This industry, however, mainly targets massive corals such as various *Porites* spp, which were less affected by the bleaching event than *Acropora* (Wilkinson *et al.,* 1999).

In terms of fishery resources, the critical question is how bleaching and subsequent coral mortality will influence fish abundance and species composition. In this study, a 39% increase in fish numbers was seen between 1997 and 1998, while species diversity remained fairly constant. An analysis using the multivariate ANOSIM test showed that the fish community changed significantly between years ($p < 0.001$). According to the SIMPER test, various herbivorous fishes such as scarids, acanthurids and grazing pomacentrids made the most significant contribution to the shift in the fish community composition. The increasing abundance of herbivores may be an indirect effect of coral mortality, which often leads to an increase in algal growth. However, the relationship between food resources and fish densities is not straightforward, since fish populations may be limited by recruitment (Doherty & Fowler, 1994) or other factors. In a study carried out at the Great Barrier Reef, for example, herbivores did not respond to increased algae cover following a Crown-of-thorns starfish infestation (Hart *et al.,* 1996).

The consequences that a fish population shift may have on the future development of the fish community on Tutia Reef is difficult to anticipate, and it is difficult to foresee its implications for the fishery. A range of biotic and abiotic factors influences coral reef fish communities and, in addition, a reef fishery is typically multi-technique and multispecific (Öhman, 1999). Fishermen at Mafia Island commonly use small-meshed nets, indiscriminately targeting a range of fish species, including smaller reef fish (pers obs).

This study did not show any reduction in fish abundance as a result of the coral mortality following the coral bleaching event. Hence, the impact on fishery resources could be of minor importance. The crucial factor, however, is the fate of reef structure and complexity. As many reef-fish species are closely associated with the reef habitat, coral destruction is likely to affect the fish community (Jones & Syms, 1998).

Many habitat variables have been shown to relate to fish community parameters, and habitat degradation could alter fish numbers (Sano *et al.,* 1984; 1987; Munday *et al.,* 1997; Öhman *et al.,* 1997; 1998; Öhman & Rajasuriya, 1998). The results of this study suggest that reef structure is important for fish density and species diversity. There was a significant correlation (Spearman rank correlation) between structural complexity and fish abundance ($r = 0.86$, $p < 0.05$), as well as between structural complexity and the number of fish taxa ($r = 0.76$, $p < 0.05$) after the bleaching. Hence, if the corals break down and are turned into rubble, it could severely reduce fish numbers. For the same reason, a rich fish community could proliferate if the reef structure remains intact.

ACKNOWLEDGEMENTS

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Consequences of the 1998 coral bleaching event for the islands of the Western Indian Ocean

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CONTEXT

Coral reefs are vital for coastal populations and for human activities in general, as they provide people both with living resources and with "services" such as shore protection, sand accretion and coastal tourism.

The coral bleaching event of 1997–1998 summer is the most geographically wide spread and severe ever recorded. In the Indian Ocean, warm waters migrated from the South to the North during the first six months. As temperature stress was extreme and/or prolonged, mortality was catastrophically high in many areas (Kenya, Comoros, Seychelles, Tanzania, Maldives), the amount of dead corals ranging from 50–90%. Therefore, ITMEMS (International Tropical Marine Ecosystems Management Symposium) held in Townsville on 24 november 1998 recommended that a multi-disciplinary taskforce immediately be set up.

THE CORAL BLEACHING EVENT OF SUMMER 1997/1998.

Coral bleaching is a response to environmental stress, in particular high temperature, but it seems to be a multi-factorial response to a combination of temperature and other factors, such as irradiance and salinity changes.

According to the available data, Indian Ocean sea surface temperatures (SST) in the summer of 1997/1998 have been higher than previous years, and in some Seychelles reef flats 37°C was recorded (Robert, pers comm). SST data (IRD courtesy) indicate that hot spots affected the Mozambique Channel from December 97 to May 98.

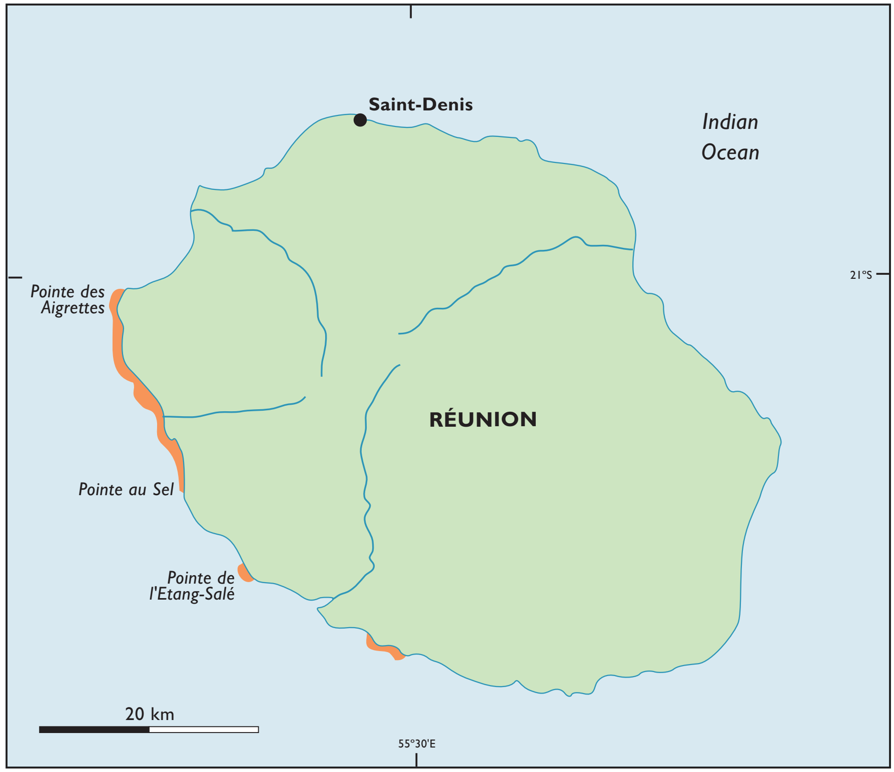
Coral bleaching, affecting both hard corals and other symbiotic organisms, periodically occurs in the Western Indian Ocean region. Frequency and intensity of the precedent episodes have varied from place to place, but are generally underreported: 1983/84 summer, 1987, 1997/98 summer. For the Western Indian Ocean islands, the peak event occurred during March and April 1998.

CORAL BLEACHING IN FRENCH ISLANDS OF THE INDIAN OCEAN

Réunion

Coral reefs are only fringing ones (12 km^2), lying exclusively on the leeward (west) coast, but in the south-

The fringing reefs of Reunion are all located on the western side of the island. Bleaching was moderate, and in many areas the reefs have now, May 1999, recovered.



east region, corals may significantly cover volcanic substrates (see map). The lagoonal areas are very shallow and few, but of great importance to tourism and recreational activities. Tourism is now the main source of income on the island.

Most of the inhabitants of Réunion live in the coastal zone (80% of 720,000 people). Overfishing of demersal fish (350 tonnes/year) has made the island dependent on seafood supply from external sources. Reefs have another important function: they protect the only white sandy beaches from cyclones waves.

Coral communities in Réunion have been studied for 20 year now, and are well-known. The reefs include 55 genera and 149 species. The state of coral reefs is also well-known. Today, 28% of the reef flats are considered to be severely degraded by human activities (sewage pollution, destructive fishing practices, etc).

After a week of heavy rainfall, the 1998 bleaching and mortality event was noticed in late February at the Planch'alizé reef flat station (Milleporidae, Acroporidae, Pocilloporidae, Poritidae families). No bleaching was observed in the nearby station of Trois Chameaux, but bleaching was also noticed in the Saint Leu lagoon and on the outer slope, and in Sainte Rose (in the south-east).

The extent of the bleaching in Réunion was moderate, affecting only pre-stressed colonies. Recovery was good, except in Planch'alizé and Sainte Rose. Dead colonies are now covered by algal turfs with associated damselfish (*Stegastes* sp.).

Mayotte

Mayotte is a high volcanic island with a barrier reef (1,500 km^2 wide) with a deep lagoon (depth 70 m) – it's one of the known double-barrier reefs in the world.

Fish associated with the coral reefs supply a major part of the animal protein, and is caught by nearly 3,600 fishermen. Fishing is reported as the second largest economic sector of Mayotte. The lagoon (*le Grand Lagon*) is a vital centre for tourism (9,000 visitors/year) and the potential for eco-tourism is great.

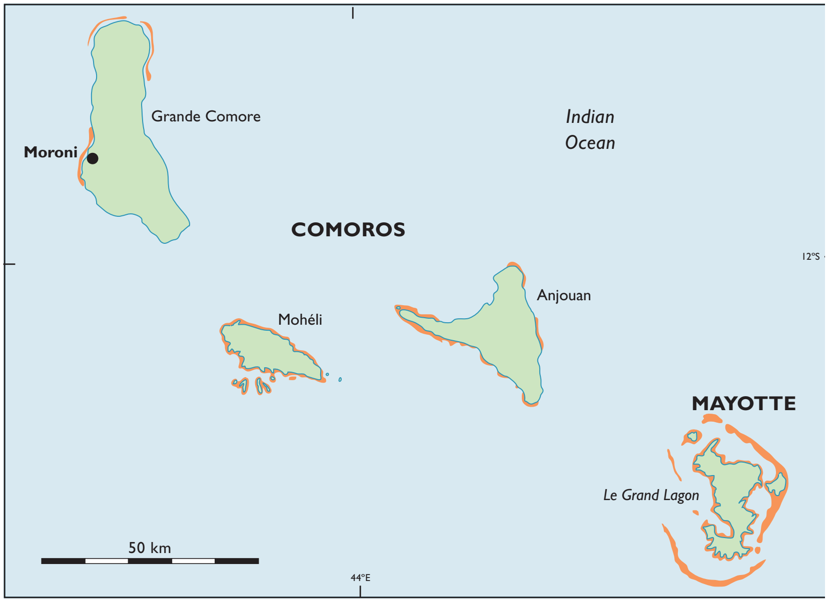
Around Mayotte, more than 200 species of coral have been identified, and the biodiversity of sponges, fish and other organisms is high (239 species has been counted in one place). The state of the fringing reefs is well-known: 50% are in good condition and 36% were degraded or dead before the 1998 bleaching event because of a strong, but less extensive, bleaching event in 1982/1983.

The 1998 bleaching and mortality event was intense and severe. All coral communities in the 0–10m range seem to have experienced moderate or severe bleaching. From April to August, local divers and scientists reported death as widespread, both in the lagoon and on the outer slopes. Up to 80% of the tabulate *Acropora* on the outer slope are now dead and covered by algal turfs and sediment. In August, bleaching of *Fungia* and soft corals was noticed in deep lagoonal places (15 m) by the local Fisheries and Marine Environment Service (SPEM).

One of the monitored side-effects of the bleaching was the massive contamination of dead colonies by the potentially toxic and epiphytic dinoflagellate *Gambierdiscus toxicus*. Samples collected by SPEM show that densities of this bioindicator exploded from 300 cells/g algae (average in 1993–1997) to 60,000 cells/g algae (October 1998). The environmental conditions are still suitable for contamination, and dinoflagellate density in December 1998 was 20,000 cells/g algae. Local authorities are now worried about the socio-economic consequences; this potential increase in the toxin production of the coral ecosystems of Mayotte could enter the food web and cause poisoning effects in humans.

Scattered islands

A number of scattered islands are located in the Mozambique Channel (Glorieuses, Juan de Nova, Bassas de India, Europa) and north of Réunion (Tromelin). Reef formations around these islands are either coral atolls or



The Comoros islands are surrounded by fringing reefs. After the 1998 bleaching event, 55% of the corals were reported dead. Mayotte has got one of the known double-barrier reefs in the world. It was severely affected by bleaching and subsequent mortality, and the dead colonies have been contaminated by potentially toxic dinoflagellates.

platforms (21 km^2). As human activities in the area are few and restricted to meteorological stations, these reefs are some of the last examples of undisturbed coral reefs in the Indian Ocean region.

Very few studies have been conducted in the area in the past 20 years (except on marine turtles), and coral biodiversity remains unknown.

The extension and gravity of the 1998 bleaching and mortality event is only known as anecdotal reports from military scuba divers. Around the islands in the Mozambique Channel, bleaching seems to have been massive.

CORAL BLEACHING IN OTHER COI ISLAND STATES

Comoros

Comoros consists of an archipelago of three islands, Grande Comore, Mohéli and Anjouan, surrounded by fringing reefs (see map, page 55). In 1995, the Comoros population was 0.6 million.

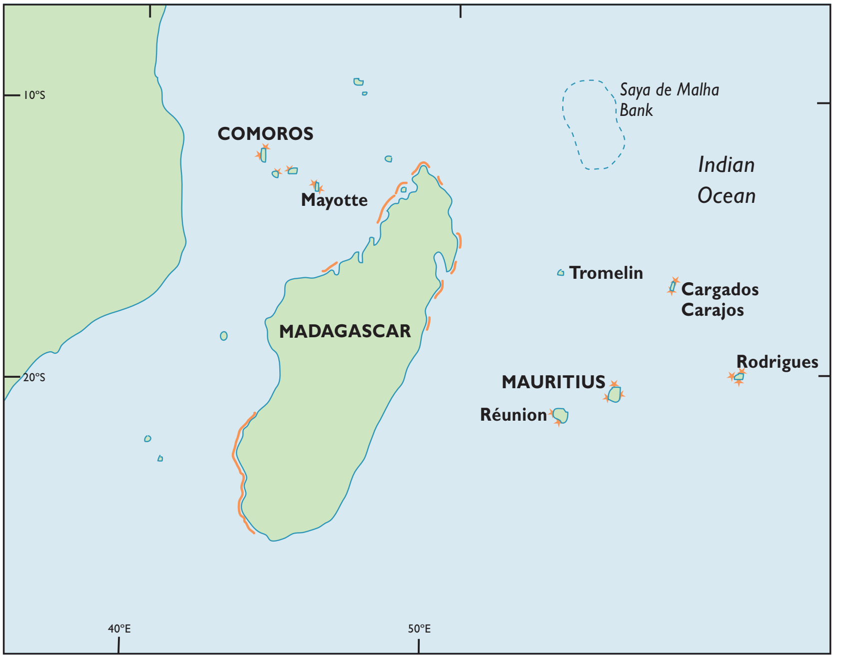
In May 1998, bleaching was observed around Grande Comore and Mohéli islands. Local scientists involved in the COI-Reef Monitoring Programme reported that roughly 55% of the corals had died during the 1997/98 bleaching event. On the reef slopes of Grande Comore, bleaching was observed as 50 m round patches, probably linked to underground freshwater runoff.

Madagascar

With a coastline of 4,800 km, Madagascar has well-developed reefs, including barrier reefs on the East coast (Masoala area, Tamatave) and mainly on the West coast (from south to north). Reef formations cover more than 1,000 km around the island. The reefs of Tuléar (south-west) are scientifically well-known and are surveyed by IHSM (Institut Halieutique et des Sciences Marines).

In 1995, the Madagascar population was 14.9 million and in 1996, tourism arrivals were 85,000.

Bleaching was first reported in March 1998, by diving clubs in Belomer (south-west). A scientific expedition showed that 30% of the hard corals were



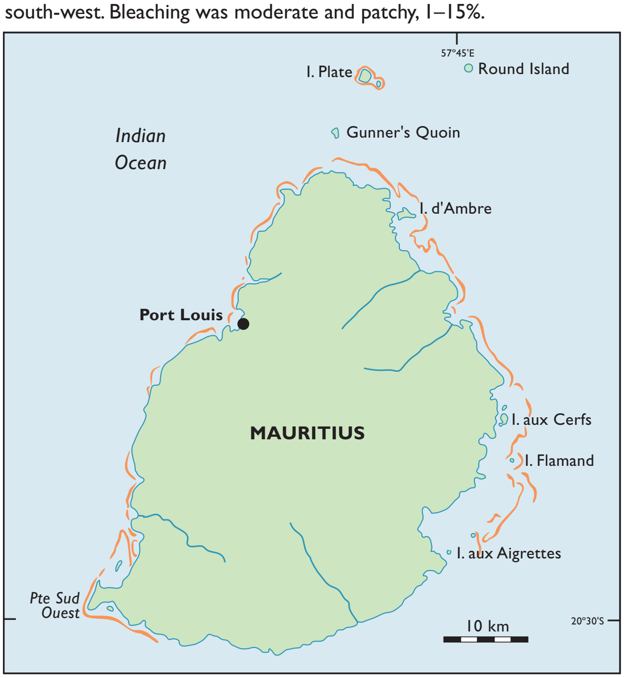
Coral reefs around the western Indian Ocean islands (marked with red). Some of the areas are also depicted in greater detail (see pages 54, 55 and 57). Madagascar has well-developed reefs, including barrier reefs. Some areas experienced 30% bleaching during 1998.

bleached (Maharavo, 1998). In February and March, temperatures were 32–33°C. Discolouration of photosynthetic, non-symbiotic marine organisms such as macroalgae was also noticed. Other locations around the island subject to bleaching were: Masoala, Mananara-Nord, Mitsio archipelago, Tuléar, Nosy Bé and Sainte Marie.

Mauritius

In 1995, the Mauritius population was 1.2 million. In Mauritius, tourism is particularly well-developed, with about 487,000 arrivals in 1996. As lagoons, which offer sheltered waters and sandy beaches, are very attractive for tourism and recreational activities, preservation of coral reefs is important.

Around Mauritius, the extension of coral reefs is 300 km^2 of fringing reefs and a barrier reef in the south-west. In the large lagoon of Rodrigues, the lagoon cover 200 km^2, and on the Cargados Carajos shoals 190 km^2 (Salm, 1996).

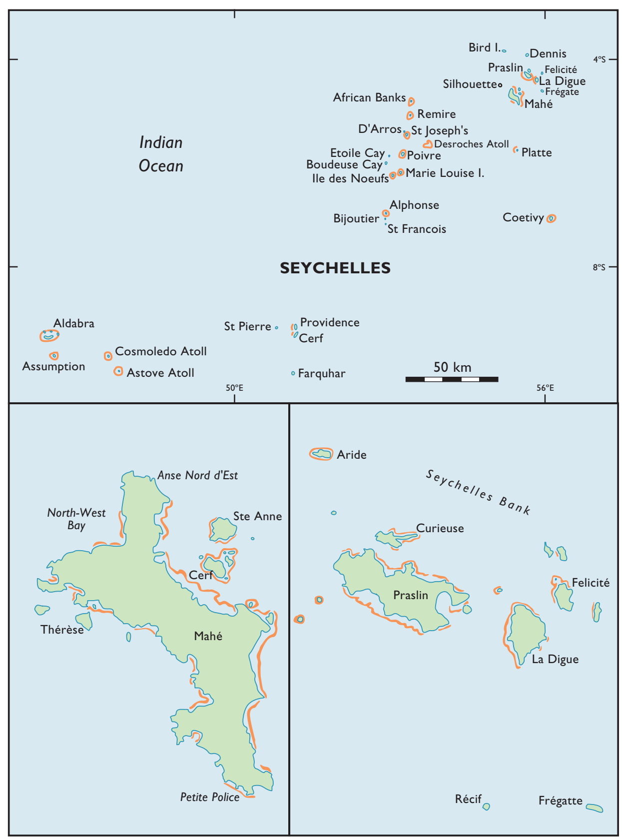


Mauritius has got extensive fringing reefs and a barrier reef in the south-west. Bleaching was moderate and patchy, 1–15%.

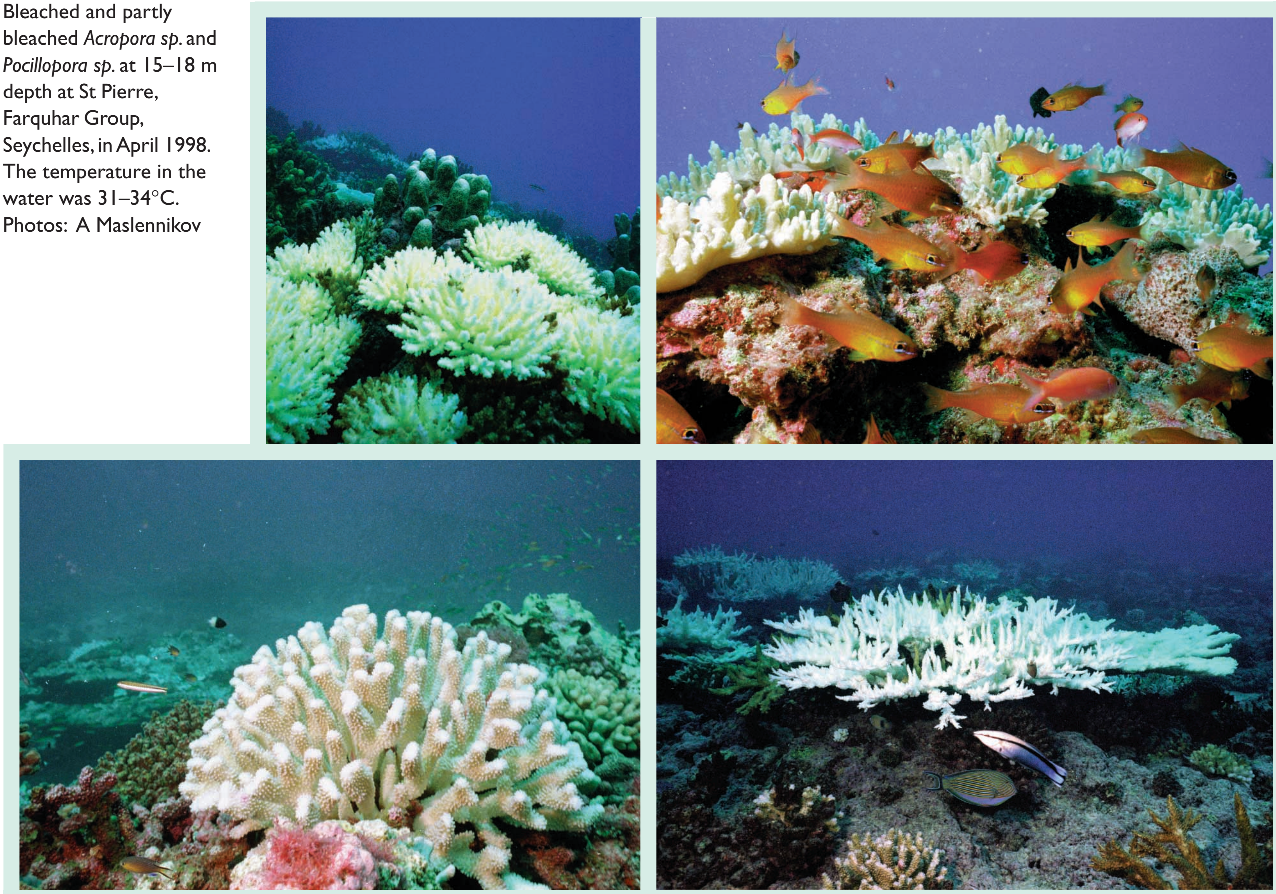
There was a minor bleaching event in Mauritius in 1998, with moderate and patchy occurence in localised areas. Surveys showed 1–15% bleaching in many locations (see also Status report Mauritius, page 60). Temperatures were about 3°C above the normal 27°C (Wilkinson, 1998). No data are available for the islands of Rodrigues and Cargados Carajos (also known as St Brandon Islands).

Seychelles

The Seychelles, made up of 115 scattered islands, also covers 1,374,000 km^2 of ocean. Fringing reefs are found



In Seychelles, visitors find fringing reefs, patch reefs and coral islands. They are of great importance to the tourism industry. In 1998, Seychelles Marine Park Authority found extensive bleaching and mortality at 14 different locations. Subsequent coral death ranges from 50–90%.



Bleached and partly bleached *Acropora sp.* and *Pocillopora sp.* at 15–18 m depth at St Pierre, Farquhar Group, Seychelles, in April 1998. The temperature in the water was 31–34°C. Photos: A Maslennikov

around the granitic islands of the Mahé group, and coral islands and patch reefs are the main reef formations around the other islands.

In 1995, Seychelles population was 0.1 million. Through tourism and fishing, coastal and marine resources contribute the most to the national economy. International tourism (130,900 visitors in 1996) contribute greatly to the economy of Seychelles. Fish is the main source of protein in the Seychellois diet (75 kg/person a year), and in 1997 a fleet of approximately 400 boats landed around 4,000 tonnes of fish. Both tourism and fisheries are dependent on the quality of the marine environment.

In May 1998, Goreau's team assessed the bleaching event in 14 locations around the Seychelles islands, as part of a monitoring programme run by the Seychelles Marine Park Authority (MPA). Baseline data on the locations were available on videotapes, recorded in mid-1997. The extent of recent coral death was ranging from 50% to more than 90%. From March to May, extensive bleaching down to 23 m was reported for Aldabra, Providence and Alphonse groups. Temperatures recorded *in situ* were high, from 29–34°C, with the exceptional 37°C in some lagoons. *Acropora* spp. and other shallow water branching species were most affected. Bleaching of other marine organisms was also recorded, for example soft corals, sea anemones and giant clams. Since then, some signs of recruitment has been seen on the outer atolls.

In January 1999, dead corals around the main island of Mahé were covered by numerous filamentous algae. The density of potentially toxic dinoflagellates living on the dead colonies was assessed through the COI/REP programme VIGITOX.

CAPACITY OF THE ISLANDS COUNTRIES IN TERMS OF EXPERTISE AND PHYSICAL RESOURCES

At a regional level, the Environmental Programme of the Indian Ocean Commission (COI/REP) has focused its activities on two areas:

1. The Reef Programme

A functional network was established in 1997, with national focal points (sub-nodes). A coral reef methodology monitoring handbook has been approved by the countries and is now available. The Indian Ocean Commission Reef Action Plan (PAR/COI) includes monitoring of coral reefs as an important activity.

In 1998, GCRMN-COI surveys were carried out in the five countries before and during the bleaching event, in March and in July/December. Twenty-four stations were monitored according to the adapted manual, using parameters such as coral cover, algae, abiotic substrate and ichtyologic population. One addition to the English *et al*. (1994) manual was the assessment of reef flats, which are directly affected by human-based activities.

In April/May 1999, PAR/COI will conduct a new survey which will include more monitoring stations and a post-bleaching assessment. These activities are partly founded by the European Union and partly through national resources. Reef network stakeholders will meet in June to exchange collected data, including bleaching impacts.

The Reef network connects all the relevant focal institutions from the five member countries. The activities are considered as national components of the global GCRMN, and COI is a sub-node for ICRI-GCRMN. For the period 2000–2004, funding from the World Bank should be available for implementation of the GCRMN programme, but only for the four ACP countries (Comoros, Madagascar, Mauritius and Seychelles). Réunion, as part of the European Community, cannot be supported by these funding agencies.

2. The Ecotoxicology Programme

The Ecotoxicology Programme was created in 1998 and the action plan for 1999 will focus on a VIGITOX programme and a field-guide handbook on collection and treatment of microalgal and fish material . A VIGITOX assessment is already underway, a quick response to investigate the eventual links between coral bleaching and the risk for human poisoning through consumption of reef fishes, through contamination of dead corals by toxinogenic microalgae. Pilot reefs affected by coral bleaching have been selected for data collection, and the levels of toxicity in fish bioindicators will be evaluated.

Status report Mauritius

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INTRODUCTION

Mauritius is located in the western Indian Ocean, its main island approximately 800 km east of Madagascar (see maps, pages 56–57). The main island is volcanic with a high, humid central plateau. It is surrounded by fringing (and one barrier) coral reefs, except for short stretches of rock cliffs on the west and south-east coasts. The republic also include five unpopulated offshore islands on the northern shelf, plus the populated volcanic island of Rodrigues at 63°20E, 19°45'S, a fisheries station on sand cays of St Brandon Islands (also known as Cargados Carajos) at 59°30'E, 16°30'S and a cocoa plantation on Agalega sand cay much further north (estimate 56°E, 14°S).

Mauritius has a mixed population of more than 1.2 million people. They make their living on sugar cane agriculture, light industry and textiles, tourism (mostly high quality beach resorts, with over 250,000 guests per year), fishing (reef fishing and offshore bank fishing) and offshore banking. Rodrigues has a population of 30,000 people of African origin, who make their living on subsistence fishing, octopus fishing, cattle grazing and very small scale tourism.

CORAL REEF BIOTOPES

Fringing reefs protect extensive shallow lagoons nearly all way around the islands of Mauritius and Rodrigues. Most are well-established spur and groove reefs with an algal ridge. The lagoons have large beds of branching and tabular corals (*Acropora formosa*, *A. cytherea*, *A.hyacinthus*) and patches of *Pavona, Porites, Platygyra, Galaxea, Montipora* are common. There is extensive seagrass in lagoons, and sparse *Rhizophora* mangrove on the south-east coast of Mauritius, which recently was introduced to Rodrigues.

The marine ecosystems of the main islands are heavily degraded. On Mauritius, degradation is caused by pollution, eutrophication and fishing above sustainable yield. On Rodrigues, soil erosion and sedimentation are the main problems. On St Brandon, there is some fishing impact, but Agalega is probably pristine.

BLEACHING EVENT

Coral bleaching is characterised by the expulsion of symbiotic algae (zooxanthellae) is an increasing problem worldwide. Global warming has been implicated as one cause, but the phenomenon cannot be fully comprehended without an understanding of the variability of zooxanthellae populations in field conditions (Fagoonee *et al.*, 1999). Results from a 6-year field study provide evidence of density regulation, but also of a large variability in the zooxanthellae population, with regular episodes of very low densities. These bleaching events are likely to be part of a constant variability in zooxanthellae density caused by environmental fluctuations superimposed on a strong seasonal cycle in abundance.

SST anomaly data indicates that Mauritius, Rodrigues, and probably St Brandon and Agalega were affected by increasing temperatures from 10/1/98 until 7/3/98. A warm water mass, stretching from the northern tip of Madagascar to the western Australian coast, expanded into a massive warm water area, >1.5°C warmer than normal, covering mid-, south and western Indian Ocean; eventually moving north of Mauritius around 7/3/98, right across the central Indian Ocean.

EFFECTS ON CORAL REEFS

Mauritius and Rodrigues do not appear to have suffered mass bleaching events, although bleached coral colonies were evident on reefs and in lagoons.

During February 1998, Goorah, D., Rathacharen, B.D. and Kulputeea, D. of the Albion Fisheries Research Centre, Mauritius, surveyed for coral bleaching at two unregulated marine parks within lagoons (Balaclava on the west coast and Blue Bay on the southeast coast). They concluded that bleaching affected 39% and 31% of live corals in Balaclava and Blue Bay marine parks respectively, with total bleaching being 12% and 4% of live cover, and partial bleaching 27%.

In April, Turner concluded from observations at Trou D'Eau Douce on the east coast that many (up to 25% in some areas) *Acropora formosa* thickets in lagoons were partially bleached, but in most cases alive. Some *Acropora cytherea* was bleached. The few dead colonies had begun to be colonised by filamentous algae. Bleached colonies were often adjacent to unbleached colonies. Some *Porites* and small faviids on the reef and in the lagoon were bleached, some completely, most partially. Anemones were bleached, but soft corals and *Millepora* seemed to be unaffected. Similar observations have been reported since April from around the island by other workers.

In April 1999, Turner, Klaus, Hardman, Baghooli, Persand, Daby and Fagoonee surveyed 34 sites, both inside lagoons and outside the reef to 20 m depth around the entire coast of mainland Mauritius. Up to 50% of the *Acropora formosa* was partially bleached, usually on the upper surfaces of horizontal branches only. Of the *Acropora cytherea* tables, 30–50% were bleached. Some massive corals (especially *Galaxea, Goniastrea, Porites* in water less than 10 m deep) showed partial bleaching on their upper surfaces only. There were no large areas of dead, standing coral that could be attributed to the bleaching event of 1998, other than possibly the tabular corals on the reef flat of the barrier reef at Mahebourg. Tabular corals (mostly *Acropora cytherea*) at some sites (e.g. Balaclava, Trou aux Biches and Flat Island) were clearly overturned by a recent cyclone and storms (January/February, 1999).

SOCIO-ECONOMIC EFFECTS

Lagoons and reefs are already overfished and heavily degraded due to light industry, fertiliser, pesticide runoff and sewage. While bleaching has not caused major additional degradation this year, the weakened reefs are extremely vulnerable to future events, threatening fishing and tourism industries. Long term data of Fagoonee, Baghooli and Turner (unpublished) indicates an overall trend (independent of season): zooxanthellae densities within *Acopora formosa* have decreased over nine years, potentially making them vulnerable to future impacts.

WHY HAS MAURITIUS BEEN SO LITTLE AFFECTED?

1. Weather conditions in March/April were windy and often overcast, and hence calm conditions and low tides during the hottest parts of the day may not have occurred. Meterological Office data have been requested to analyse solar radiation, rainfall, wind and cloud cover since January 1997.
2. Mauritius' lagoons receive much freshwater run-off percolating through the lagoon floor and reef and from rivers, and are often cooler than the sea outside the reef (Daby, 1994).
3. Coral reef organisms in Mauritius are regularly exposed to widely fluctuating conditions (Fagoonee *et al.*, 1999).
4. Unknown, localised oceanographic conditions.

OTHER RELEVANT WORK IN THE REGION

The reef structure of Mauritius and Rodrigues was described in the 1980s by Pichon, Montaggioni and Faure. Degradation of reefs around Mauritius was described in the early 1990s by Muller *et al.*. An EC report to the Government of Mauritius includes percentage incidences of bleached corals in 30 minute swims at numerous sites in two lagoons. Other reports on the status of coral reefs are: Charpy, up to October 1998; Fagoonee, November 1998; and Watt, December 1998.

Several surveys of the coral reefs around Mauritius were carried out during 1998. Albion Fisheries Research Centre, Mauritius, have monitoring sites at locations around Mauritius, and conducted a coral reef bleaching survey at Balaclava and Blue Bay in February 1998. There are no observations for St Brandon or Agalega. Shoals of Capricorn Programme will begin work around Rodrigues, the Mauritius shelf, the outer islands and St Brandon in 1999, including a bleaching monitoring project.

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Status report Socotra Archipelago

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INTRODUCTION

The Socotra Archipelago is located in the north-western Indian Ocean, on the boundary of the Arabian Sea, 225 km east of Horn Africa, at 53–54°E, 12°30'N. It is a part of the Democratic Peoples Republic of Yemen. Four islands make up the archipelago, main Socotra and the Brothers: Abd el Kuri, Semha and Darsha. They are exposed, high and arid granitic islands with limestone plateaus and fluvial plains. The coastline consists of exposed, rocky coasts with cliffs, rocky headlines, cobble shores, and some sand beaches and dunes. Mangrove only occur behind sand berms or in sheltered wadis/ quorhs.

The size of the human population on Socotra is not known – estimates range from 30,000 to 80,000. (Mountain communities are probably uncensored.) Most of them are goat herders, fishermen and date palm grove growers. People on the islands live in extreme poverty, with poor health and low life expectancy. No development.

FISHING AND TOURISM

Fishing communities are scattered all around the islands. They fish lobster, reef fish and sharks for their fins. Fishing techniques most commonly used are catch nets, throw nets, line and a few cages. A cold store has been built, but is not yet operating. Thus, there is no market for fish unless Omani, UAE or Taiwan buyer boats are in the area. Fishing is probably well below sustainable yield, although small sharks (< 50 cm) may be overfished.

The islands have not been accessible for foreigners, and there is no tourism.

CORAL REEF BIOTOPES

The south coasts of the islands are rock/boulder dominated by macroalgae. There are also small (< 25 cm) faviids, small massives and encrusting corals and soft corals subordinate to the algal meadows. North and eastern coasts support low profile spur and groove coral structures and coral on limestone platform down to 8–9 m. They are mostly made up of *Acropora formosa*, *Acropora clathrata* (up to 2 m on Socotra, better developed up to 3 m on Semha), *Acropora valida* with *Stylophora pistillata* and *Turbinaria frondens*, *Goniastrea*, *Platygyra daedala* and *Porites*. Massives are generally < 0.5 m, except at one site where they are > 3 m. Small faviids and encrusting corals subordinate everywhere, also in deeper water.

The environment of Socotra is pristine, except immediately adjacent to the two small towns and the fishing villages.

BLEACHING EVENT

SST anomaly data indicate that Socotra was affected by increasing temperatures from 12/5/98 to 30/5/98. A 0.5°C rise off Somalia 14/4/98 reached the western tip of Socotra 17/4/98, and surrounded Socotra by 28/4/98. Warmer waters (1°C rise) developed off the South Yemen coast around 2/5/98 and a large warm water mass (+ 1–2°C) developed off the north coast of Socotra from 12/5/98. This mass enveloped Socotra and the south coast of Yemen and Oman by 19/5/98. From 23/5/98 to 26/5/98, it spread from the bottom of the Red Sea to the Gulf, bordering the north coast of Socotra. Cooling began 30/5/98, to less than 1°C, and no anomaly occured after 9/6/98.

EFFECTS ON CORAL REEFS

Corals were reported to be alive in March 1996 (Kemp, M.E.P.). Bleaching was first observed in mid to late May 1998 by De Vantier. Post-bleaching, dead coral was observed in November 1998 (Turner, Klaus, Simoes & De Vantier). By March/April 1999, coral, especially branching *Acropora* washed up on beaches as high berms after storms (Simoes). In April 1999, unbleached live coral was found around the Brothers (Abd el Kuri) (Krupp, 1999), and in deeper water off the north coast of Socotra (> 10 m) (Zajonz, 1999).

In November 1998, Turner, Klaus, Simoes and De Vantier found that 99% of the tabular, branching and massive corals surrounding Socotra were dead. Small faviids, at > 7 m depth, were mostly unaffected. Many soft corals, especially *Sinularia*, were bleached but alive. The coral structure was still standing in most places, and was still used as habitat by fish, though covered in filamentous algae. Areas of mobile coral rubble were developing. Of the Brothers, only Darsha and Semha were surveyed. Surprisingly, they were barely affected by bleaching.

In March to April 1999, another survey was carried out by Simoes, Krupp and Zajonz. They found that storms had caused breakage of branched corals, which were then swept up onto the beaches.

SOCIO-ECONOMIC EFFECTS

In November 1998, it was suggested that storms during the monsoon would probably cause break-up of the coral structure. This had happened by March 1999.

Fisheries will be severely effected – the lobster fishery may decline, and the fishermen may need to turn to deep-sea fishing. A decline in fisheries could cause poor protein diet and even greater poverty.

No further erosion effects are expected, due to the already severe exposure.

ARTICLES ON
THE SCOPE OF CORDIO

Remote sensing as a tool for assessing reef damage

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INTRODUCTION

This paper is a written version of an oral presentation of the planned subproject *Remote sensing as a tool for assessing reef damage* within CORDIO, *Coral Reef Degradation in the Indian Ocean,* held at the CORDIO planning meeting in Colombo, Sri Lanka 26–28 January 1999. It is mainly based on the report *Possibilities of observing coral bleaching using satellite data* by Katinka Lindquist and Bertil Håkansson at the Swedish Meteorological and Hydrological Institute (Report 1999 No 5). Dr Bertil Håkansson is responsible for the Marine project within the Swedish remote sensing program RESE (*Remote Sensing for the Environment*). The report was prepared after a request from the author of this paper and two of the promotors of CORDIO, MISTRA (*The Swedish Fundation for Strategical Environmental Research*) and FRN (*The Swedish Council for Coordination of Research)*.

BACKGROUND

The approach is to take advantage of the research that is done within the Swedish remote sensing program. RESE is a Swedish user-adapted environmental remote sensing research program, funded by MISTRA, involving 60 researchers based at eight institutions at four different universities. The main goal of the research programme is "*to improve environmental management and research, by developing methods where information from remote sensing satellites is used operationally*". This fits in with the ambitions of CORDIO:

"*The proposed program will focus on the ecological and socio-economic effects of coral mortality in the coastal areas of eight participating countries. In addition, the program will investigate the possibilities of introducing mitigation or rehabilitation measures and study the natural patterns of recovery of coral reef communities. Furthermore, the program will establish a long-term, regional monitoring program for assessment of the status of coral reefs in the central and western Indian Ocean. The program also aims at identifying and initiating pilot activities to provide alternative livelihood activities to affected communities.*"

The RESE-program is organised in a matrix with five thematic projects in vertical columns and three, more technical, supporting projects in horizontal rows. One of the thematic projects deals with marine ecosystems, and among the technical projects one deals with sensor and atmospheric corrections and another with image analysis. Where these projects cross, the COR-

DIO-question: *Is it possible to detect the health of coral reefs in satellite images?* will be evaluated.

WHICH SATELLITE SENSOR CAN BE USED?

A satellite sensor is the "camera" on board a satellite that transmits the digital registrations received at Earth, transferred to images or data sets. One can choose an image resolution in the range of 4,000–6,000 m, depending on the type of application. The greater the resolution, the more detail is provided. However, this comes at the expense of image width and thus also the time interval at which images of a specific area are recorded. Table 1 shows image resolution for a number of sensors, as well as the number of pixels each sensor uses to describe coral reef areas of different sizes. If a coral reef area has a diameter of at least 100 m (approx 7,850 m^2) and the area is measured with SPOT XS, where a pixel covers 400 m^2, the area will be represented by 20 pixels. If the same sensor is used for a coral reef area with a diameter of 200 m, the area will be represented by just over 100 pixels. For coral reefs that are even larger, for example a diameter of 500 m, the number of pixels increases considerably. In order to describe a coral reef, an image resolution that provides 100 pixels is required (see Table 1).

THE USE OF SATELLITES TODAY

For a methodological study of coral bleaching based on satellite images, one would have to avoid areas that are very close to the coast. It is important to avoid land-based influences, for example in the form of sediments, as much as possible. Remote islands are the most suitable. When chosing a method, it is also important to pay regard to the type of reef. To control for human impact, it is also necessary to use validation and correction methods.

Today, information from satellites is used by, among others, the US Coral Reef Initiative (USCRI). With information provided by the NOAA-AVHRR sensor, hot spot-charts of sea surface temperature anomalies of +1°C or more are published more or less daily on the World Wide Web: http://psbsgi1.nesdis.noaa.gov:8080/PSB/EPS/SST/climohot.html.

WHAT DOES THE SATELLITE RECORD?

The optical sensors on board a satellite register the reflectance of objects. The registration doesn't always show the truth. Disturbances are caused by the contents of different particles in the atmosphere, the influence of the water column and the amount of seaweed on the coral structure. It is necessary to control for those

Table 1. Image resolution and number of pixels for describing reefs of different size.

Satellite and sensor	Image resolution (m)	Number of pixels describing a coral reef with a diameter of at least 100 m	Number of pixels describing a coral reef with a diameter of at least 250 m	Number of pixels describing a coral reef with a diameter of at least 500 m
SeaWiFS	1,130	0.01	0.04	0.2
NOAA AVHRR	1,100	0.01	0.04	0.2
MODIS-AM*	1,000	0.01	0.05	0.2
IRS-P3 MOS	500	0.03	0.2	1
Envisat MERIS*	300	0.1	1	2
Landsat MSS	80	1	8	31
Landsat TM	30	9	55	218
SPOT (XS)	20	20	123	491
Quick Bird*	4	491	3,068	12,272
Ikonos-2*	4	491	3,068	12,272

*Planned sensors, not yet in operation.

parameters and apply correction and validation methods to the data.

HOW DOES BLEACHING OCCUR AND WHAT CAUSES THE CHANGE IN COLOUR?

Bleaching of coral reefs occurs when the photosynthetic microalgae (zooxanthellae) and/or their pigment desert the coral temporarily or permanently. This is caused by some sort of stress, anthropogenetic or natural. Local bleaching is caused by, for example, high temperature, solar radiation, exposure to air, sediments, addition of fresh water (e.g. rain) and inorganic nutrients. The causes of large scale coral reef bleaching, i.e. involving more than 100–1,000 km^2, are increased sea surface temperatures and high solar radiation (particularly UV-radiation), which often occur together.

Bleaching occurs when the density of zooxanthellae and/or the concentration of photosynthetic pigment in the zooxanthellae is reduced. Most corals normally contain between one and five million zooxanthellae per cm^2, depending on the species, and 2–10 pg of chlorophyll per zooxanthella. When corals are bleached, they usually lose 60–90% of their zooxanthellae, and each zooxanthella can lose 50–80% of its photosynthetic pigment. The bleaching process is rapid, it may be over in a couple of days.

When the coral is bleached, its colour changes from a shade of yellow, brown or olive to more or less white. This causes reflectance to increase at all wavelengths. In a reflectance spectrum, the curve for an area with bleached corals will be displaced upwards compared to one with healthy corals.

AREAS FOR COMPLEMENTARY RESEARCH

To get a good picture of the spectral signature of healthy corals and of bleached corals in different stages, airborne hyperspectral technology can be used. For big areas it is a very expensive technique, but the most important wavelengths can be identified through pilot studies. For correct interpretation, it is also important to do ground surveys (ground-truthing) and compare field data with satellite registrations. During 1999, a launch of satellites with very high geometric resolution is planned, and those could provide very good data for this type of detection/monitoring.

LITERATURE SEARCH

Various databases were searched. The word coral bleaching produced quite a few hits. Glynn (1996) reported facts on coral bleaching in detail and others also often quote him. There is also a good article on coral bleaching in Scientific American (1994). Wilkinson described global distribution of bleaching in 1997–1998 in detail in a report published by AIMS (Australian Institute of Marine Science). However, a more specific search for remote sensing in combination with coral, yields only the occasional hit. In a new article, Mumby *et al.* (1997) discuss the possibility of mapping coral reefs with SPOT and Landsat data. Remote sensing also includes airborne observation techniques, and this gives a number of hits.

A combination of coral bleaching and remote sensing produces almost only hits from a group of collaborating researchers: Holden, LeDrew and others. Together, they have published five to ten articles, primarily in connection with conferences. The research of Holden *et al.* (1997; 1998) involves surveillance of coral health, and their articles deal with things such as identification of coral health based on their spectrum as measured with a handheld measuring instrument. They also use hyperspectral analysis, i.e. measurements are taken at very small wavelength intervals (1.4 nm). In order to determine which wavelength intervals to use to distinguish between healthy and bleached corals, these measurements are then subjected to so called “principal component analysis”. Magnitude of the reflectance is a significant factor.

In an article from 1997, Holden *et al.* discuss the possibility of using SPOT-images. The problem with seeing coral bleaching from a distance is that the coral spectrum is difficult to separate from other substrata, and that the water column above the coral causes optic fade-out of the spectrum. On a "normal" SPOT-image, where corals can barely be discerned as light-blue shadows, a type of transformation is applied so that they appear clearly. The next step is to convert digital data to reflectance spectra. This is done by correcting for fade-out in the column of water. Their analysis shows that reflectance spectra can be distinguished to a depth of 10 metres. They conclude: "these results lend confidence to the development of procedures that will use satellite or airborne digital imagery to detect and map coral ecosystem stress".

Holden *et al.* also suggest an area in need of further research – development of radiative transfer algorithms and general model development to correct the image for effects of a water column of varying depth. The problem is that brightness of the substrate substantially contributes to the radiation sensed at the sensor. So the three main variables are: water depth, water quality (attenuation coefficient) and bottom brightness. If you know two of these, then simple algorithms are available for correction of the digital image, but what if you don't know the depth for each pixel (which is often the case)? (pers comm).

Image data from SPOT and Landsat are "geocoded" with aid of the method "Ordnance Survey Maps" and are corrected radiometrically for sensor calibration, time of year and atmospheric conditions. The variation in ocean depth is one of the most cited difficulties with remote sensing of submarine environments. For example, the spectral signature of sand at 20 m can be similar to that of seaweed at 3 m. In order to get around this problem, Mumby *et al.* use a special model for correction for ocean depth. Their objective is not to look at coral bleaching specifically but, in the first stage, to distinguish between four types of seabed substrata (coral, algae, sand and seaweed) and, in the second stage, to determine the species of the seabed flora. Various satellite sensors are compared to airborne remote sensing equipment. Results show that distinguishing coral from the other three seabed substrata on satellite images is no problem.

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Coral bleaching effects on reef fish communities and fisheries

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ABSTRACT
Large proportions of the world's coral reefs were affected by the 1997 and 1998 coral bleaching event. This may have a profound impact on coral reef fauna, especially when the coral bleaching leads to coral mortality. Reef fishes are influenced by the structure of the reef habitat, and as habitat degradation through coral mortality will affect a large variety of interactions within the coral reef system, the composition and size of fish stocks may be altered. This, in turn, could imperil resources for a large number of people depending on fish for subsistence purposes or as a source of income. Due to the variety of factors that regulate reef fish numbers it is difficult to anticipate how coral reef fish assemblages are affected by coral mortality, and only a few studies have considered this issue. The effects of coral mortality could vary from one reef to another, depending on the fish community composition and habitat interactions before the impact, recruitment dynamics, and habitat structure before and after the disturbance. When the dominant coral fauna is affected and there are close interactions between corals and the existing fish populations, a shift in community composition can be expected. If large-scale habitat destruction follows coral mortality (i.e. the corals are broken into coral rubble), fish abundance and species diversity may decrease. In addition, coral mortality could decrease fish catches, which may have profound socio-economic effects. The impact of coral mortality on reef fisheries is likely to depend on aspects such as the nature of the fish community, target species and their habitat requirements, as well as the fishing techniques used.

INTRODUCTION
In 1997 and 1998, large proportions of coral reefs around the world were affected by coral bleaching. Corals are susceptible to variations in temperature (Drollet *et al.*, 1994; Kobluk & Lysenko, 1994; Fang *et al.*, 1997; Jones, 1997; Kushmaro *et al.*, 1997; Lesser, 1997; Podesta & Glynn, 1997) and the bleaching event is believed to be related to increasing water temperatures due to the 1997–1998 El Niño (Wilkinson *et al.*, 1998; 1999). Temperature stress can cause corals to expel their symbiotic algae (zooxanthellae). As a consequence, they appear white and if the stress is prolonged it will lead to coral death. During 1997–1998, coral bleaching and subsequent coral mortality was reported from reef areas in East Africa, the central Indian Ocean, the Middle East, the Indian sub-continent, South-East Asia, East Asia, large parts of the Pacific, as well as the Caribbean and the Atlantic (Baird & Marshall, 1998; Huppert & Stone, 1998; Winter *et al.*, 1998; Wilkinson *et al.*, 1998; 1999).

Profound effects on the coral reef ecosystem are to be expected in areas of coral bleaching, especially where bleaching leads to coral mortality (Glynn, 1984; Brown & Suharsono, 1990; Szmant & Gassman, 1990; Meesters & Bak, 1993; Fagerstrom & Rougerie, 1994; Ware *et al.*, 1996; Davies *et al.*, 1997). How coral bleaching and subsequent coral mortality may affect the reef-associated fish fauna is of specific interest. The fish community is a conspicuous part of the coral reef ecosystem with more than 4,000 species recorded world wide (Sale, 1980). Reef fishes are affected by the structure of the reef habitat and the resources it may offer in terms of food and shelter (Williams, 1991; Jones, 1991). As habitat degradation through coral mortality will influence the large variety of interactions within the coral reef system, the standing stock of fish may be altered (Jones & Syms, 1998). This, in turn, could jeopardize resources for a large number of people depending on fish for subsistence purposes or as a source of income.

The purpose of this paper is to consider the effects that coral bleaching and subsequent coral mortality may have on coral reef fish communities and reef fisheries.

FISH – HABITAT ASSOCIATION

Fishes that proliferate on coral reefs typically interact with corals and other reef structures. Variable preferences among fish populations and the patchiness characterising the reef environment allow for among-habitat distribution patterns at various scales (Williams, 1991; Syms, 1995; Ault & Johnson, 1998; Tolimieri, 1998). At the scale of microhabitats, a type of coral colony, for example, will attract a unique fish community (Ormond *et al.*, 1996; Munday *et al.*, 1997; Öhman *et al.*, 1998 a). Similarly, in patches at the size of tens of metres, such as monospecific stands of coral beds or areas of coral rubble, unique fish assemblages may aggregate (Meekan *et al.*, 1995). However, the most visible patterns, even for a casual observer, are large-scale habitats or zones (10s to 100s of m) (Green, 1996; Letourneur, 1996; Öhman *et al.*, 1997; 1998 b). Beyond differences within reefs are differences among reefs; one reef may hold a fish community observably different from another, due to a distinctive combination of habitat characteristics (Williams, 1991).

In addition to assemblage-specific habitat preferences, general habitat features may influence various fish population measures such as abundance and diversity. Of specific interest in terms of coral bleaching effects, is the relationship between fish and live coral. Positive correlations between fish densities and live coral cover have been reported in a number of studies (Bell & Galzin, 1984; Bouchon-Navaro & Bouchon, 1989;

Coral reef fishes associate with the reef habitat. If reef structure changes it may have profound effects on the fish community. Photo: Marcus C. Öhman.

Chabanet *et al.*, 1997; Öhman & Rajasuriya, 1998). Coral growth also contributes to overall reef structure and influences habitat complexity, and fish species diversity has been reported to increase with structural complexity of the habitat (Luckhurst & Luckhurst, 1978; McClanahan, 1994; McCormick, 1994). However, some studies show little or no correlations between fish and coral growth (McManus *et al.*, 1981; Bell *et al.*, 1985).

CORAL BLEACHING EFFECTS ON REEF FISH COMMUNITIES

Because of the close relationship between fish assemblages and reef structure, any alteration in habitat composition, such as coral bleaching, could influence the associated fish fauna. However, there are difficulties involved in predicting the outcome of a coral bleaching event. Bleaching may influence different habitats in different ways and sensitivity to bleaching may even vary among clones within the same species (Edmunds, 1994; Öhman *et al.*, 1999), hence general principles are difficult to anticipate. In addition, partial or total recovery has been noted in various areas (pers obs), which further complicates the issue.

A given reef fish assemblage is rarely structured by a single factor (Jones, 1991; Caley *et al.*, 1996; Jones & Syms, 1998) and a single event such as coral bleaching may have little or no effect, as other processes may be more important. For example, a fish population within a coral reef may be limited by recruitment and not by resource availability (Doherty & Fowler, 1994).

A few studies have considered the effects of coral bleaching on reef fish communities. Wellington & Victor (1985) investigated the effects of coral bleaching on a damselfish population. Even though the species in focus (*Stegastes acapulcoensis*) proliferate in close association with the substratum, the bleaching caused no alteration in fish numbers. Coral feeders should be expected to be more sensitive to a coral bleaching event and subsequent coral death than fish in other feeding categories. However, population densities of a corallivorous pufferfish (*Arothron meleagris*) were not affected in

The 1997/1998 coral bleaching event mainly affected fast-growing branching corals. Such corals are easily broken and a bare coral skeleton is more sensitive to disturbance than a living coral colony. Photo: Marcus C. Öhman.

a consistent manner by coral mortality in the eastern Pacific following the 1982–1983 El Niño (Glynn, 1985; Guzman & Robertson, 1989). Apparently its feeding preferences were more general than first anticipated, since it changed its diet. Öhman *et al.* (1999) conducted a study on how coral bleaching had influenced reef fishes at Tutia reef, Tanzania. The disturbance (which caused large-scale coral mortality) resulted in a shift in fish community composition, while total numbers were less affected. After the bleaching event, Öhman *et al.* (1999) also detected an increase in the numbers of several herbivores.

Coral bleaching effects could be anticipated by considering the effects of other factors of disturbance. A number of natural disturbances frequently modify the

If corals are broken into rubble, fish abundance and species diversity will decrease and an overall shift in fish community composition will follow. Other species, such as the neon damsel (*Pomacentrus coelestis*), that prefer rubble habitats will dominate over species that depend on living corals for food and shelter.
Photo: Marcus C. Öhman.

reef habitat. Storms, for example, may cause large-scale destruction to a reef and have been reported to influence fish fauna through habitat alteration (Kaufman, 1983; Lassig, 1983; Letourneur *et al.*, 1993). However, what is more relevant for comparison is an impact that bears similarities to coral bleaching. The crown-of-thorns starfish (COTS) feeds on coral polyps and may devastate whole reefs when occurring in large enough numbers (Cameron *et al.*, 1991). Although one difference between coral bleaching and COTS infestations is that the latter will not leave any dead polyp tissue, there are similarities in that the coral colony is standing and the structure of the reefs is more or less intact. Munday *et al.* (1997) reported a reduction in coral-dwelling gobies that directly corresponded with the decline of live corals following a COTS outbreak on the Great Barrier Reef. Also, when COTS caused a decrease in live coral cover in Tahiti, the number of butterflyfishes declined with almost 50% (Bouchon-Navaro *et al.*, 1985). In another study on COTS effects, Sano *et al.* (1984; 1987) detected that coral mortality led to a decrease in both fish species diversity and abundance. However, Williams (1986) and Hart *et al.* (1996) showed that coral death had little impact on the associated fish community.

The severity of coral mortality caused by increased temperatures, COTS or any other type of disturbance is largely dependent on the subsequent developments of the reef structure. A coral skeleton still holds architectural complexity and far from all reef fishes are dependent on a coral substrate that is alive (Godwin & Kosaki, 1989; Jennings *et al.*, 1996; Öhman *et al.*, 1997; 1998 b). Hence, as long as there is a structure for reef fishes to associate with there may be an abundant fish community. However, an exposed coral skeleton is more susceptible to bioeroders and other degrading factors, which may break corals into rubble at a faster rate. This has been shown to decrease fish abundance and species diversity and to change community composition (Lewis, 1997; Öhman *et al.*, 1997). Öhman *et al.* (1999) found that there was a clear positive correlation between structural complexity of the reef and fish abundance and a negative relationship to the proportion broken corals.

CORAL BLEACHING EFFECTS ON REEF FISHERIES

Coral reefs are utilised as natural resources for a large proportion of the human populations (Cesar *et al.*, 1997; Berg *et al.*, 1998). Dive tourism is a significant part of the tourist industry and coral reefs are attractive dive sites (Hawkins & Roberts, 1994; Davis & Tisdell, 1995; Wilhelmsson *et al.*, 1998). Considering that reef fishes often are the main attraction for a diver (Milon, 1993), the status of the reef fish community is of utmost importance to this industry. Another considerable industry depending on the status of the reef fish fauna is the aquarium trade, which is selling live caught fish for ornamental purposes (Wood, 1985).

The most important industry on coral reefs, however, is the fishery (Russ, 1991; Munro, 1996). If coral mortality, following a coral bleaching event, decreases fish catches it is likely to have profound socio-economic effects. Most reef fisheries are carried out for subsistence purposes or as small-scale businesses (Ruddle, 1996). Hence, coral bleaching could directly influence food availability for a large number of people. It is difficult to predict coral bleaching effects on reef fisheries due to the complex nature of reef fish communities. Furthermore, reef fishing is multi-specific: a range of species is targeted and a variety of fishing techniques is used (Russ, 1991). In addition, potential fishing yields per unit area may vary from one reef to another (Bellwood, 1988; Dalzell, 1996). In fact, Arias-Gonzales *et al.* (1994) listed 48 yield estimates from around the world and catches ranged from 0.1 to 36.9 t/km^2/year. Hence, generalisations on coral bleaching effects on reef fishing will be difficult.

Another important aspect of coral bleaching effects on reef fisheries is the kind of fish species targeted and how these species may interact with coral bleaching. The 1997/1998 coral bleaching event had severe impact on fast growing corals in shallow waters, especially *Acropora* (Wilkinson *et al.*, 1999). Such shallow reef areas, with fast-growing branching or foliaceous species, are typically dominated by smaller fishes such as various damselfishes, wrasses and butterflyfishes (e.g. Öhman *et al.*, 1997), which are more likely to be affected by coral mortality. Smaller fishes are caught in the fishery in some areas (e.g. in Jamaica, Tanzania and Seychelles; pers obs) but the main target is larger species (Russ, 1991) such as groupers, snappers and grunts that dominate deeper waters (Williams, 1991). Hence, if coral bleaching is limited to certain habitats, only a part (if any) of the fishery will be affected.

CONCLUSIONS

Coral bleaching that leads to coral death will alter the reef structure. In general, coral reef fishes are closely associated with the reef habitat. Hence, coral bleaching would be expected to influence the fish fauna. However, because of the complexity characterising these fish populations and due to the variety of factors that regulate their numbers, it is difficult to determine what the consequences of coral bleaching might be. The effects may vary from one reef to another, all depending on the fish community composition, habitat interactions before the impact, recruitment dynamics, and habitat structure before and after the disturbance. If the dominant coral fauna is affected and there are close interactions between corals and the existing fish populations, then a shift in community composition is likely to occur. If large-scale habitat destruction follows coral bleaching, i.e. the corals are broken into coral rubble, chances are that there will be a major decrease in fish abundance and species diversity.

Coral mortality due to a bleaching event could have a major impact on the fishing yield. The extent of the impact will depend on aspects such as the nature of the fish community, target species and their habitat requirements and the type of fishing techniques used.

As a consequence of the coral bleaching event decreased fish catches may follow. It depends on the nature of the fish community and the kind of species targetted, as well as the kind of fishing techniques used. If the architectural structure of the reef is intact (i.e. the coral skeleton does not break) the reef could still hold large fish densities.
Photo: Marcus C. Öhman.

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Rehabilitation of degraded coral reefs

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DESTRUCTION AND RECOVERY OF CORAL REEFS

The mass mortality of corals during El Niño has accentuated the need for coral reef conservation and rehabilitation. The intact reef framework made up by dead corals may provide suitable conditions for coral recruitment, but the capacity for coral recolonization is often reduced by chronic disturbances. Several factors related to anthropogenic influences can prevent the recovery of coral reefs. Eutrophication leads to increased growth of algae, which compete for space with the corals and inhibit the recruitment of larvae (Wittenberg, 1992). Likewise, sedimentation caused by terrestrial run-off or dredging smother corals and prevent settlement of coral larvae (Maida, 1994; Babcock, 1991; 1996; Bak, 1979; Hodgson, 1990; Yap, 1990). In addition, recruiting coral larvae may be scarce as a result of the widespread coral mortality. Thus, it appears that colonization by coral larvae in many cases may be a bottle-neck for the recovery of degraded coral reefs.

Fragmentation is probably the predominant mode of reproduction among many of the major reef-building corals, and therefore important for the growth of coral reefs and for the recovery of coral communities after disturbances (Highsmith, 1982). Hence, rehabilitation of coral reefs through transplantation of corals could be seen as a way to bypass the critical stages of larval recruitment and early coral growth by using the coral's inherent ability to reproduce through fragmentation.

REHABILITATION OF CORAL REEFS

So far, rehabilitation of coral reefs has not been widely applied as a management option, but several studies have been undertaken in order to develop suitable methods. Most of the previous experiments on coral reef rehabilitation have aimed at either (1) improving the conditions for natural colonization by placing artificial substrates on the seabed (Clark, 1995; Harriott, 1988; Schumacher, 1994; Fitzhardinge, 1989; Thongtham, 1998) or by clearing or consolidating loose sediment (Hudson, 1988; Miller, 1993) or (2) transplanting corals to the degraded areas (Kaly, 1995; Guzmán, 1991; Auberson, 1982; Bowden-Kerby, 1996; Harriott, 1988; Maragos, 1974; Birkeland, 1979; Yap, 1992). These two methods have been combined, by transplanting corals to artificial substrates (Clark, 1995). Corals have also been transplanted in order to move populations away from threatened habitats, such as areas affected by effluent from a thermal power-plant (Plucer-Rosario, 1977) or by land reclamation (Newman, 1994). In order to improve fisheries or provide sites for recreation, coral reefs could also be created in areas previously devoid of corals (Oren, 1997; Schumacher, 1994; Bouchon, 1981; Bowden-Kerby, 1996).

The usefulness of coral transplantation and other methods for reef rehabilitation has been questioned since most of the suggested methods are very expensive (Clark, 1995; Hatcher, 1989; Harriott, 1988). Corals transplanted to benign environments often survive and grow, but damage and loss of transplanted corals due to wave action is common (Birkeland, 1979; Bowden-Kerby, 1996; Clark, 1995; Harriott, 1988). Some of the methods applied so far to fix corals on the seabed involve the use of underwater epoxy glue (Kaly, 1995; Yap, 1992), terracotta tiles (Plucer-Rosario, 1977; Birkeland, 1979), steel bars hammered into the substrate (Guzmán, 1991) or large concrete structures placed on the seabed (Clark, 1995). These methods are labour-intensive and require SCUBA diving and expensive materials and equipment, and therefore their application may be restricted to the reefs with the highest economic value, such as sites for dive tourism and recreation. However, most of the countries that are most seriously affected by coral reef degradation have limited resources for natural conservation, and it is clear that large-scale coral reef restoration can never be a realistic option in developing countries unless simpler methods are developed, methods that can be applied by the local community of reef-users without specialist skills and without great investments in materials.

The need for more cost-effective methods for reef rehabilitation has led to the suggestion that corals should be transplanted to low-energy environments without being attached (Woodley, 1989; Yap, 1990; Kojis, 1981). Studies on transplantation of unattached corals performed so far (Birkeland, 1979; Bouchon, 1981; Bowden-Kerby, 1996; Lindahl, 1998; Harriott, 1988; Plucer-Rosario, 1977) have yielded variable results, possibly due to the different species, methods and habitats that have been used.

Staghorn corals and other branching corals in the genus *Acropora* generally show good survival and rapid growth after transplantation, and the most promising results stem from studies of unattached staghorn corals placed in shallow habitats protected from strong wave action (Bowden-Kerby, 1996). However, this growth form has often been dislodged and killed by strong wave action after transplantation (Bowden-Kerby, 1996; Harriott, 1988). Likewise, Clark and Edwards (1995) found higher mortality of branching acroporids transplanted to a high-energy environment compared to species with massive growth forms. The branching growth form and small area of attachment of staghorn corals makes them vulnerable to strong water movement even if the corals are firmly attached to a stable substrate, whereas in a protected or moderately exposed environment this growth form has the ability to survive and attain stability even on loose substrate (Gilmore, 1976; Bowden-Kerby, 1996; Tunnicliffe, 1981).

In a recent two-year study, aimed at developing simple and cost-effective methods for reef rehabilitation, transplanted staghorn corals showed good survival and growth on unconsolidated substrate in a moderately exposed environment (Lindahl, 1998). The method of tying the corals together on strings before placing them on the seabed was shown to significantly increase their ability to colonize the target area.

Staghorn corals are common in shallow waters on many reefs worldwide; they grow rapidly and have a natural ability to reproduce through fragmentation and to colonise unstable substrate. Connell (1985) noted that small patches and clearings within existing coral populations are invaded quicker by branching and fragmenting species than by massive growth forms. Therefore, staghorn corals are especially suitable for rehabilitation purposes, not only because of their capacity to populate a specific target area, but also for the possibility of rapid regeneration of clearings and other damages on the source populations. This may not be the case with most of the slow-growing massive corals, and that should make them less suitable for transplantation. However, the usefulness of staghorn corals may be restricted to habitats with ”sufficient” shelter from wave action.

IDEAS FOR FUTURE RESEARCH

Experimental data is needed on the suitability for transplantation of a wide range of coral species in different habitats (i.e. depth, wave-exposure, water quality and sediment structure), and on the effects of interspecific competition among transplanted corals. A wider selection of donor species would reduce the risk of over-harvesting local populations, and a more diverse community of transplanted corals would also increase habitat complexity and resistance to diseases. The effects of transplanting corals between different habitats are poorly known. Intraspecific variability and adaptations to different environments may occur either through phenotypic plasticity or through genetic differentiation (Veron, 1995; Oliver, 1983).

Ecologically sound management of coral transplantation projects will not be possible without realistic estimations of the effects of coral collection on donor populations. Such estimations have been made on some coral species with distinct colonial growth forms based on data on abundance, recruitment, growth and survival (Oliver, 1985; Ross, 1983; Grigg, 1983). However, pruning and re-growth of dense thickets of branching corals, and the effects of coral collection on intraspecific competition have not been studied. Furthermore, culturing of corals may be an alternative to harvesting natural populations (Franklin, 1998).

The transport of corals for transplantation is critical, since it is impractical to store large quantities of corals submerged in water. Previous studies have indicated that staghorn corals can survive up to two hours of emersion if shaded (Harriott, 1988), and unpublished data show that this time could be more than doubled if some simple precautions are taken. Further studies of methods to alleviate desiccation stress on corals in different climates would be useful.

The economic incentives for reef rehabilitation vary greatly, e.g. between areas exploited for dive-tourism and reefs used by artisanal fishermen. The value of a coral reef may be difficult to estimate in economic terms (Berg, 1998; Spurgeon, 1992), but nevertheless, cost-benefit analyses of coral reef rehabilitation are needed for effective management. Previous estimations of the costs of coral reef rehabilitation have been based on more complicated methods, using SCUBA and/or expensive materials for attachment. For estimation of the benefit of reef rehabilitation, we also need more information on the capacity for long-term natural recovery of degraded coral reefs.

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Socio-economic aspects of the 1998 coral bleaching event in the Indian Ocean

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INTRODUCTION

Coral reefs are often referred to as the rainforests of the sea, with amazing beauty and incredible biodiversity. They are also the life support system for millions of coastal inhabitants who derive their livelihoods from them and benefit from the multiple services that reefs provide, such as shoreline protection, nutrient cycling, recreation, tourism and fisheries. Increased pressures on reefs brought about by demographic growth in the coastal zone, expanding tourism, changes in agricultural practices, destructive fishing and the influence of climate change all contribute to threaten the coral reefs.

During the period February to June 1998, a significant rise in the surface water temperature in the Indian Ocean and elsewhere was observed. This temperature anomaly, reported to be around 4–6 degrees above normal over an extended period of time, resulted in extensive coral bleaching and widespread mortality. Hard hit were large areas of coral reef, from Sri Lanka and the Maldives in South Asia to the East African coastal line stretching from Kenya and Tanzania to Madagascar and the Seychelles.

Such widespread bleaching has not been observed in recorded history. In certain areas, such as around the central granite islands of the Seychelles, only a few percent of the reefs are reported to have survived. The start of bleaching in February 1998 coincided with a large El Niño event, and bleaching stopped just as the Asia-Pacific climate switched over to a strong La Niña in June. The massive coral bleaching and mortality of 1998 should be considered against the backdrop of decades of rapidly deteriorating coral reefs all over the world, mainly due to human activities. What was alarming about the 1998 bleaching event, was the widespread occurrence and that many reefs previously regarded as near-pristine were seriously affected.

The bleaching and subsequent mortality may result in serious socio-economic impacts, particularly for those nations whose economies are heavily dependent on the revenues generated by reef-based tourism and reef-based fisheries. The situation raises several important questions such as: (a) whether the bleaching event is merely a one time occurrence, or whether such phenomena will be more frequent as the world's atmosphere and waters warm up; (b) Is there evidence that the reefs may recover? If so, what is the rate of recovery and what, if any, measures can be put in place to enhance recovery; and (c) socio-economic implications and the definition of remedial measures for mitigation of these impacts.

SOCIO-ECONOMIC CONSEQUENCES

With 135 persons per km^2, the Indian Ocean region is the most densely populated coastal region in the world (WRI, 1998). The majority of the population is poor and dependence on fisheries for income and animal protein intake is high. In the Southern Indian Biosphere Reserve in the Gulf of Mannar, nearly 200,000 people earn their livelihoods directly from the sea (one-third of the population) and 90% of fisherfolk are artisanal relying on harvesting nearshore reef-related fisheries and seaweed resources. Overfishing is already a major threat and the coral bleaching effect could worsen this. For instance, along the reef coastline of Eastern Africa, around 50% of the estimated 100,000 full-time fishers and several hundred thousand part-time fishers risk losing their livelihood if the overfishing trend is allowed to continue (Moffat *et al.*, 1998). Besides, some of the fish available may even become toxic, as levels of ciguatera poisoning in the French territories of the Indian Ocean have increased in recent months, linked to the coral bleaching event[2].

In other areas, diving and other coastal tourism activities are the main income generators. In the Maldives, for example, 45% of GNP stems directly and indirectly from tourism revenues. Coastal tourism is already under pressure in places like Kenya, where 90,000 out of 150,000 employees have lost their jobs in recent years (Moffat *et al.*, 1998).

Furthermore, the land area around the Indian Ocean is prone to seasonal cyclones and coral reefs form natural barriers to protect the coastline from erosion. In Sri Lanka, severe coastline erosion has already occurred in areas where the reef substrate has been heavily mined and further damage to the reef structure from bio-eroded dead coral could carry a heavy financial cost. Revetments, groynes and breakwater schemes to prevent further erosion are already costing the Sri Lankan government around US$ 30 million (Berg *et al.*, 1998).

Given this dependency on functions and services that the coral reef ecosystem provides, the impacts of massive coral bleaching on people in this region are likely to be severe. However, a precise estimate of the human impacts is difficult to make at this stage. This is due to the uncertainty surrounding many of the relationships between coral bleaching and mortality on the one hand and ecosystem services, such as fisheries, tourism and coastal protection on the other hand. Besides, the recovery rate of reef areas after wide-spread mortality is difficult to predict. The following two extreme scenarios, as well as many intermediate pathways, are conceivable: (1) damage to the reef is not too bad and recovery is relatively quick; (2) damage is severe and recovery is very slow or non-existent, in which case the long-term impacts will be severe.

In the optimistic first scenario discussed above, the likely socio-economic effects are:

- a possibly slight decrease in tourism-generated income and employment, as some dive tourists may stay at home or go elsewhere. Most tourists will not alter their behaviour.
- some change in fish species composition, both in the water and in fishery landings. Initially, total fish productivity may increase with larger populations of herbivores, though catches of certain target fish for niche markets, such as the ornamental fish trade, may be reduced.
- no major change in the coastal protection function, as bio-erosion of dead reefs and coral growth of new recruits might even each other out.

In the pessimistic second scenario described before, the socio-economic effects could be very severe:

- there may be major direct losses in tourism income and employment as the word gets out in the diving community through dive magazines and the Internet. This is especially likely when charismatic marine fauna disappears as a result of the bleaching and subsequent mortality.
- fish productivity may drop considerably as the reef structure disintegrates, resulting in reduced catches for fishermen, less protein in the diet, particularly for coastal communities, lower health status and possible starvation, particularly among the poorer segments of the community. Fishermen could

experience a major loss of income and reduced ability to purchase other food.

- a possible collapse of the protective barrier function of the reef, which could result in greater coastal erosion. This might be exacerbated by sea level rise.
- a major outbreak of ciguatera with significant human mortality can't be excluded.

VALUATION OF ECONOMIC DAMAGE

A very preliminary attempt to estimate the economic value of these two possible scenarios is presented in Table 1. This estimation is based on the valuation per square km of coral reef by Costanza *et al.* (1997) and data presented in Cesar (1997). These values are multiplied by the area of reefs in the Indian Ocean (i.e. 36,100 km^2; WCMC data-set as quoted in Bryant *et al.*, 1998). These economic estimates should really be seen as first back-of-the-envelope calculations, based on very rough incomplete impressions of the actual damage to the reef ecosystem functions, as well as large uncertainty about each of the relationships discussed above[3]. Further research, both bio-physical and socio-economic, is needed to get a better grip on the truth.

Table 1 gives a very preliminary idea about the possible damage involved. In the pessimistic scenario, the total damage over a 20-year time period could be over US$ 8 billion, primarily from coastal erosion (US$ 2.2 billion), tourism loss (US$ 3.5 billion) and fishery loss (1.4 billion US$). In the optimistic scenario described above, the losses are still considerable but an order of magnitude less than in the pessimistic scenario, stemming mainly from loss in tourism (US$ 0.3 billion) and fisheries (US$ 0.3 billion). However, the full human suffering as a result of the coral bleaching and mortality event, due to possible malnutrition and increasing poverty, as well as unemployment is more than dollar values can express.

CONCLUSIONS AND DISCUSSION

The coral bleaching event of 1998 has already led to severe ecological consequences. Much less is known about the socio-economic impacts. It can be expected, given the severity of the coral mortality following bleaching, that the overall socio-economic consequences are considerable and perhaps disastrous, especially for countries largely dependent on coral reefs for their income, such as the Maldives. The valuation of these impacts is preliminarily estimated at ranging from US$ 706 million to US$ 8,190 million.

However, large uncertainties exist with respect to these socio-economic consequences. Therefore, more applied research and field work is needed to assess the damage to the peoples and the economies around the Indian Ocean.

Table 1: Estimates of the economic damage due to 1998 Indian Ocean coral bleaching (Net Present Value in million US$ over a 20 year time horizon with a 10% discount rate)

Coral reef ecosystem services	Optimistic scenario	Pessimistic scenario
Food production (e.g. fisheries)	260	1,361
Tourism and recreation	332	3,477
Disturbance regulation (coastal protection)	0	2,152
Other services	114	1,200
Total	**706**	**8,190**

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ENDNOTES

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2. J.-P. Quod (pers. comm.) reports that there has been an increase in ciguatera in Reunion and other French territories in the Indian Ocean, apparently as a result of the bleaching disturbance.
3. Values per km^2 for food production (US$ 220/ha/yr) and other services (US$ 97/ha/yr) are taken from Costanza *et al.* (1997). Calculated values for tourism and recreation (US$281/ha/yr), as well as disturbance regulation (US$174/ha/yr) are based on values given in Cesar, H.S.J.1996. Economic Analysis of Indonesian Coral Reefs. Environment Department, Series 'Work in Progress', World Bank, Washington DC, USA. The calculations for tourism and coastal protection were based on the assumption that in the Indian Ocean, around 25% of reef areas have medium to high value infrastructure and 75% low value infrastructure and that around 50% of the reef areas have high tourism potential and 50% have low tourism potential. For this calculation, the present value data of Cesar (1996) were annualized based on a 10% discount rate per year. Note that these data are considerably lower and more realistic than in Costanza *et al.* (1997), which has high estimates for tourism and coastal protection: US$ 3,008/ha/year and US$ 2,750/ha/year respectively. In the pessimistic scenario, it is assumed that the bleaching and mortality witnessed in the Indian Ocean leads to a loss of 25% of reef-related fisheries from year 5 until year 20. In the first five years, this percentage grows linearly from 0% to 25%. All the other services are assumed to decline 50%, starting from year 5, with a linear growth from 0% to 50% in the first five years. These percentage losses in services are multiplied by the annual value of the services, and summed up across the services to give total annual losses per ha per year. This number is multiplied by the 3.61 million ha (36,100 km^2) of reefs in the Indian Ocean. Finally, the net present value over a 20-year period is taken with a 10% discount rate.

Sustainable energy and wastewater treatment as alternative/sustainable livelihood for costal communities

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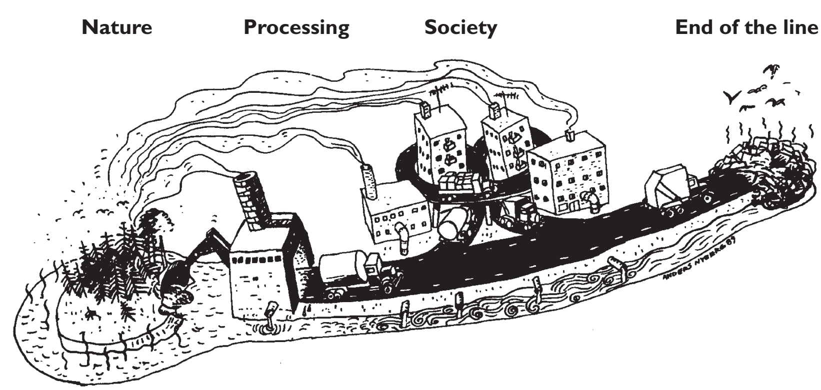
Energy is the basic resource for development and economic growth, but its use affects regional ecosystems, the global environment and the human condition.

Two billion people world-wide depend primarily on wood for their energy needs, while biomass burning removes the forest cover and contributes up to 40 percent of global emissions of carbon dioxide and other greenhouse gases. The energy situation has started to cause serious concern in many regions, especially the dependence on and the increasing scarcity of fuel-wood.

To avert the crisis, suitable programmes for introducing alternative energy should be developed. Renewable energy technologies, such as solar cells and windmills, can promote energy self-sufficiency in developing nations, preserve the environment and reduce the threat of global warming.

Over the past 40 years, the world's agricultural, health and energy problems have largely been addressed from a technological standpoint. As populations increase and global energy demand doubles over the next 20 years, a new strategy will be needed.

Appropriate technology and renewable energy seem to be the obvious solutions, particularly in developing nations. However, many believe that renewable energy



Most societies have a straight flow of raw materials, energy and waste. This has to be changed in order to achieve a sustainable society.

is an enigma. Everyone is in favour of it, but few take it seriously.

Twenty years of research and innovation, however, have made energy technologies more robust and far less expensive. The price of photovoltaics, for example, has dropped as rapidly as that of computers, or more than 90% since 1980. Energy security and environmental protection for developing nations will depend on developing and disseminating such new technologies.

Rapid advances in energy technologies will create great opportunities for developing countries in the next two decades. If they can avoid investing heavily in antiquated coal and oil technologies and choose alternative energy sources, such as wind power, solar cells and biogas instead, they could even move ahead of their industrial country counterparts.

Nearly unnoticed by governments and industry, the world energy economy has entered a period of rapid change that may be as far-reaching as the computer and telecommunications revolutions. Oil and coal-fired power plants may soon be relics of the industrial revolution. In Europe and United States, wind power is now often less expensive than coal, and more than 200,000 homes in developing countries already get their electricity from solar cells. Major corporations such as Shell, BP, Mitsubishi, Westinghouse, Siemens and Enron have announced investments in advanced fuel cells and solar cells. International oil and energy companies are now buying land areas in deserts to install solar cell plants in the future.

WIND ENERGY

Wind power is the world's fastest growing power source. The world's wind power capacity has doubled in three years. Wind turbines generate roughly 21 billion kWh — enough for 3.5 million suburban homes. Denmark is the leader in global wind power industry. Over 8% of the country's electricity is generated from wind power. It is the third largest export industry in Denmark, generating thousands of jobs. Danish companies have also formed successful joint venture manufacturing companies in for instance India, which has led to a rapid transfer of wind energy technology. The nations that could benefit most from further growth of the wind industry are in the developing world, where power demand is growing rapidly and most countries lack adequate indigenous supplies of fossil fuels. India is the leader so far, with more than 900 MW in place.

As the technology continues to improve , further cost declines can be expected. This could make wind power the most economical new source of electricity in many

In India, there is a continuous development of renewable energy sources, such as wind power and solar cells. At Tamil Nadu Agricultural University in Coimbatore, the Department of Bio Energy is developing small-scale units suitable for rural areas. They also have a "Technology dissemination" programme to spread new technology in the region. Photo: Niki Sporrong.

countries in the next decade. Wind energy is a domestic source of energy and can improve a nations degree of self-sufficiency. Wind power plants of, for example, 50 MW can be in operation in less than a year from signing the contract.

Wind turbines can be used competitively as a dispersed energy production technology in areas with dispersed electricity consumption.

Wind power has proved to be a reliable technology. It is modular, more power can be added quickly as the demand increases and it is a cost effective technology in many developing areas and nations. The most common ownership of wind turbines are through a co-operative or community.

Besides the classical applications, electricity producing wind turbines are used in hybrid systems, together with for example solar cells and a backup diesel-driven generator system. These integrated systems are very suitable in thinly populated areas or areas where electrification is not yet fully implemented. The advantage is that the investment in the wind turbine and solar cells can be paid for by the fuel saved for the diesel generator.

Example:
The Mexican village of Xcalac (pronounced Sca-Lac) is a fishing and tourist village of 250 people. It has some of the best fishing and skin-diving in Mexico, but is relatively undeveloped.

The closest power lines are 110 km away and the cost to extend the grid to Xcalac has been estimated to $3.2 million. The village has been powered by diesel generators, but reliability of the diesels has been very poor.

In 1992, Xcalac was re-electrified, at a cost of ~$450,000, with a wind and solar hybrid system. Until mid-1995, the system did not have a working backup diesel, so the electricity came solely from wind and sun. Even now, the backup generator is used infrequently due to high operating costs.

SOLAR ENERGY

The first solar cells were developed at Bells Laboratories in the 1950s. The cost of the electricity delivered by these cells were a thousand times higher than the normal price of electricity. Today, the price is much closer to the price of a traditional system. The price of

This solar power unit suitable for export to the developing world was developed by the University of Sydney. It consists of a combination of solar cells for electricity and sun panels for heating of water. Photo: Bull/Greenpeace.

solar cells is estimated to decrease by 20% each time the production doubles. The cost of producing solar cells are twenty times lower today than in the 1970s.

Around two billion people in the world have no electricity at all. In many cases, it is already cheaper to install locally electrified systems based on solar cells than to build large power stations or grid systems.

The development of more efficient and cheaper cells is very rapid. In Arizona, USA, a solar plant is producing electricity for 5,5 cents/kWh. In the US, the average price for electricity is 6–7 cents/kWh.

Several international companies are now marketing solar shingles that can replace existing roofing materials and produce electricity. This will decrease the cost even more.

Solar panels carry on through rain, dust and snow and work for at least 30–40 years. The systems are designed to be consumer friendly, although the battery needs periodical maintenance. This maintenance can be carried out by a local villager who is specially trained for the job.

BIOGAS

Biogas is an environmentally friendly and economically viable source of energy in rural areas.

Biogas has been used in China, India and Pakistan for more than a thousand years. In China, for instance, there are more than seven million biogas plants.

Denmark is seen as a technical leader in biogas production. The technique is sophisticated and the Danish government has decided to double the biogas production by the year 2000 and is aiming for a ten times increase by year 2020. The potential is calculated to 8,33 TWh/y (30 PJ).

The possibilities of biogas are enormous. The gas can be used for production of heat, electricity or as fuel for cars. The most modern biogas plants prove that the technique is safe and tested, and the development of standardised plants shows that safe and stabile plants can be established to a decent price.

The economic attractiveness of an installation is based on the significant fuel cost savings that it generates. The fuel cost savings can pay back the capital costs of the system within a couple of years.

Animal dung is the most commonly used input, mainly because of its availability, but any biodegradable organic material can be used for processing. Plant materials like wood chips, palm nut shells, stalks of cotton, rice hulls, maize cobs, soy husks or coconut shells can all be used.

In India, Pakistan and China, biogas has been used for more than a thousand years. In this village, Islamnagar, outside Bhopal in India, 36 biogas plants have been installed. Animal dung is collected and mixed with water (left). The mix is poured into a concrete tank with a steel drum (right), often directly connected to a gas stove in the kitchen. Afterwards, the dung is used as fertiliser in the fields. Photos: Niki Sporrong.

WASTEWATER

Wastewater problems are becoming acute in many parts of the world and, for the future of cities, wastewater treatment is one of the most critical areas of development.

The discharge of sewage into coastal waters can have a destructive impact on coral reefs and coastal ecosystems. The population in coastal areas grows rapidly, and the use of freshwater and discharge of sewage will increase. As this has destructive effects on coastal environments, in particular coral reefs, it is essential that especially cities and tourist resorts aim to reduce the amount of freshwater used and discharged as sewage. This can be achieved by implementing alternative ways of use, and treatment of the sewage.

Biological treatment of organic wastes has been used for centuries. Composting, for example, is a natural way to enhance nutrient cycling. Nature sees sewage as a resource, while modern society sees sewage as a problem, and often thinks the solution is to transport it to rivers or directly to the sea.

We need to seriously change our way of thinking. Instead of discharging treated or untreated sewage into the sea, it should be kept inland for some productive uses. Several demonstration projects shows that complete use of wastewater for aquaculture and agriculture is possible.

The Chinese developed aquaculture systems several thousand years ago. These systems use the sewage/nutrients and produce fish. Today China is the world's leading producer of farmed fish (Figure 1).

Another way of doing it is to separate the sewage at source. Today, most sanitation systems mix faeces and urine. In the human body, urine is separated from faeces. If we keep it that way, we will get two valuable resources. The faeces can be composted to produce biogas, which in turn can be used for cooking or to generate electricity. The urine can be used as fertiliser on farmland or in greenhouses.

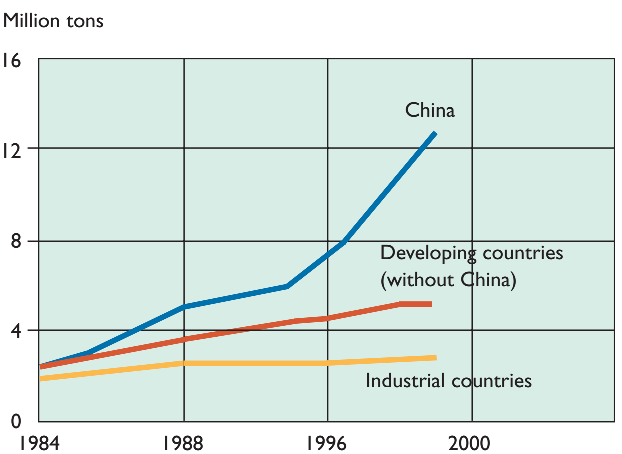


Figure 1. Aquaculture production by region 1984–1995.
Source: FAO

Table 1. Toilet water content

	Urine	Faeces
Nitrogen (N)	5,6 kg	0,09 kg
Phosphorus (P)	0,4 kg	0,19 kg
Potassium (K)	1,0 kg	0,17 kg

By implementing modern technology, a community can be self-sufficient on energy and by using existing resources, pollution of coastal waters can be avoided and instead sewage can be used to supply the community with food products. This will strengthen the economy of the community, as well as increase the quality of life. A better environment will also strengthen the tourism. By re-using the nutrients for food production and fertilising plants, communities can support the tourist resorts and thereby create a source of income.

LIST OF CORDIO PROJECTS 1999

East African Region

Regional co-ordinator: Dr David Obura
Institute: CORDIO East Africa

KENYA

Country co-ordinator: Dr N. H. Muthiga
Institute: Kenya Wildlife Service, Mombasa

1. Annual monitoring of the impacts of the 1998 El Niño on coral reef community structure in Kenya

This activity will extend existing annual monitoring of coral reefs in Kenya to deeper reefs, through training and supporting protected area rangers in the Kenya Wildlife Service. The Kiunga Marine Reserve was completed in March 1999, with five other sites to be surveyed later in the year. Monitoring of shallow lagoonal patch reefs has been undertaken for over 15 years by the Coral Reef Conservation Project (T. McClanahan), and of some deeper reefs for 6 years (D. Obura). This information will be summarized as baseline data for CORDIO.
Co-ordinator: Dr N. H. Muthiga
Institute: Kenya Wildlife Service

2. Investigation of the effects of the 1998 El Niño-related coral bleaching on bio-physical and fisheries aspects of Kenyan coral reefs

Four projects have been proposed by KMFRI scientists for funding by CORDIO, focusing on various aspects of the coral reef physical and biological environment. The projects have been organized as a group proposal to a) provide a comprehensive description of physical, biological and resource use dynamics of a typical Kenyan coral reef lagoon and fringing reef (Mombasa), and b) build on past group projects conducted by KMFRI in Mombasa, Watamu and Gazi-Shirazi.
Co-ordinator: Mr David Kirugara
Institute: Kenya Marine and Fisheries Research Institute (KMFRI)

Project 1. Physical – Ultraviolet and temperature interactions

This study will investigate annual patterns of UV-radiation and temperature as they change with water transport over the fore reef and lagoon areas of a typical fringing reef in Kenya.
Researcher: D. Kirugara

Project 2. Biological – Zooxanthellae and chlorophyll dynamics

The objective of this study is to improve knowledge of zooxanthellae and chlorophyll concentrations and how they change with bleaching. This projected is also intended to develop an indicator for assessing bleaching status and coral health.
Researchers: R. Mdodo & P. Wawiye

Project 3. Biological – Bioerosion and algal succession

Algal succession patterns and bioerosion of coral reef

lagoons will be studied to determine the degree of coral reef degradation resulting from the 1998 bleaching event.
Researchers: S. Mwachireya, J. Uku & P. Wawiye

Project 4. Fisheries – Coral reef fisheries
Artisanal fisheries catch statistics and socio-economic surveys of fishermen will be conducted to investigate nay long-term effects of coral mortality on fisheries, and of the awareness of fishermen of potential impacts. The project will be linked with similar CORDIO projects in South Asian and the Indian Ocean Islands.
Researchers: D. Obura & G. Mwatha

TANZANIA

Country co-ordinator: Christopher Muhando
Institute: Institute of Marine Science, University of Dar es Salaam

1. Extent of coral mortality at selected sites in Tanzania

The extent of coral mortality is to be determined and permanent monitoring stations established at several sites along the coast of Tanzania. As much as possible, monitoring will be conducted in collaboration with local research, mangement and/or conservation instutitions.
Co-ordinator: Christopher Muhando
Institute: Institute of Marine Science
Collaborating institutions: Fisheries Department, Tanga Coastal Zone Management Project, Mafia Island Marine Park, Frontier Tanzania

2. Determining the socio-economic impact of coral bleaching and mortality in Tanzania

The impact of the 1998 coral mortality on coral reef resource users will be investigated using informal and formal survey methods, focusing on the fisheries and tourism industries. Socio-economic survey tools developed for South Asia through other CORDIO activities will be incorporated for comparison around the region.
Co-ordinator: Narriman Jiddawi
Institute: Institute of Marine Science

3. Individual study projects – Changes in the competition between hard corls and sea anemones (corallimorpharia) following the 1998 coral mortality.

Past studies have shown that on degraded reefs, sea anemones (especially *Rhodactis* spp.) can outcompete corals to dominate reef surfaces. This study will investigate if reefs degraded due to the 1998 bleaching will become dominated by sea anemones and how this may relate to past findings.
Researchers: B. Kuguru, E. Mbije & C. Muhando
Institute: Institute of Marine Science

MOZAMBIQUE

Country co-ordinator: Helena Motta
Institute: Ministry for Co-ordination of Environmental Affairs (MICOA)

1. Preliminary assessment of coral bleaching in Mozambique

Rapid assessment surveys were conducted along the entire coast of Mozambique in March/April 1999 to determine the impacts of the 1998 El Niño on coral bleaching and mortality. Coral bleaching and mortality were significant, on average 30–80% of the corals at any single site. Suitable permanent monioring sites and training needs were identified for further CORDIO-related activities.
Co-ordinator: Helena Motta
Institute: Ministry for Co-ordination of Environmental Affairs (MICOA)

2. Training and establishment of permanent coral reef monitoring sites in Mozambique

The training of research officers and graduate students in coral reef monitoring techniques was identified in (1) as a priority activity to build national capacity for monitoring and establish a human resource base for development of research activities on coral reef issues. The training course is scheduled for September 1999, followed by establishment of monitoring sites by course attendees.

Funding: These activities will be covered by MICOA, with support from CORDIO through participation of the East Africa Co-ordinator and generalization of course structure and materials for use elsewhere in the region.

Co-ordinator: Helena Motta

Institute: MICOA

Collaborating institutions: CORDIO and Dr Michael Schleyer, Oceanographic Research Institute, South Africa

South Asia Region

Regional co-ordinator: Dan Wilhelmsson
Institute: CORDIO South Asia/SACEP

REGIONAL

1. Socio-economic impacts of the 1998 coral bleaching event in the Indian Ocean

In this regional project, impacts of the 1998 coral mortality on tourism and fisheries will be investigated. The study will especially focus on the effects on tourism in Maldives and on ornamental fisheries in Sri Lanka (see Sri Lanka 2).
Co-ordinator: Herman Cesar, researcher/consultant
Institute: Institute of Environmental Studies, Free University, Amsterdam

SRI LANKA

Country co-ordinator: Arjan Rajasuriya
Institute: National Aquatic Resources Research and Development Agency (NARA)

1. Impact of coral bleaching on reef communities

The impact of the 1998 coral bleaching and mortality will be investigated through monitoring of the loss of coral cover, coral recovery, abundance of reef fish, invertebrates and algal communities. Reef productivity, reef ecology and coral diseases will also be studied, as well as the impact of bioeroders and changes in their populations. At Hikkaduwa Marine Sanctuary, experimental reef restoration will be tested by transplanting corals.

2. Monitoring and assessment of socio-economic aspects of coral bleaching and degradation in Sri Lanka

The broad objective of the study is to identify and assess the socio-economic implications of coral bleaching in selected sites of Sri Lanka, focusing on ornamental fisheries, coastal demersal fisheries and tourism. The ornamental fisheries study will be carried out together with Herman Cesar (see Regional project above).

3. Develop alternative livelihoods for people dependent on coral reef resources

The aim of this project is to attempt to develop various alternatives to fishing in coastal areas. One example is to introduce young fishermen to ornamental fish cultivation as an alternative livelihood.

MALDIVES

Country co-ordinator: Dr H. Maniku
Institute: Marine Research Centre (MRC), Ministry of Fishery

1. Reef recovery processes: Evaluation of succession and coral recruitment in the Maldives

In this project, the spatial and temporal patterns of coral recruitment will be investigated, using permanent quadrats and experimental settlement plate studies to determine natural distribution and abundance of juvenile corals in different zones on the reef.

2. Assessing bioerosion and its effects on reef structure following a bleaching event in the Maldives

The objective of this project is to provide valuable information about the magnitude and direction of change in the reef framework and topographical complexity of shallow reef-flats, and finally to be able to predict the time-scales of reef recovery with greater accuracy.

3. Building a data base on the economics of coral reef deterioration with special reference to bleaching

The objective of the study is to determine the fishing communities socio-economic situation for the pre- and post-bleaching scenario. The aim is to integrate the socio-economic findings with the biophysical results of the national reef monitoring program, which would lead to more effective planning and policy making at the national level. Data will be entered and analyzed using a Geographic Information System (GIS).

INDIA

Country co-ordinator: Dr M. V. M. Wafar
Institute: National Institute of Oceanography

1. Recovery and monitoring of coral reefs

Through environmental monitoring of coral reefs, assessments of changes in live coral cover and coral biodiversity over time, and rates of recruitment will be made. Studies will be carried out in four different areas: Gulf of Kutch, Lakshadweep Islands, Gulf of Mannar and Andaman Islands.

2. Assessment of the effects of coral mortality on reef communities

Changes in community composition over time, regarding macro- and microalgae and bioeroders, will be studied and compared with historical records.

3. Socio-economic effects of bleaching on local populations and tourism

This study aims to identify and assess the socio-economic implications of coral bleaching on tourism and on local populations directly dependent on reef resources for sustenance.

Central Indian Ocean islands

Regional co-ordinators: Susie Westmacott & Dr Jean Pascal Quod
Institutes: CORDIO and ARVAM (Agence pour la Recherche et la Valorisation Marines)

Island Focal Points
Comoros: Fouad Abdou Rabi, AIDE
Madagascar: Edouard Mara, Inst Halieutique et Sc Mar (IHSM)
Mauritius: Dav Daby, University of Mauritius
Mayotte: Bertrand Wendlling, Direction de l'Agriculture/SPEM
Reunion: Jean Pascal Quod, ARVAM
Rodrigues: Iain Watt, Shoals of Capricorn
Seychelles: John Collie, Marine Parks Authority (MPA)

1. To establish a simple and effective identification scale for bleached coral reef organisms

The underwater identification guide will be aimed at the non-specialist diver on how to detect a bleached coral organism, and how to assess the amount of bleaching. In addition, it will include assessments for algal growth, coral diseases and lesions. It will also provide data on basic spatial assessments.
Co-ordinators: Dr Jean Pascal Quod and Dr John Turner
Institutes: ARVAM (Agence pour la Recherche et la Valorisation Marines) and the University of Wales

2. To establish a rapid assessment and identification methodology of Ciguatera risk by contamination level on bleached reefs

A rapid methodology will be developed for both sample collection and analysis. Initially, analysis of the samples will be done in Reunion at ARVAM, but eventually the technique could be taught to other interested CORDIO countries. With continuous sample collection and monitoring, the risk map may show spatial and intensity changes in the toxic dinoflagellate, which may be connected to increased algal cover after the bleaching event. Recommendations will enable health authorities to deal with any potential outbreaks of Ciguatera.
Co-ordinator: Dr Jean Pascal Quod
Institute: ARVAM (Agence pour la Recherche et la Valorisation Marines)

3. Assessment of post-bleaching status of coral reefs around island states

This activity aims at providing an immediate, accurate and rapid status report of the biological impact of the bleaching around the island states. In addition to the biological data, a general socio-economic description of

each site will be conducted. This will be based on a simple checklist. The rapid assessment of reef condition will utilise simple techniques such as manta tows at as many sites as possible. Representative or unsurveyed sites will be chosen. Existing, available data will be compiled into the reporting process when possible. The rapid socio-economic assessment of reef uses and users will be carried out at each monitoring site, utilising simple forms developed specifically for CORDIO. Collection, analysis and reporting of data will be facilitated and organised by island focal points with external expertise where necessary and assistance from CORDIO co-ordinators.
Co-ordinators: Dr Jean Pascal Quod and Susie Westmacott
Institutes: ARVAM (Agence pour la Recherche et la Valorisation Marines) and CORDIO

4. Long-term monitoring of biophysical and socio-economic factors

This project will compile and assess monitoring activities currently undertaken and other relevant programmes and projects implemented throughout the islands. This will result in an overview status report on which suggestions for database requirements, additional monitoring parameters and stations can be based. This assessment can also help to expand the current monitoring efforts.
Co-ordinator: Dr Jean Pascal Quod and Susie Westmacott
Institute: ARVAM (Agence pour la Recherche et la Valorisation Marines) and CORDIO

5. Development of a database of pictures and videos of marked colonies at CORDIO monitoring sites

This project will provide a photographic database at colony level for lagoonal and outer reef sites. This will enable assessment of long-term changes and comparisons to other sites. Data collection will be facilitated by island focal points.
Co-ordinator: Dr Jean Pascal Quod
Institute: ARVAM (Agence pour la Recherche et la Valorisation Marines)

APPENDIX

Coral Reef Degradation in the Indian Ocean
Planning meeting, Colombo Hilton, Sri Lanka
January 26–28 1999

AGENDA

Tuesday 26
9.00 a.m.–10.00 a.m.
Introduction: background, project structure
Sida
World Bank
Global Coral Reef Monitoring Network
Presentation of participants

10.00 a.m.–3.00 p.m.
Presentations from the different groups in following order:

10.00 a.m.–10.20 a.m.
Sri Lanka (Mr Arjan Rajasuriya)

10.20 a.m.–10.40 a.m.
India (Mr Ramachandran, Mr Wafar)

10.40 a.m.–11.00 a.m.
Maldives (Mr Hassan Maniku)

11.00 a.m.–11.20 a.m.
Kenya (Mr David Obura)

11.20 a.m.–11.40 a.m.
Tanzania (Mr Christopher Muhando)

11.40 a.m.–12.00
Mozambique

12.00–1.00 p.m.
Lunch

1.00 p.m.–1.20 p.m.
Madagascar, Reunion, Comores (Mr Jean-Pascal Quod)

1.20 p.m.–1.40 p.m.
Mauritius, Socotra (Mr John Turner)

1.40 p.m.–2.00 p.m.
Seychelles (Mr David Rowat)

2.00 p.m.–2.20 p.m.
British Indian Ocean Territories (Mr Charles Sheppard)

2.20 p.m.–2.40 p.m.
Australia (Mr Chris Simpson)

2.40 p.m.–3.00 p.m.
Space Agency (Mr Ulf von Sydow)

3.00 p.m.–3.30 p.m.
Coffee break

3.30 p.m.–5.00 p.m.
Conclusion of information and background data in perspective of the project.

Dinner

Wednesday 27
08.00 a.m.–08.30 a.m.
The economics of coral reef deterioration with special reference to bleaching (Mr Herman Cesar)

08.30 a.m.–09.00 a.m.
Coral transplantation for recovery (Mr Ulf Lindahl)

09.00 a.m.–09.30 a.m.
Fish communities and bleached reefs (Mr Marcus Öhman)

09.30 a.m.–10.00 a.m.
Sustainable energy and wastewater treatment as alternative livelihood for coastal communities (Mr Rune Leithe-Eriksen)

10.00 a.m.–10.30 a.m.
Coffee break

10.30 a.m.–12.00
Plan the activities of the project on basis of the reviews of the previous day.
Discussion

12.00–1.00 p.m.
Lunch

1.00 p.m.–5.00 p.m.
Continued discussion

Thursday 28
08.00 a.m.–12.00
Development of an action plan.

12.00–1.00 p.m.
Lunch

1.00 p.m.–5.00 p.m.
Afternoon session

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