THE STATUS OF THE ALDABRA ATOLL CORAL REEFS AND FISHES FOLLOWING THE 1998 CORAL BLEACHING EVENT

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INTRODUCTION

It is important to establish benchmark reef locations that are remote from centres of human activity and free from anthropogenic disturbances, against which human impacts elsewhere can be assessed and rates of recovery evaluated. Aldabra Atoll in the southern Seychelles, is free of anthropogenic disturbances and an ideal location in which to study reefs and adjacent ecosystems. It has further significance with it being in the middle of a region which has been classified as having a number of reefs at high risk (Bryant *et al.*, 1998) and has been designated as a UNESCO World Heritage site.

Aside from acting as a regional benchmark there are a number of practical reasons why Aldabra provides a key component to monitoring the effects and long-term impacts of the bleaching event. Many studies of coral bleaching have concentrated upon documenting the degradation of structural reefs into algal-dominated systems. Yet, the reverse set of processes are of considerable importance: the ability of a coral reef to replenish lost coral populations, reinstate framework growth and recover reef structural complexity. The recovery from high bleaching related coral mortality of these oceanic reefs, such as those around Aldabra, is of much regional interest. The systematic monitoring of the Aldabra reef environment will provide a greater understanding of the natural reef processes acting locally, with implications to understanding reef dynamics elsewhere in the region.

Albabra Atoll

Aldabra Atoll (9°24' S, 46°20' E) is a large (34 km long, maximum 14.5 km wide) raised atoll 420 km north of Madagascar (Map, Figure 1). Raised reef limestones, averaging 2 km in width and up to 8 m above sea level, enclose a shallow central lagoon. A tidal range of 2 to 3 m results in large-scale hydrodynamic exchanges between the lagoon and open ocean through two main channels and a number of small ones. The climate is heavily influenced by NW monsoon winds from November to March bringing the heaviest rainfall with SE trades blowing throughout the remainder of the year.

Previous studies proposed that the reef front areas of Aldabra Atoll could be classified into six morphological categories, based on exposure to wave and storm action in the shallower depths, and on light attenuation in the deeper reef zones (Barnes *et al.*, 1971; Drew, 1977). The western reefs are characterised by a 460 m wide reef flat, a reef ridge margin and reef front slopes of 20° to 45°. The topography of reefs on the northern coast of Aldabra varies very little.

Characteristically, there is a very short reef flat that slopes gently down to 10 m, below which the reef drops at an incline of approximately 35° - 45°. At between 20 m and 25 m the reef shelves off to form a sandy ledge with patches of coral growth and then drops off steeply again at between 35 m and 40 m. The east and southeast coasts are the most severely exposed and have neither a reef flat nor a reef ridge. No hermatypic corals are present. Finally, on the southern, less exposed shore the reef flat is present but not delimited by a prominent ridge. The reef front itself is characterised by large areas of dead coral which vary greatly in extent.

There is a long history of Aldabra reef fish studies extending back over 100 years (i.e. Jatzow & Lenz, 1899; Regan, 1912). The fishes of Aldabra were included in a description of 820 marine fish of the Seychelles (Smith & Smith, 1969). This list was expanded and revised by numerous studies during the period 1969-1979 to 883 species in the region (Polunin, 1984). Specific studies of the fishes at Aldabra found a high diversity, with 185 species recorded in a 300 m2 section of reef habitat in 1973. However, there were substantial variations in species and abundance between habitats (reef-slope – 228 species, back-reef – 146 species; Polunin, 1984). Fish surveys conducted at Aldabra Atoll in April-May 1998 noted 287 species from 35 Families (M. Spalding, University of Cambridge, unpublished).

Coral Bleaching in Aldabra in 1998

Localised sea-surface temperature (SST) records for Aldabra indicate that SSTs for 1998 were the highest of the previous three and a half decades (Figure 2). Anomalous temperatures began with a rapid increase in SSTs from November 1997 to a +1° C SST anomaly by January 1998. Peak SSTs (30.65° C) were reached in March, representing a +1.31° C anomaly above the long-term mean maximum SST for that month. The +1° C anomaly persisted until April 1998 indicating a duration of almost four months (Figure 3). All temperatures recorded for the period leading up to the bleaching event and those following ranged from +0.5º C to +1º C higher than the long-term average of the monthly mean maximum temperatures (1961-1997).

In April 1998, close to the peak of the coral bleaching event, 41% of corals (coral coverage = 37%) were bleached or displayed recent mortality on the outer reef slopes (3 m -25 m) from the western to north-eastern sides of Aldabra (Cambridge Coastal Research Unit (CCRU), Southern Seychelles Atoll Research Programme – SSARP). Bleaching intensity in Aldabra was not as high as other areas in the southern Seychelles possibly because peak warming was 0.5º C lower than other areas in the region (Spencer *et al.*, in press). Bleaching and related mortality was primarily seen in the branching and tabular species of coral (*Pocillopora* and *Acropora*), and partial to patchy in most massive species (*Porites* and *Pavona*). Bleaching in some areas was confined to a single side of the coral colony. However, a high proportion of the massive species of corals displayed signs of previous mortality, as indicated by a thick layer of algal overgrowth and the presence of encrusting and boring invertebrates. As in other areas, soft corals showed high levels of bleaching and mortality. Although no quantitative data were gathered for the reef communities in the lagoon, extensive observations were made in all of the channels and in the western half of the lagoon. Most of the coral species found in the channels, with the exception of isolated incidences of branching corals, were observed to be alive and displaying no obvious signs of perturbation. Lagoonal patch reefs and individual heads of massive coral species displayed very limited bleaching. Distinctive species such as *Galaxea*, *Seriatopora*, *Acropora* and *Pocillopora*

were completely bleached, particularly with increased distance from the flux of water within the channels.

METHODS

In November 1999, a series of seven permanent transects were established on the northern and western coasts of Aldabra Atoll (Figure 1). At each site quantitative baseline surveys of the corals and reef fishes were conducted along each transect. Primary transects were placed from a depth of 20 m to the reef crest at 3 m - 5 m. Secondary transects were established at 20 m and 10 m following the depth contour. The benthos at each site was surveyed using digital videography. Video imagery was analysed recording live and dead, hard and soft coral growth forms (branching, tabular, massive, encrusting and foliose). The occurrence of coral genera within each of these growth form categories was also noted, as well as incidences of mushroom corals, *Heliopora* (blue coral) and *Millepora* (fire coral). Additional observations of the substrate were noted in pre-defined categories: sand, rubble, rock, turf, *Halimeda* and other macro-algae.

Settlement plates were located at six sites, three on reefs around the outside of the atoll, and three within the atoll (Figure 1). Of the six tiles, two were oriented in the horizontal plane, two at approximately 45° to the horizontal, and two in the vertical plane.

Rapid visual fish surveys were conducted using species, number and size of fish recorded in a 2 m corridor extending out from either side of the transect, and vertically to the surface. Six total length categories were used: 0-5 cm, 6-10 cm, 11-20 cm, 21-30 cm, 31-40 cm and >40 cm. Each section was first surveyed for larger/ conspicuous fishes, and then immediately re-surveyed for small/cryptic fishes. Fish size classes have been condensed to three grouped categories for this paper.

RESULTS

Coral and general benthic composition

There was a range of variation in percent cover of live coral (11% - 27% ± 6% (± 1 standard deviation) and of dead coral (11% - 30% ± 7%). Live coral cover was strongly correlated with depth. From the shallow depths of 5 m - 10 m to >15 m there was an increase of 10% - 20% of live coral cover. Conversely, dead coral cover was higher in shallow waters (<10 m) at 44%, decreasing with depth (>20 m) to 10% - 20% of the coral cover.

There was a general increasing trend for cover of live and dead coral from east to west on the whole atoll (Figure 4), coinciding with decreasing levels of exposure to strong hydrodynamic conditions. The least exposed sites with the highest mean live coral cover were sites 1 (25%), 2 (24%), 6 (16%) and 7 (21%) (Figure 4). Note that site 5, at the highly exposed eastern corner of the atoll, was treated separately from other sites as it was distinctly different from the others surveyed, dominated by a high percentage of a sand, rubble and rock matrix (56%) and macro-algae, primarily *Halimeda* spp. (40%). Site 5 did have isolated coral heads but only 1.5% live coral and 2.0% dead coral of the total substrate cover.

Across the range of the sites examined *Halimeda* spp. was the dominant macro-alga, with localised high concentrations of *Dictyota* spp., *Caulerpa* spp. and *Lobophora* spp.. *Thalassodendron* spp. was present but was not considered to be a major component of the outer reef slopes. In most areas red encrusting coralline algae were observed especially where incidences of dead upright coral and coral rubble were present. On massive coral heads small patches of red encrusting algae were beginning to colonise in presumed bleaching related dead areas.

Soft corals (*Sinularia* spp., *Lobophytum* spp. and *Sarcophyton* spp.) were present as small isolated colonies and comprised no more than 5% of the substrate at any given location. Soft corals show a slight increase in abundance moving east along the northern coast.

The dominant live coral growth forms were massive, branching, encrusting and foliose at both shallow and deep sites. Massive corals were dominant at deep and shallow sites (63% and 45% of live coral cover, respectively). *Physogyra* sp. was the dominant massive coral on deeper transects (65% of massive spp.) but was virtually absent (3%) from 10 m depth sites. Other prominent massive genera were *Favia*, *Favites*, *Galaxea*, *Gardineroseris*, *Goniastrea*, *Leptoria*, *Lobophyllia* and *Porites*. The majority of branching corals found at both shallow and deep sites were *Pocillopora* and *Porites* spp., representing 20% of the total live coral cover. Live tabular coral species were not encountered at any of the sites surveyed but they were noted at the seaward edge of the western channels to the lagoon. Foliose (*Echinopora*, *Pachyseris*, *Turbinaria* spp.) and encrusting corals (*Montipora* spp.) were also common, but foliose corals were almost exclusively in deeper waters. *Millepora* and *Heliopora* were rare at all sites and depths, amounting to <4% of total coral cover. Extensive stands of dead *Millepora* were observed at transect 4 as deep as 23 m.

Although mortality was not as high in massive corals as in others, there was evidence of tissue death which was spatially patchy on individual coral heads. In some cases live tissue remained on the sides or underside of the colony. In sites where branching corals have survived it is often the case that the colony has suffered only partial mortality. It is noteworthy that plate and fine branching corals were not abundant at any of the sites visited, probably because of relatively high hydrodynamic activity present in the vicinity of the atoll. It is also possible that with the onset of mortality the structural integrity of these growth forms, would be rapidly compromised in the first incidence of high wave action.

Sites 1, 2, 4 and 7 were previously surveyed by the SSARP in April 1998 close to the peak of the coral bleaching event (Spencer *et al.*, in press). At 10 m depth, the majority of the bleached corals in 1998 had suffered subsequent mortality, translating into an increase of 22% in dead coral cover by November 1999, with minor increase of normal live coral cover (+7%, Figure 5a). At 20 m depth, the proportion of bleached corals in 1998 was higher than at 10 m, however rates of recovery were much better with an increase of 52% of live coral coverage, from 14% in 1998 to 66% in November 1999 (Figure 5b).

Fish communities

Fish surveys gave quantitative information on 164 species representing 27 families. An additional 48 species and six families were recorded in qualitative surveys, giving a total of 212 species for November 1999 at Aldabra.

The densities of fishes ranged from 352 per 100 m^2 from 33 species and 16 families at Site 5, to 7162 per 100 m^2 from 90 species and 23 families at Site 6 (Figure 6). The density and species of fish at Site 5, near the eastern end of Aldabra Atoll, were clearly different from the six other sites along the northern shoreline and at the western end of the atoll. Disregarding site 5, there was little variation in families of the fish in the surveys at the other sites. The lowest density of fishes at Sites 1-4, 6, and 7 was 645 per 100 m^2 from 70 species at Site 3. The large differences in the density of fish resulted from large schools of a few species from the families Serranidae (groupers and basslets), Apogonidae (cardinalfishes) and Pomacentridae (damselfishes). When the fish density exceeded 1000 per 100 m^2, these three families accounted for between 80% and 94% of the fishes.

The sizes of the fishes in the transects at Sites 2-7 were dominated by those in the 0 cm -10 cm total length category, which contained from 86% - 98% of the fishes surveyed (Figure 6). At Site 1, 72% of the fishes were in the 11 cm -20 cm total length group, due to an unusually large school of Caesionidae (fusiliers) that contributed 63% of the total fishes in this size group. The abundance of fishes in the 0 cm -10 cm category was caused primarily by large numbers of small-sized species, and secondarily by juvenile life-stages.

No significant correlations were found between overall measures of fish community structure (density and species number) and habitat variables (longitudinal gradient, live coral cover and dead coral cover). However, the families Chaetodontidae, Labridae, and Serranidae each have several species that are commonly associated with live corals and habitat structure formed by erect dead corals. Significant positive correlations were found for a) species richness and density of Chaetodontids with respect to live coral habitat ($r^2 = 0.88$ and 0.71, respectively), and b) density of Labrids ($r^2 = 0.61$) with live coral cover, and c) species richness of Serranids ($r^2 = 0.59$) with live coral cover.

DISCUSSION

The 1998 coral bleaching event had pronounced effects upon the reef complex. Shallow corals suffered the greatest mortality and lowest recovery, perhaps due to the long period of exposure to high and increasing SSTs as shown in figure 2. Although bleaching levels were greater for deeper corals in 1998, recovery was higher and mortality lower than for shallow corals. It may be that penetration of warmer SSTs to deep water sites took longer and may have had a shorter duration than in the shallows. Shorter duration and magnitude of anomalous temperatures may have led to high recovery at depth (see Brown, 1997), and the timing of the onset of bleaching may be important. The 1998 survey was conducted at the end of the anomalous period, recording high bleaching cover. This suggests that the bleaching may only have started at the end of the three-month period of anomalous SSTs.

Coral communities in Aldabra may have undergone a shift in species composition as a result of the bleaching, which is likely due to susceptibility to bleaching. *Physogyra* sp., abundant

between 15 m and 25 m, and *Pachyseris,* abundant below 20 m - 25 m, are now dominant corals. The dominance of *Physogyra* sp. across all deep water sites suggests a particular robustness of this species to the perturbation of the ambient environment. In areas where currents were strong, particularly the channel exits, *Tubastraea micrantha* is abundant.

There is no evidence that the death of large numbers of corals has led to an explosion of macro-algae, as these were not abundant on dead coral surfaces. Dead corals had been covered or partially covered by red encrusting algae which not only cement and maintain the structural integrity of the coral, but may also create suitable substrate for coral larval settlement. It is essential that the substrate be fixed and/or consolidated for coral development to occur.

The recovery of reefs at Aldabra from the bleaching event is underway. In areas where coral had died, there was evidence of acroporid and pocilloporid recruits up to 3 cm in diameter. Many corals suffered only partial, not full, mortality, and the live patches will be monitored to assess whether these will re-grow over the dead areas. With live coral colonies on the deeper outer slopes, in the lagoon and channels local coral larval recharge may occur. Future recovery of settlement plates put out during the surveys will provide insight into coral recruitment levels in and around Aldabra, and to further monitor and understand the recovery process.

The diversity of fish species and families found in coral reef ecosystems is indicative of the productivity or health of the system (Sale, 1991). The vertical relief and three dimensional complexity of the reef habitat provided by both live coral and erect dead coral structures is not only crucial for fish survival, but is also an aggregation attractant for reef fishes. This habitat complexity is often positively correlated with the diversity of fishes on the reef (see Ebeling & Hixon, 1991; Sebens, 1991; Williams, 1991; Turner *et al.*, 1999). Alterations and reorganisations of the reef structure following a bleaching related mortality event may, in turn, have varied spatial affects through a range of temporal scales on non reef dwelling fishes in the system.

There is often a time-lag in the responses of reef fishes to the loss of live coral habitat (Turner *et al.,* 1999). The November 1999 surveys may have captured essentially pre-bleaching event diversity of the fishes at Aldabra Atoll. This makes the quantified baseline information from these surveys exceedingly valuable for long-term monitoring of the natural recovery of this remote coral and reef fish ecosystem. Future surveys will be critical to fully understand the responses of the ecosystem, and for developing a comprehensive management plan for this and similar coral reefs.

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