



Coral Reef Resilience Assessment of the Pemba Channel Conservation Area, Tanzania

G. Grimsditch, J. Tamelander, J. Mwaura, M. Zavagli, Y. Takata, T. Gomez

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IUCN CLIMATE CHANGE AND CORAL REEFS WORKING GROUP





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*NOTE - This report follows a format to facilitate communication of the main findings of the report to managers and non-technical readers. The **executive summary** (section 1) and **main discussion and findings** (section 3) contain the primary findings. The detailed methods and results are presented in subsequent sections (sections 2 and 4)*

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1 Executive Summary

This report outlines results of an International Union for the Conservation of Nature (IUCN) assessment of the resilience to climate change of Pemba's coral reefs. The coral reefs of Pemba, Tanzania, are among the most diverse in East Africa. However, they are extremely vulnerable to climate change. Thirteen reef sites on western Pemba covering a range of reef habitats were surveyed using a recently developed resilience assessment methodology, covering coral and algal community, herbivorous fish populations and specific resilience indicators.

Coral reef conditions were highly variable. The highest hard coral cover (86%) and the highest coral diversity (42 genera) were recorded in the no-take zone at Misali island, while degraded sites such as Paradise and Fundo Outer had low coral cover (3% and 5% respectively), low coral diversity (23 and 33 genera respectively) and are dominated by rubble and turf algae.

Overall patterns showed that the healthiest sites are fringing sites such as Misali or Mandela or channel sites such as Manta or Kokota. Inner sites such as Fundo Lagoon, The Hole or Msuka Bay had lower coral cover due to lack of recruitment. The most degraded sites were fringing sites such as Fundo Outer or Paradise, probably due to stresses such as coral predation by crown-of-thorns starfish, bleaching or destructive fishing.

Acropora, massive *Porites* and *Ecninopora* dominate overall coral cover, accounting for 46% of total coral area. *Acropora* dominance is restricted to a few sites (e.g. Misali and Mandela), and most other sites have higher cover of bleaching resistant genera such as *Porites*, indicating that susceptible corals may have been eliminated by previous bleaching stress, and a shift in the coral community composition of Pemba's reefs appears to be occurring.

The coral size class distribution of Pemba's reefs shows lower numbers of juvenile corals (sized 2.5 to 5 centimetres) and large corals (1.6 to 3.2 metres) than is usual for a healthy reef ecosystem. The absence of corals sized 1.6 to 3.2 metres is due to high mortality during the 1998 bleaching event, while the low number of juvenile corals indicates recent failures in recruitment/survivorship, and is probably related to recent stress events such as bleaching or crown-of-thorns outbreaks. This recent decrease in recruitment/survivorship is a worrying sign that stress events are affecting the recovery potential of coral populations.

Highest coral recruitment was recorded at sites with low coral cover and dominated by turf algae (Simba, Fundo Outer and Paradise). Sites with high coral cover such as Misali, Manta or Mandela all have lower recruitment rates because less suitable substrate is available for coral larvae to colonize. However although recruitment may be higher in degraded sites, recruit survivorship is much lower and it is clear that local stresses are preventing coral recruits from reaching large sizes.

One observed threat comes from corallivorous *Acanthaster planci* (crown-of-thorns starfish). High incidence of crown-of-thorns predation was observed at Paradise and a population outbreak was observed at Fundo Inner. Removal of crown-of-thorns starfish through over-fishing, improved survival of larvae due to land-based nutrient inputs and increasing sea-surface temperature have all been postulated as potential triggers. It is important to identify and understand the triggers for crown-of-thorns starfish population outbreaks in order to mitigate this threat.

Overall, differences in resilience between sites appeared to be mostly driven by differences in coral populations and associated species, while little variation was found in connectivity and anthropogenic influences, with the exception of Misali which is closed to fishing. Resilience was ranked highest at Misali, Manta and Mandela due to better coral and associated species populations, while sites such as Paradise and Fundo Outer scored poorly.

A major threat to resilience is from overfishing and destructive fishing. Small-bodied herbivorous Acanthuridae (surgeonfish) and Scaridae (parrotfish) were the most abundant families found, followed by Lutjanidae (snappers) and Caesionidae (fusiliers). Commercially valuable families such as Haemulidae (sweetlips), Mullidae (goatfish) and Serranidae (groupers) were recorded at low numbers. No sharks were seen. Within herbivorous functional groups, grazers (surgeonfish) and scrapers (small parrotfish) were the most abundant, followed by browsers (chubs and batfish), while small excavators (*Chlorurus* spp., *Cetascarus* spp less than 35cm long) were twice as abundant as large excavators, which were very rare. Hardly any bumphead

parrotfish (*Bolbometopon* spp.), a large excavator, were seen. Scrapers and small excavators play a similar role in coral reef resilience as they are crucially important for preventing the establishment of macro-algae, removing algal turf and preparing the substrate for colonization by coral recruits. Losing this crucial functional group can lead to phase shifts from coral to algal dominated reefs after major disturbances. Misali, being the no-take zone, has the highest fish densities, and is differentiated from other sites by higher numbers of browsers (mostly Kyphosidae – chubs), higher numbers of scrapers and small excavators (Scaridae – *Chlororus* species less than 35 cm long), as well as higher numbers of non-herbivorous (e.g. Lutjanidae, Haemulidae, Carangidae). The vast majority of fish seen were <10 cm in length and only few individuals larger than 40 cm were seen during the entire survey. The high dominance of small fish and low populations of commercially-valuable non-herbivores are clear indicators of overfishing and have serious implications for coral reef community resilience. If measures are not taken to curb fishing activity in the area, then the ecosystem is at serious risk of collapse and a future phase shift to an algae-dominated reef is possible. Furthermore, evidence of destructive fishing through beach seines and dynamite fishing was evident. This needs to be addressed both through enforcement of regulations and livelihoods enhancement among fishing communities.

The resilience of Pemba's coral reefs to climate change is under serious threat. However, these threats are manageable. Some possible first steps include:

1. Use resilience data to inform management spatial planning by identifying resilient reefs

The data collected in these surveys allow us to classify sites by ecological condition and resilience capacity, therefore giving management authorities information on which to base spatial management plans. There was no site found in pristine condition due to the effects of overfishing and the poor fish populations. However, we recommend that sites with good coral populations that are not already fully protected (e.g. Mandela and Manta) should be considered for no-take zoning in order to maintain them as source reefs for surrounding biodiversity and replenishment of fish stocks. Buffer zones where limited fishing activity is allowed around these no-take zones should also be established and enforced in order to avoid spill-over effects from overfishing in surrounding areas. Sites in 'medium' condition (lower coral cover and lower quality of ecological interactions, although large colonies and good coral recruitment are present) and 'low' condition (very low coral cover and high mortality of coral recruits with no large corals present) are recommended for moderate protection, i.e. restrictions of destructive fishing gear, mesh sizes and species extraction. Furthermore, crown-of-thorns starfish monitoring with possible removal programmes should be set up in order to understand and manage this threat.

Condition	Sites	Comments	Recommendations
Good	Misali, Mandela, Manta	Good coral populations but poor fish populations (slightly better at Misali). All outer fringing or channel sites with good coral recruitment, good ecological interactions and good currents, cooling and flushing.	Full protection, to maintain biodiversity and allow fish populations to recover in order to be effective source reefs for fishing and other sites. Buffer areas with limited fishing around these no-take zones should also be established and enforced
Medium	Fundo Inner, The Hole, Njao Gap, Kokota, Fundo Lagoon, Swiss Reef, Simba, Msuka Bay	Variety of habitats, from lagoons to fringing and channel reefs. Lower coral cover but still presence of larger colonies and high recruitment (except for Fundo Lagoon). Poor fish populations.	Moderate protection, minimizing damage and including fishery regulations. Monitoring programmes of crown-of-thorns starfish populations and coral predation should also be established, possibly with starfish removal programmes.
Low	Paradise, Fundo Outer	The two most degraded sites are outer fringing sites. There is high predation and mortality of coral recruits at these outer sites, although recruitment is high. No large corals are present and herbivorous fish populations are poor.	Moderate protection combined with rehabilitation provisions where possible. Monitoring programmes of crown-of-thorns starfish populations and coral predation should also be established, possibly with crown-of-thorns starfish removal programmes.

2. Tackle the overfishing and destructive fishing problems

Overfishing is one of the major threats to Pemba's coral reefs. Fish biomass is concentrated in small bodied (less than 10 cm long) fish and there is a lack of vital predators and herbivores. The no-take zone Misali has healthier fish populations than other sites due to larger populations of browsers (especially chubs) and small excavators, and the possibility of creating more no-take zones should be explored (for example at Mandela and Manta sites). Fishing activity in the reserve should also be supervised according to PeCCA regulations, and destructive fishing methods such as beach seining with small mesh sizes or dynamite fishing should be controlled or banned. However, we understand that fishing is a complex socio-economic issue as well as an ecological one, and alternative livelihoods to fishing should exist for fisherfolk. If sustainable fishing practices could be successfully implemented around the island, then coral reef resilience to climate change and other disturbances will improve and degraded reefs will have a better chance of recovering.

3. Understand the crown-of-thorns problem

Crown-of-thorns starfish are a major cause of mortality of coral recruits in Pemba, and the cause for the recent increases in population should be studied and understood in order to provide solutions to the problem. Crown-of-thorns starfish population outbreaks have been linked to overfishing of predators (e.g. triton shells), nutrient input or increasing sea surface temperature that increase larval survival. Possible direct management actions to counteract this threat are crown-of-thorns starfish monitoring and removal programmes involving environmental protection agencies and local dive operators.

4. Promote ecological resilience through protection of functional processes and alleviation of local stresses rather than technological fixes

Technological fixes to environmental or climate problems are becoming increasingly popular due to the dire situation and the looming threat of collapse of ecosystems. An example is the deployment of reefballs in degraded coral reefs in order to promote coral recruitment. Although reefballs may provide good substrate for settlement, they do not alleviate the fundamental stresses that are causing recruit mortality and therefore are not likely to promote ecological resilience.

Successful settlement of coral recruits is not the problem for Pemba's degraded reefs (e.g. Paradise or Fundo Outer). Recruits are settling well, but are then not surviving and growing into larger colonies. This indicates that substrate quality is adequate for coral settlement, but that there are other stresses (e.g. crown-of-thorns starfish, destructive fishing or bleaching) that are causing coral mortality. Adding artificial reef substrate with reefballs does not remove these stresses, and recruits that settle on them will also be subjected to them and be at risk of mortality. If reefballs are to be deployed, we would recommend to do this in areas dominated by unconsolidated rubble where *Acropora*-dominated patches have died leaving broken coral pieces that are easily dislodged by water movement and do not allow coral recruits to settle. Some areas of Misali or Paradise would be appropriate. However, we do not recommend deploying reefballs on degraded substrates that are consolidated.

Rather than using this technological fix, it is more important to protect fundamental ecological processes through protection of resources and alleviation of local stresses. Reducing overfishing and destructive fishing practices, for example, would allow crucial planktivorous, herbivorous and carnivorous fish populations to recover and thus promote greater control of crown-of-thorns starfish and macro-algal populations that cause coral mortality.

The IUCN Climate Change and Coral Reefs Working Group (www.iucn.org/cccr) is ready and willing to give technical advice and support on implementing these management strategies. Please contact Dr David Obura (Head of CORDIO East Africa, dobura@africaonline.co.ke) or Jerker Tamelander (jerker.tamelander@iucn.org) for further advice.

2 Introduction

2.1 The study

This survey was conducted by invitation by the Manta Resort, a hotel on the northwest coast of Pemba, and Pemba Alive, a non-governmental organization dedicated to marine conservation and improving the livelihoods of fisherfolk in Pemba. The purpose of the study is to provide information that enables identification of sites that are resilient or vulnerable to climate change in the Pemba Channel Conservation Area (PeCCA) along Pemba's west coast, as well as to make recommendations for improved management of this crucial biodiversity hotspot. Specifically, the study objectives are:

- 1- To implement a bleaching and resilience rapid assessment protocol that meets the needs of MPA planning and implementation in Pemba and to make recommendations for the protection of this unique environment;
- 2- To assess the resistance of coral reefs in Pemba to coral bleaching and climate change;
- 3- To assess the resilience of coral reefs in Pemba and their potential ability to recover following a bleaching event;
- 4- To make recommendations on zoning, design and management of coral reefs within the PeCCA based on the survey findings.

Members of the survey team incorporated staff from the following partner organizations:

Organization	Survey team
IUCN/CORDIO	Gabriel Grimsditch Jerker Tamelander
CORDIO	Jelvas Mwaura
The Ramsar Convention	Monica Zavagli
University of Florida	Yukari Takata
Pemba Alive	Tanausu Gomez

More information on the IUCN Climate Change and Coral Reefs Working Group can be found at www.iucn.org/cccr

2.2 Reef resilience

Coral reefs and their associated seagrass beds and mangrove habitats support the highest marine biodiversity in the world. More than 500 million people worldwide depend on them for food, storm protection, jobs, and recreation. Their resources and services are worth an estimated 375 billion dollars each year, yet they cover less than one percent of the Earth's surface. To the people of Pemba, coral reefs are highly valuable as sources of food through fishing, aquaculture and revenue through tourism.

Climate change is now recognized as one of the greatest threats to coral reefs worldwide. One of the main threats associated with changes in the climate is coral bleaching, a phenomenon associated with above-average temperature and light conditions that result in corals expelling the symbiotic micro-algae (zooxanthellae) that live within their tissue and provide them with crucial energy and pigmentation. Temperature and light stress damages this symbiosis, leading to corals losing their zooxanthellae and colour and leaving them white and weakened. A coral in a bleached state is extremely vulnerable to mortality by disease or by algal attack, but if favourable environmental conditions exist and stress levels decrease it is possible for corals to regain their zooxanthellae and survive bleaching events.

The coral reefs of Pemba are among the healthiest, most diverse and most important in East Africa. Local people rely on them heavily for income from fishing, aquaculture and tourism. However, these corals are also extremely vulnerable to climate change. In 1998, they bleached heavily, and mortality caused coral cover to fall from 54% average around the island to 12% in 1999. Corals have recovered slowly, up to 16% in 2002 (Obura, 2002), but they still have a long way to go to recover their former glory and future bleaching events seriously threaten them again. Consequently, the value of the reefs for the local people is decreasing, and it is important that they be conserved effectively to continue to support livelihoods on land. Recent assessment data from the area are scarce.

Two general properties determine the ability of coral communities to persist in the face of rising temperatures: their sensitivity and their recovery potential. Sensitivity relates to the ability of individual corals to experience exposure without bleaching, and if they bleach to survive. Recovery potential relates to the reef community's capacity to maintain or recover its structure and function in spite of coral mortality. These properties at the

coral colony and coral community level are termed 'resistance' and 'resilience', respectively (West and Salm 2003, Obura 2005, Grimsditch and Salm 2006). Together, they determine the resilience of coral communities to rising sea temperatures.

Resistance – when exposed to high temperature and other mitigating factors, the ability of individual corals to resist bleaching, and if bleached to survive.

Resilience – following mortality of corals, the ability of the reef community to maintain or restore structure and function and remain in an equivalent 'phase' as before the coral mortality.



A photo illustrating resilience in Misali. On the left, an area that has been bleached but recovered to very high coral cover and Acropora-dominance. On the right, an area that has bleached but where coral recruitment has not been successful due to the unconsolidated nature of the coral rubble. © Jerker Tamelander, IUCN.

The natural resilience of reefs is also being undermined by local stresses associated with human activities. These local pressures reduce the resilience of the system by undermining its ability to cope with additional stresses, such as from climate change. Unmanaged, these stresses have the potential to act in synergy with climate change to functionally destroy many coral reefs and shift them to less diverse and productive states dominated by algae or suspension feeding invertebrates. Increasingly, policy-makers, conservationists, scientists and the broader community are calling for management actions to restore and maintain the resilience of the coral reefs to climate change, and thus avoid worst-case scenarios, ie collapse of coral reef ecosystems and phase shifts from highly diverse coral reefs to low diversity algal reefs with little structural function, low fish biomass and high microbial biomass in the water column.

In Pemba, the main direct stresses associated with human activities are overfishing and destructive fishing methods. Beach seines, gill nets, and dynamite fishing are typical of destructive methods in the area that cause significant damage to habitats, reef structure, juvenile fish populations, and critical herbivorous and carnivorous fish populations. Furthermore, population outbreaks of Crown-of-Thorns Starfish *Acanthaster planci*, a voracious corallivore, have appeared on Pemba's reefs (Obura et al, 2004). Although this organism is a natural part of the coral reef ecosystem, population outbreaks such as those on Pemba can cause severe and widespread coral mortality and reduce a coral reef's capacity to recover from other disturbances.

The approach used in this study was developed by the IUCN Climate Change and Coral Reefs working group (www.iucn.org/cccr), led by CORDIO East Africa, which has outlined a series of protocols to quantify basic resistance and resilience indicators for coral reef assessments. These methods are designed to assist management authorities in focusing management effort to priority areas. The ability of managers to adapt to climate change will be critical to the future of coral reefs, and also for the social and economic services that they provide.

2.3 The Pemba area

The Island of Pemba lies just 50 km off the Tanzanian Coast, in the Indian Ocean, and forms part of the Zanzibar Archipelago. It is thought to have been isolated from the continent by a deep channel for several million years, and is classified as a true oceanic island (Archer and Turner, 1993). Pemba is low lying, reaching just c. 100 m at the highest point, with a topography characterised by numerous small valleys and hills. The island has a total surface area of 1040 km² (Pakenham, 1979). Its underlying layers are built of highly porous coral rag, a karst-like, limestone deposit composed principally of ancient coral. The climate is tropical and can be broadly divided into two monsoon periods, the Northeast monsoon with trade winds blowing from the northeast between December and April, and the Southeast monsoon with trade winds blowing from the southeast between May and November. The Northeast monsoon is generally characterized by lower wind speeds, calmer seas and higher sea surface temperatures, and the late Northeast monsoon is the usual bleaching period in this region. The Southeast monsoon is generally characterized by higher wind speeds, rougher seas and lower water temperature.

Mean rainfall is c. 1860 mm per annum, which falls mostly between March and May ('long rains') and November and December ('short rains'). Terrestrial temperature varies between 21 and 34°C (Beentje, 1990). The island is dominated by indigenous forest and agro-forestry is practiced in some areas in the Island. The main crops cultivated include banana, cassava, maize, a variety of vegetables, and coconut palm. Other plantations include the mango trees and seasonal crops.

The shoreline consists of relatively short stretches of sandy beach interspersed with low limestone cliffs and headlands. Off-shore, there are shallow fringing reef flats which drop off rapidly into the ~2000 metre deep Pemba Channel. Artisanal fishing activities by the local community have been going on for hundreds of years in the area. Most of fishers who fish in the area are of low income using traditional fishing boats such as outrigger and dugout sailed canoes with hand lines, beach seines and fishing traps. The fishers cannot usually access distant areas due to these constraints, so most fishing is relatively close to shore and the nearby reefs are thus intensely fished, including with destructive methods such as beach seining and dynamite. There are several smaller islands in the area to the west of Pemba that was surveyed, creating tidal channels between them and sheltered lagoon-like areas behind them west of the Pemba main island. The islands (from north to south) include Njao, Fundo (the largest of the islands), Uvinje and Misali. Coral reefs ring the islands and are present in the tidal channels, the lagoons/bays and fringing the western edges of the islands.

On September 23rd 2005, the Zanzibar Revolutionary Government declared the Pemba Channel Conservation Area (PeCCA) through the Fishing Act. Management of the area falls under the Marine and Coastal Environmental Management Project. The Pemba Channel Conservation Area is positioned to the west of Pemba Island and it covers 42 nautical miles stretching from the southern tip to the northern one. It has a two-mile width stretching from Fundo Island. Four boats were ordered from South Africa to strengthen the surveillance capacity of the Conservation Area to guard against invasion by illegal fishing vessels. There is a no-take zone around Misali island and certain fishing gears are allowed in the reserve stretching along the rest of the western coast. However, enforcement of fishing regulations is challenging and illegal fishing activities still pervade the area.

Survey sites

Thirteen sites in a range of reef habitats along the northwest of the island were surveyed. Sites were chosen to represent a variety of habitats characteristic of the area – lagoons, outer fringing sites and tidal channel sites. Furthermore, a range of depths from 3 to 18 metres was sampled. One site surveyed is non-protected (Msuka Bay), one is fully protected no-take zone (Misali) while the rest of the sites are in the reserve of the PeCCA. Certain fishing gears are allowed in the reserve (e.g. hook and line), while spear fishing, beach seining and dynamite fishing are banned. However, enforcement is not evident in reserve sites and illegal fishing methods are routinely utilized in reserve sites too.

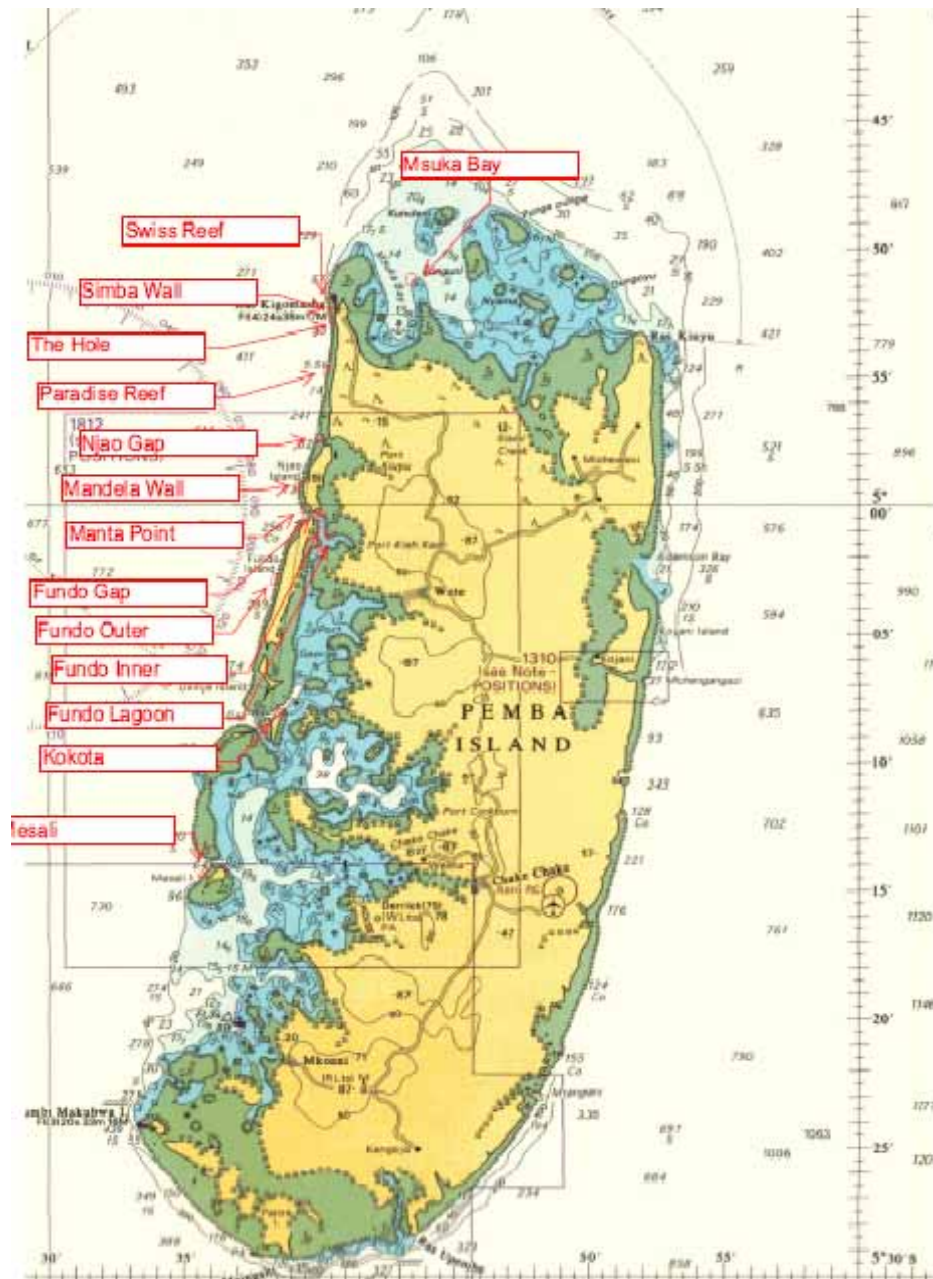


Table 2.1. Sites surveyed in Pemba in February 2009. Geographic coordinates and depth of sampling shown.

Date	Site	Sampling Depth (m)	Lat (S)	Long (E)
8 Feb 09	The Hole	6	4.88720	39.67632
8 Feb 09	Simba Wall	9	4.87575	39.67349
9 Feb 09	Paradise	13	4.91282	39.67093
9 Feb 09	Swiss	18	4.86786	39.67046
10 Feb 09	Njao Gap	10	4.95911	39.66748
11 Feb 09	Mandela	8	4.99694	39.65576
11 Feb 09	Manta	10	5.00146	39.65607
11 Feb 09	Fundo Inner	9	5.00924	39.66755
12 Feb 09	Fundo Outer	10	5.04207	39.64161
12 Feb 09	Fundo Lagoon	3	5.02569	39.67309
13 Feb 09	Msuka Bay	4	4.86164	39.7036
14 Feb 09	Misali	9	5.23958	39.5952
14 Feb 09	Kokota	11	5.1374	39.63824

Site descriptions

- *The Hole* – Enclosed sandy bay in a reef flat to the north of the main island directly opposite the Manta Resort. Reserve site.
- *Simba Wall* – Fringing reef in the north of the main island. Coral community interspersed by sandy channels. Top of a reef slope. Reserve site.
- *Paradise* – Fringing reef in the north of the main island dominated by rubble and with very little coral cover. Top of a reef slope. Reserve site.
- *Swiss* – Series of reef ridges deeper down the reef slope from Simba Wall. Reserve site.
- *Njao Gap* – Outer section of tidal channel between Pemba and Njao Islands. Gentle slope of reef flat leading to vertically steep reef slope. Reserve site.
- *Mandela* – Steep fringing reef slope/wall north of Fundo tidal channel. Reserve site.
- *Manta* – Reef pinnacle at the entrance of the Fundo tidal channel created by Fundo Island and Njao Island. Reserve site.
- *Fundo Inner* – Northeast facing reef in the Fundo tidal channel. A crown-of-thorns outbreak was observed at this site. Reserve site.
- *Fundo Outer* – Fringing slope about halfway down Fundo Island dominated by rubble and with little coral cover. Reserve site.
- *Fundo Lagoon* – Flat sandy area in a sheltered bay created by Fundo Island and Pemba island. The Fundo tidal channel feeds into this bay creating strong tidal currents. Reserve site.
- *Msuka Bay* – Large shallow reef flat to the north of the main island. Outside the Pemba Channel Conservation Area.
- *Misali* – No-take zone. Reef ridge to the west of Misali Island. Very high coral cover and diversity. The site surveyed that is furthest to the south.
- *Kokota* – Tidal channel between Kokota and Uvinje Islands. Reserve site.

2.4 Overview of methods

The methods applied in this study were developed by the IUCN working group on Climate Change and Coral Reefs, specifically to examine the resilience of coral reefs to climate change (high seawater temperature). The full methodology ('Resilience Assessment of Coral Reefs' by David Obura and Gabriel Grimsditch) is attached. Several components of the reef ecosystem were measured at varying levels of detail, as follows:

1. Benthic cover – provides the main overall indicators of reef state, and particularly the balance between corals and algae. Benthic photographs were used to assess benthic cover. Photos were taken from about 1 metre above the substrate and were later analysed using Coral Point Count software.
2. Fleshy algae – provides information on the main competitors to corals on degrading reefs. Fleshy algae cover (%) and height (cm) was estimated in 1m² quadrants.
3. Coral community structure – provides an overview of the relative abundance of coral genera, and that are susceptible or resistant to coral bleaching. The abundance of all coral genera was estimated during field visits along a five-point scale from rare to dominant. Coral species diversity was also recorded for each site.
4. Coral size class distribution – provides detailed information on the demography and sizes of coral colonies, and can show indications of past impacts by the presence or not of large colonies. It includes sampling of recruitment and small corals in 1 m² quadrants, and larger corals in 25*1 m belt transects.
5. Coral threats – gives an indication of the current health of the coral community, and includes observations on coral bleaching, disease, and mortality, and presence of predators and threats such as crown of thorns stars.
6. Fish herbivores and other functional groups – fish exert primary control on the reef community, and on algae through herbivory, thus controlling competition between algae and corals. The numbers of fish in different functional groups, including herbivore functional groups, was measured using three 50*5 m belt transects with a long swim transect made to count large mobile fish first. Five herbivorous functional groups were surveyed: excavators, scrapers, grazers, browsers and grazers and grazers/detritivores

7. Resilience indicators – these are factors that affect the resistance of corals to bleaching and the resilience or recovery potential of the reef community. A broad range of indicators in different classes is measured, including of aspects in 1-6 above, but at less quantitative levels. The main classes of indicators are listed below:

Group	Factor	Explanation
Benthic Cover	Cover	Primary indicators of reef health, particularly of coral and algal dominance and competition.
Coral community	Current	Indicators of the current condition of the coral community, including recruitment, aspects of size class structure, condition, etc.
	Historic	Indicators of the historic condition of the coral community, including past impacts and recovery to date.
Ecological – reef community	Positive	Associates that are positive indicators of coral health – e.g. resident fish in branching corals, obligate feeders that don't harm corals.
	Negative	Associates that are negative indicators of coral health – e.g. boring organisms, encrusting sponges, etc.
	Fish herbivory	Health of the fish herbivore community
Physical	Substrate	Substrate health, critical for settlement and survival of young corals
	Cooling & flushing	Factors that cause mixing and cooling of water, which can reduce the high temperatures experienced by a reef
	Shading & screening	Factors that reduce light penetration in the water, thus reducing synergistic stress to corals from temperature and light.
	Acclimatization	Factors that cause high variability in environmental conditions, that promote acclimatization of corals to stress.
Connectivity	Larval source/sink	Size and spatial relationships of healthy coral communities and reefs from the local to regional scale.
	Transport	Transport of water between reefs
Anthropogenic	Water	Human impacts to water quality, that reduce the recovery ability of reefs and increase stress to corals
	Substrate	Human impacts to the reef substrate, that reduce the recovery ability of reefs and increase stress to corals
	Fishing	Degree of fishing and its impact on recovery ability of reefs.

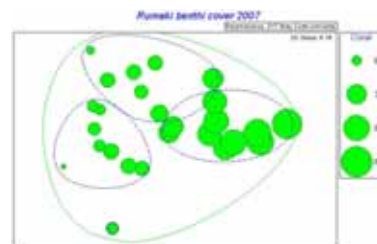
2.5 Analysis

Analysis proceeded through the following broad steps, for each dataset collected:

1. Calculation and plotting of basic distributions for each variable, across all study sites. These are done first to illustrate the basic patterns shown by individual variables and indicators. Ex: Chart titled *Rumaki Coral Community-genera*



2. Multi-dimensional Scaling (MDS) analysis helps to reveal patterns in datasets that include multiple variables, and particularly usefulness where parametric tests (e.g. ANOVA) are not appropriate. Ex: Chart titled *Rumaki benthic cover 2007*.



By projecting all variables onto x and y axes, an MDS plot helps illustrate which points are close to one another and which are distant. Thus the physical distance of points on the plot (upper right) illustrates their relative distance in the dataset. By superimposing a variable in the dataset on the points, where the size of a circle represents the magnitude of the variable, 'bubbleplots' (below right) can help to illustrate which variables are most important in determining the relatedness among points on the plot. The circles around clusters of points illustrate significant groupings of sites, and help interpretation of the results. Basically the larger the bubble, the healthier that component of the coral reef ecosystem is.

3 Major findings

This section summarizes the main findings from the Detailed results (section 4), which can be read for greater understanding of the points mentioned here.

Coral populations

Average hard coral cover around the island was 23% (pg 17), with large variations from 86% in the no-take zone Misali to 3% and 5% in degraded sites such as Paradise and Fundo Outer respectively (pg 18). Coral reef conditions were thus highly variable, with healthier sites (Misali, Mandela, Manta) being dominated by hard coral while degraded sites (Paradise and Fundo Outer) are dominated by rubble and turf algae. In total, 47 hard coral genera were found, with Misali having the highest (42) and Paradise having the lowest (23) (pg 22). Sites in bays or sheltered areas behind islands (Msuka Bay and Fundo Lagoon) also had lower diversity. Coral composition was relatively homogenous across sites, with 10 genera present at every site, and 35 genera found at >70% of sites (pg 23). *Acropora*, massive *Porites* and *Echinopora* dominate the hard coral cover, accounting for 46% of coral area, while *Pocillopora* are by far the most numerous colonies, accounting for 24% of all coral colonies (pg 24). This is due to this genus' life-strategy. It has high recruitment rates and colonizes spaces early but then does not live long or attain large sizes. The co-dominance by *Acropora* and massive *Porites* is interesting as these genera often indicate different stages in coral reef ecological succession. *Acropora* is a fast-growing susceptible genus that is characteristic of an undisturbed reef. Before 1998, Pemba was dominated by *Acropora* corals and today only certain sites still maintain that dominance (e.g. Misali and Mandela). Massive *Porites* is a slow-growing resistant genus that survives in sites that have been subjected to disturbance. Most sites had a higher proportion of resistant corals by area, except for Misali, Kokota, Fundo Lagoon and Mandela that have a higher proportion of area covered by susceptible *Acropora* colonies (pg 26). The general dominance of resistant corals in many sites shows that susceptible corals in these sites may have been eliminated by previous bleaching stress, and a shift in coral community composition on Pemba's reefs appears to be occurring.



Left: Misali – a site dominated by susceptible coral genera and with very high coral cover. © Jerker Tamelander, IUCN.
Right: A resistant species of coral – Massive *Porites lutea* bommie. © Jerker Tamelander, IUCN.

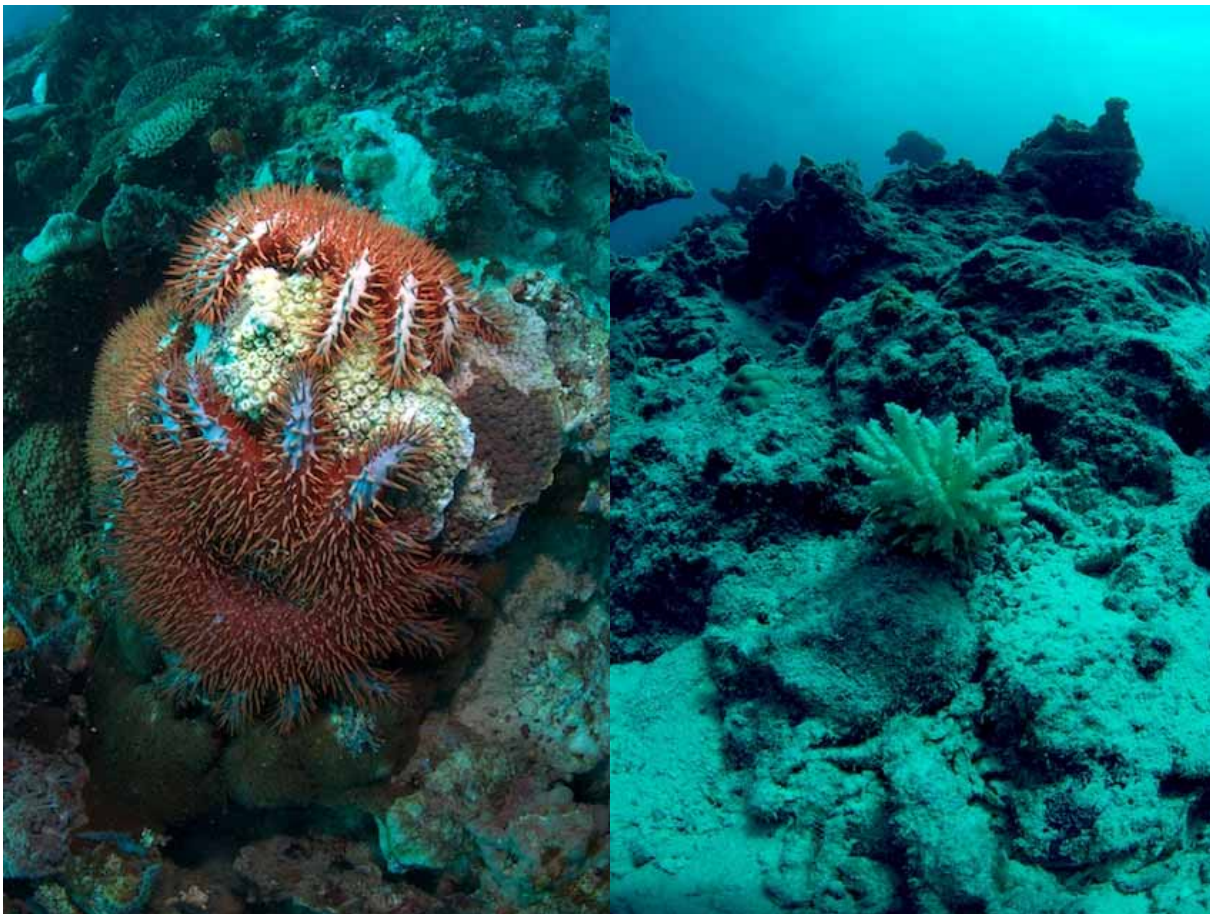
Coral size class distributions are indicative of the history of mortality of reefs' coral population. The coral size class distribution of Pemba's reefs shows a lower numbers of corals sized 2.5 to 5 centimetres and 1.6 to 3.2 metres than is usual for a healthy reef ecosystem (pg 23). The dip in the population of corals sized 1.6 to 3.2 metres is indicative of a massive past mortality event, very likely the 1998 bleaching event. The dip in the population of corals sized 2.5 to 5 is evident in all coral genera except for *Pocillopora* and *Acropora*. This dip indicates recent failures in recruitment/survivorship, and is probably related to recent stress events such as bleaching or crown-of-thorns outbreaks. This failure in recent recruitment/survivorship is a worrying sign that stress events are affecting coral populations and their recovery potential.

Overall, coral recruitment is largely dominated by *Pocillopora*, followed by a second tier of genera including *Acropora*, *Porites*, *Pavona* and *Seriatopora* while other genera show very low recruitment (pg 27).

Interestingly, coral recruitment is actually higher at the degraded than the healthy sites. The sites with highest recruitment are Simba, Fundo Outer and Paradise, all sites with low coral cover dominated by turf algae. Sites with high coral cover such as Misali, Manta or Mandela all have lower recruitment rates because less suitable substrate is available for coral larvae to colonize (available substrate is already taken by other corals) (pg 27). This means that the low coral cover in the degraded sites is not due to lack of larval supply but rather to stress

on the site that is not allowing recruits to grow. Two sites stand out as having very low recruitment (pg 27); Msuka Bay and Fundo Lagoon, probably due to their geographical positioning. Msuka Bay is to the north of the island, not connected to the dominant currents in the area, and in a high wave energy, *Sargassum*-dominated area where it is difficult for coral recruits to settle. Fundo Lagoon is in a sheltered bay area, and although there is tidal exchange of water, it appears that coral larvae do not successfully reach or settle there. However, although recruitment may be higher in degraded sites, recruit survivorship is much lower. The number of corals bigger than 2.5 centimetres decreases dramatically in sites such as Paradise or Simba. This trend continues with larger size classes, as fewer and fewer corals reach bigger sizes at these sites. In fact, only in Misali is there a full range of coral size classes with high cover of medium size (21-40 cm) and larger (>80 cm) corals characteristic of healthy reef ecosystems (pg 25-26). Therefore it is clear that local stresses in currently degraded sites are preventing coral recruits from reaching large sizes. If threats are identified and mitigated, it would be possible for currently degraded sites to recover as coral recruits survive and grow.

One plausible explanation could be increasing populations of crown-of-thorns starfish. At Paradise the high incidence of crown-of-thorns predation scars on corals (5% of colonies predated) indicates that these corallivores are a major cause of recruit mortality (pg 28). A crown-of-thorns outbreak was also observed at Fundo Inner, with over 50 individuals sighted. It is unknown what the trigger for population outbreaks is. Removal of starfish predators through over-fishing, improved survival of larvae due to land-based nutrient inputs and increasing sea-surface temperature have all been postulated as potential triggers. Crown-of-thorns starfish outbreaks have recently become a regular occurrence on Pemba's reefs, and are a major cause of coral mortality on the island. It is important to identify and understand the triggers for crown-of-thorns starfish population outbreaks in order to mitigate this threat.



Left: Crown-of-thorns outbreak at Fundo Inner. Three individual starfish are eating one *Echinopora* coral colony. Over 50 individuals were seen at this site with subsequent high mortality. © Jerker Tamelander, IUCN.

Right: Typical scene from Paradise. An *Acropora* recruit on a framework of dead coral, completely predated by crown-of-thorns starfish. © Jerker Tamelander, IUCN.

Algae communities

Msuka Bay had the highest macro-algal cover (35%) due to dominance by the brown macro-algae *Sargassum* (pg 19). However, this is probably the natural state for this site, as it is more exposed to wind and wave energy from the northwest and these are conditions typically associated with *Sargassum* dominance. Msuka Bay also had the highest incidence of algal attack on corals, with 9% of hard corals being attacked, killed and overgrown by macro-algae. All other sites had macro-algal cover lower than 15%. *Dictyota* (brown algae), *Cyanophyta* (blue-green bacteria), *Sargassum* (brown algae) and *Jania* (red algae) were the most common macro-algae found (pg 19). Overall, macro-algae are not yet dominating Pemba's western reefs, meaning that a complete phase shift to an algal reef has not yet occurred and with careful management this could be avoided.



Msuka Bay- *Astreopora* coral being overgrown by *Sargassum* algae. © Jerker Tamelander, IUCN.

Fish populations

Fish data show that Pemba is being extremely overfished. During surveys, herbivorous fish were classified into different functional groups depending on their feeding modes and preferred diet. Each functional group plays a different role in coral-algal dynamics and thus a unique implication for coral reef resilience. Large excavators such as *Bolbometopon* spp. *Chlorurus* spp. >35 cm in Length are major agents of bioerosion on reefs, taking larger bites of the dead substratum as they feed and expose hard surface for coral recruitment. Small excavators and scrapers (parrotfish) are important for preventing the establishment of macro-algae, removing algal turf and preparing the substrate for colonization by coral recruits. Grazers (surgeonfish,

rabbitfish, angelfish) are important for removing algal turf and preventing the establishment of macro-algae. Browsers (unicornfish, batfish, some parrotfish) feed on macroalgae, and are important in reversing phase shifts to macro-algal dominated reefs. Predatory fish which are commercially important and good indicators of fishing pressure were also surveyed.

Fish populations in Pemba varied greatly among sites surveyed, from over 250 individuals per 250 m² (Misali) to 50 individuals per 250 m² (Msuka Bay). Small-bodied herbivorous Acanthuridae (surgeonfish) and Scaridae (parrotfish) were the most common fish found. Very few (<10 individuals per 250m²) large excavators, commercially valuable Serranidae (groupers), Haemulidae (sweetlips) or Mullidae (goatfish) and no sharks were seen, a clear indication of overfishing as large bodied predators, herbivores and commercially valuable species have been removed from the food chain. Within the herbivorous functional groups, grazers and scrapers were the most abundant, followed by browsers, while small excavators (<35cm) were twice as abundant as large excavators. Hardly any bumphead parrotfish (*Bolbometopon* spp.) which are large excavators were seen (pg 28). Again, this is an indication of overfishing, as large bodied excavators are usually among the first to disappear on an overfished reef. Misali, the no-take zone, has the highest fish densities, and is differentiated from other sites by higher numbers of browsers (mostly Kyphosidae – chubs) and small excavators (Scaridae – *Chlororus* species less than 35 cm in length) (pg 29). Fundo outer had the second-highest fish abundance, probably due to its distance from shore and thus low accessibility to fisherman. Unfortunately, overall the vast majority of fish seen were <10 cm long, and only four individuals larger than 40 cm were seen during the entire survey (one grouper at Njao Gap, one grouper at Fundo Inner and two parrotfish at Misali) (pg 30). This is clearly an overfished coral reef and this has serious implications for resilience. If measures are not taken to curb fishing activity in the area or provide alternative livelihoods to fisherfolk, then the ecosystem is at serious risk of collapse and a future phase shift to an algae-dominated reef is possible.

Furthermore, evidence of destructive fishing was evident on a daily basis. Beach seines were routinely being used in the reserve and high densities of fishermen were seen. Dynamite blasts were also regularly heard during dives (up to five blasts during a 1½ hour dive). These indiscriminate destructive methods not only destroy habitat but also remove sexually-immature juveniles as well as rarer species and their use should be banned effectively.



Small fish are common in the water column, but very few large fish were present. © Jerker Tamelander, IUCN.

Resilience factors

Differences in resilience factors (collected on a semi-quantitative 1-5 scale) were mostly driven by differences in coral population (recruitment, fragmentation, dominant size classes and largest corals) and coral associates (branching residents, obligate feeders, competitors, bioeroders and corallivores) (pg 31-32). Misali ranked highest of the sites, followed by Mandela and Manta. Paradise and Fundo Outer ranked lowest. These results correspond well with hard coral cover (highest at Misali, Mandela and Manta but lowest at Paradise and Fundo Outer). Both these factors can be promoted by good management, meaning that degraded sites could be rescued if appropriate measures are taken.

Very little variation was found in connectivity between sites, as they are influenced by similar prevailing currents and there is little evidence to identify larval sources. Anthropogenic influences also did not vary greatly between sites- most sites are heavily fished (except for Misali the no-take zone) or influenced by overspill effects of overfishing in neighbouring sites, while there is little overall effect from land-based pollution or nutrients. Water quality seemed to be good as there was very little coral disease or bioerosion by boring sponges or polychaete worms. Sheltered sites such as Msuka Bay and Fundo Lagoon have higher potential for acclimatization of corals to higher temperatures due to ponding of water, but are not protected from bleaching events by cooling from upwelling. Outer fringing sites (e.g. Paradise and Fundo Outer) have higher protection from bleaching by cooling due to their proximity to deeper cooler water and the potential for upwelling (pg 32-33).

*Management recommendations***1. Use resilience data to inform management spatial planning by identifying resilient reefs**

The data collected in these surveys allow us to classify sites by ecological condition and resilience capacity, therefore giving management authorities information on which to base spatial management plans. There was no site found in pristine condition due to the effects of overfishing and the poor fish populations. However, we recommend that sites with good coral populations that are not already fully protected (e.g. Mandela and Manta) should be considered for no-take zoning in order to maintain them as source reefs for surrounding biodiversity and replenishment of fish stocks. Buffer zones where limited fishing activity is allowed around these no-take zones should also be established and enforced in order to avoid spill-over effects from overfishing in surrounding areas. Sites in 'medium' condition (lower coral cover and lower quality of ecological interactions, although large colonies and good coral recruitment are present) and 'low' condition (very low coral cover and high mortality of coral recruits with no large corals present) are recommended for moderate protection, i.e. restrictions of destructive fishing gear, mesh sizes and species extraction. Furthermore, crown-of-thorns starfish monitoring with possible removal programmes should be set up in order to understand and manage this threat.

Condition	Sites	Comments	Recommendations
Good	Misali, Mandela, Manta	Good coral populations but poor fish populations (slightly better at Misali). All outer fringing or channel sites with good coral recruitment, good ecological interactions and good currents, cooling and flushing.	Full protection, to maintain biodiversity and allow fish populations to recover in order to be effective source reefs for fishing and other sites. Buffer areas with limited fishing around these no-take zones should also be established and enforced
Medium	Fundo Inner, The Hole, Njao Gap, Kokota, Fundo Lagoon, Swiss Reef, Simba, Msuka Bay	Variety of habitats, from lagoons to fringing and channel reefs. Lower coral cover but still presence of larger colonies and high recruitment (except for Fundo Lagoon). Poor fish populations.	Moderate protection, minimizing damage and including fishery regulations. Monitoring programmes of crown-of-thorns starfish populations and coral predation should also be established, possibly with starfish removal programmes.
Low	Paradise, Fundo Outer	The two most degraded sites are outer fringing sites. There is high predation and mortality of coral recruits at these outer sites, although recruitment is high. No large corals are present and herbivorous fish populations are poor.	Moderate protection combined with rehabilitation provisions where possible. Monitoring programmes of crown-of-thorns starfish populations and coral predation should also be established, possibly with starfish removal programmes.

2. Tackle the overfishing and destructive fishing problems

Overfishing is one of the major threats to Pemba's coral reefs. Fish biomass is concentrated in small bodied (less than 10 cm long) fish and there is a lack of vital predators and herbivores. The no-take zone Misali has healthier fish populations than other sites due to larger populations of browsers (especially chubs) and small excavators, and the possibility of creating more no-take zones should be explored (for example at Mandela and Manta sites). Fishing activity in the reserve should also be supervised according to PeCCA regulations, and destructive fishing methods such as beach seining with small mesh sizes or dynamite fishing should be controlled or banned. However, we understand that fishing is a complex socio-economic issue as well as an ecological one, and alternative livelihoods to fishing should exist for fisherfolk. If sustainable fishing practices could be successfully implemented around the island, then coral reef resilience to climate change and other disturbances will improve and degraded reefs will have a better chance of recovering.

3. Understand the crown-of-thorns problem

Crown-of-thorns starfish are a major cause of mortality of coral recruits in Pemba, and the cause for the recent increases in population should be studied and understood in order to provide solutions to the problem. Crown-of-thorns starfish population outbreaks have been linked to overfishing of predators, nutrient input or increasing sea surface temperature that increase larval survival. Possible direct management actions to counteract this threat are crown-of-thorns starfish monitoring and removal programmes involving environmental protection agencies and local dive operators.

4. Promote ecological resilience through protection of functional processes and alleviation of local stresses rather than technological fixes

Technological fixes to environmental or climate problems are becoming increasingly popular due to the dire situation and the looming threat of collapse of ecosystems. An example is the deployment of reefballs in degraded coral reefs in order to promote coral recruitment. Although reefballs may provide good substrate for settlement, they do not alleviate the fundamental stresses that are causing recruit mortality and therefore are not likely to promote ecological resilience.

Successful settlement of coral recruits is not the problem for Pemba's degraded reefs (e.g. Paradise or Fundo Outer). Recruits are settling well, but are then not surviving and growing into larger colonies. This indicates that substrate quality is adequate for coral settlement, but that there are other stresses (e.g. crown-of-thorns starfish, destructive fishing or bleaching) that are causing coral mortality. Adding artificial reef substrate with reefballs does not remove these stresses, and recruits that settle on them will also be subjected to them and be at risk of mortality. If reefballs are to be deployed, we would recommend to do this in areas dominated by unconsolidated rubble where *Acropora*-dominated patches have died leaving broken coral pieces that are easily dislodged by water movement and do not allow coral recruits to settle. Some areas at Misali or Paradise would be appropriate. However, we do not recommend deploying reefballs on degraded substrates that are consolidated.

Rather than using this technological fix, it is more important to protect fundamental ecological processes through protection of resources and alleviation of local stresses. Reducing overfishing and destructive fishing practices, for example, would allow crucial planktivorous, herbivorous and carnivorous fish populations to recover and thus promote greater control of crown-of-thorns starfish and macro-algal populations that cause coral mortality.

The IUCN Climate Change and Coral Reefs Working Group (www.iucn.org/cccr) is ready and willing to give technical advice and support on implementing these management strategies. Please contact David Obura (dobura@africaonline.co.ke) or Jerker Tamelander (jerker.tamelander@iucn.org) for further advice.

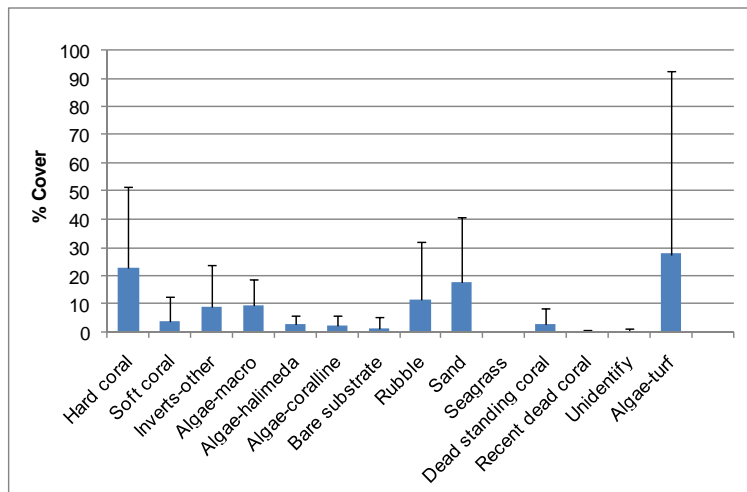


Reefballs could be useful to facilitate coral recruitment in areas with unconsolidated rubble fields such as here in Misali. However, they are not a major driver for increasing reef resilience. Alleviation of local threats is a more effective management strategy. © Jerker Tamelander, IUCN.

4 Detailed Results

Due to the complex datasets in this study, results and discussion will be presented together in numbered sections for each dataset, with more synthetic discussion and findings presented in section 3.

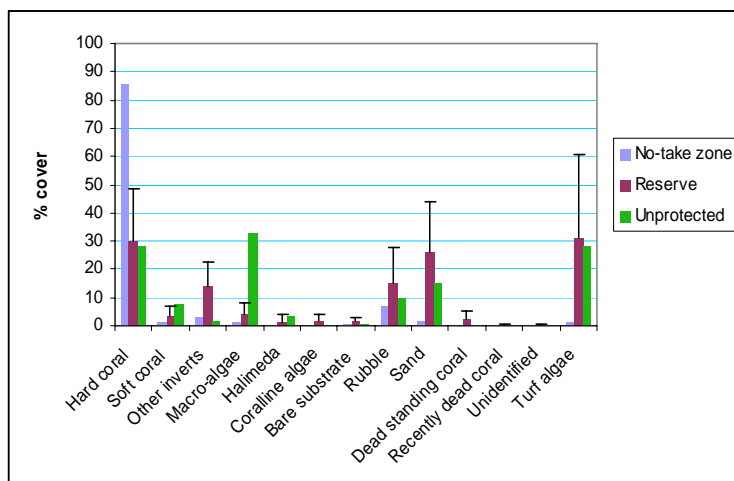
4.1 Benthic cover



All benthic types

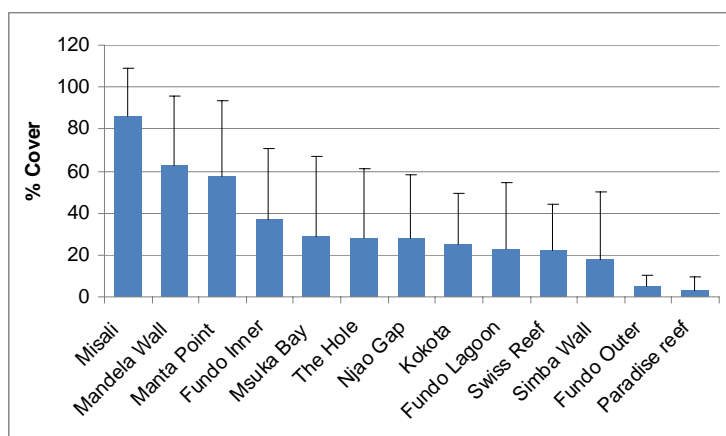
Benthic cover for all sites in February 2009

Algal turf (28%) and hard coral (23%) are dominant substrate types in the sites surveyed with sand (18%) and rubble (12%) also making up an important part of the substrate. Soft coral (4%) and coralline algae (2%) are minor components, while macroalgae cover 9% of the benthos.



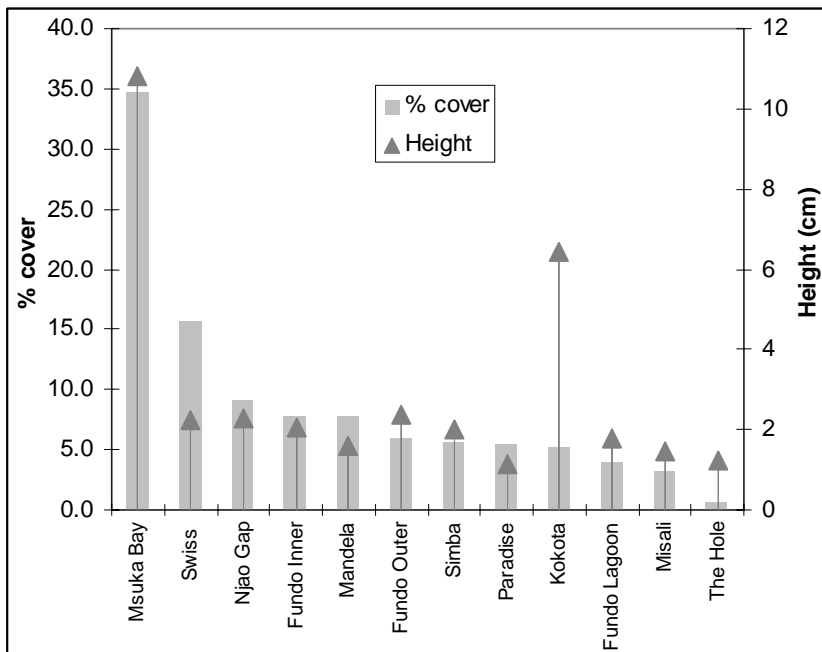
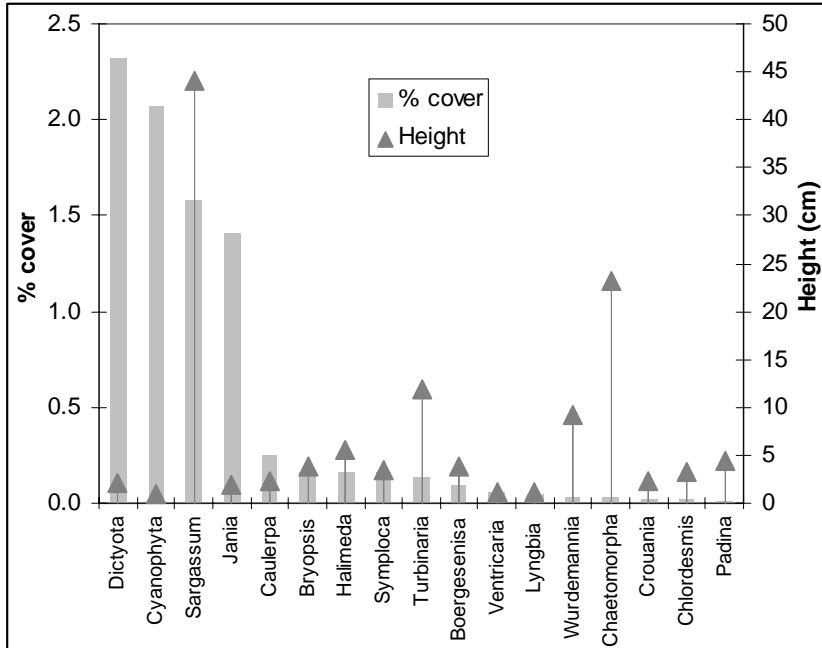
Benthic cover by level of protection

Sites are classified by level of protection, either in the no-take zone (Misali), in the reserve or unprotected (Msuka Bay). The no-take zone site (86%) has a much higher coral cover compared to the reserve (30%) and unprotected areas (29%) that have similar hard coral cover. The no-take zone site (1%) has very little algal turf, while the reserve sites (31%) and unprotected area have similarly high algal turf covers. The unprotected site has the highest macro-algal cover (33%) while the reserve sites have the highest sand (26%) and rubble (15%) cover



Hard coral cover by site

Hard coral cover varied greatly from 86% in Misali (no-take zone) to 3% in Paradise Reef and 5% in Fundo Outer, two highly degraded sites.

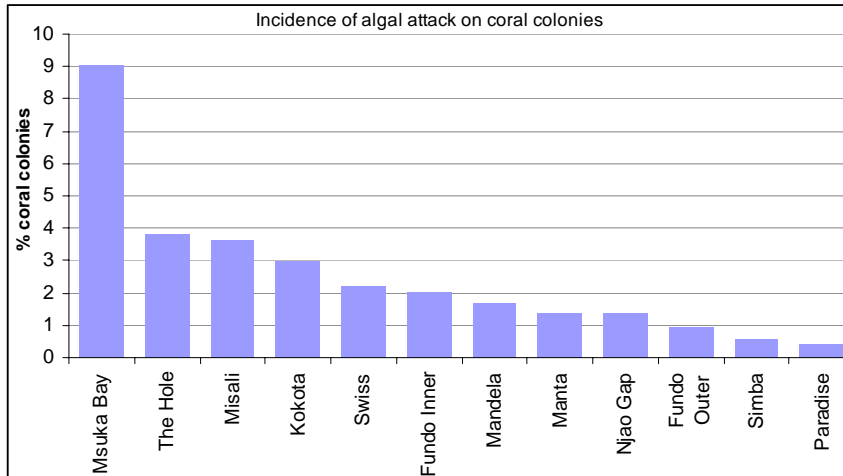


Fleshy algae

These data were recorded in 1 m² quadrats along transects. Algae were identified to genus level and percentage cover and algal frond height were recorded. Algal fronds were generally long, varying from 1 to 44 cm depending on genus and 1 to 11 cm depending on site, indicating low levels of herbivory and little control of the algal population.

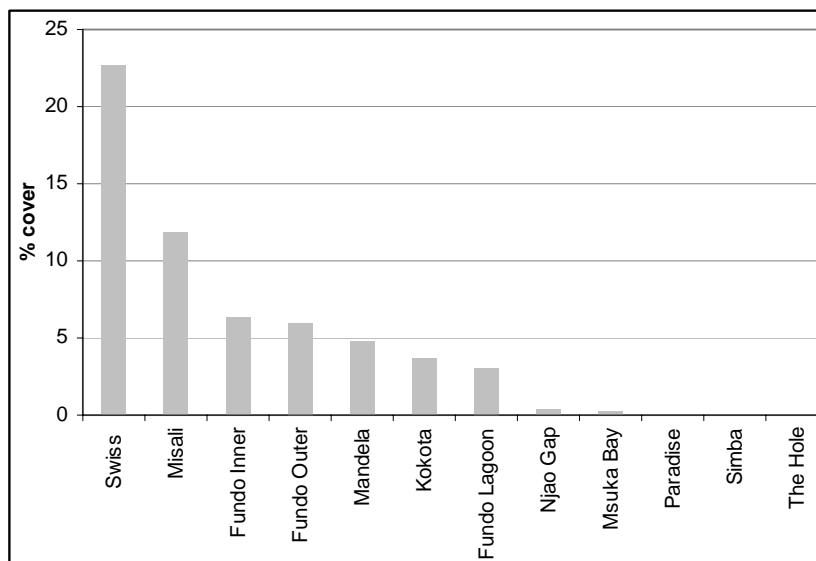
Dictyota, *Sargassum*, both brown algae, and *Jania*, a red algae, are the most common macro-algae genera found on Pemba's reefs, with other genera only present in small abundance. *Cyanophyta*, which are blue-green or cyanobacteria that photosynthesise, were also relatively common. *Cyanophyta* are nitrogen-fixers, and their presence often indicates elevated nutrient levels in the water. They were present at all sites except for the three most northern sites – The Hole, Simba Wall and Swiss Reef.

Msuka Bay has the highest algal cover with the longest fronds and is dominated by *Sargassum*, a brown macro-algae with long fronds that is often indicative of low herbivory. Msuka Bay is the most northern site, in a bay sheltered by Kundeni and Funguni reefs but still relatively exposed to winds and higher wave energy from the northwest.



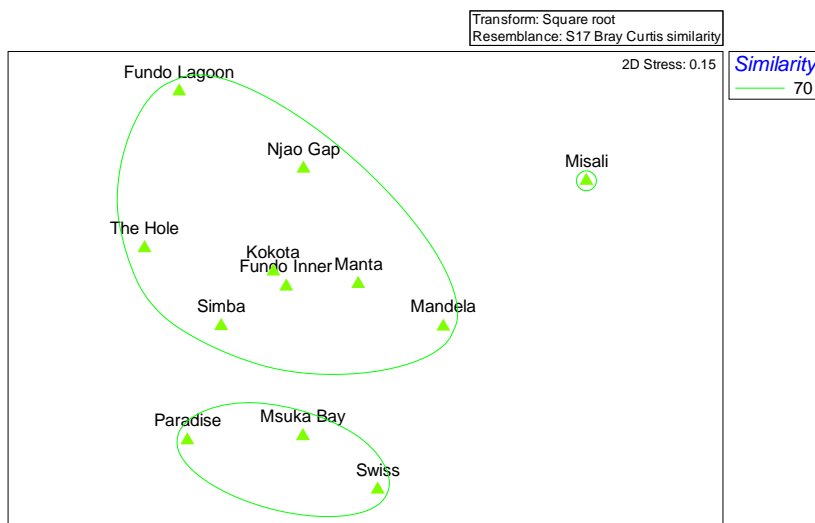
Incidence of algal attack of coral colonies

Incidence of algal attack of coral colonies is also highest in Msuka Bay with 9% of colonies being encroached by macro-algae



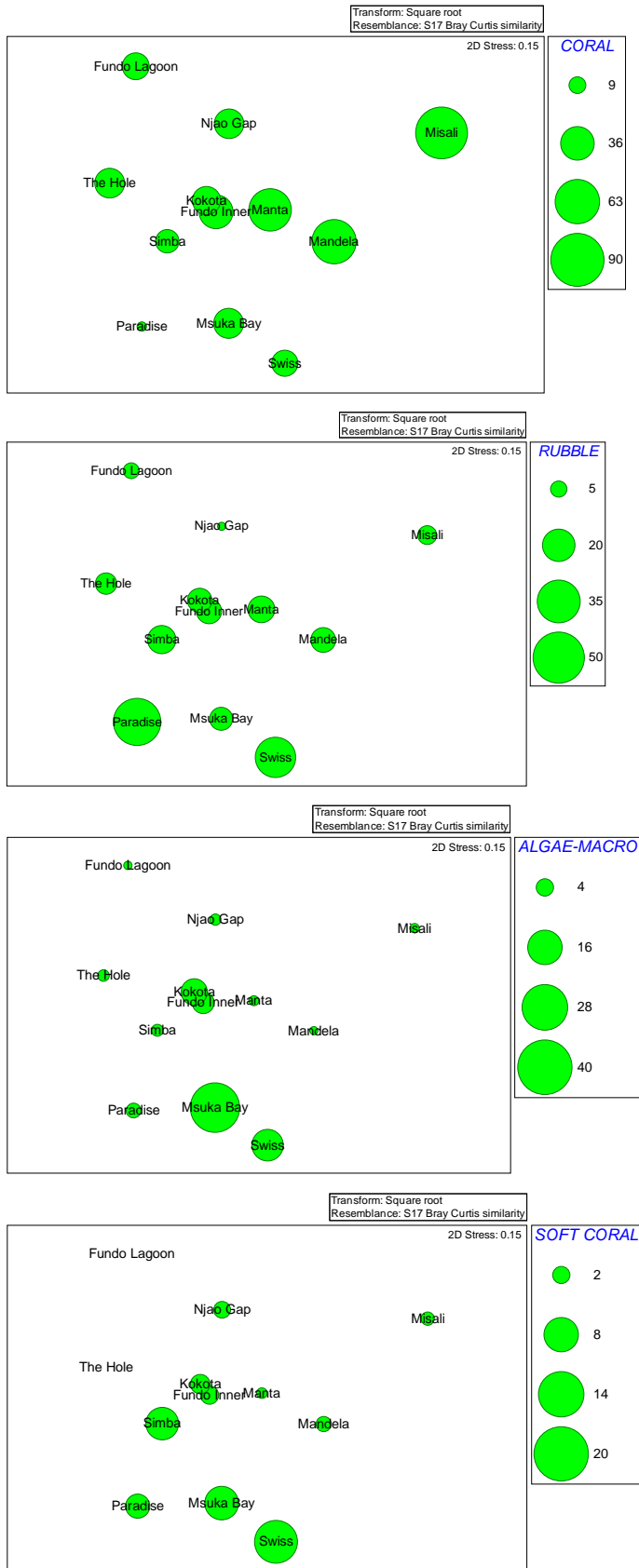
Coralline algae

Coralline algae are characterized by a hard thallus due to calcareous deposits in the cell walls. They are crucial for consolidating reef structure as well as facilitating scleractinian coral settlement by producing chemicals that promote coral larval settlement. The most common coralline algae on Pemba's reefs was *Neogoniolithon*, a crustose rhodophyte. It was most common on Swiss Reef and Misali, but absent in Paradise, Simba and The Hole.



Benthic Cover Multi-Dimensional Scaling

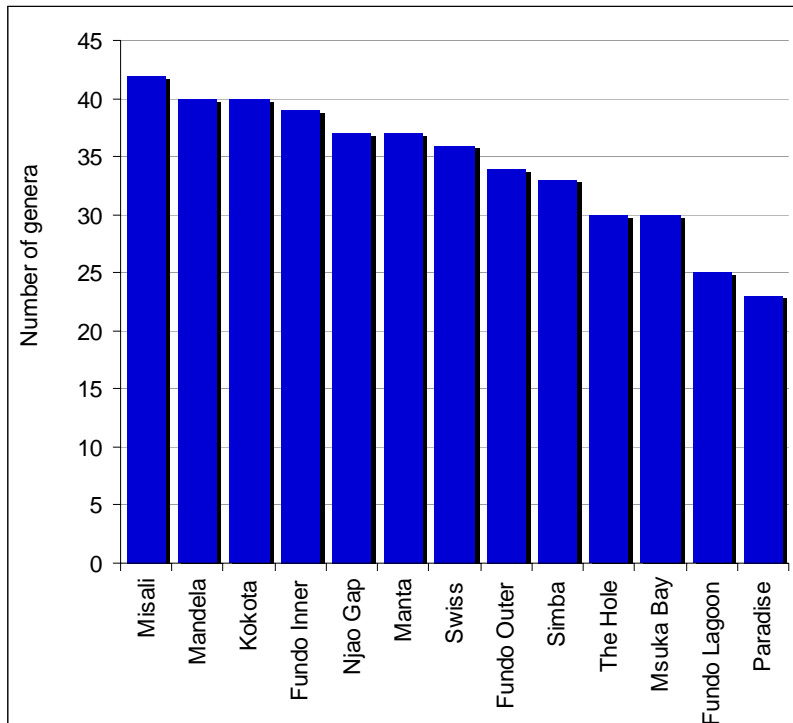
MDS plot of benthic cover results. At 70% similarity three clusters are clear. Misali is an outlier due to its very high coral cover, while Msuka Bay, Paradise Reef and Swiss Reef group together due to higher rubble, macro-algal and soft coral cover.



Different Substrate Types at Each Site

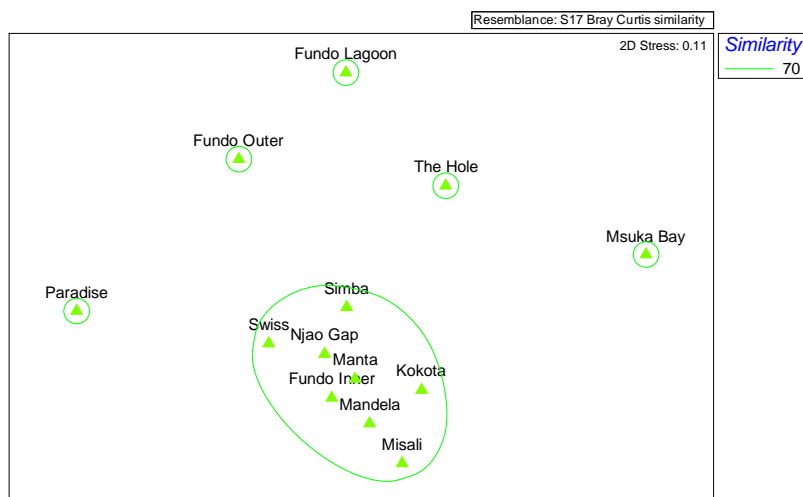
The bubble plots show the importance of different substrate types at each site. Plots for hard coral, rubble, macro-algae and soft coral are shown. Misali, the only no-take zone surveyed, shows the best recovery from past disturbances as it has the highest coral cover and low macro-algal cover, followed by Mandela and Manta. Degraded sites such as Paradise and Swiss have high rubble cover, but there is higher soft coral cover at Swiss. Msuka Bay is dominated by macro-algae, and this is probably its natural state due to its exposure to higher wind and wave energy coming from the northwest.

4.2 Coral community structure

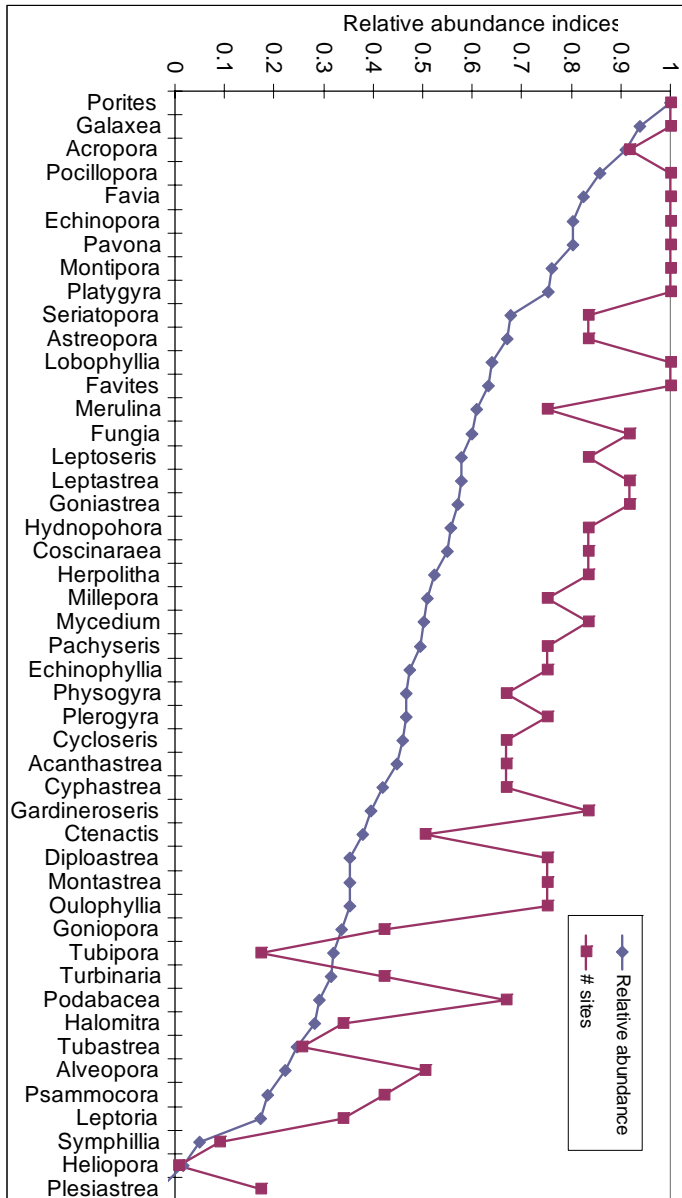


Site diversity

The total number of coral genera found was 47, with a maximum of 42 found in healthy Misali and a minimum of 23 in degraded Paradise. Fundo Lagoon, The Hole and Msuka Bay also have low diversity, probably due to their geographical position and lack of local connectivity to larval sources.



In a Multi-Dimensional Scaling plot, the main outliers are the degraded Paradise and Fundo Outer sites, as well as the low diversity habitats Fundo Lagoon, The Hole and Msuka Bay that probably receive less coral larvae than the fringing and tidal channel reefs. Other sites show a homogenous composition of coral genera.



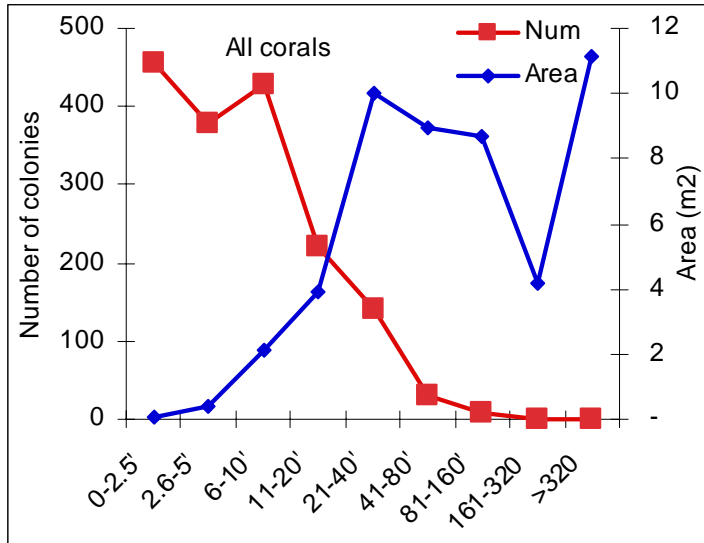
Coral genera by rank abundance

Two different abundance statistics are shown, scaled from 1 (highest) to zero (lowest). The number of sites shows genera present at all sites ($p=1$) to those present in only one site ($p>0$), with a red line and squares. The blue line with diamonds combines information on relative abundance of each genus at each site. 47 genera were recorded, with *Porites* being dominant, followed by *Galaxea* and *Acropora*. The relatively smooth initial descent of the Relative abundance line shows that coral communities are relatively homogenous, with the steeper descent toward the end of the line indicating rare genera. 10 genera were present at every site, and 35 genera (75% of genera recorded) were found at > 70% of sites. One genus was found at only one site (Msuka Bay) – *Heliopora*.

4.3 Coral population structure

Size class data was collected for a restricted set of coral genera, based on them being generally abundant, and fall on a range from low to high susceptibility to bleaching. The genera sampled are:

- High susceptibility: *Acropora*, *Montipora*, *Pocillopora*, *Seriatopora* and *Stylophora*
- Intermediate: *Coscinaraea*, *Echinopora*, *Favia*, *Favites*, *Fungia*, *Galaxea*, *Goniastrea*, *Hydnophora*, *Leptastrea*, *Lobophyllia*, *Platygyra*, *Porites* (branching)
- Low susceptibility: *Pavona*, *Porites* (massive)

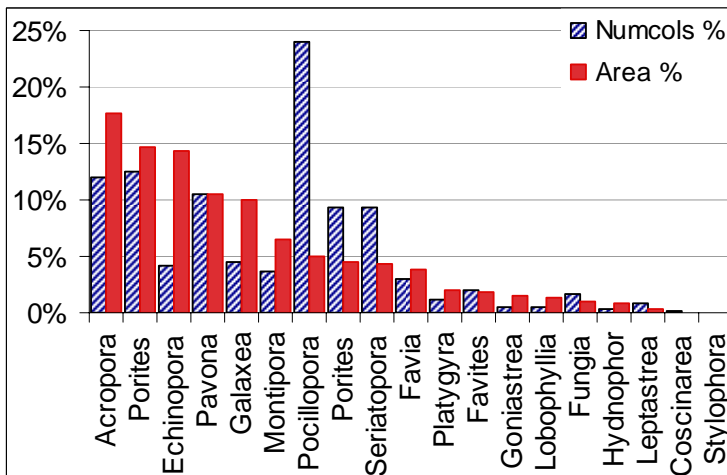


Coral size classes

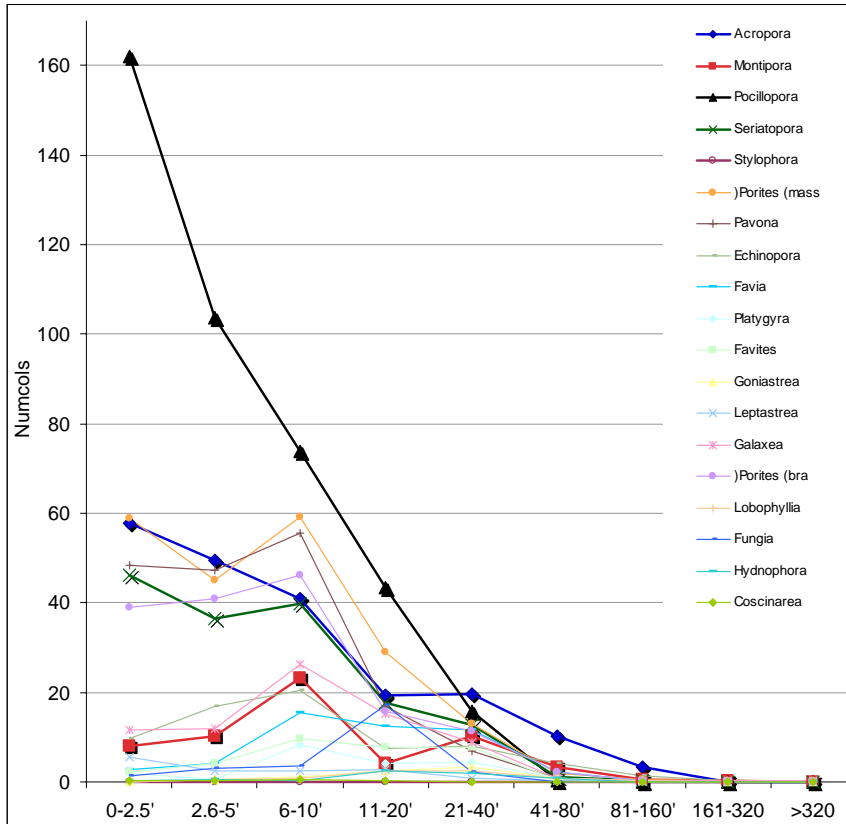
The distribution of size classes is shown by number of colonies, and by area of colonies for all size classes. On average, there were 1665 colonies in an area of 100m².

The dominant size classes by area were >320, 21-40, 41-80 and 81-160 cm. The low contribution of large colonies of 1.6-3.2 m indicates a large scale mortality event in the past with subsequent lack of coral reproduction, possibly due to the mass bleaching event in 1998.

The drop in the number of colonies for 2.6-5 cm corals is perhaps indicative of low coral reproduction and recruitment for this cohort and could be linked to bleaching events or crown-of-thorns outbreaks in the last decade. A crown-of-thorns outbreak was observed in the Fundo Inner site, and it is known that more outbreaks have recently been observed on Pemba's reefs (Obura, 2004).



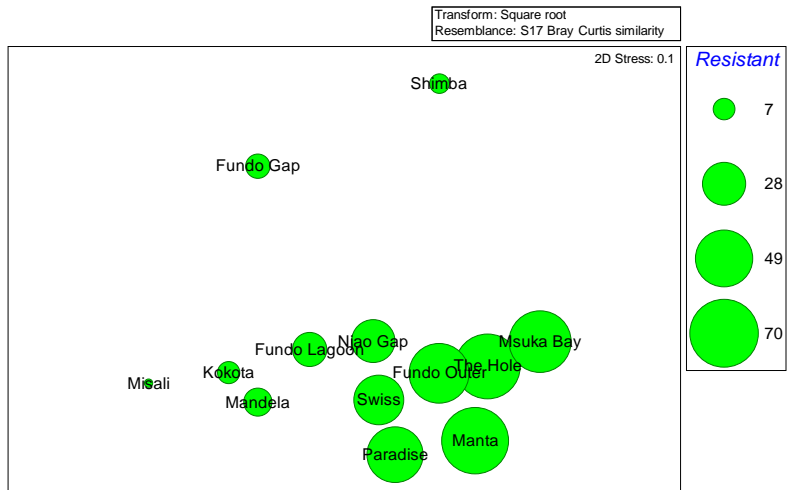
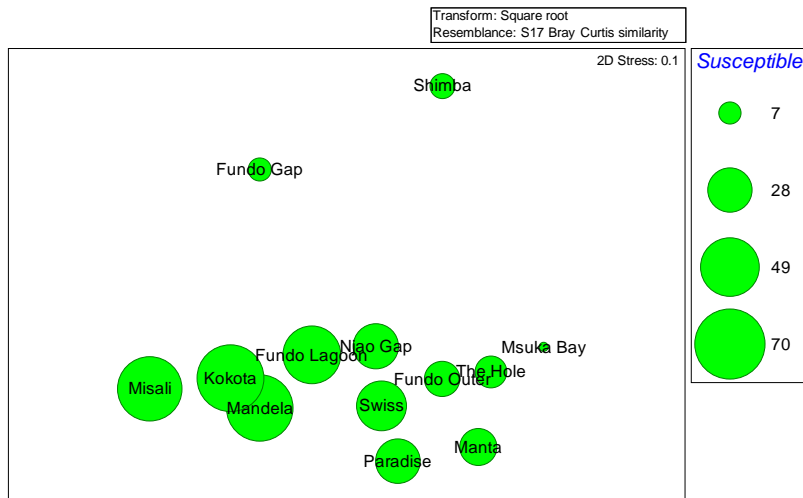
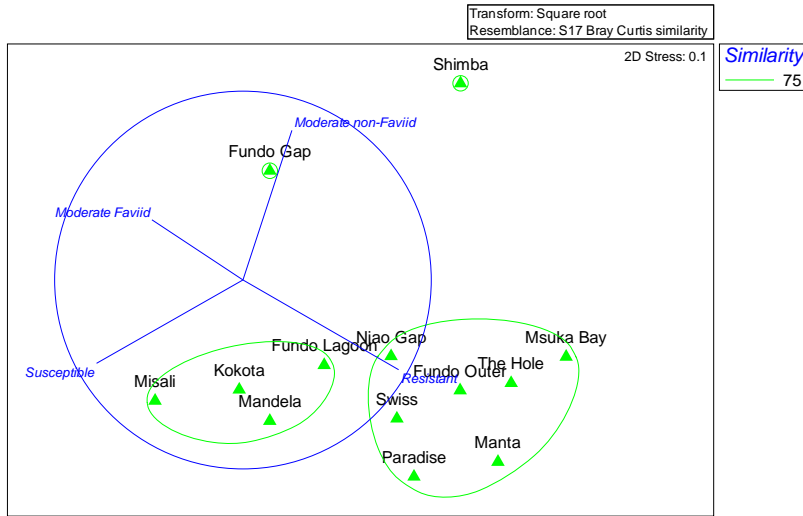
Acropora, *Porites* massive and *Echinopora* dominate coral cover, accounting for 46% of coral area, while *Pocillopora* are by far the most numerous colonies, accounting for 24% of all coral colonies. This corresponds to the *Pocillopora* life strategy, an early colonizing coral that reproduces quickly and colonizes disturbed environments but does not grow to a large size or old age.



All coral genera – colony sizes and area distributions

Large (>320 cm) corals were found for a range of resistant (*Porites* massive and *Pavona*) and medium tolerance (*Galaxea* and *Echinopora*) genera, indicating that these colonies have survived disturbances over a long time-scale. *Acropora* colonies are observed to reach 81-160 cm in size, but no colonies larger than 160 cm were observed. This may be due to a past disturbance (e.g. the 1998 bleaching event as *Acropora* are one of the most susceptible genera to this stress) as well as to tabulate corals collapsing under their own weight or due to bioerosion when they reach a certain size (often observed in the field). For genera where colonies did not reach sizes of >81 cm, the mid size 21-40 and 41-80 size classes were the largest contributors to coral cover.

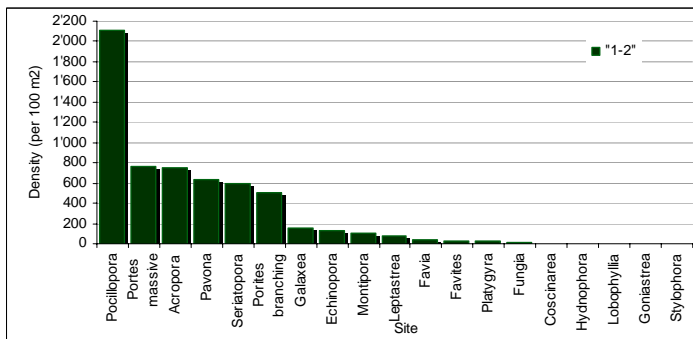
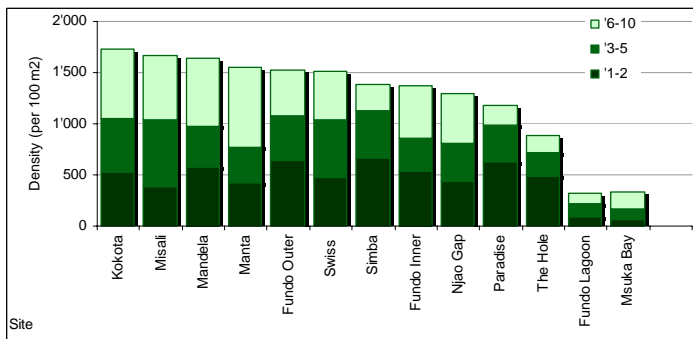
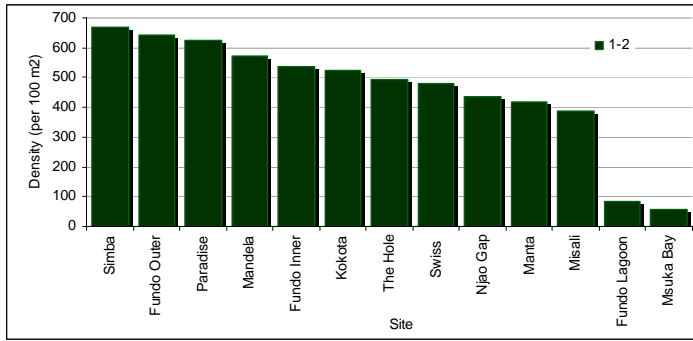
The number of colonies in a size class distribution normally has a decreasing slope from small to large colonies, reflecting mortality over time. This is evident in *Acropora* and *Pocillopora* populations, but all other genera show dips in population in the recruit 0-2.5 or juvenile 2.5-5 cm size classes. The higher number of 6 to 10 cm juvenile corals could be indicative of a high recruitment pulse a few years ago. On the other hand, the dip in population between 2.5-5 cm and 6-10 cm size classes may indicate major disturbances in the last years, perhaps from bleaching events, crown-of-thorns outbreaks or an increase in destructive fishing methods.



Genus susceptibility by site

Genera were categorized into groups depending on their bleaching responses. Four groups were identified – Susceptible (*Acropora*, *Pocillopora*, *Stylophora*, *Seriatopora* and *Montipora*), Resistant (*Porites* massive and *Pavona*), Moderate tolerance Faviidae (*Favia*, *Favites*, *Leptastrea*, *Echinopora*, *Platygyra*) and moderate tolerance non-Faviidae (*Galaxea*, *Porites* branching, *Lobophyllia*, *Fungia*, *Hydnophora*, *Coscinarea*). The proportion of total coral cover occupied by each bleaching response group was calculated, and sites were compared using Multi-Dimensional Scaling analysis. Two outliers were identified- Simba Wall and Fundo Inner (Gap), both of which had a high cover of moderate tolerance non-Faviid genera due to the presence of very large *Galaxea astreata* colonies that distort the data. Most sites had a higher proportion of resistant corals by area, except for Misali, Kokota, Fundo Lagoon and Mandela that have a higher proportion of area covered by susceptible *Acropora* colonies. The general dominance of resistant corals in many sites shows that susceptible corals in many sites have been eliminated by previous bleaching stress, and a shift in coral community composition is occurring. Only certain sites such as Misali are still dominated by susceptible genera.

The bubble plots show these trends, with the upper plot showing sites with higher cover of susceptible corals (larger bubbles at Misali, Kokota, Mandela and Fundo Lagoon), while the lower plot shows sites with higher cover of resistant genera (larger bubbles at Manta, Paradise, Msuka Bay, The Hole and Fundo Outer).



Coral recruitment

The top graph shows that Simba, Fundo Outer, Paradise and Mandela had the highest coral recruitment (1-2 cm size corals) despite having lower coral cover than sites such as Misali, Mandela and Manta. This could be due to the fact that more available substrate is available because of the lower coral cover, and they are directly exposed to water currents flowing northwards and southwards along the island and thus plenty larvae are carried to these sites. Fundo Lagoon and Msuka Bay have significantly lower recruitment, probably due to their geographical positioning. Msuka Bay is to the north of the island, not connected to the dominant currents in the area, and in a high wave energy, *Sargassum*-dominated area where it is difficult for coral recruits to survive. Fundo Lagoon is in a very sheltered bay area, and although there is tidal exchange of water, it appears that coral larvae do not successfully reach or settle there.

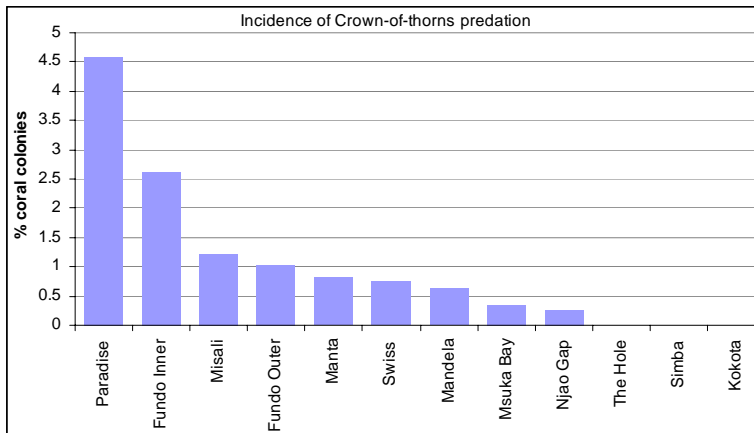
However, the graph in the middle shows recruit survivorship, that is the number of recruits that survive to become juvenile corals (3-10 cm), and the pattern changes. Sites such as Kokota, Misali, Mandela, Fundo Inner or Manta show higher than or equal recruit survivorship to outer fringing sites. Recruit survivorship is particularly low in Paradise, Simba and The Hole. Although recruitment is low in Fundo Lagoon and Msuka Bay, recruit survivorship is high. It thus appears that even though recruitment is high at degraded low-coral cover sites, corals are not surviving into more mature life stages due to some stress (perhaps predation by crown-of-thorns, regular bleaching or destructive fishing methods).

The bottom graph shows that recruitment is largely dominated by *Pocillopora*, followed by *Acropora*, *Porites* massive, *Pavona*, *Seriatopora* and *Porites* branching. Other genera have low recruitment.

4.4 Crown-of-thorns starfish predation

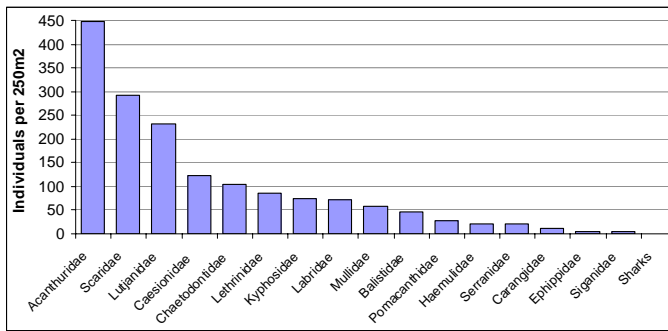
Crown-of-thorns (*Acanthaster planci*) starfish are corallivorous starfish that can cause major coral mortality on reefs if their populations explode. It is unknown what the trigger for population outbreaks is. Removal of predators through over-fishing, improved survival of larvae due to land-based nutrient inputs and increasing sea-surface temperature have all been postulated as potential triggers. Crown-of-thorns starfish outbreaks have recently become a regular occurrence on Pemba's reefs, and are a major cause of coral mortality on the island.

Paradise had the highest incidence of crown-of-thorns starfish feeding scars observed on coral colonies, with 5% of colonies being predated (graph below). This high predation rate could explain the low survivorship of coral recruits at this site. A crown-of-thorns starfish outbreak (over 50 individuals seen during one dive) was also observed at Fundo Inner, explaining the high incidence (3%) of predated coral at this site.



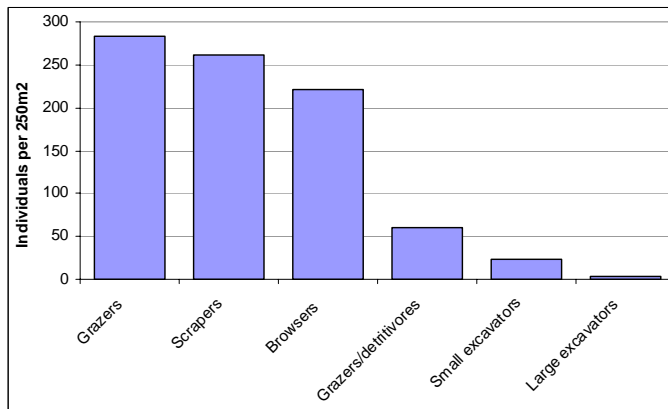
4.5 Fish community structure

Herbivorous fish were classified into different functional groups depending on their feeding modes. Each functional group plays a different role in coral reef resilience. Excavators and scrapers (parrotfish) are important for preventing the establishment of macro-algae, removing algal turf and preparing the substrate for colonization by coral recruits. Grazers (surgeonfish, rabbitfish, angelfish) are important for removing algal turf and preventing the establishment of macro-algae. Browsers (unicornfish, batfish, some parrotfish) feed on macroalgae, and are important in reversing phase shifts to macro-algal dominated reefs. Pemba island is showing very strong signs of extreme over-fishing.



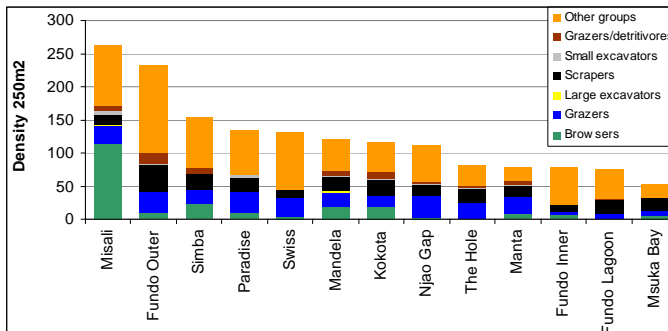
Major Fish Families

The bar graph shows that small bodied herbivorous Acanthuridae (surgeonfish) and Scaridae (parrotfish) are the most common fish surveyed in Pemba. No sharks and very few Serranidae (groupers) were seen, a clear indication of overfishing showing that very large bodied predators are left in the food chain. The main predators are Lutjanidae (snappers), but mostly small individuals were seen.



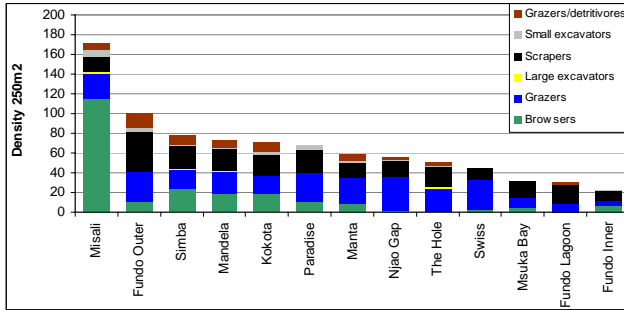
Fish Herbivory

The bar graph shows that within the herbivorous functional groups, grazers, scrapers and browsers are most common. Hardly any Bolbometopon spp. which are large excavators were seen. Again, this is an indication of overfishing, as large bodied excavators are usually among the first to disappear on an overfished reef.



Fish Densities for all Functional Groups

The bar graph shows fish densities for all functional groups including non-herbivores ('other groups') at the site level.

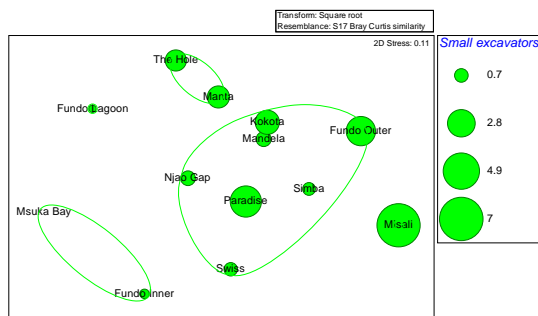
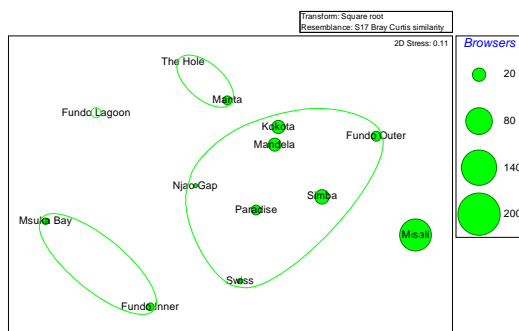
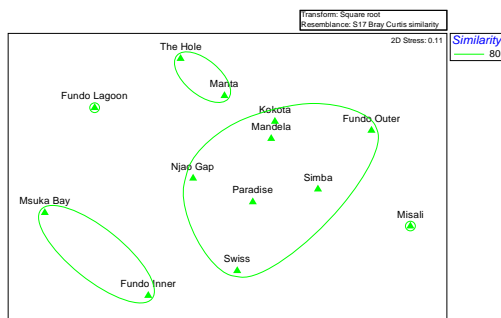


Herbivorous Fish Densities

This bar graph shows only densities for herbivorous functional groups. Misali, the no-take zone, has the highest fish densities, and especially high numbers of browsers (mostly Kyphosidae – chubs). It also has higher numbers of small excavators (Scaridae – certain species of parrotfish) than other sites, so these groups seem to be recovering well with the no-take zone. Fundo Outer also has high fish densities compared to other sites. However, this is mostly driven by higher numbers of Lutjanidae (snappers) and Lethrinidae (emperors) that are both predators. Fundo Outer also has higher densities of scrapers (Scaridae – certain species of parrotfish) than other sites probably due to its larger distance distance from shore and consequent lower fishing pressure. Msuka Bay, Fundo Lagoon and Fundo Inner have the lowest fish densities.

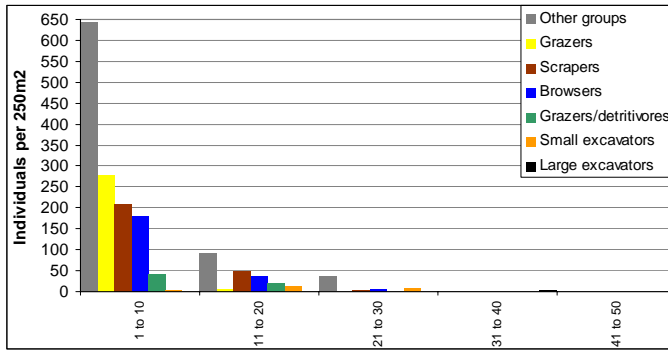
Sites and fish community composition

In the Multi-Dimensional Scaling, Misali is an outlier due to the high densities of browsers, while Fundo Lagoon is an outlier due to overall low densities of fish, although relatively high densities of scrapers. Msuka Bay and Fundo Inner form an outlying group due to their low fish densities.



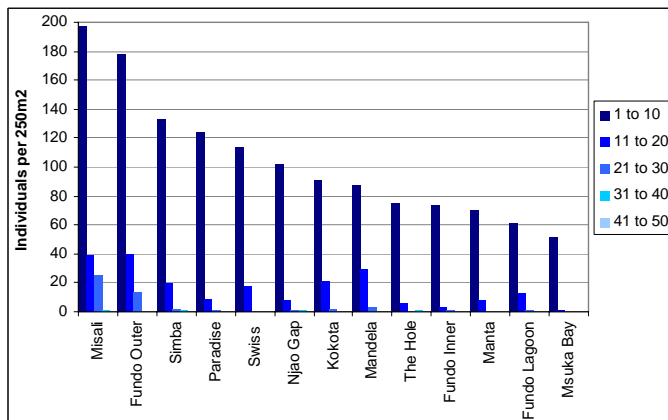
Browser Density in Misali

The two bubble plots show the high densities of browsers (top plot) and small excavators (bottom plot) that distinguish Misali, the no-take zone. The family making up the most number of browsers in Misali are Kyphosidae, or chubs.



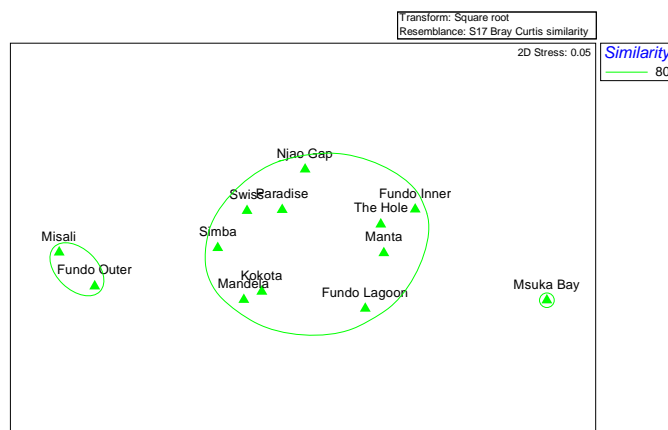
Fish abundance by size class

Another very strong indication of overfishing is the fact that hardly any large fish were seen during the surveys. The bar graph shows that the vast majority of fish seen were <10 cm long, showing that fish populations in Pemba is on the brink of collapse and coral reef resilience is being severely eroded. The worrying absence of large fish is ubiquitous across predators and herbivorous functional groups. Furthermore, use of destructive fishing methods were routinely observed within the reserve with beach seines regularly being used by fishermen and dynamite blasts being heard underwater. These destructive fishing methods remove juvenile and sexually immature fish, not allowing reproduction to sustain future generations.



Number of Large Bodied Fish

Encouragingly, the bar graph shows that Misali had the highest number of large bodied fish, showing that the no-take zone is working to some extent. However, even fish populations in Misali cannot be described as healthy, so some spill-over effects from neighbouring overfished sites is probable. The only fish >40 cm seen during the entire survey were 1 grouper at Njao Gap, 1 grouper at Fundo Inner and 2 parrotfish at Misali. This is clearly an overfished coral reef with serious implications for future resilience.



Site Similarities in Fish Size Class Distributions

The Multi-Dimensional Scaling of fish size class distributions shows that Misali and Fundo Outer are outliers due to the higher number of larger bodied fish present. In Misali fish in the 21-30 cm size class were mostly Kyphosidae (chubs), Carangidae (jacks), Scaridae (parrotfish) and Lethrinidae (emperors). In Fundo Outer fish in that size class were mostly Lethrinidae. Therefore, as well as having higher numbers of larger fish, Misali has a higher diversity of large fish. Msuka Bay stands out as an outlier due to the low fish densities.

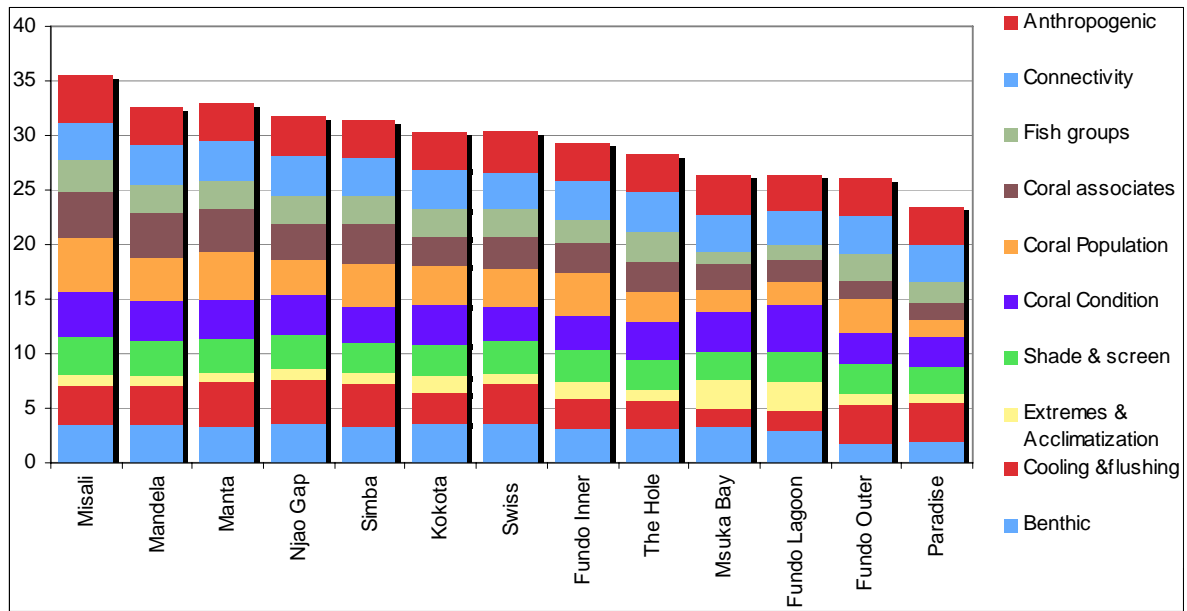
4.6 Resilience indicators

For each indicator, levels 1 to 5 were assigned according to local minimum/maximum levels and the distribution of values in between. A total of 55 variables were scored, that were grouped into the following factors:

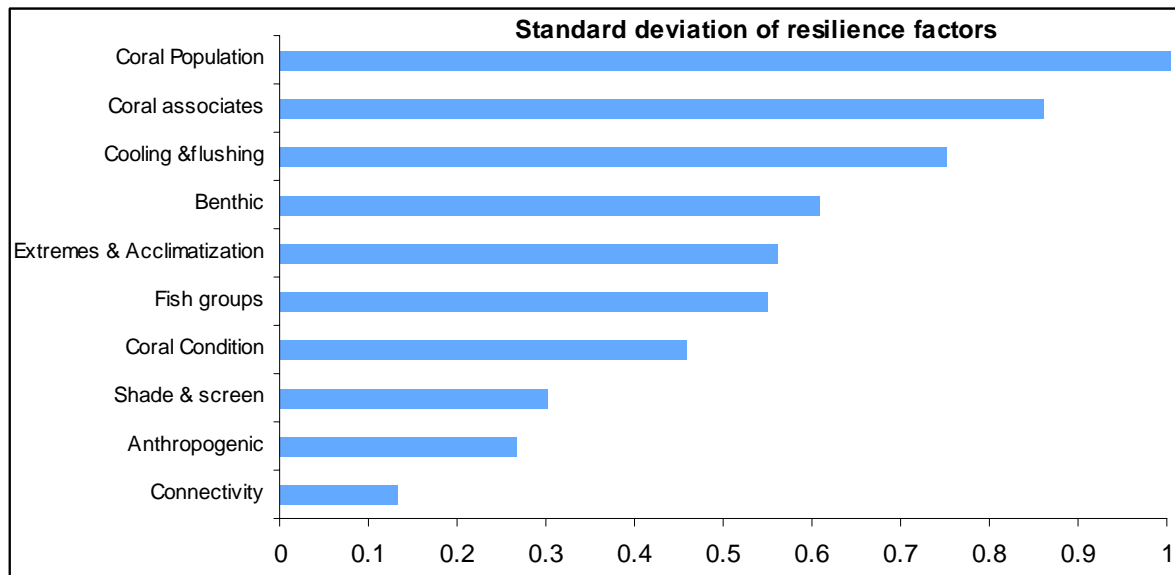
Group	Explanation	Factor	Explanation
Cover	Benthic cover	Benthic	Benthic cover – combined estimates of hard and soft corals, and algae
Coral	Condition of coral community	Current	Current status shown by bleaching, disease, sexual recruitment and fragmentation of corals.
		Historic	Past impacts to coral community as shown by evidence of past mortality, evidence of recover potential and size class distributions
Ecological	Broader ecological factors that affect corals	Negative	Negative associates of corals – such as predators and epiphytes on coral surfaces
		Positive	Positive associates of corals, such as obligate feeders (butterflyfish) and invertebrates and fish in branching corals.
		Herbs	Herbivorous fish populations
Physical	Environmental and habitat features that affect corals	Acclimatization	Past and present temperature dynamics that may protect corals by acclimatization/adaptive responses
		Cool & flush	Degree of cooling/flushing of deeper and/or oceanic waters
		Shade & screen	Degree of shading or screening of corals by turbid water, reef slope, canopy corals, etc.
		Substrate	Substrate quality, such as sediment type and thickness, amount of rubble.
Connectivity	Connectivity and larval supply	Larvae	Estimate of larval supply from contiguous reefs, separated reefs and distant reef systems
		Transport	Currents providing transport of larvae and effect of barriers to dispersal.
Anthropogenic	Human pressures on reef sites	Fishing	Degree of fishing, shown by fish populations and/or other data
		Substrate	Anthropogenic alterations to substrate – from sediment, damage, etc.
		Water	Anthropogenic alterations to water quality – from runoff, pollution, etc.

Each factor was scaled from 1 (poor conditions for corals) to 5 (good conditions for corals), and the sites ranked from highest overall resilience to the lowest.

Overall site resilience rankings

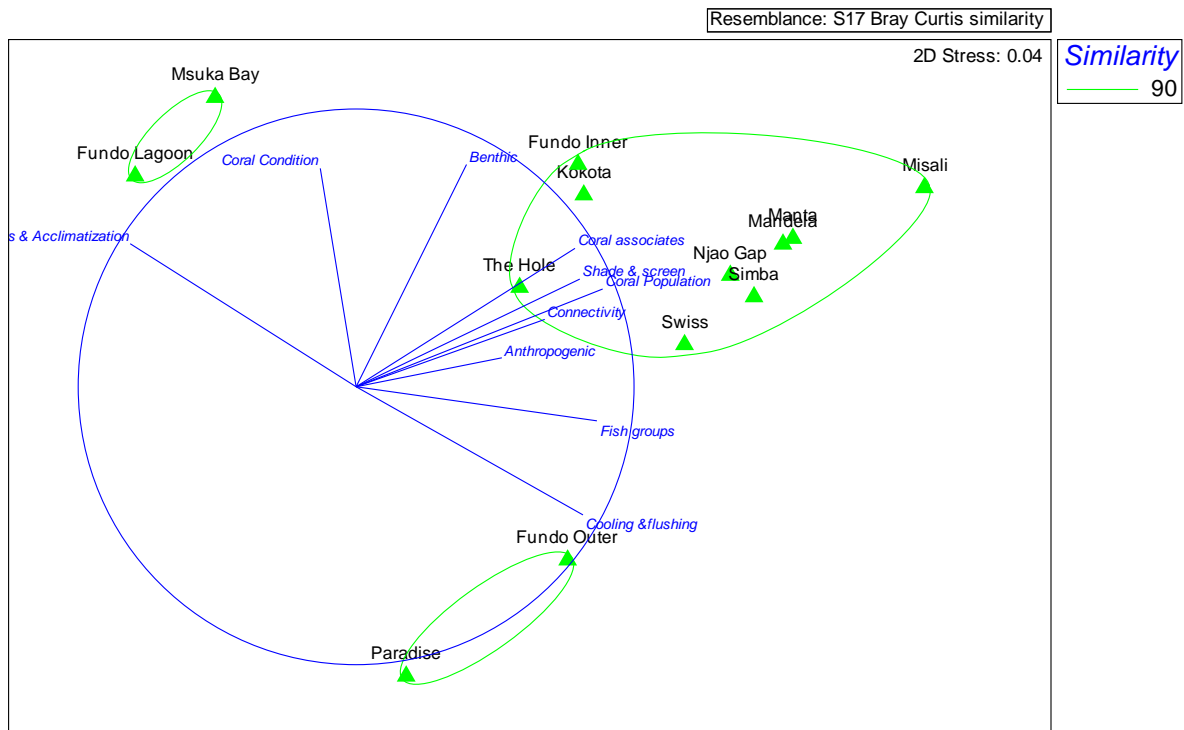


Misali ranked highest of the sites, followed by Mandela and Manta. Paradise and Fundo Outer ranked lowest. These results correspond well with hard coral cover (highest at Misali, Mandela and Manta but lowest at Paradise and Fundo Outer). As we shall see, the differences in resilience factors between healthy and degraded sites are mostly driven by factors relating to coral population (recruitment, fragmentation, dominant size classes and largest corals) and coral associates (branching residents, obligate feeders, competitors, bioeroders and corallivores).



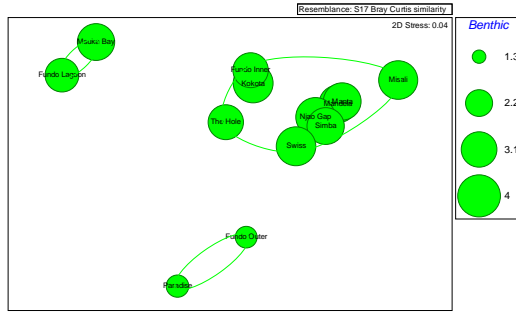
Standard deviation of resilience indicators between sites shows that the largest variations are caused by factors related to coral population and coral associates between degraded and healthier sites. Very little variation was found in connectivity between sites, as they are influenced by similar prevailing currents and there is little evidence to identify larval sources. Anthropogenic influences also did not vary greatly between sites- most sites are heavily fished or influenced by overspill effects of overfishing in neighbouring sites, while there is little overall effect from land-based pollution or nutrients.

Influence of resilience factors



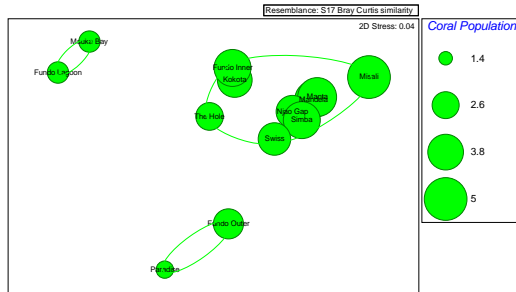
Multi-Dimensional Scaling analysis shows that shallower sheltered sites such as Msuka Bay and Fundo Lagoon have higher potential for acclimatization of corals to higher temperatures due to ponding of water, but are not protected from bleaching events by cooling from upwelling. Outer fringing sites (e.g. Paradise and Fundo Outer) have higher protection from bleaching by cooling due to their proximity to deeper cooler water and the potential for upwelling. Resilience potential at sites with higher coral cover (e.g. Misali, Manta and Mandela) is driven by healthier ecological interactions (e.g. coral associates), more favourable benthic quality and higher shading potential due to higher topographical complexity. Connectivity and Anthropogenic threats have the shortest vectors and thus have the least influence on the trends displayed.

The Multi-Dimensional Scaling plots below show the relative quality of each resilience factor at each site. Short descriptions of main findings are provided to the right of the plots.



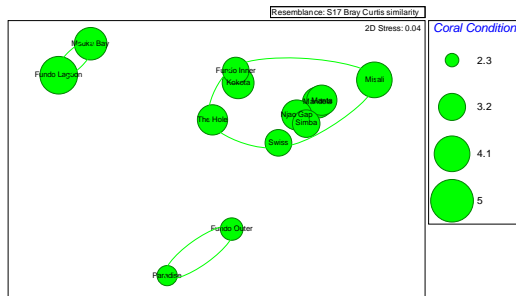
Benthic

Benthic quality is low at Paradise and Fundo Outer due to higher unconsolidated rubble cover. Benthic quality does not vary much between other sites.



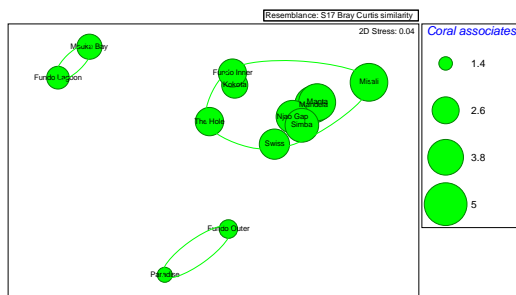
Coral Population

Coral population quality is low at Paradise, Fundo Outer, Msuka Bay and Fundo Lagoon. It is highest at Misali.



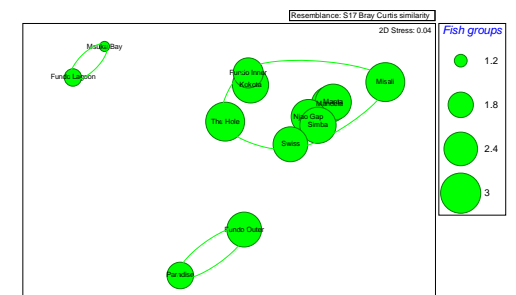
Coral Condition

Coral condition is lowest at Paradise and Fundo Outer and highest at Misali.



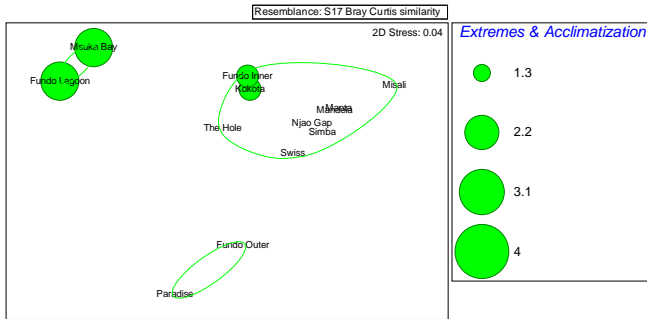
Coral associates

Ecological interactions between coral associates are healthiest at Misali and unhealthiest at Paradise, Fundo Outer, Msuka Bay and Fundo Lagoon.



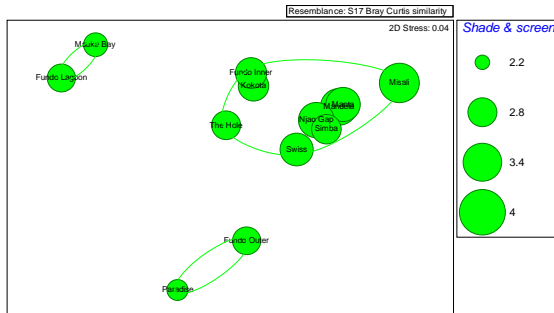
Fish groups

Fish populations are healthiest at Misali and unhealthiest at Msuka Bay and Fundo Lagoon.



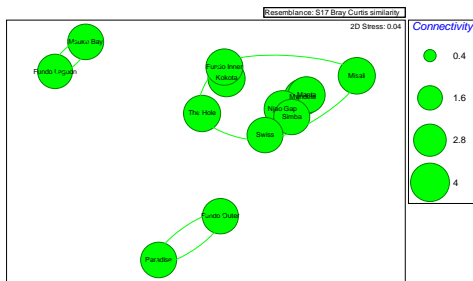
Cooling and flushing

Cooling and flushing is lowest at Msuka Bay and Fundo Lagoon, but does not vary greatly between other sites.



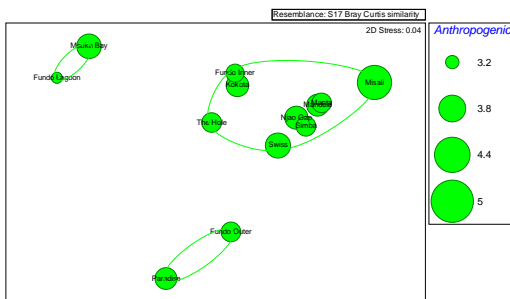
Acclimatization

Acclimatization potential is high at Msuka Bay and Fundo Lagoon, but low at all other sites.



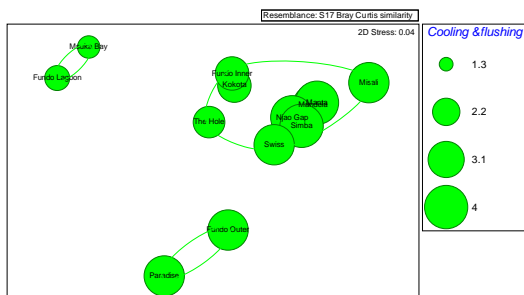
Shading and screening

Shading potential is low at Paradise and Fundo Outer due to lack of topographic complexity.



Connectivity

Connectivity does not vary greatly between sites.



Anthropogenic

Misali has the lowest anthropogenic pressure because it is a no-take zone. Other sites are heavily fished, but with little threat from land-based pollution and nutrients.

5 References

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