three 1 m$^2$ quadrats placed at regular intervals along each transect (15 in total). In 2010 colony size was binned in varying-width size classes (Obura and Grimsditch, 2009), while in 2016 length was estimated to the nearest 5 cm. The condition of colonies with obvious damage (bleaching, disease or mortality within the past 6 months) was also recorded. Overall coral genus richness (presence/absence) was recorded in random swims across the entire sites.

### 2.3. Reef condition and vulnerability to coral bleaching

Reef condition was defined using the indicators: coral cover, coral genus richness, biomass of fishery target species and the coral fish diversity index (CFDI) (Table 1). Coral cover was obtained from the analysis of photoquadrats and coral genus richness was obtained from coral belt transects. Reef fish taxa targeted by artisanal fishing in PNM consist of Lutjanidae, Lethrinidae, Epinephelidae and Haemulidae (Freed and Granek, 2014). CFDI is a biodiversity index that estimates species richness based on six specious reef fish families (Chaetodontidae, Pomacanthidae, Pomacentridae, Labridae, Scarinae (Labridae) and Acanthuridae, Allen and Werner, 2002).

Equation 1. Vulnerability equation sensu Cinner et al., 2012

$$\text{Vulnerability (V)} = \frac{[\text{Exposure (E)} + \text{Sensitivity (S)}]}{\text{Recovery (R)}} \quad (1)$$

Vulnerability to bleaching was calculated for sites in Mohéli by