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DEMISE OF MADAGASCAR'S ONCE GREAT BARRIER REEF – CHANGE IN CORAL REEF CONDITION OVER 40 YEARS

BY

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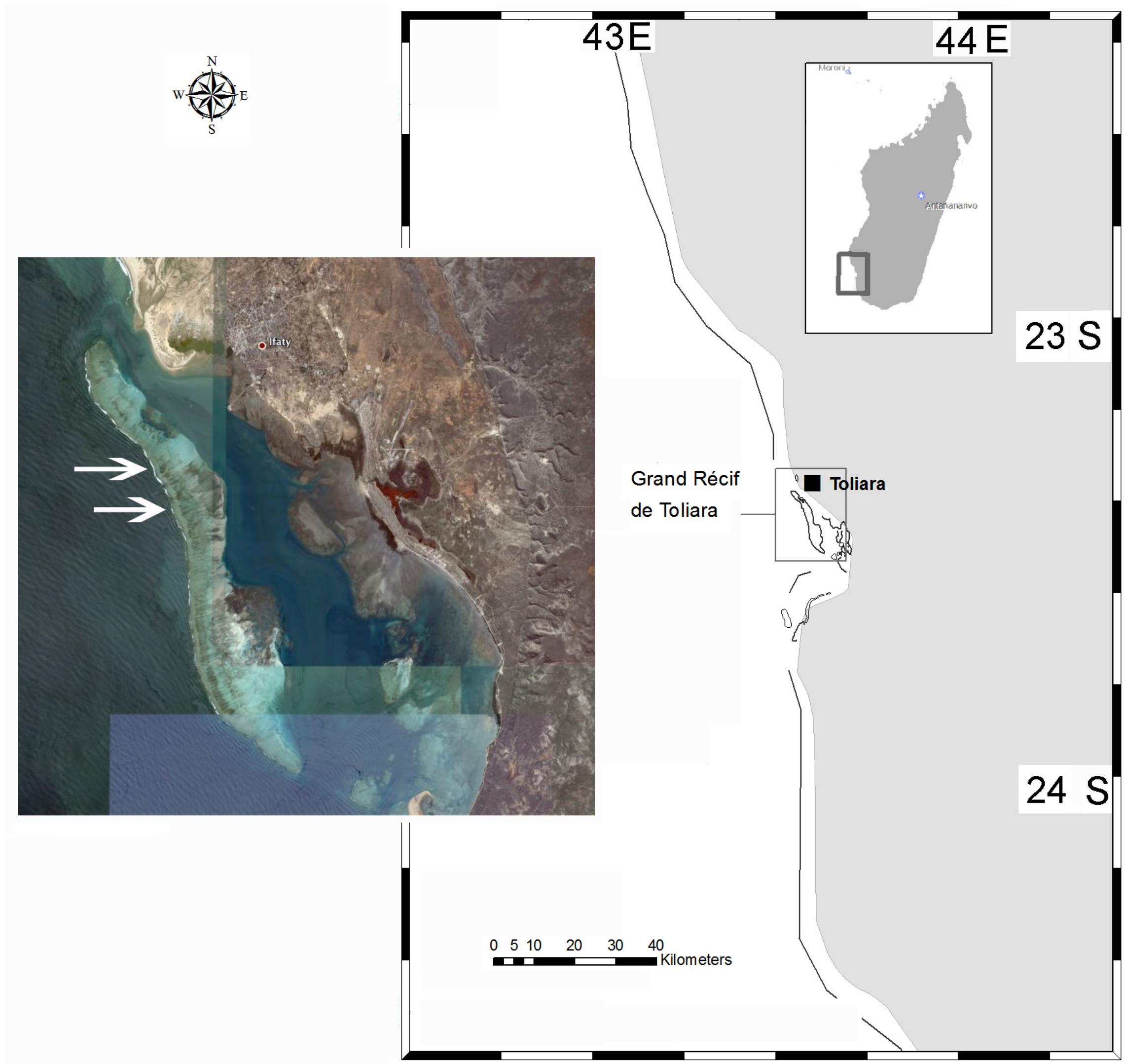

Figure 1. Location of Toliara, with Landsat 7 image of the Grand Récif. Arrows mark the two survey sites.

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ABSTRACT

In the 1960s and 1970s the biology and geology of the Grand Récif of Tuléar, (now Toliara) in southwestern Madagascar, was thoroughly studied and reported. Toliara is the largest city in the south of the country, and the Grand Récif offshore provides both artisanal fisheries and coastal protection to the growing regional capital. Substantial research on the comparatively pristine reef was described in a volume of *Atoll Research Bulletin* in 1978. Since then, published scientific study of this reef has been largely lacking. The present study compares the condition of the Grand Récif of circa 40 years ago, with that seen in a brief resurvey undertaken in 2008, on transects corresponding to some of those documented previously. The trend has been of severe degradation; hard coral cover on the fore-reef slopes has declined substantially, and there has been a near total loss of the "architectural species" in particular. Coral has been replaced to great extent by fleshy algae. Observations also indicate severe decline on the broad reef flat, back reef and lagoon areas. Perhaps most seriously for the local fisheries and human communities, is that the fore reef is almost depleted in reef fish today.

Comparisons are made of coral cover, coral morphological types and fish trophic structure with other reefs in southern Madagascar, which are not located near large human populations. Although a rise in mean sea surface temperature has occurred throughout the region of approximately 1^{o}C over this 40 year period, which is probably a contributing cause of decline throughout, the Grand Récif is in much worse condition than most of the more remote reefs with which it is compared. It is suggested that the main reasons for the substantial decline in the Grand Récif over the past 40 years lies in the fact that the region's population has grown substantially, there is a complete lack of any resources management, heavy overfishing, and no pollution control, resulting in massively increased discharges of sewage, sediments and other pollutants.

Reef condition today is unrecognisable from that described in the 1970s. Unless far-reaching and effective management interventions are adopted to safeguard the Grand Récif the remaining ecosystem services upon which Toliara and its population depend will soon all but disappear.

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INTRODUCTION

Coral reefs run continuously for over 450 km along Madagascar's southwestern coastline (Figure 1). The central geographical feature of this predominantly fringing reef system is the geomorphologically distinct *Grand Récif,* which is 19 km in length, has a shallow reef area of approximately 33 km^2, and which lies 1.5-12 km directly seaward of the coastal city. The city's port lies protected within the reef's lagoon, less than 2 km from the back-reef slope.

The Grand Récif has historically been the most well-studied in Madagascar, and was the focus of intensive research efforts out of Toliara's Marine Station from 1961-1970; during that period approximately 400 scientific reports were published on the region's marine environment, culminating with respect to biological work in a 490 page volume of *Atoll Research Bulletin* (Pichon, 1978). These studies described the predominantly anthozoan communities of the Grand Récif and adjacent reef systems, and provide a valuable insight into the condition of Madagascar's southwestern coral reefs prior to recent increased levels of direct anthropogenic and climatic disturbance. At that time, Toliara's coral reef was amongst the world's most well-studied. Its coral genus count of 62 was the highest recorded for the entire Indo-Pacific, though Pichon (1978) acknowledges that this was an artifact caused by his intensity of sampling; Rosen's (1971) compilation and the predictive biogeographic maps of Stehli and Wells (1971) already indicated, for example, that highest diversity resided in the Southeast Asian region, but that a secondary high diversity locus probably existed in the Western Indian Ocean.

Following this, very little research from Toliara's coral reefs was published over the intervening decades, when the city's population increased markedly. A search of the words 'coral' and 'Madagascar' in the online bibliographic reference archive *Scopus* yields a total of 54 items published since 1971, of which just 6 refer to ecological and fisheries issues relating to Toliara's reefs, none of which provide quantitative information on the ecological condition of coral reefs in light of the growing anthropogenic and climatic stresses. A small number of non-peer reviewed studies shed some light on the status of, and threats to, nearby reef systems but, notably, there are no records of occurrences of coral bleaching in Toliara between 1998 and 2002, a period which saw several mass coral bleaching and mortality episodes elsewhere in the Indian Ocean. It is likely that Toliara's reefs suffered widespread bleaching on at least one occasion during this time (Ahamada et al., 2008). Many people living in the region have described this to the present authors, but it has been undocumented.

Toliara's population increased by 53% between 1993 and 2008, and is forecast to increase by a further 49% over the next 14 years (INSTAT, 2007). Population growth comes inevitably with a concomitant increase in artisanal fishing pressure in adjacent reefs. Mangrove stands once lining the shoreline between the city and the *Grand Récif'*s lagoon have been almost entirely removed in recent decades. There is no centralised organic waste disposal system for the region, and human waste is commonly disposed of on the deforested mudflats for removal by each outgoing tide. Lagoonal water is highly turbid, and there are no management controls in place to regulate artisanal fisheries, pollution or waste disposal. Those environmental regulations that do exist are rarely implemented due to a lack of enforcement capacity.

A series of sedimentalogical and geomorphological surveys carried out between 1990 and 1995 on the shallow reef flat of the Grand Récif provides valuable biological information of the very shallow areas from that time (Thomassin et al., 1998; Vasseur et al., 2000). Notable changes in the condition of the reef flat include a reduction in the height and width of the outer boulder tracts; a decrease in coral cover within the "inner moat" of the reef flat, with greatly reduced living coral cover; widespread mortality of most branching and digitate corals (*Acropora humilis*, *A. muricata*, *A. arbuscula*); a considerable increase in sea urchin abundance (*Diadema*, *Echinothrix*, *Echinometra*); substantially increased algal growth on all shallow hard substrates, predominantly brown algae (*Sargassum*) in summer and green algae (*Enteromorpha, Ulvaria*) in winter; and increased cover (up to 90% benthos in some cases) of zooanthids (*Palythoa*) and soft corals on the outer reef flat in habitats previously dominated by *Acropora*. On soft substrates, there was almost complete disappearance of seagrass beds within the lagoon, where the once dominant *Syringodium*, *Thalassia* and *Thalassodendron*, were by then replaced by a sparse coverage of *Halodule uninervis* and *Cymodocea rotundata* only. Regarding wave energy, a reduction in the sheltering effect of the barrier reef against heavy swells was noted, with waves breaking on the reef flat landwards of the boulder tract, whereas in the 1960s it was noted that waves did not break landwards of the boulder tract. These studies also inferred an increase in current velocity across the reef surface, as well as an overall reduction in the roughness of the reef surface over time as a result of decreased coral cover and complexity (Thomassin et al., 1998; Vasseur et al., 2000). The changes in the condition of the reef flat were considered to be caused by over-fishing, particularly of herbivorous species, pollution from Toliara, and heavy sedimentation from deposition of silts and clays from the nearby Onilahy and Fiherenana rivers (Vasseur, 2008 and personal communication).

The present study presents results from a brief but quantitative assessment of coral cover and fish composition of the reef slope of Toliara's *Grand Récif*. It compares today's fore-reef slope condition with that of circa 40 years ago. The comparison has the limitation that much of the older work was heavily descriptive rather than quantitative, but sufficient re-analyses and inferences can be made for comparative purposes.

METHODS

Surveys were undertaken on the outer reef slope of the Grand Récif in July 2008. Survey localities were as close as possible to those examined and described in detail by Pichon (1978). Firstly, the reef slope in four areas was surveyed to 30 m depth at intervals of 5 m. Using approximately 20 replicate visual quadrats of approximately 5x5 m at each depth, percent cover by coral, soft coral, algae, sponge, coralline algae, bare rock and sand was recorded. Secondly, line intercept transects were used at 10 m depth to examine that region in greater detail, where the composition of benthic and substrate types were recorded in two replicate 10 m line intercept transects (LIT) (English et al., 1997). Stony coral community composition was recorded along each transect line by measuring the longest diameter of every coral lying within a 10 m^2 belt running 50 cm either side of each LIT. Corals with >50% of their surface area within the 10 m^2 belt were recorded. These corals, identified to genus, provide size frequency data on the major components. Wherever possible, these data are presented with data extracted from the largely descriptive work of Pichon (1978). In the latter work, the cover of different categories of reef occupancy was derived from Figure 3; in his "kite diagram," the width of the black blocks represents the relative cover of each group, and these were used to infer the percentage cover of each category. For each depth, the widths for each category appear to sum to the same value (taken to be 100%). One complication which cannot be properly resolved in this case, however, is the apparent absence or non-recording of sand in the 1970s data. In 2008, sand was a very minor component (1-2%) down to depths of 15 m, and, being an exposed reef, this is likely to have been fairly similar in the 1970s, but from 15 m depth and deeper, sand occupies up to 18% of the substrate.

Simultaneously, fish diversity and biomass were measured at a depth of 10 m using an underwater visual census (UVC) technique. At each site a 50 m line was laid along the reef benthos and all fish seen within 2.5 m either side of the line were identified and recorded, with length assigned to 10 cm size classes from 0-80 cm, or >80 cm. Each transect was passed four times, with 1-3 fish families sampled during each pass along the transect.

Finally, HadISST1 monthly sea surface temperature (SST) (Rayner et al., 2003) data were obtained for Toliara, with a spatial resolution of 1 degree latitude and longitude.

RESULTS

Figure 2 shows cover profiles of corals and algae with depth, in 2008. Hard coral declines with increasing depth while algae broadly increase in cover with depth. Sand provided significant substrate cover, while a fourth category, labelled 'bare rock' is also shown, which is substrate devoid of macro algae and animal life but which is covered mainly with filamentous or turf algae. Soft corals accounted for 11% of cover in the shallowest region, but became negligible below 15 m, while sponges, which were very conspicuous 40 years ago between 20-30 m depth, were negligible throughout in this study. In Pichon (1978) there is no similar quantitative data on cover, but a kite diagram of relative percentages (Figure 3) showed a decline in the proportion of coral cover with depth and a simultaneous increase in fleshy algae. Bare substrate and sand appeared to be unmeasured in Pichon (1978) but are clearly high in 2008.

More detailed LIT results at 10 m depth, and extraction of approximate, equivalent data from Pichon (1978), further show deterioration at this formerly high diversity region. There is now greatly reduced coral and soft coral cover, reduced coralline algae, and a massive increase in macro and turf algae (Figure 4).

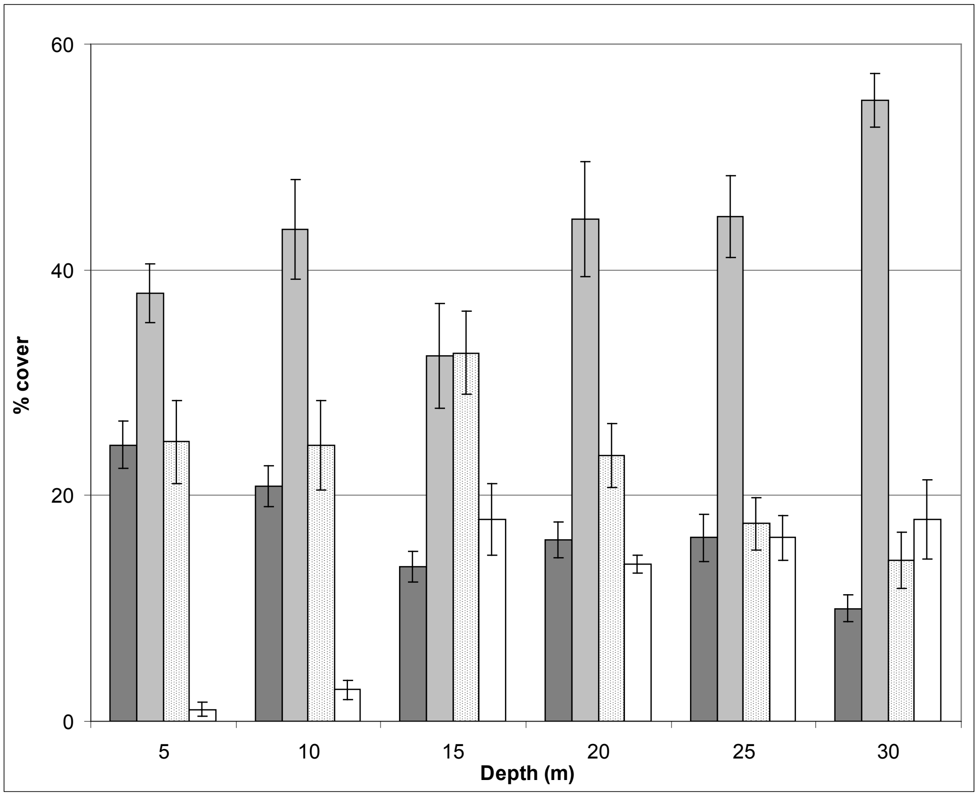

Figure 2. Hard coral (dark grey), fleshy algae (light grey), bare substrate (patterned) and sand (open) cover of fore-reef slope of the Grand Récif to 30 m depth.

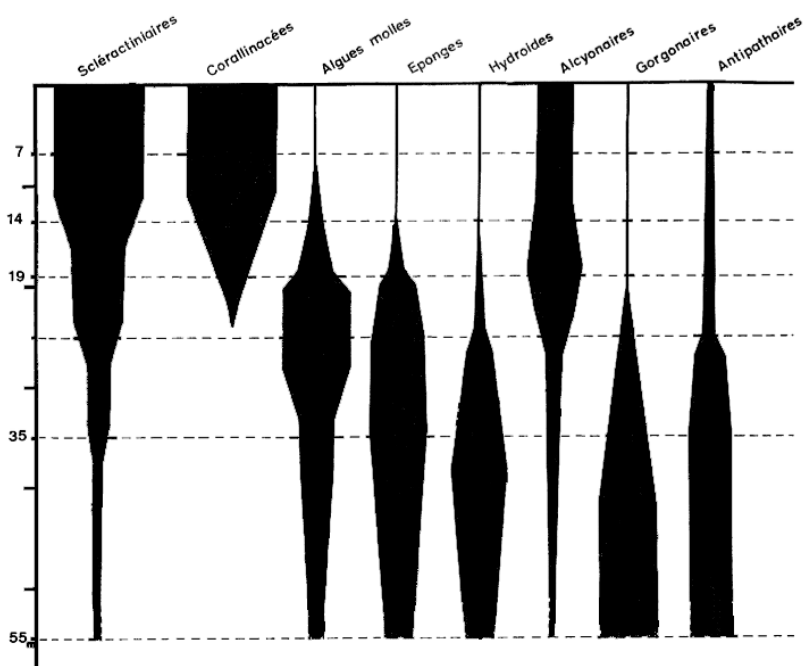

Figure 3. Relative cover of the main biotic groups from Pichon (1978).

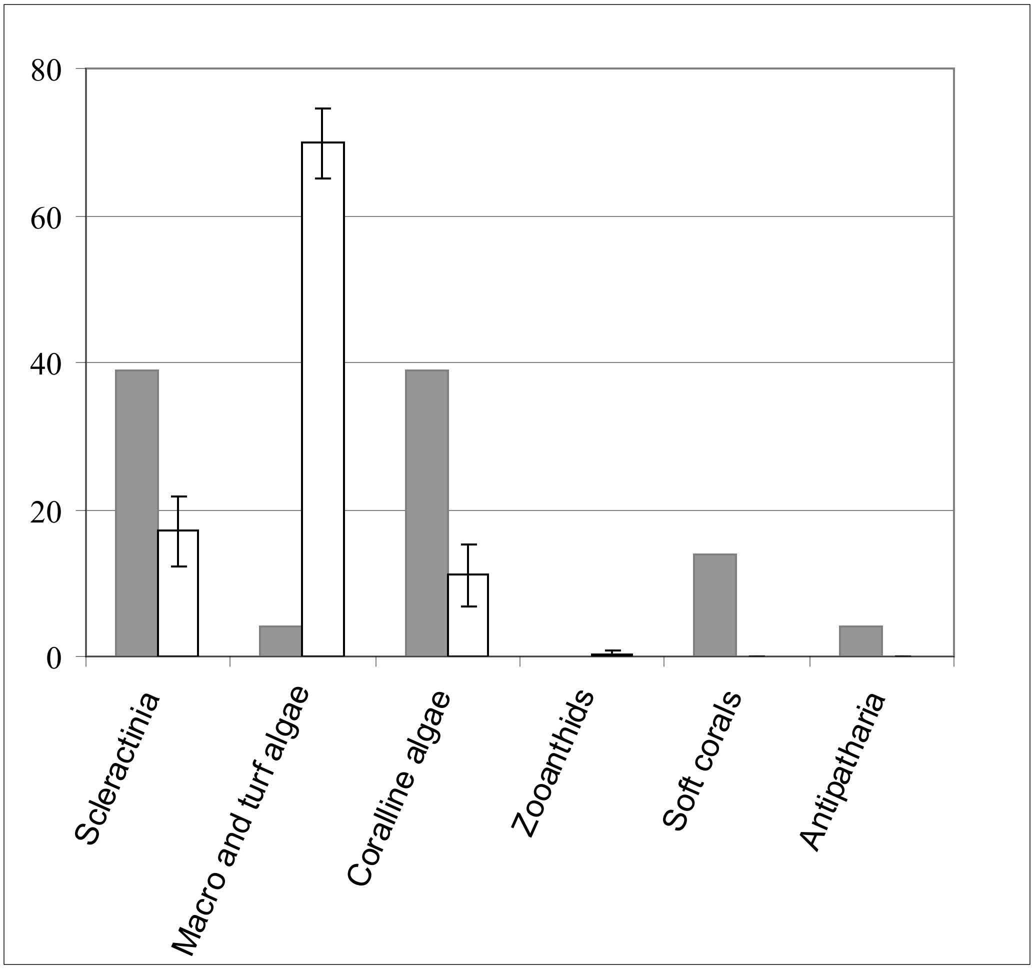

Figure 4. Relative percentage composition of living benthos categories at 10 m depth from LITs in 2008 (white bars with s.e.) compared with data inferred from Pichon (1978) (figure 3) (grey bars) from the same depth.

Comparing results from the two methods used in 2008, estimates of hard coral cover obtained by LITs showed an average cover of 13% ± 5.0 SE, which is slightly lower (but with overlapping error bars) than the mean result of 20% obtained using the visual quadrat estimates taken at the same time. For erect fleshy and turf algae both sets of values were similar. With both 2008 methods, the deterioration over 40 years is marked.

Of the corals present, only 1.6% ± 1.3 SE of the benthic composition in 2008 were of structurally complex hard coral growth forms (branching, digitate or tabular colonies). The present paucity of architecturally complex coral genera is reflected in the coral community composition data. Only 15% and 7% of colonies recorded belonged to the families Acroporidae and Pocilloporidae. However, although sparser, corals remained diverse, with 30 genera encountered in 2008 with a median colony size of 20cm maximum diameter. Colony density averaged 539 colonies 100 m^{-2}, the community being dominated by massive and encrusting Poritidae and Faviidae. The two most dominant genera were *Echinopora* and *Porites*. Large expanses of *Acropora* of several kinds recorded by Pichon (1978) were missing in 2008, and no evidence existed of any dead or eroded tabular coral framework, suggesting that the widespread loss of *Acropora* had taken place several years previously.

On the reef flats, there was, in 2008, very little live coral. This contrasts markedly with photographs of reef flats shown in Pichon (1978) (Figure 5).

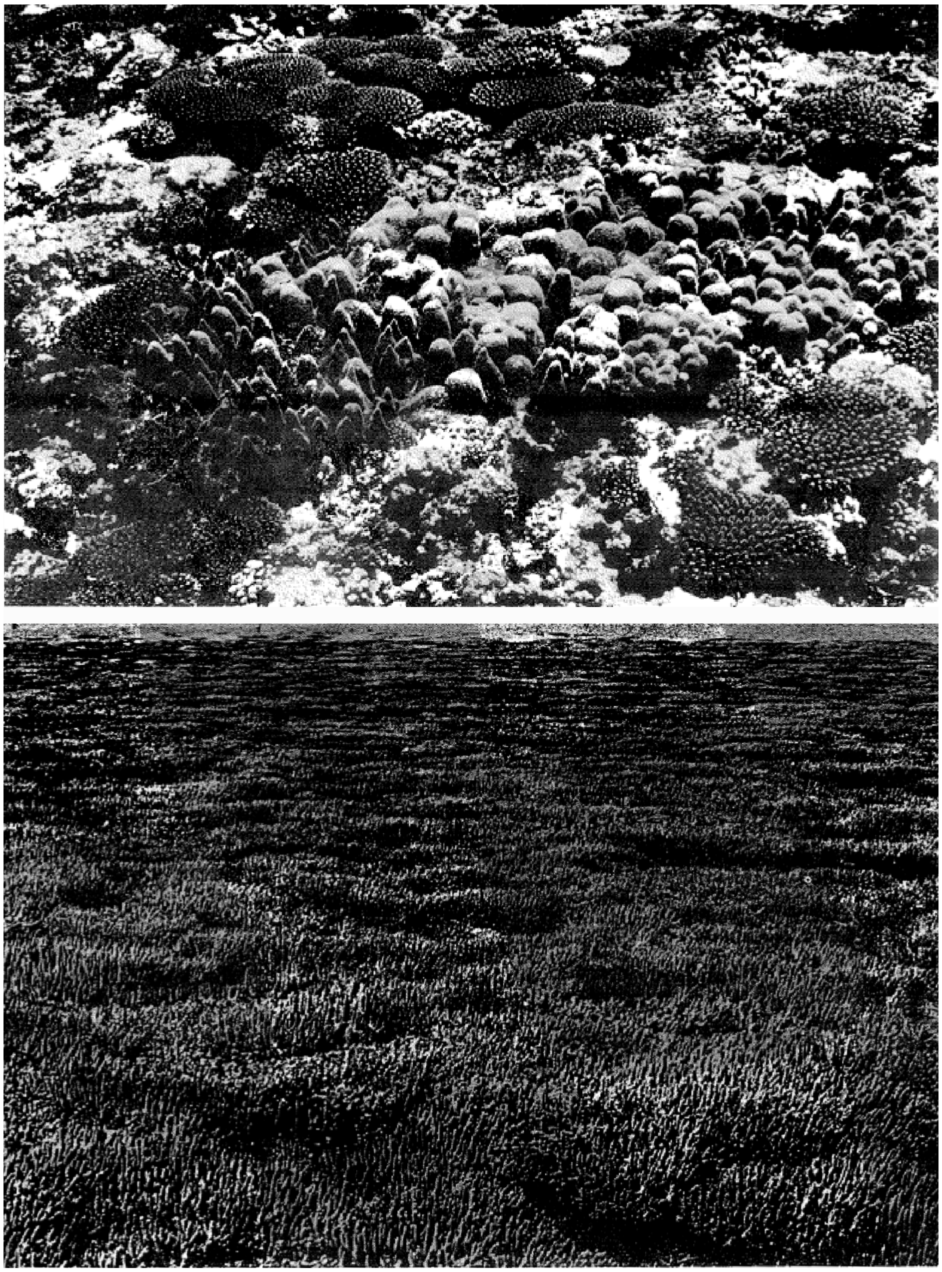

Figure 5. Photographs from Pichon (1978): **Top**: Pichon's Figure page 38, 'Plateforme supérieur des éperons. Peuplement à *Acropora cf penguis* et *Acropora humilis*.' **Bottom**: Pichon's Figure 63: 'Champ de Scléractiniaires branchus (Récif sud-Ifaty).'

Fish species richness was particularly low in 2008, with a total of just 14 reef fish species observed during the survey. Mean reef fish biomass was estimated to be 134.6 kg ha^{-1} (± 33.9 SE) in 2008. Seventy five percent of the fish species were herbivorous, a trophic composition which differs markedly with that seen in 1979 (Figure 6) (Harmelin-Vivien, 1979).

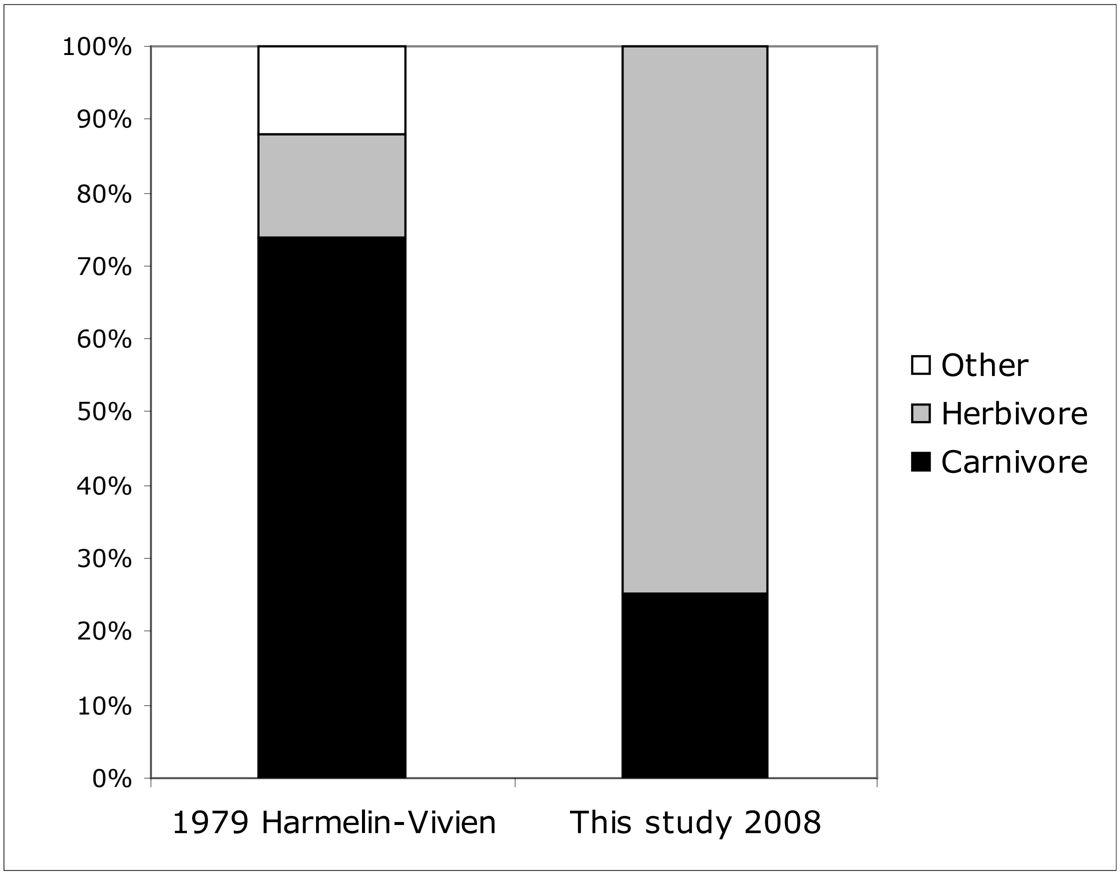

Figure 6. Reef fish trophic-guild composition at the Grand Récif in 2008 (right column), compared with data from Harmelin-Vivien (1979) (left column).

Sea surface temperature for this region has risen over the time span considered (Figure 7). The linear rise of mean SST is over 1°C, and warm summer peaks are seen in both 2005 and 2007, with the latter at 29.12 being the highest in the data series. No quantitative observations of widespread coral bleaching have been recorded in the Toliara region in recent decades, but regular monitoring has only been carried out in southwestern Madagascar since 2003, 5 years after the Indian Ocean-wide mass bleaching and mortality episode that may have heavily impacted the region's reefs.

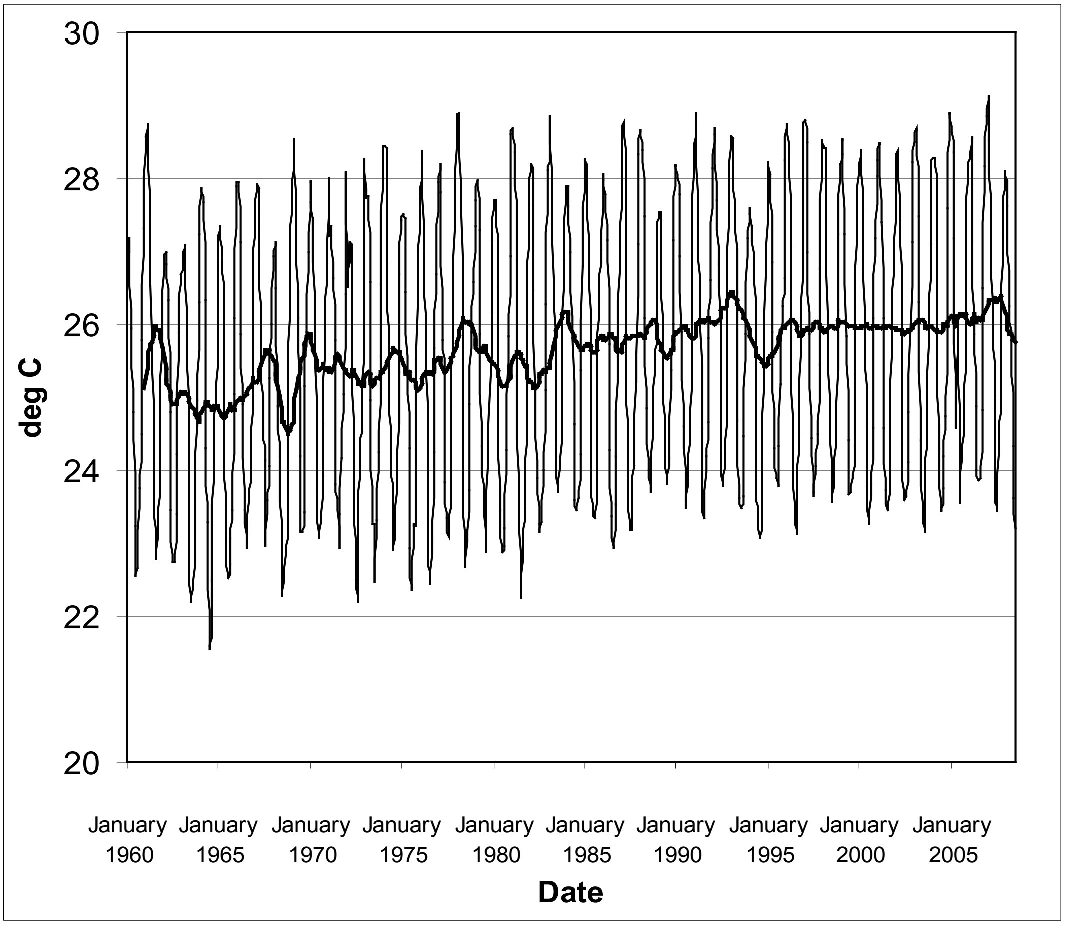

Figure 7. Sea surface temperature (HadISST1 data) for the Toliara region. Trend line is the 12 month moving average.

Comparison with Other Sites in Madagascar

The benthic composition of the Grand Récif today is similar to that on seaward slopes of the barrier islands of Nosy Fasy and Nosy Hao, which are both similar reef structures located some 200 km north of the Grand Récif (Figure 8) (unpublished data and Nadon et al. 2007). In these sites also, coral cover is very low at 8-14%, with similarly high coverage of fleshy macroalgae of around 60%. Colony density is similar too, at between 200 and 600 colonies 100 m^{-2} (unpublished data). These sites, including the Grand Récif, contrast greatly with two protected reef sites in the southwestern region that lie within the Velondriake marine protected area (established in 2008, but previously benefiting from *de facto* managed status from low fishing effort); in the latter, coral cover approaches 80% and colony densities are three times higher with around 1,400 corals 100 m^{-2}. Moreover, these protected reefs show a far higher relative abundance of structurally complex genera, with approximately 15-40% of colonies belonging to the architecturally complex Acroporidae and Pocilloporidae respectively. In the protected area, human populations are very much lower, the region being populated by remote fishing villages and settlements of nomadic fishers, with no major towns.

Fish diversity and biomass on the Grand Récif may also be contrasted with other reef surveys conducted in the region (Figure 9). Both parameters on the Grand Récif are dramatically lower than in the more remote and less populated areas.

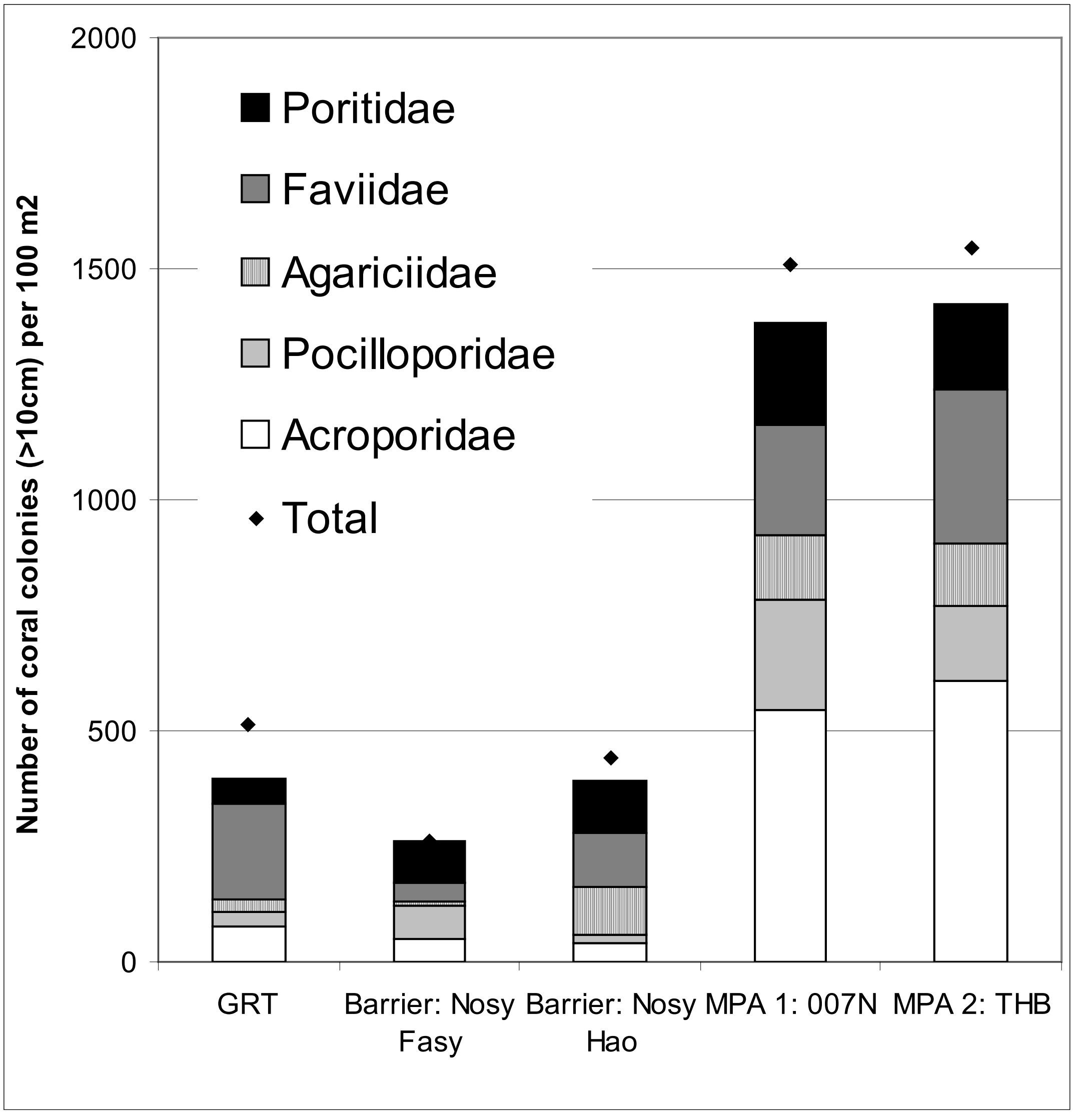

Figure 8. Comparison of hard coral colony density of major scleractinian families of Grand Récif Tuléar (GRT) with four reefs located approximately 200 km north. These are two barrier reefs which are fished and (right pair) two patch reefs within a marine protected area with comparatively low human population density.

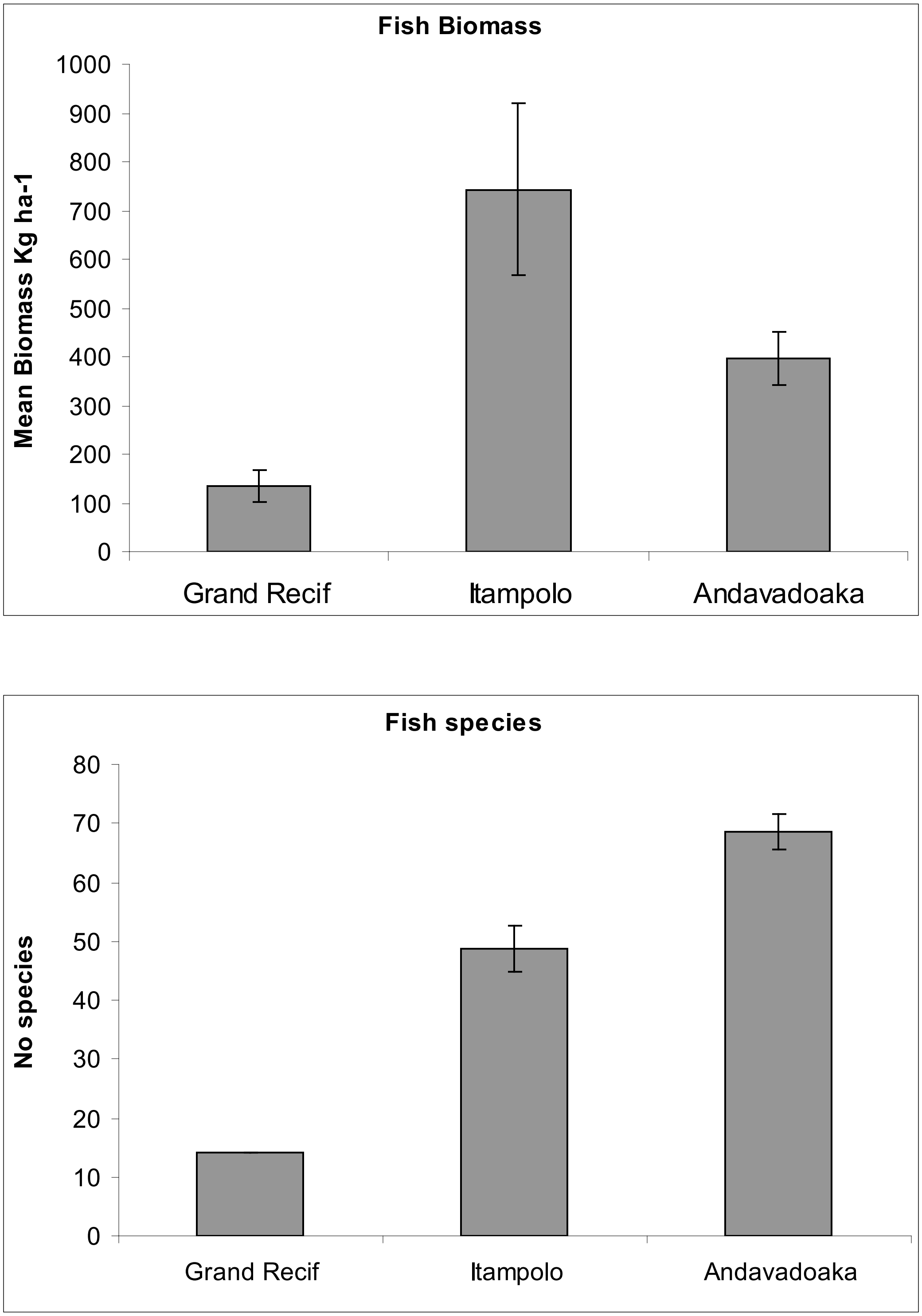

Figure 9. Reef fish of Grand Récif compared with those of other surveys conducted in southwest Madagascar. **Top**: reef fish biomass, **bottom** reef fish species diversity.

DISCUSSION

Pichon's (1978) description of coral zonation at that time is clear, even if quantitative data are unavailable: "The upper zone (0-7 m) owing to the exposed conditions, exhibits an impoverished aspect of the community found slightly deeper (7-14 m)". "The lower zone (14-20 m) … is an area of transition between the communities of the upper outer slope and of the coral flagstone". This zone is the most diverse with highest coral cover. "Flagstone" is used to describe the reef structure below 20 m and there "a markedly different community is to be found, in which the major components are: fleshy algae, Porifera, Hydroida, Gorgonaria, Antipatharia." He states that corals in the zone 20-25 m remained abundant, dominated by Pectiniidae, but deeper than 25m "The intermediate zone (25-35 m) shows a sharp decrease in species diversity and coverage of hermatypic corals. These are mostly Pectiniidae, several species of *Leptoseris* and of Mussidae. Fleshy algae are abundant". Below 35 m, "Antipatharia and Gongonaria cover increases, while that of algae and Porifera is reduced."

This description of Toliara's outer reef slope was typical of several Indian Ocean reefs from a period of approximately 40 years ago (reviews in Stoddart and Yonge, 1971; Jones and Endean, 1971). One unusual characteristic of the Grand Récif is the huge spur and groove system, whose origin was thought to derive primarily from old, erosion features as well as algal construction, these being much wider and deeper than most purely constructional spur and groove systems. Descriptions of this from Pichon (1978) show the dominant benthic groups to be corals, soft corals and calcareous algae, with much less fleshy algae. *Millepora platyphyllia* and *Acropora* spp were the dominant corals within the most exposed upper slope regions. In the present survey, coral cover in the shallowest regions of the reef slope was much lower, and lacked the *Acropora*, although coral cover overall was still higher here than in deeper regions.

Causes of mortality in the Grand Récif may include warming episodes, which are likely to have caused mass bleaching in this region, as well as overexploitation and pollution of the reef. Of these factors, SST is not likely to have been markedly different to that on reefs in adjacent areas with low human population where much better coral cover and fish populations remain. It is being repeatedly shown that even where warming is causing reef deterioration, recovery can be rapid where there are minimal direct impacts, and that recovery may not occur at all where there is also pollution and over-fishing (Harris and Sheppard, 2008; Sheppard et al., 2008; Hagan et al., 2008). In the Grand Récif, it is more likely that the rapid rise of discharged, untreated sewage from the growing city is very important, along with the rapid rise in human population with its associated artisanal fishery.

Important also is likely to be increased sediment inflow from the rivers Onilahy and Fiherenana, which drain inland areas which, as is the case for much of southern Madagascar at least, are suffering from very substantial inland deforestation. Sediment quantities, however, remain unmeasured.

Several environmental problems may follow from the continual demise of the Grand Récif. The reef height has already been lowered by the loss of the once abundant reef flat corals (see Figure 5). The distance between the upper surface of a reef and the sea surface is known to considerably affect the breakwater effect of reefs (Sheppard et al., 2005), such that a lowered reef surface which is seen when reef top corals decline, results in significantly greater wave energy reaching the coast. This effect, sometimes termed "pseudo sea level rise," causes a loss of breakwater function and increased erosion of shorelines. Additionally, the loss of corals equates with a loss of reef rugosity arising from the smoothing of the reef flat, and this is almost as important as the loss in absolute height in reducing a reef's breakwater effect (Sheppard et al 2005). This has potentially severe consequences for the city of Toliara which lies on a flat coastal plain only marginally above sea level, relying on protection by the Grand Récif from inundation by storms. Heavy oceanic swells of southern ocean origin and amplitude of 1-3 m are common to Toliara, occurring independently of local weather, with swells of 3-5 m being not exceptional (Pichon, 1978). Cyclonic activity in southern and western Madagascar is also high, with severe damage to affected areas occurring approximately annually. The result may be greater exposure to wave energy on the coast, a point already commented on by Thomassin et al. (1998) and Vasseur et al. (2000).

Reef and coral rugosity are responsible in large part for the creation of the physical and ecological niches that support the high biodiversity of fish and invertebrates within a healthy reef ecosystem. The pervasive collapse and loss of three-dimensional structural and topographic complexity of coral reefs inevitably results in drastic reductions in the abundance and diversity of fish populations (Pratchett et al., 2008; Berumen and Pratchett, 2006), and this is seen here for the Grand Récif also. Indeed the paucity of fishes on this reef was extreme, and, as shown in Figure 6, the trophic guild composition has changed markedly, showing a shift from top predator and carnivore control to a community dominated by herbivorous species. Harmelin-Vivien (1979) suggests that carnivore levels on a healthy reef in the region should be between 60 and 80% depending on geographic location. The observed loss of fish species and change in trophic composition may be linked to over-fishing, where the primary extraction of larger, more commercially valuable piscivorous fish species such as Serranids and Lutjanids causes 'trophic cascades' (Coleman and Williams, 2002). Larger carnivorous fish have a tendency to show greater longevity and lower fecundity than smaller fast growing species, making their populations more susceptible to overfishing (Roberts, 2007). With such a low biomass of fish and low numbers of carnivores (no groupers, snappers or emperors) it can be said that the fishery has collapsed.

Water quality in the lagoon between the Grand Récif and Toliara city is currently the focus of a study by Franco-Malagasy research partnership (Arfi et al., 2007). However, while the lagoonal water has always been extremely turbid, the outer slope water was much more transparent, presumably on account of high water movement from the reef's exposed oceanic setting and the generally northerly current of the region. It is possible that much of the discharge from the city is swept northward. While it is not possible to determine with the data so far obtained whether nutrient enrichment or heavy fishing pressure is the primary driver of the large increase in fleshy algae, it is likely that all these factors have contributed to the extensive degradation of the Grand Récif. Although threats such as warming cannot be managed at a local scale, the compounding factors such as over-fishing and sewage discharge could be.

Given the scale and immediacy of the climate threat, the future of Toliara's Grand Récif clearly now depends on the introduction of sufficient management measures to mitigate these direct local impacts. Studies have shown direct correlation between the depletion of local fish stocks and their proximity to national or even local markets (Brewer et al., 2009). Coupled with the resource demands of a burgeoning coastal population, the proximity of Toliara's coral reef to regional fisheries collection and export centres is likely to be a major driver of overfishing of the most sought-after fish species. Highly desired species such as groupers, snappers and emperors were absent from the field surveys in 2008. Failure to respond to this critical management challenge may have terminal consequences to the Grand Récif and the vital ecosystem services it provides.

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