Coral Reefs of the Mascarenes, Western Indian Ocean
Author(s): John Turner and Rebecca Klaus
Source: *Philosophical Transactions: Mathematical, Physical and Engineering Sciences*, Vol. 363, No. 1826, Atmosphere-Ocean-Ecology Dynamics in the Western Indan Ocean (Jan. 15, 2005), pp. 229-250
Published by: Royal Society
Stable URL: http://www.jstor.org/stable/30039795
Accessed: 25-09-2017 13:23 UTC

JSTOR is a not-for-profit service that helps scholars, researchers, and students discover, use, and build upon a wide range of content in a trusted digital archive. We use information technology and tools to increase productivity and facilitate new forms of scholarship. For more information about JSTOR, please contact support@jstor.org.

Your use of the JSTOR archive indicates your acceptance of the Terms & Conditions of Use, available at http://about.jstor.org/terms

Royal Society is collaborating with JSTOR to digitize, preserve and extend access to *Philosophical Transactions: Mathematical, Physical and Engineering Sciences*

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms

PHILOSOPHICAL
TRANSACTIONS
OF
THE ROYAL
SOCIETY A

Phil. Trans. R. Soc. A (2005) **363**, 229–250
doi:10.1098/rsta.2004.1489
Published online 17 November 2004

Coral reefs of the Mascarenes, Western Indian Ocean

By John Turner and Rebecca Klaus

School of Ocean Sciences, University of Wales, Bangor,
Marine Science Laboratories, Menai Bridge,
Anglesey LL57 5AB, UK (j.turner@bangor.ac.uk)

The reefs of the Mascarenes differ in structure and stage of development. Mauritius is the oldest island, bound by a discontinuous fringing reef and small barrier reef, with large lagoon patch reefs. Rodrigues has nearly continuous fringing reefs bounding an extensive lagoon with deep channels and few patch reefs. Réunion, the youngest island, has short stretches of narrow fringing reefs along southwestern coasts. The islets of St Brandon are bound to the east by an extensive arc of fringing reef. Reef mapping of the Mascarenes using satellite imagery provides an estimate of 705 km^2 of shallow reef habitats. These areas have been modified over geological time by changes in sea level, ocean–atmosphere disturbances and biological and chemical forcing. Further modification has resulted from historical changes in land-use patterns. Recent economic development has placed many of these reefs at risk from anthropogenic impact. The reefs of the Mascarenes have escaped mass mortality from bleaching to date, which increases their conservation significance within the wider Indian Ocean. The reefs are poorly protected. A case study shows how a geographic information system incorporating reef-habitat maps can help formulate and demonstrate Marine Protected Area boundaries.

Keywords: Mascarenes; coral reefs; satellite remote sensing; GIS; habitat mapping; marine protected areas

1. Introduction

Conservation of coral-reef resources requires an understanding of reef-habitat distribution and extent, and identification of the natural and anthropogenic impacts acting upon the reefs. Recent impacts are best placed in a historical context with consideration of man's early impact on reefs (Jackson 1997). Satellite imagery is used here to create modern maps of reef habitats across the Mascarene region, and the coral reefs of Mauritius, Réunion, Rodrigues and St Brandon are described. Long-term controlling factors such as sea level, cyclones and historical changes in land use are discussed, and the major threats to the coral reefs of the region and future research are identified. A case study is demonstrated to show how reef-habitat maps can be used as a basis for Marine Protected Area (MPA) boundaries for conservation management.

One contribution of 24 to a Discussion Meeting 'Atmosphere–ocean–ecology dynamics in the Western Indian Ocean'.

© 2004 The Royal Society

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms

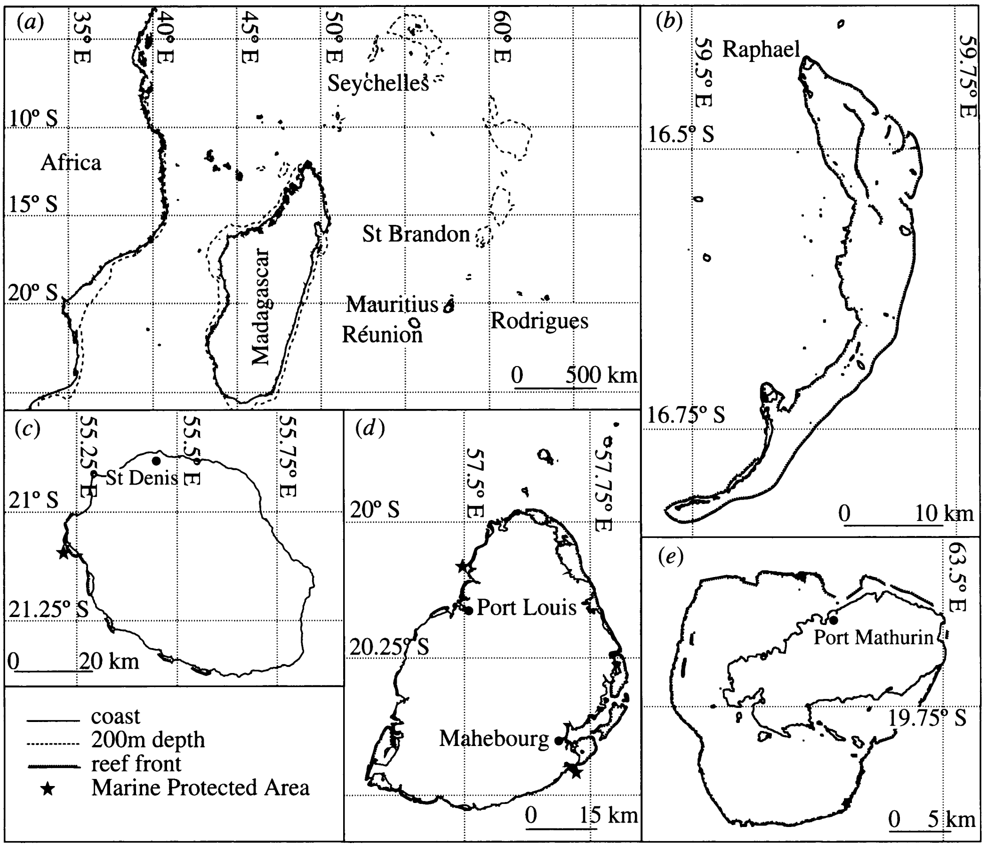

Figure 1. The islands of the Mascarenes. (*a*) Location within Western Indian Ocean. (*b*) St Brandon. (*c*) Réunion. (*d*) Mauritius. (*e*) Rodrigues, showing coral reefs and sites of MPAs excluding the Fisheries Reserves.

2. Background and historical context

The Mascarene marine environment has been reviewed, with an emphasis on Réunion by Naim *et al.* (2000) and from a Mauritius–Rodrigues perspective by Turner *et al.* (2000). The present-day Mascarene reefs are less than 5000 years old, and probably matured only 2000–3000 years ago (Camoin *et al.* 1997; Montaggioni & Faure 1997). The structures of the reefs have previously been described by Pichon (1971), Salm (1976), Montaggioni & Faure (1980) and Bouchon (1981). The islands are shown in figure 1, and their characteristics in table 1. The coasts of the three volcanic islands were formed at different times by seaward flows of lava, which have been eroded by hydrodynamic forces and biological and chemical processes. The islands have no continental shelf, and deep water exists off their coasts. Reef development is extensive but discontinuous around most of Mauritius, nearly continuous around Rodrigues and very restricted at Réunion (see figure 2*a*–*c*). The region also includes the well-developed coral-reef arc and sand cays of St Brandon, which lie on the St Brandon Bank to the north of the volcanic islands (figure 2*d*).

The reefs of the Mascarenes as observed today, although relatively healthy and vigorous away from major pollution hotspots, are no longer pristine due to background

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms

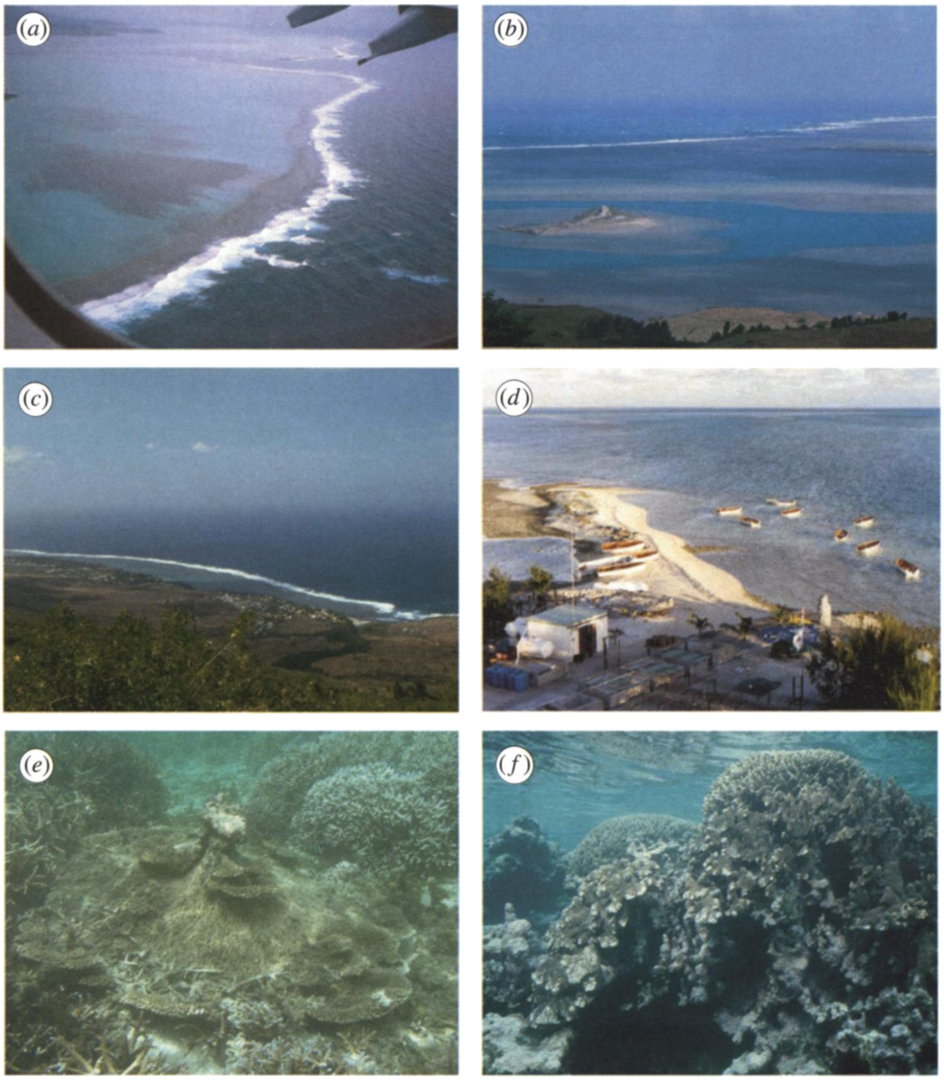

Figure 2. (a) Fringing reef in foreground and barrier reef in background, and lagoon patch reefs, southeast coast Mauritius. (b) Wide lagoon with fringing reef and channel reefs, south coast Rodrigues. (c) Narrow fringing reef, west coast Réunion. (d) Lagoon at Raphael Island, St Brandon (image courtesy of Persands). (e) *Acropora cytherea* tables in a lagoon in Mauritius, upturned by a cyclone, but displaying new growth from the broken bases. (f) Strong *Acropora* colonies such as those of *A. danai* and *A. robusta* dominate reef fronts above 5 m depth on Mascarene reefs.

contamination and human activity. The most pristine reefs may be those of St Brandon, although cyclone disturbance may limit their development. The reefs of the Mascarenes will have been pristine prior to man's arrival, and although visited by Arabic and Portuguese sailors, the islands were not colonized until the early 1600s. The first settlers on Mauritius exploited the ebony forests and introduced alien species, which severely damaged the islands ecosystems and indigenous species through over-

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms

Table 1. *Characteristics of the Mascarene islands of Mauritius, Rodrigues, Rèunion and St Brandon*

	Mauritius	Rodrigues	Rèunion	St Brandon
island type	volcanic oceanic	volcanic oceanic	volcanic oceanic	coralline oceanic
location	20°15′ S, 58°37′ E	19°43′ S, 63°21′ E	21°07′ S, 55°32′ E	15°23′ S, 59°27′ E
age	20 kyr to 7–8 Myr	1.5 Myr	20–2 Myr	bank unknown, sand cays 2–3 kyr
land area (km^2)	1869	110	2531	7.75
coastline length (km)	258	94	215	127
maximum altitude (m)	828	400	3069	4.6
shelf area (0–200 km^2)	1300	950	336	9680
tidal range	0.6	1.2	0.5	unknown
human population	1 200 000	37 000	706 300	0

grazing and predation. Sugar cultivation on Mauritius and Rèunion began under French governance in the 1720s and this period was characterized by establishment of the agricultural economy and motivation to sustain and increase productivity of the land, using slave labour. Fishing probably started in Rodrigues in 1792 and land clearance by fires for agriculture and introduction of cattle began in the early 1800s and continued through the 1900s. Early accounts of Rodrigues (Leguat 1708) and Mauritius (Pitot 1899) refer to exceptionally abundant fish in the lagoons. When the British took Mauritius in 1810, they abandoned slavery and indentured 100 000 labourers from India to work the sugar plantations, resulting in rapid population increase and further land clearance.

During colonial times, the author Bernardin de Saint Pierre visited Mauritius, and in his letters (Bernardin de St Pierre 1773) he made detailed descriptions of the island's colonial society, geography and fauna and flora, including descriptions of corals and reef fauna which indicate that the reefs may still have been pristine. In 1768 he wrote in letters home:

> I have to tell you about the sea and its creations, after which you will know as much as that of the Portuguese who first set foot on the island.... Mauritius is completely surrounded by corals. They are stone like vegetation in the shape of plants and bushes. They are so abundant that whole reefs are made up of them.

His descriptions are sufficiently accurate that it is possible to recognize reef species present today. 'There are lobsters and crawfish of monstrous size. Their claws are not large. They are blue, marbled with white' accurately describes *Panulirus versicolour*, large individuals of which can still be seen on the reef fronts of Rodrigues; '... you can find large living creatures, like boudins [blood sausages], red and black' identifies the Holothurians *Holothuria leucospilota* or *Holothuria atra*, which are common through-

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms

out the lagoons. 'The common sea urchin with small spikes looks like a chestnut in its shell' is *Echinometra mathaei.* It was evident that turtles were already heavily exploited, and that dugongs were still present: 'In the olden days, one found many sea turtles on the shore, but today you hardly see any... we were served sea cow which I found tough, like beef'.

Cheke (1987) described the ecological history of the Mascarene islands, and documented deforestation and change in land use. On Mauritius, natural vegetation cover reduced to less than 1% of original cover, with most clearance having taken place between 1773 and 1835, and a similar pattern of change in natural vegetation occurred later on Rodrigues, and on Réunion, where rugged topography preserved more of the natural vegetation. Once thriving dugong populations were eliminated by over hunting by 1800, and pig predation on eggs and hunting of adults made green and hawksbill turtles rare.

The impact on reefs over the colonial period may have caused much greater change and degradation than those changes of the past 25 years. Rapid deforestation will have caused soil erosion, resulting in wind- and rain-borne-sediment input onto reefs. It is difficult to make estimations of reef degradation since man's first arrival in the Mascarenes, because there is no pristine reef baseline.

Previous research on Mascarene reefs is insufficient to establish an early baseline. Darwin (1842) visited Mauritius and his observations of the fringing reefs were instrumental in forming his subsidence theory of reef development. He did not visit Réunion, Rodrigues or St Brandon. Gardiner (1936) collected corals from Mauritius and the St Brandon Bank during the Percy Sladen Expedition of 1905. Although some studies on specific taxonomic groups were undertaken in Mauritius in the intervening period, no further coral-reef studies were made in the region until those of Pichon (1971), Faure (1974, 1975, 1977, 1982), Faure & Montaggioni (1971*a*, *b*, 1976), Bouchon (1981) and Montaggioni & Faure (1980), the latter study representing the baseline for Mascarene reefs, appropriately just prior to the recent period of rapid development on the main islands. Black-and-white aerial photographs of coastal sectors of Mauritius, Réunion and Rodrigues were truthed by undertaking field surveys along shore-to-reef transects, and maps were produced inferring the reef-habitat classes in the photographs. Satellite remote sensing can now be used to map coral reefs (Green *et al.* 2000) and the technique is especially valuable for providing data over large inaccessible areas, such as St Brandon, which cannot be covered easily by ground teams (Turner & Klaus 2003).

3. Mapping Mascarene reefs by satellite remote sensing

(*a*) *Introduction*

Mascarene reef habitats were mapped using satellite remote sensing and field survey in collaborations by the University of Wales Bangor, University of Mauritius, Shoals Rodrigues and the Mauritius Institute of Oceanography (Daby 1990; Klaus 1995; Turner 1995; Dykes 1996; Orme 1997; Eastwood 1998 (Mauritius); Chapman 2000; Chapman & Turner 2000, 2001, 2004 (Rodrigues); Tyack 2002 (St Brandon)). The methodology used in these studies to detect reef habitats is explained here for Mauritius and Rodrigues, and the knowledge of reef-habitat signatures is then applied to classify images of the remote reefs of St Brandon.

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms

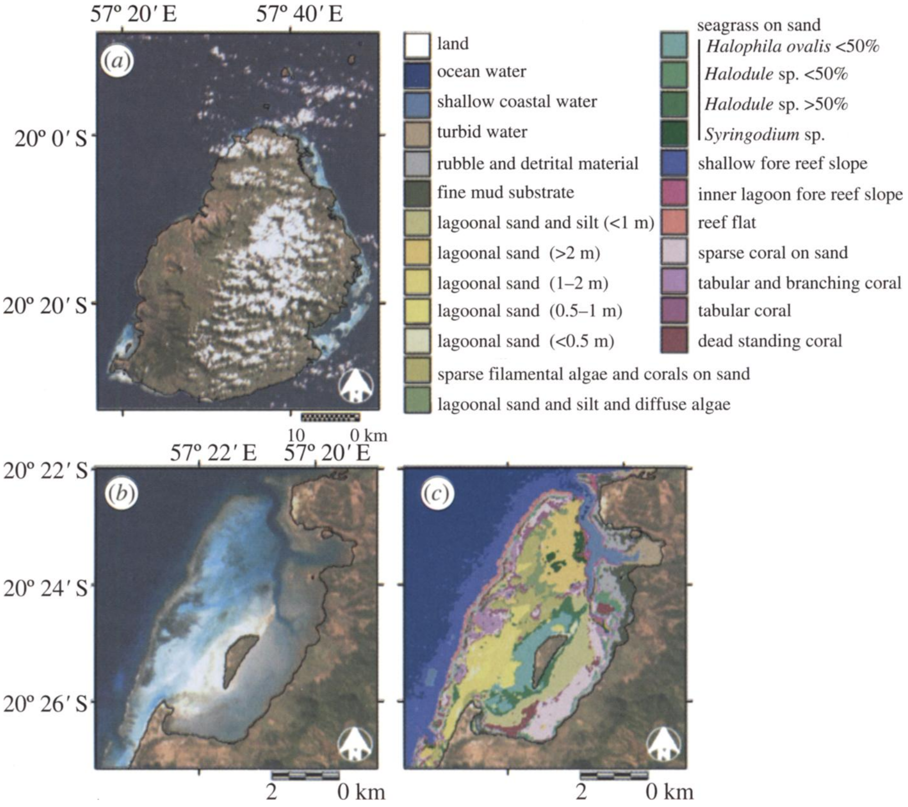

Figure 3. (*a*) Landsat 4TM satellite image of Mauritius, with (*b*) true-colour section of southwest lagoon and (*c*) same section classified into biotopes.

(*b*) *Ground-truthed mapping of Mauritius and Rodrigues*

Multi-spectral satellite data from the Landsat series (table 2) were processed using ERDAS Imagine software (Leica Geosystems GIS and Mapping Ltd) and corrected for geometric distortion using map coordinates and ground control points (GCPs) recorded using hand-held global-positioning-system (GPS) devices. The data were corrected for the effects of atmospheric scattering and absorption using standard radiometric correction techniques (Green *et al.* 2000) and 6S codes (Vermote *et al.* 1997) to make images similar for comparison. True-colour composite maps were prepared and areas of reef and lagoon were surveyed to characterize the different areas of reflectance seen in the images. Snorkel and scuba surveys were carried out at sites selected on a random stratified distribution within the major areas of lagoons and reefs. At each site, the central position of an area of 90 m × 90 m (equivalent to 3 pixels × 3 pixels in the image) was recorded using the GPS. The physical habitat characteristics, substratum composition and biological cover were recorded by a team of four observers using a six-point SACFOR relative abundance scale:

(6) superabundant, 76–100% cover or greater than 100 individuals;

(5) abundant, 51–75% cover or 51–100 individuals;

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms

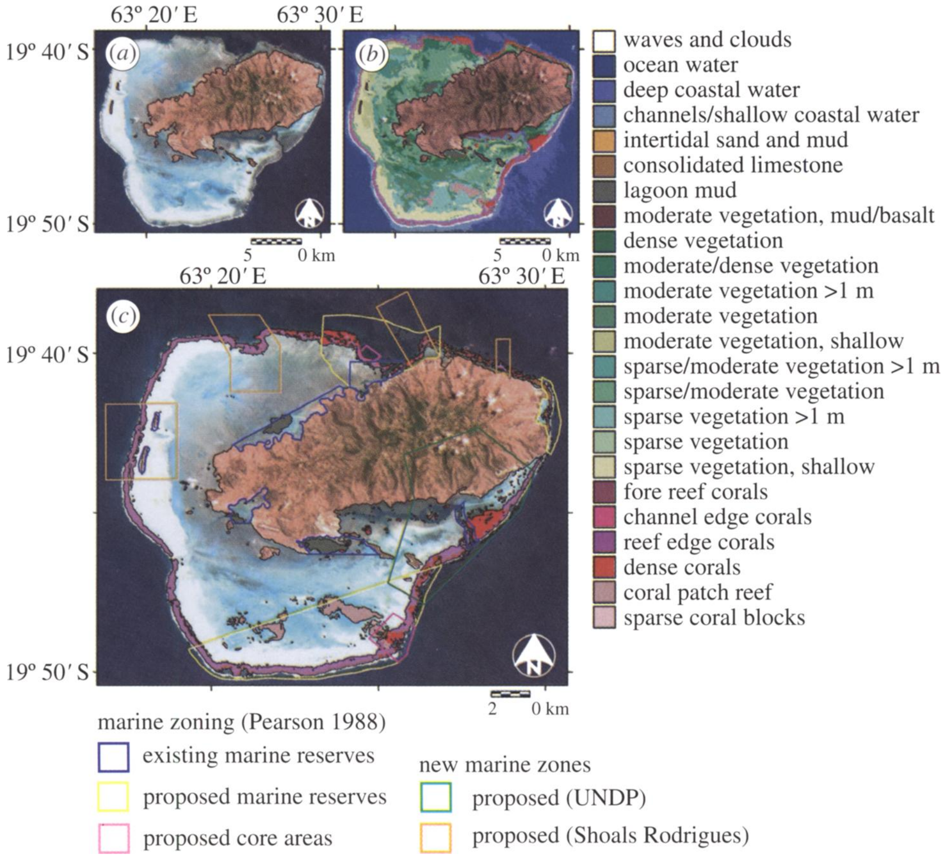

Figure 4. (*a*) Landsat 7ETM+ satellite image of Rodrigues and (*b*) biotope classification map. (*c*) GIS map of Rodrigues showing the proposed Marine Protected Areas, overlaying a biotope map layer showing Coral (red and pink infill) and Lagoon Mud (brown infill) biotopes only, for clarity. Existing Fisheries Reserves, proposed by Fisheries Act 75 (1984) (blue boundaries); Marine Reserves (yellow boundaries) and Core Areas (pink boundaries) proposed by Pearson (1988); New MPAs proposed by Shoals Rodrigues (2003) (orange boundaries); proposed by UNDP (2004) (green boundary).

(4) common, 31–50% cover or 21–50 individuals;

(3) frequent, 11–30% cover or 11–20 individuals;

(2) occasional, 1–10% cover or 2–10 individuals;

(1) rare, less than 1% or one individual.

Photographs of habitat and species were made using 200 ASA Kodachrome film in a Nikonos V underwater camera with 28 mm lens and strobe. In addition, underwater video was recorded along three to five 50 m transects, using a Sony Hi8 camera in a Stingray housing with wide-angle lens at an angle of 45° and at a distance of 0.5 m from the substrate. The benthic cover was assessed in 100 captured images. Field data were analysed using Bray Curtis similarity coefficients in Plymouth Routines in

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms

Table 2. *Characteristics of the satellite image data and processing methods used to prepare the habitat maps presented in this study for the islands of Mauritius, Rodrigues and St Brandon*

	Mauritius	Rodrigues	St Brandon
satellite	Landsat 4	Landsat 7	Landsat 7
sensor	TM	ETM+	ETM+
image acquisition date	1 June 1990	20 October 1999	24 August 2000
World Reference System path/row	152/074	148/074	151/072
image preprocessing	geometric correction, radiometric and atmospheric correction 6S codes	geometric correction, radiometric and atmospheric correction 6S codes	geometric correction, radiometric atmospheric correction 6S codes
ground control points	25	366	25
supervised classification method	Maximum Likelihood Classifier	Maximum Likelihood Classifier	Maximum Likelihood Classifier
number of classes mapped	22	21	21
accuracy assessment points	785	851	40
overall Kappa coefficient	0.854 0.854	0.788 0.788	0.800 0.800

Table 3. *Areas* (km^2) *of major coral-reef habitats derived from classified Landsat satellite image biotope maps of Mauritius, Rodrigues and St Brandon*

(Réunion is represented by reef area from Naim *et al.* (2000) only. Totals do not add up exactly because of pixels in non-habitat classes, which are omitted (e.g. waves, turbid water).)

	Mauritius	Rodrigues	Réunion	St Brandon	total for Mascarenes
total reef habitat	240.4	230.6	7.3	227.0	705.3
fine sediment	14	2.6	—	0	16.6
sand	54.7	110.2	—	168.5	333.4
seagrass and macro-algae	45.5	64.9	—	0	110.4
limestone and rubble	14.7	3.1	—	25.1	42.9
lagoon corals	28.4	11	—	20.2	59.6
reef flat and crest	9.7	17.4	—	7.5	34.6
reef front[a] and slope	19	2.1	—	5.7	26.8
deep channels	6.0	19.4	—	0	25.4

[a] Reef front under-estimated in analysis of satellite imagery because of the steepness of slope and depth to which blue light penetrates.

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms

Multivariate Ecological Research software (PRIMER-E Ltd) to cluster sites according to the similarity of habitat and community components. Biotope descriptions were prepared based on the major physical modifiers (depth, exposure, turbidity) and the species responsible for the observed clustering. Biotopes were grouped by habitat features according to the classification, and a hierarchical biotope classification scheme was developed for each island from the field survey data. Mapping was undertaken using the ground-truthed data to identify the spectral signatures of similar areas of reflectance in the satellite image. A final signature set was used to map the image according to class. Contextual editing (Groom *et al.* 1996) of the classified image employed a set of decision rules to recode areas of the classification that were obviously out of context, such as reef-edge corals in the interior of the lagoon or coral patch reef in areas of tidal sediment close to shore. Accuracy assessments of the classified images used independently observed site data to indicate an overall classification accuracy of the proportion of pixels correctly classified (table 2). The satellite images and biotope classification maps are shown in figures 3 and 4, from which were derived estimates of the extent of reef habitats, listed in table 3.

(*c*) *Mapping of remote reefs at St Brandon*

Satellite remote sensing was used to produce an unverified habitat map (figure 5) of the relatively inaccessible reefs of St Brandon, located 390 km northeast of Mauritius (Tyack 2002). Landsat 7 ETM+ imagery of St Brandon was radiometrically and atmospherically corrected as for Mauritius and Rodrigues. The image was geometrically corrected using points from a digitized Ordnance Survey map (1986) and by 25 GCPs collected by hand-held GPS devices. Mapping was achieved using spectral signature sets of reef features gained from processing the Mauritius and Rodrigues satellite image, together with decision rules for contextual editing. Accuracy assessment of the image was carried out by interpretation of 1:25 000 black and white aerial photographs (Institute Géographique National, France). The extent of reef habitats mapped for St Brandon are also presented in table 3.

4. Descriptions of Mascarene coral-reef habitats and communities

(*a*) *Coral reefs of Mauritius*

In Mauritius, there are 240.4 km^2 of reef habitats, of which 5.8% (14 km^2) is fine sediment, 22.8% (54.7 km^2) is sand, 18.9% (45.5 km^2) is seagrass and macro-algae, 6.1% (14.7 km^2) is rubble, 11.8% (28.4 km^2) is lagoon coral, 7.9% (19 km^2) is reef front, 4% (9.7 km^2) is reef crest and 2.5% (6 km^2) is lagoon channel. Fore-reefs were underestimated by satellite image analysis because of the steepness of slope and the limitations imposed by the depth to which blue light penetrates. Lagoons are mostly less than 3 m deep, ranging from 0 to 8 km from beach to reef, and may contain a variety of habitats including beaches, mangroves, channels, sand, seagrass beds, sparse coral heads, patch reefs and coral reef. Sediments in the lagoons are derived from terrigenous inputs from rivers and carbonate inputs from the reef. The fringing reef is a narrow rim, less than 25 m wide, almost surrounding the island, and sheltered reefs border 6–35 m deep channels or occur as patch reefs within the peripheral reefs. These lagoon reefs consist of branching and tabular *Acropora*, *Porites* massives, foliaceous *Montipora* and *Pavona*, and sand consolidated with seagrass. A small

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms

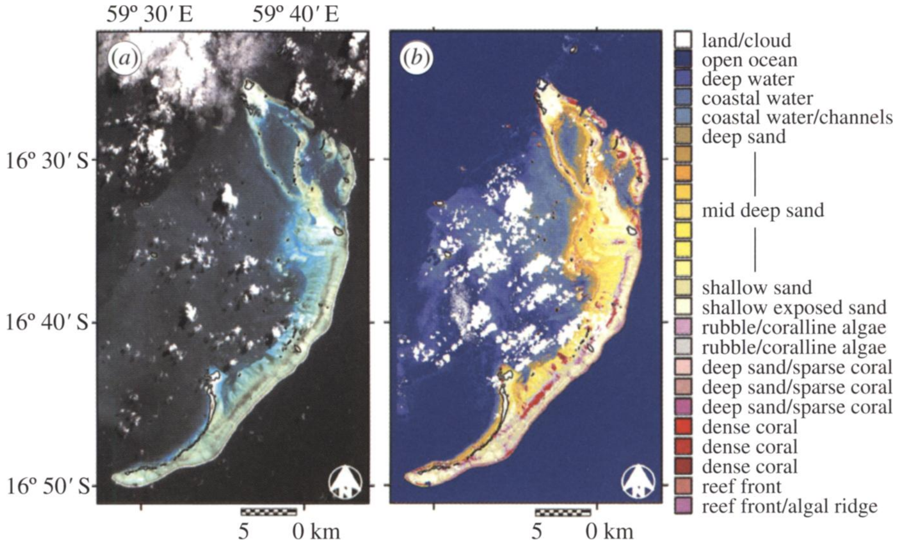

Figure 5. (*a*) Landsat 7 ETM+ images of St Brandon and (*b*) biotope classification map.

(10 km long, 0.5–2 km wide) barrier reef exists on the southeast coast, separated by 3–5 km of lagoon and a 15–30 m deep channel. Where reefs are absent (15.5 km in the south and 10.5 km on the west coast), corals grow on the younger volcanic flows and may represent young stages of future reefs. Reef passes of variable width and 5–20 m depth contain corals and macro-algae, and thin populations of the seagrass *Halophila* or, where more exposed, encrusting calcareous algae. The narrow reef flats consist of dead coral platform, some corals and macro-algae, and although an algal-ridge is present in places (e.g. northwest coast), the shallow reef front is normally dominated by robust *Acropora* corals such as *A. danai* and *A. robusta* to a depth of 5 m. The spurs and grooves of the outer slopes are composed of a diverse range of hard and soft coral genera (e.g. *Pocillopora*, *Millepora*, *Hydnophora*, *Montipora*, *Oxypora*, *Echinopora*, *Leptoria*, *Favia*, *Favites*, *Alveopora*, *Porites*, *Sarcophyton* and *Lobophyton*), and vary from steep (north coast) to gradual (west coast) slopes. At greater depths (20–50 m), basalt rock is colonized by corals, soft corals, sponges and algae. The narrow reef flat does not tend to accumulate sediment deposits, which are swept into the lagoon. 161 species of scleractinian coral have now been reported from Mauritius (Pillay *et al.* 2002).

(*b*) *Coral reefs of Rodrigues*

Rodrigues has 230.6 km^2 of reef habitat, of which 1.1% (2.6 km^2) is fine sediment, 47.8% (110.2 km^2) is sand, 28.1% (64.9 km^2) is seagrass and macro-algae, 1.3% (3.1 km^2) is limestone platform, 4.8% (11 km^2) is lagoon coral, 7.5% (17.4 km^2) is reef flat, 0.9% (2.1 km^2) is reef front and 8.4% (19.4 km^2) is lagoon channel. The steep reef slopes and the platform reefs to the north of the island are not included in this estimate. The narrow reef flat is covered by extensive areas of sand, dead coral platform and sparse corals, with branching *Acropora muricata* and tabular *A. cytherea* close to the seaward edge. Small patch reefs occur in the northwest and southwest areas of the lagoons, dominated by branching and tabular *Acropora*, *A.*

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms

humilis and *Montipora aequituberculata*. These patches are especially well developed close to major passes in the north and south, where the corals *M. tuberculosa*, *M. digitata*, *Pavona decussata* and *Fungia* sp. are also found. Fore-reef slopes in the northwest and northeast consist of steep walls or more gradual spur and groove formations, rarely exceeding 20 m depth, where they meet a coarse sand or fine sediment seabed. An extensive platform of coral reef, of unknown area and variable depth of 15 to 30 m is found outside of the fringing reef off the north coast. The most abundant corals on Rodrigues reef slopes are *A. abrotanoides*, *A. austera*, *A. danai*, *A. robusta*, *A. clathrata*, *A. cytherea*, *A. digitata*, *A. striata*, *A. valida*, *M. tuberculosa*, *M. aequituberculata*, *Echinopora forskaliana*, *Favia stelligera*, *Goniastrea pectinata*, *Pachyseris speciosa*, *Porites rus*, *Porites* massives and *Platygyra daedalea*. Platy coral growth forms are very common on reefs, especially at the base of the reef slope in the more sheltered turbid waters of the northeast coast. Lagoon channels run parallel and perpendicular to the reef, and especially around sand cays and rock islets, and back reef channels run parallel to the coast. The larger channels (up to 40 m deep and 200 m wide) have *Millepora*, *A. muricata* and soft corals on their side walls and increasing hard coral cover to 30 m where rubble and sand form their bases. The lagoons are heavily silted, especially close to shore, and soft bottom communities of shrimps, crabs and polychaete worms are plentiful. Sediments trapped in the shallow lagoons are resuspended by waves. Seagrass beds are uncommon, but macro-algae, especially of the genus *Caulerpa*, is abundant. Most of the coast is basalt rubble on terrigenous sediments, and there are only five small sand beaches. Two sand cays support nesting seabird colonies, but their beaches are no longer used by turtles. *Rhizophora mucronata* mangrove has been planted to stabilize river-borne sediments in bays in the west of the island. 132 coral species have been reported from Rodrigues (Fenner *et al.* 2001, 2004).

(*c*) *Coral reefs of Réunion*

The small areas of reef in Réunion were not mapped by satellite imagery in this study, but some ground observations were made. The reefs cover 7.3 km^2 (Naim *et al.* 2000); lagoons are up to 500 m in width, and their habitats are poor compared with those of Mauritius and Rodrigues, as they consist of rubble, coral patches (*Pocillopora damicornis*, *M. circumvallata*, *A. pharaonis*, *Porites nigrescens*, *Pavona cactus* and *Millepora)* and seagrass *Syringodium isoetifolium*. The reef flat consists of coral rock cut by sandy channels, and the main corals are *A. pharaonis*, *Pavona divaricatam* and *M. circumvallata*, with increasing areas of *A. danai* nearer the reef fronts. The reef front is *ca.* 20 m wide, lacks an algal ridge and is characterized by *A. danai*, *Montipora*, *Porites* and *Millepora* along the surge channels. Montaggioni & Faure (1980) report that deep channels connect to the grooves of the outer slope, which stretch gently and evenly down between spurs for *ca.* 400 m to a depth of 20 m. *Pocillopora damicornis*, *A. digitifera*, *A. danai*, *A. palmerae*, *A. robusta*, *Favia stelligera* and *Millepora* are typical corals of this region. Beyond 20 m depth, volcanic rock is colonized by scattered coral colonies such as *Pocillopora damicornis*, *Astreopora myriophthalma*, *Porites lutea* and *Galaxea fascicularis* and, at 30 m, the rocks are colonized by calcareous algae and encrusting foraminifera, with some *Leptoseris* and *Turbinaria* species. 148 coral species have been reported from Réunion (C. A. F. Bourmaud 2004, personal communication).

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms

(*d*) *Coral reefs of St Brandon*

There are 227 km^2 of reef habitat on St Brandon, of which 74.2% (168.5 km^2) is sand, 11.1% (25.1 km^2) rubble, 8.9% (20.2 km^2) is lagoon coral, 3.3% (7.5 km^2) is reef flat and 2.5% (5.7 km^2) is reef front. No fine sediment or vegetation classes were recorded. At present, there is no specific ground-truth information to assess the accuracy of the habitat map for St Brandon, but a general description of the reefs can be drawn from Kaly & Brown (1998). The eastern side of the St Brandon bank consists of reef slope extending down from a depth of between 10 and 40 m to the ocean floor, but no detailed study of this deep habitat has been made. Above the reef slope is a gently sloping low-relief reef terrace at a depth of 3–40 m depth, dominated by coral rock, sand patches and variable cover of hard corals and encrusting coralline algae, with deep grooves parallel to the reef. Typical corals are *Porites*, *Favia*, *Montipora*, *A. hyacinthus*, *Astreopora* and *Hydnophora*. Shallow spur and groove regions between 0 and 3 m are formed from alternating ridges of rock and deep grooves exposed to the breaking waves. Large numbers of sharks and parrotfish occupy a 1.5 m channel parallel to the back of this zone. The reef crest comprises reef rock and rubble, extending to several hundred metres wide, being composed of calcareous algae on the lagoon side. A back reef is composed of large colonies of *Heliopora*, *A. palifera* and *Porites cylindrica* on sandy rubble, and small colonies of *Stylophora pistillata*, *Pocillopora damicornis* and *Acropora* harbouring small reef fish, clams, holothurians, *Halimeda* and sponges. Two large passes cut into the lagoon and are regularly occupied by white-tip reef sharks and other larger reef fish. St Brandon has three main lagoons up to 7 m deep, separated by reef crest walls. The lagoons have sand floors either heavily bioturbated by worms, crustaceans, bivalves and gastropods, or covered by blue-green algal mats. Patch reefs grow to 3 m in diameter in the lagoons, often having dead or rubble tops, around which larger fish aggregate. The St Brandon bank has a less-developed western reef crest standing *ca.* 1.5 m above the lagoon floor and 4 m above the St Brandon Sea floor. The main corals in the habitat are *A. hyacinthus*, *A. cytherea*, *A. latistella*, *Favia stelligera*, *Stylophora pistillata*, *Alveopora*, *Cyphastrea*, *Platygyra* and soft corals. The St Brandon Sea is a shallow area 4–40 m deep bound by the western reef margin, lagoons and islands, and has a sandy mud bottom with rocky patch reefs dominated by algae, foliose sponges and soft corals and some hard corals such as *Platygyra*, *Acropora*, *A. hyacinthus*, *Heliopora* and *Hydnophora*. To the west of the St Brandon Sea, the seabed slopes into the deep Mascarene Basin.

5. Natural and anthropogenic impacts on Mascarene coral reefs

(*a*) *Introduction*

Natural impacts have long been major modifiers of Mascarene reefs, and the continued presence of reefs around the islands suggests that reefs acclimatize and adapt to such factors. In contrast, many anthropogenic impacts have heightened over the last 25 years, causing significant degradation in some areas.

(*b*) *Sea level*

Sea levels were higher than present in the late Pleistocene period (70–190 kyr BP) and ancient reefs from this period can be seen in Mauritius 2 m above current sea level

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms

in the southwest lagoons, within sugar cane on land, and at Gabriel Island. Camoin *et al.* (1997) conclude from drill cores that, throughout much of the Holocene, rates of vertical reef growth have been 1.75 m kyr^{-1} in Réunion and 2 m kyr^{-1} in Mauritius, with maximum accretion rates of 2.55 mm yr^{-1} and 4.73 mm yr^{-1}, respectively. These reefs displayed a rise of 6 mm yr^{-1} between 10 000 and 7500 yr BP to catch up with sea level prior to stabilizing, and subsidence rates for the islands are estimated at only 0.04 mm yr^{-1}. Carbonate budget estimates made on living reefs in Réunion (Conand *et al.* 1997) indicate a gross carbonate deposition of 3.5–8 kg m^{-2} yr^{-1}, the lower level being for a degraded area and the upper for a healthy reef flat, and twice the global average rate. Sea level is predicted to rise by 50 cm (range 20–86 cm) by 2100 (Intergovernmental Panel on Climate Change Third assessment, Scenario IS92a, IPCC 2001), which will force upward growth in those reefs sufficiently healthy and physiologically capable of responding (Spencer 1995). The back reef and lagoon areas that make up much of the Mascarene shallow marine environment are unlikely to attain high deposition rates, and mean values suggest that, for Réunion reefs at least, deposition and bioerosion are currently in balance. While it is known that species such as *A. muricata* can grow fast (20 cm yr^{-1}) (Done 1999), it is significant to note that Guillaume (1993) reported very high growth rates (up to 3.5 cm yr^{-1}) for the usually slow-growing massive coral *Porites lutea* in over-nutrified waters in Réunion. There is, however, insufficient information to predict how the region's coral reefs, most of which are no longer pristine, may be able to respond to future sea-level-rise forcing.

(*c*) *Cyclones*

The Mascarenes receive an average of nine (range 2–16) cyclones each year, mostly between November and March, of which a mean of 2.5 are intense and winds of 280 km h^{-1} may be experienced, with waves reaching 100 m inland and 2 m above sea level. They last from three hours to three weeks, though most have lives of 5–10 days. St Brandon is subject to nearly twice as many cyclones as the volcanic islands. High winds, heavy rainfall, elevated sea level pressed against the coast and a dome of water travelling beneath the low pressure at the centre of the cyclone combine as a major modifier of coral reefs, affecting coral growth, morphology and the pattern of sediment accumulation (Done 1992, 1993). Naim *et al.* (2000) estimated that 27% of Réunion reef flats are degraded by cyclones. In Mauritius and Rodrigues, branching corals such as *A. muricata* are broken away from patches and moved across lagoons, and some fragments grow and establish new colonies. *A. cytherea* can be turned upside down, and many show new growth of plates from the original colony base (figure 2*e*). Stronger branching *Acropora* colonies such as those of *A. danai* and *A. robusta* dominate reef fronts above 5 m (figure 2*f*), and living portions of their colonies can be found in lagoons after cyclones, accounting for colonies of these species occasionally growing on reef flats and back reefs. Platy corals such as *Pachyseris speciosa* and *Montipora* sp. are broken or removed by cyclones in deeper water on the reef slopes of Rodrigues. Although cyclones cause damage to Mascarene reefs, they also create new space and may therefore increase diversity through disturbance. There has been no thorough study of cyclone impact on the ecology of reefs of the Mascarenes, although the impacts on Réunion fish communities have been examined (Letourneur *et al.* 1993). Future trends in severe weather events are difficult

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms

to predict because of their relatively rare occurrence and large spatial variability. The IPCC found little consistent evidence to suggest that the frequency and area of formation of tropical cyclones would change. Theoretical and modelling studies have, however, suggested an increase in intensity and precipitation (Timmermann *et al.* 1999). Since cyclones only occur once sea temperatures reach a critical value (thought to be 28 °C in Mauritius), it is feasible that cyclonic activity may increase with increased sea temperatures, perhaps coinciding with bleaching events.

(*d*) *Coral bleaching*

The impact of coral bleaching on the reefs of the Mascarenes has been much less severe than at other Indian Ocean locations such as the Seychelles (Spencer *et al.* 2000; Turner *et al.* 2000*b*), Socotra (Turner 1999*b*; Klaus & Turner 2004), Chagos Archipelago (Sheppard 1999; Sheppard *et al.* 2002), Maldives (McClanahan 2000) and Andaman islands (Turner *et al.* 2001). Analysis of advanced very-high-resolution-radiometer (AVHRR) Pathfinder sea-surface temperature (SST) satellite data illustrates that the volcanic island reefs experienced slightly higher mean summer maximum temperatures in 1998 relative to the mean for the period 1985–1997 (Klaus 2004). However, these high temperatures were not constant and appeared to oscillate over the period between January and March. The reefs of St Brandon experienced even higher sea-surface temperatures, of 30 °C on a number of occasions over the same period, and bleaching may have occurred there. Bleaching events occurred in Mauritius during the summers of 1986 and 1987, 1998 and 2003. Fewer than 10% of corals bleached on shallow reef fronts and lagoons in 1998, probably because of the mitigating affects of a cyclone producing a disturbed sea state, dense clouds and high rainfall (Hardman 1999; Turner 1999*a*; Turner *et al.* 2000*a*). In April 2003, coral bleaching became severe in southwest coast lagoons and on fore-reefs, but a late tropical storm in May changed conditions and recovery was evident by November 2003. No coral bleaching was observed at Rodrigues in 1998, but a localized bleaching event in March 2002 caused very high coral mortalities to 3 m depth on some areas of reef flat in the northwest of the island (Hardman *et al.* 2004). Similarly, the coral reefs of Réunion were largely unaffected by bleaching in 1998, with less than 10% of shallow corals affected and most recovering (Quod & Bigot 2000; Ahamada *et al.* 2002). Extensive bleaching was observed in lagoons by the authors in April 2003. Baker *et al.* (2004) found in Mauritius only 3% of coral colonies contained the thermally tolerant clade D *Symbiodinium* zooxanthellae, suggesting that these reefs are particularly vulnerable to future increases in SST. Unless corals can acclimatize or adapt (Gates & Edmunds 1999), it seems inevitable that coral reefs will be threatened by more bleaching events (and maybe coincident cyclones) as the seas warm (Hoegh-Guldberg 1999) and the reefs of the Mascarenes may yet have to respond to the most rapid environmental changes that they have ever experienced.

(*e*) *Indirect impacts from land*

The reefs of the volcanic islands continue to be threatened by anthropogenic impacts, many of which have indirect effects on reefs, and the lagoons and their patch reefs are most vulnerable. Agricultural and urban runoff, ground water discharge and effluents cause eutrophication, sedimentation and probably lead to macro-algal phase shifts and bioerosion. Most of the cultivatable land on Mauritius and Réunion is given

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms

Table 4. *Mean inorganic nutrient concentrations for Mauritius (Daby 1999) and Réunion (Naim et al. 2000)*

	Mauritius		Réunion	
	inside reef	outside reef	inside reef	outside reef
nitrate ($\mu g\,l^{-1}$)	5.0–807.0	5.0–40.0	49.0–148.8	0.0–12.4
phosphate ($\mu g\,l^{-1}$)	5.0–54.0	5.0–9.0	29.4–30.4	14.3–28.5
silicate ($\mu g\,l^{-1}$)	6570.0	60.0–420.0	340.7–920.0	276.2

over to sugar cane, and the largest quantities of fertilizer (600 kg ha^{-1} yr^{-1}) and pesticides (7.4 kg ha^{-1} yr^{-1}) are applied in Mauritius (Dwivedi & Venkatasamy 1991), much of which runs off the volcanic substratum. In Réunion, nutrient-enriched submarine groundwater discharges (Chazottes 1996) cause algae to dominate over corals in the summer (Naim 1993) and over-nutrification affects 27% of the reefs. Nutrient levels are very high in lagoons compared with outside reefs (table 4). In Mauritius and Réunion, urbanization and dense coastal populations create effluents (especially from the textile industry on Mauritius), and sewage is discharged within 500 m of the shore. All Mauritian lagoons are now contaminated by pathogens from sewage (Daby 2001; Daby *et al.* 2002). Réunion has greater levels of sewage treatment. In contrast, there is no industry or sewage system on Rodrigues, and the productivity of coastal waters is reduced by the silting of rivers and lagoon channels. The Rodriguan population is scattered in hamlets all over the island, and depends on agriculture and fishing. The steeply sloping land and deep valleys are stripped of vegetation, and overgrazing and terrace damage by cattle further erode the nutrient-poor soil. Overall, marine pollution is low in the Mascarene region, but pollution hotspots associated with urban, industrial and agricultural activities are prevalent and the effects are most severe near coastal towns and river mouths. New initiatives, such as an improved sewage system in Mauritius, improved pollution monitoring and control in Mauritius and Réunion, and erosion protection measures on Rodrigues, will reduce many land-based impacts in the future.

(*f*) *Artisanal reef fishing*

Artisanal fishing is important in Rodrigues, with local consumption of fish, octopus and lobster of 500 t yr^{-1}, and 100–130 t are exported to Mauritius (Dwivedi & Venkatasamy 1991). The silted channels rarely provide access to the outside sea, and hence most fish are either caught from the coral communities along the edges of the channels (which support octopus, snappers, triggerfish, parrot fish and groupers) or from deeper areas of the lagoon where shrimp and crabs are caught. Fisherman use a variety of methods, including hook and line, basket trap, seine nets, gill nets, canard nets, cast nets and harpoons in the lagoon and on the reefs. In Mauritius, 2800 fisherman catch *ca.* 1600 t yr^{-1} from lagoons and reefs, which exceeds maximum sustainable yield. Coastal fishing is less well developed in Réunion, and involves some 500–600 fishermen, mostly using long lines around fish aggregating devices in open waters, but also catching 100–150 t yr^{-1} of reef fish. At St Brandon, temporary settlements of fisherman operate from Raphael Island, where 30–40 fishermen fish to a depth of 35 m using hand lines and basket traps in the St Brandon Sea amongst

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms

coral patches and around the reefs, catching 350–600 t of fish per year, which are sent to the Mauritius mainland. There are no indications yet of over fishing at St Brandon (Kaly & Brown 1998). Besides the removal of fish from natural food webs and increased algal growth due to reduced grazing, coral colonies are broken by anchors, poles to drive fish into seine nets and colonies are broken and abraded by deployment of basket traps. Around Mauritius, fishing is increasingly better regulated by enforcement patrols, licensing, closed seasons, net-size limits and landing catch at fish-landing stations, but less well enforced in Réunion and Rodrigues. Fisheries in the wider region are reviewed elsewhere (van der Elst *et al.* 2005).

(*g*) *Mascarene reefs at risk*

The reefs of the Mascarenes are thus at significant risk from local anthropogenic impact, especially in Mauritius and Réunion. The map-based analysis conducted by the World Resources Institute, using four threat categories of coastal development (marine pollution, over-exploitation and destructive fishing, inland pollution and erosion (Bryant *et al.* 1998; Spalding *et al.* 2001)), concludes that 80% of the reefs of Mauritius are calculated to be at risk, 100% of Réunion's reefs are at risk and Rodrigues and St Brandon are at low risk. The importance of marine environmental protection is realized in the Mascarenes, but environmental legislation, integrated approaches to coastal zone management, mandatory environmental impact assessment, education and awareness and MPAs are only very slowly being made effective (Turner *et al.* 2000).

(*h*) *Protected areas*

There are six Fishing Reserves in Mauritius and Rodrigues (covering 84 and 15 km^2, respectively) where no net fishing is allowed, and the Fisheries Act (1980) regulates the number, type and size of nets as well as the period of use and allowable mesh size of basket traps in lagoon fisheries. Six Fishing Reserves in Réunion (area unquantified) are closed to fishing (except on foot and by line) on a rotational basis for a period of two to three years. Nine islets in Mauritius and Rodrigues are Nature Reserves (which have no statutory protection), because they have important reef areas or are home to seabird nesting colonies and endemic plants and animals. There are two coral-reef Marine Parks in Mauritius at Blue Bay/Le Chaland and Balaclava/Arsenal Bay, covering less than 1 km^2, and one in Réunion at Cap la Houssaye/St Joseph, covering *ca.* 23 km^2. St Brandon has been suggested, but not yet submitted as a World Heritage Site. The total area currently under some level of statutory protection within the Mascarene region is about 15–20% of reef environments. However, institutional structures, lack of enforcement, funding and gaps in information regarding the status of many species, habitats and marine resources constitute major difficulties in taking further precautionary approaches to secure the future of Mascarene coral reefs.

6. Geographic information systems for reef resource protection

(*a*) *Introduction*

A geographic information system (GIS) can been used to integrate data on biodiversity distribution, environmental factors governing distribution, fishing activity and

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms

MPAs. A GIS can thereby provide a useful tool to establish the conservation and sustainable use of the island's marine resources, and a highly visual and interactive system, valuable for education and public-awareness purposes.

(*b*) *Methodology*

A GIS was established for Rodrigues (Chapman & Turner 2000, 2001, 2004) using MapInfo Professional software (MapInfo Corporation Ltd). The Landsat satellite image was used as a base layer and a relational database (Access, Microsoft Corporation) was linked to the GIS to store and display site-based data, including descriptions and photographs of biotopes, lists and illustrations of species and physical data such as depth and turbidity. The classified biotope map was converted into a polygon vector layer in the GIS (figure 4*c*, displaying coral and mud habitats only). Each biotope class was linked to photographs and descriptions of the constituent biotopes across the image. Existing and proposed MPAs for Rodrigues were illustrated as a layer in the GIS over the biotope map.

(*c*) *GIS as a tool for MPA planning*

In making recommendations on the artisanal fishery of Rodrigues, Pearson (1988) surveyed the Fisheries Reserves declared under Fisheries Act 75 of 1984 (figure 4*c*, blue boundaries where fishing activities are regulated by net size and closed seasons) and concluded that these areas had become non-productive due to sedimentation from terrigenous sources. He thus proposed additional Marine Reserves (yellow boundaries) and Core Areas (pink boundaries). The Marine Reserves were planned to be managed areas, with restrictions on certain fishing gear types, and areas rotated in time to allow for stock replenishment and recovery of benthic fauna and flora. The Core Areas were identified as having well-developed coral communities. The MPA boundary overlay on the biotope map supports the view that Pearson held in 1988, that the original Fisheries Reserves are now heavily impacted, for three of the coastal reserves that were originally channels now include areas identified as lagoon muds. The GIS reveals that the Core Areas might be better placed to protect large single areas of coral biotope (shown in red in figure 4*c*). The proposed Marine Reserves (yellow boundaries), which include the Core Areas, cover a total of 13.1 km^2 of coral habitat, 30 km^2 of sand and rubble with marine vegetation, 1.3 km^2 of consolidated limestone and no lagoon muds. In addition, these proposed reserves cover 0.1 km^2 of lagoon channels and 17 km^2 of deeper water beyond the reef edge, comprising outer reef slope coral habitat. It is not yet possible to reliably estimate the percentage of the total coral resource covered by the Marine Reserves without further research to determine the extent of the deeper fore-reef corals. Of the coral habitat that is identified by image classification (a total area of 30.5 km^2 within the shallow lagoon out to the reef edge), 47% (14.3 km^2) lies within the original Fisheries Reserves and proposed reserve areas. The proposed MPAs should have protected 61.5 km^2 (26.7%) of the reef environment, but unfortunately these reserves have not been declared in 16 years, and hence the areas adopted require reassessment. New MPAs are currently being developed by *Shoals* Rodrigues (orange boundaries covering 37 km^2) and the United Nations Development Programme integrated marine and terrestrial protected area (green boundary covering 45 km^2 land and sea, of which 23 km^2 is lagoon). (Note that, because these MPAs are under review, the boundaries shown

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms

are approximate.) Together, these new MPAs may potentially protect 26% of the shallow marine environment of Rodrigues, which approaches the recommendations on the percentage (30%) of marine areas that need to be protected against heavily exploited fisheries (Roberts 1997). Furthermore, by linking terrestrial protected areas, management should be more effective by monitoring and controlling land–sea interactions, such as soil erosion and sediment inundation, in the lagoons and on the surrounding reefs (McClanahan *et al.* 2002).

7. Conclusions and future study

Reef mapping of the Mascarenes using satellite imagery provides an estimate of 705 km^2 of reef habitats, of which fine sediments are 16.6 km^2, sand is 333.4 km^2, seagrass and macro-algae are 110.4 km^2, limestone platform and rubble are 42.9 km^2, lagoon corals are 59.6 km^2, reef flat and crest are 34.6 km^2, reef front is 26.8 km^2 (grossly underestimated) and channels are 25.4 km^2. Improved estimates of coral biotope areas occupying deep and steep reef slopes, rock slopes and platforms are required, and acoustic methodologies may provide the solution to this mapping problem. The reefs of St Brandon account for 33% of the reefs of the Mascarene region, and a comprehensive survey is a priority, since these reefs may be the most pristine, although the impacts of coral bleaching in the locality are unknown. The reefs of the main islands face similar impacts, although to varying degrees, depending largely on human population size and human activities. Over-nutrification, sedimentation and over-fishing are major causes of reef stress, and although coral bleaching has had little impact to date, this impact may become the most significant cause of degradation in the medium term. Historical human impacts on the islands suggest that the surviving reefs have endured unsuitable conditions and may already show some acclimatization and adaptation to them. Long-lived coral colonies may contain a valuable imprint of past impacts, such as periods of reduced growth due to terrigenous sediment deposition, and future coring studies (Zinke *et al.* 2005) should help quantify whether these events exceed present levels under comparable or different climatic conditions. The impact of sea-level rise on reefs has been investigated in the region, but there is insufficient knowledge of coral physiology to accurately predict the response of present-day degraded reefs. The impacts of cyclones on Mascarene reefs are poorly understood and climatic fluctuation may cause the frequency of such events to change. There is a need to assess whether degraded reefs can withstand cyclone impacts. Because the Mascarene reefs have been relatively unaffected by bleaching and the South Equatorial Current flows across them towards the African continent, they may represent important refugia, and studies of coral larval dispersal are required. The protection of large and representative areas (greater than 30% reef-habitat area) containing critical habitats and key species is a further priority in the region, and MPAs require expansion and enforcement and integration with terrestrial protected areas. The GIS can help structure, present and analyse data to assist conservation and sustainable use of the islands' marine resources, and the highly visual and interactive systems should prove valuable for education and public-awareness purposes.

Special thanks to Deolall Daby, Olivier Tyack and Bryony Chapman for making data available from their MSc theses. We thank the British Council, Rotary International Foundation, Mauritius Research Council, Esmee Fairburn Foundation, Mauritius Oceanography Institute/Indian Ocean Commission, University of Wales Bangor (UWB) and University of Mauritius for funding

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms

various parts of this study. We are grateful to Professor Indur Fagoonee, K. Seetiah, Sharveen Persands, the *Shoals* Rodrigues staff, the Royal Geographical Society (with IBG)—Royal Society *Shoals of Capricorn* Programme, Dr Colin Jago and Dr Gay Mitchelson Jacob (UWB) and many students on the MSc course in Marine Environmental Protection in the School of Ocean Sciences, UWB, who contributed to field work mentioned in this study. We thank Dr Tom Spencer and Dr Graham Oliver for their encouragement and support of some of the field research, and two anonymous referees for comments on an earlier manuscript.

References

Ahamada, S., Bigot, L., Bijoux, J., Maharavo, J., Meunier, S., Moyne-Picard, M. & Paupiah, N. 2002 Status of coral reefs in the south west Indian Ocean island node: Comoros, Madagascar, Mauritius, Réunion and Seychelles. In *Status of coral reefs of the world: 2002* (ed. C. Wilkinson), pp. 79–94. Townsville: GCRMN.

Baker, A. C., Starger, C. J., McClanahan, T. R. & Glynn, P. W. 2004 Corals' adaptive response to climate change. *Nature* **430**, 741–742.

Bernardin de St Pierre, J.-H. 1773 Voyage à l'île de France: un officier du roi à l'î Maurice 1768–1770. Paris: Maspero.

Bouchon, C. 1981 Quantitative study of the scleractinian coral communities of a fringing reef of Réunion island (Indian Ocean). *Mar. Ecol. Prog. Ser.* **4**, 273–288.

Bryant, D., Burke, L., McManus, J. & Spalding, M. 1998 *Reefs at risk: a map based indicator of threats to the world's coral reefs.* Washington, DC: World Resources Institute.

Camoin, G. F., Colonna, M., Montaggioni, L. F., Casanova, J., Faure, G. & Thomassin, B. A. 1997 Holocene sea level changes and reef development in the southwestern Indian Ocean. *Coral Reefs* **16**, 247–259.

Chapman, B. 2000 Marine biotope classification and mapping of Rodrigues using Landsat 7 ETM+ satellite imagery. MSc thesis, University of Wales Bangor.

Chapman, B. & Turner, J. R. 2000 Geographical information system for the marine resources of Rodrigues. User Guide. Report no. R030 to the Royal Geographical Society (with IBG) and Royal Society Shoals of Capricorn Programme and Esmee Fairburn Foundation.

Chapman, B. & Turner, J. R. 2001 Development of a geographical information system (GIS) for the marine resources of Rodrigues. Report no. R029 to the Royal Geographical Society (with IBG) and Royal Society Shoals of Capricorn Programme and Esmee Fairburn Foundation.

Chapman, B. & Turner, J. R. 2004 Development of a Geographical Information System for the marine resources of Rodrigues. *J. Natural Hist.* **38**, 2937–2957.

Chazottes, V. 1996 Experimental study of bioerosion and sedimentogenesis in a reefal environment: eutrophication effects (Réunion Island, Indian Ocean). *C. R. Acad. Sci. Paris Sér. II* **323**, 787–794.

Cheke, A. S. 1987 An ecological history of the Mascarene islands with particular reference to land vertebrates. In *Studies of Mascarene island birds* (ed. A. W. Diamond), pp. 5–89. Cambridge University Press.

Conand, C., Chabanet, P., Cuet, P. & Letourneuer, Y. 1997 The carbonate budget of a fringing reef in La Réunion Island (Indian Ocean): sea urchin and fish bioerosion and net calcification. In *Proc. 8th Int. Coral Reef Symp.* (ed. H. A. Lessios & I. G. Macintyre), vol. 1, pp. 953–958. Balboa, Panama: Smithsonian Tropical Research Institute.

Daby, D. 1990 A coastal zone inventory of Mauritius. MSc thesis, School of Ocean Science, University of Wales, Bangor.

Daby, D. 1999 Structure and function of two lagoon ecosystems of Mauritius. PhD thesis, University of Mauritius.

Daby, D. 2001 A review and critical assessment of coastal water quality in Mauritius. *Sci. Tech.* **8**, 59–83.

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms

Daby, D., Turner, J. & Jago, C. 2002 Microbial and nutrient pollution of coastal bathing waters in Mauritius. *Environ. Int.* **27**, 555–566.

Darwin, C. R. 1842 *The structure and distribution of coral reefs.* London: Smith Elder.

Done, T. J. 1992 Effects of tropical cyclone waves on ecological and geomorphological structures of the Great Barrier Reef. *Cont. Shelf Res.* **12**, 859–872.

Done, T. J. 1993 On tropical cyclones, corals and coral reefs. *Coral Reefs* **12**, 126–126.

Done, T. J. 1999 Coral community adaptability to environmental change at the scales of regions, reefs, and reef zone. *Am. Zool.* **39**, 66–79.

Dwivedi, O. P. & Venkatasamy, V. 1991 State of the environment in Mauritius. In *A report prepared for presentation at the UN Conf. of Environment and Development, Rio de Janeiro, Brazil.* Ministry of Environment and Quality of Life, Government of Mauritius, Port Louis.

Dykes, R. 1996 An evaluation of remote sensing using SPOT 3XS data for the classification and mapping of two Mauritian lagoonal ecosystems. MSc thesis, University of Wales, Bangor.

Eastwood, P. 1998 Geographical information system development for coastal research, education and resource management in Mauritius. MSc thesis, University of Wales.

Faure, G. F. 1974 Morphology and bionomy of the coral reef discontinuities in Rodrigues Island. In *Proc. 2nd Int. Coral Reef Symp.* (ed. A. M. Cameron, B. M. Cambell, A. B. Cribb, R. Endean, J. S. Jell, O. A. Jones, P. Mather & F. H. Talbot), vol. 2, pp. 161–172. Brisbane: The Great Barrier Reef Committee.

Faure, G. F. 1975 Etude comparative des récifs coralliens de l'Archipelago des Mascareignes (Océan Indien). *Bull. Mauritius Inst.* **8**, 1–26.

Faure, G. F. 1977 Distribution of coral communities on reef slopes in the Mascareignes Archipelago, Indian Ocean. *Mar. Res. Indonesia* **17**, 73–97.

Faure, G. F. 1982 Recherche sur les Peuplements de Scleractiniaires des récifs corallines de l'Archipel des Mascareignes (Océan Indien Occidental). Doctorat en Science, Universite d'Aix Marseilles II, Marseille.

Faure, G. F. & Montaggioni, L. F. 1971*a* Les récifs coralliens de I'Ile Rodrigues (Archipel des Mascareignes, Océan Indien): géomorphologie et répartition des peuplements. In *Symp. on Indian Ocean and Adjacent Seas, Cochin, India, 12–18 January 1971.*

Faure, G. F. & Montaggioni, L. F. 1971*b* Les récifs coralliens Sous-Le-Vent de I'Ile Maurice (Archipel des Mascareignes, Océan Indien): morphologie et bionomie de la pente externe. *C. R. Acad. Sci. Paris Sér. II* **273**, 1914–1916.

Faure, G. F. & Montaggioni, L. F. 1976 Les récifs coralliens au-vents de I'Ile Maurice (Archipel des Mascareignes, Océan Indien): géomorphologie et bionomie de la pente externe. *Mar. Geol.* **21**, M9–M16.

Fenner, D., Turner, J. R. & Chapman, B. 2001 The corals of Rodrigues. Rodrigues Marine Biodiversity Workshop Report. Royal Society and Royal Geographical Society (with the Institute of British Geographers) Shoals of Capricorn Programme.

Fenner, D., Clark, T. H., Turner, J. R. & Chapman, B. 2004 A checklist of the corals of the island state of Rodrigues, Mauritius. *J. Natural Hist.* **8**, 3091–3102.

Gardiner, J. S. 1936 The reefs of the Western Indian Ocean. I. Chagos Archipelago. II. The Mascarene Region. *Trans. Linn. Soc. Lond.* **19**, 393–436.

Gates, R. D. & Edmunds, P. J. 1999 The physiological mechanisms of acclimatisation in tropical reef corals. *Am. Zool.* **39**, 30–43.

Green, E. P., Mumby, P. J., Edwards, A. J. & Clark, C. D. 2000 *Remote sensing handbook for tropical coastal management* (ed. A. J. Edwards). Coastal Management Sourcebooks, vol. 3. UNESCO.

Groom, G. B., Fuller, R. M. & Jones, A. R. 1996 Contextual correction: techniques for improving land cover mapping from remotely sensed images. *Int. J. Remote Sensing* **17**, 69–89.

Guillaume, M. 1993 *La croissance exceptionnelle de Porites lutea, scleractiniarie hermatypique sur le récif de L'Etang-Sale à L'ile de la Réunion.* Paris: Carbonate Intertropicaux.

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms

Hardman, E. 1999 A rapid assessment of the extent of coral bleaching in Mauritius after the 1998 seawater warming event. MSc thesis, University of Wales, Bangor.

Hardman, E. R., Meunier, M. S., Turner, J. R., Lynch, T. L., Taylor, M. & Klaus, R. 2004 The extent of bleaching in Rodrigues, 2002. *J. Natural Hist.* **38**, 3077–3089.

Hoegh-Guldberg, O. 1999 Climate change, coral bleaching and the future of the world's coral reefs. *Mar. Freshwater Res.* **50**, 839–866.

IPCC 2001 *Summary for policymakers. A Report of Working Group I of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change.* Cambridge University Press.

Jackson, J. B. C. 1997 Reefs since Columbus. *Coral Reefs* **16**, S23–S32.

Kaly, U. & Brown, J. 1998 St Brandon archipelago management plan, vol. 2. Technical Report. World Bank/Government of Mauritius.

Klaus, R. 1995 An evaluation of the use of a Landsat 4 TM satellite image for the qualitative and quantitative mapping and assessment of the coastal zone habitats of Mauritius (Indian Ocean). MSc thesis, University of Wales, Bangor.

Klaus, R. 2004 Coral bleaching indices in theory and in practice: a comparative assessment of the 1997/98 coral bleaching event in the Indian Ocean. PhD thesis, University of Warwick, UK.

Klaus, R. & Turner, J. R. 2004 The marine biotopes of the Socotra Archipelago. *Fauna Arabia* **20**, 45–115.

Leguat, F. 1708 *Voyages et aventures de Francois Leguat & de ses compagnons en deux îles desertes des Indes orientales.* London: David Mortier.

Letourneur, Y., Harmelin-Vivien, M. & Galzin, R. 1993 Impact of hurricane Firinga on fish community structure on fringing reefs of Rèunion Island, SW Indian Ocean. *Environ. Biol. Fishes* **37**, 109–120.

McClanahan, T. R. 2000 Bleaching damage and recovery potential of Maldivian coral reefs. *Mar. Poll. Bull.* **40**, 587–597.

McClanahan, T., Polunin, N. & Done, T. 2002 Ecological states and the resilience of coral reefs. *Conserv. Ecol.* **6**, 18. (Available at http://www.consecol.org/vol6/iss2/art18.)

Montaggioni, L. F. & Faure, G. F. 1997 Response of reef coral communities to sea level rise: a holocene model from Mauritius (Western Indian Ocean). *Sedimentology* **44**, 1053–1070.

Montaggioni, L. & Faure, G. F. 1980 Les rècifs corallines des Mascareignes (Ocean Indian). Centre Univsersitaire de la Rèunion, Universitè Française de l'Ocèan Indien.

Naim, O. 1993 Seasonal responses of fringing reef community to eutrophication (Rèunion Island, Western Indian Ocean). *Mar. Ecol. Prog. Ser.* **99**, 307–315.

Naim, O., Cuet, P. & Mangar, V. 2000 The Mascarene Islands. In *Coral reefs of the Indian Ocean, their ecology and conservation* (ed. T. R. McClanahan, C. R. C. Sheppard & D. O. Obura), ch. 12, pp. 353–381. Oxford University Press.

Orme, C. D. 1997 The remote mapping of Mauritian coral lagoon habitats using Landsat Thematic Mapper imagery. MSc thesis, University of Wales, Bangor.

Pearson, M. P. 1988 Rodrigues. Rapid survey of the status and exploitation and environmental damage of the lagoon and coral reefs off Rodrigues. Report prepared for the project assistance to Artisanal Fishermen and Development of Outer Reef Fishery. Rome: FAO.

Pichon, M. 1971 Comparative studies of the main features of some coral reefs of Madagascar, La Rèunion and Mauritius. *Symp. Zool. Soc. Lond.* **28**, 185–216.

Pillay, R., Terashima, H., Venkatasami, A. & Uchida, H. 2002 *Field guide to corals of Mauritius.* Albion Fisheries Research Centre Ministry of Fisheries and Japan International Cooperation Agency.

Pitot, A. 1899 *L'île' de France. Esquisses historiques (1715–1810).* Mauritius: E. Pezzami.

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms

Quod, J. P. & Bigot, L. 2000 Coral bleaching in the Indian Ocean islands: ecological consequences and recovery in Madagascar, Comoros, Mayotte and Réunion. In *Coral reef degradation in the Indian Ocean* (ed. D. Souter, D. Obura & O. Linden), pp. 108–113. Stockholm: CORDIO/SAREC.

Roberts, C. 1997 Ecological advice for the global fisheries crisis. *Trends Ecol. Evol.* **12**, 35–38.

Salm, R. 1976 The structure and successional status of three coral reefs at Mauritius. *Proc. R. Soc. Arts Sci. Mauritius* **3**, 227–240.

Sheppard, C. R. C. 1999 Coral mortality in the Chagos Archipelago. In *Coral reef degradation in the Indian Ocean* (ed. O. Linden & N. Sporrong), pp. 27–32. Stockholm: CORDIO/SAREC.

Sheppard, C. R. C., Spalding, M. D., Bradshaw, C. & Wilson, S. 2002 Erosion vs recovery of coral reefs after 1998 El Niño: Chagos reefs, Indian Ocean. *Ambio* **31**, 40–48.

Spalding, M. D., Ravilious, C. & Green, E. P. 2001 *World atlas of coral reefs.* Berkeley, CA: University of California Press.

Spencer, T. 1995 Potentialities, uncertainties and complexities in the response of coral reefs to future sea-level rise. *Earth Surf. Process. Landforms* **20**, 49–64.

Spencer, T., Teleki, K. A., Bradshaw, C. & Spalding, M. D. 2000 Coral bleaching in the southern Seychelles during the 1997–1998 Indian Ocean warm event. *Mar. Poll. Bull.* **40**, 569–586.

Timmermann, A., Oberhuber, J., Bacher, A., Esch, M., Latif, M. & Roeckner, E. 1999 Increased El Niño frequency in a climate model forced by future greenhouse warming. *Nature* **398**, 694–697.

Turner, J. R. 1995 A coastal zone inventory of Mauritius. In *Proc. Soc. for Underwater Technology 2nd Underwater Sci. Symp., 11–12 March 1995, University of Stirling, UK*, pp. 51–59.

Turner, J. R. 1999*a* Status report Mauritius. In *Coral reef degradation in the Indian Ocean* (ed. O. Linden & N. Sporrong), pp. 60–63. Stockholm: CORDIO/SAREC.

Turner, J. R. 1999*b* Status report Socotra Archipelago. In *Coral reef degradation in the Indian Ocean* (ed. O. Linden & N. Sporrong), pp. 63–64. Stockholm: CORDIO/SAREC.

Turner, J. R. & Klaus, R. 2003 Remote sensing of coastal habitats. In *A field guide to the seashores of Eastern Africa* (ed. M. Richmond), pp. 44–47. SIDA-SAREC-UDSM.

Turner, J. R., Jago, C., Daby, D. & Klaus, R. 2000 The Mascarene region. In *Seas at the millennium, an environmental assessment* (ed. C. R. C. Sheppard), pp. 243–258. Elsevier.

Turner, J., Hardman, E., Klaus, R., Fagoonee, I., Daby, D., Baghooli, R. & Persands, S. 2000*a* The reefs of Mauritius. In *Coral reef degradation in the Indian Ocean* (ed. D. Souter, D. Obura & O. Linden), pp. 94–107. Stockholm: CORDIO/SAREC.

Turner, J., Klaus, R. & Engelhardt, U. 2000*b* The reefs of the granitic islands of the Seychelles. In *Coral reef degradation in the Indian Ocean* (ed. D. Souter, D. Obura & O. Linden), pp. 77–86. Stockholm: CORDIO/SAREC.

Turner, J. R., Vousden, D., Klaus, R., Satyanarayana, C., Fenner, D., Venkataraman, K., Rajan, P. T. & Subba Rao, N. V. 2001 Remote sensing and rapid site assessment survey April 2001: coral reef systems of the Andaman Islands. Government of India and United Nations Development Programme Global Environment Facility IND/95/G41: Conservation of the Coral Reef Ecosystem in the Andaman and Nicobar Islands.

Tyack, O. 2002 Preliminary resource mapping of Cargados Carajos (St Brandon) Archipelago by remote sensing using Landsat 7 ETM+, SPOT 4 HRVIR and aerial photography. MSc thesis, University of Wales, Bangor.

van der Elst, R., Everett, B., Jiddawi, N., Mwatha, G., Afonso, P. S. & Boulle, D. 2005 Fish, fishers and fisheries of the West Indian Ocean: their diversity and status. A preliminary assessment. *Phil. Trans. R. Soc. Lond.* **363**, 263–284.

Vermote, E. F., Tanre, D., Dueze, J. L., Herman, M. & Morcrette, J.-J. 1997 Second simulation of the satellite signal in the solar spectrum, 6S: an overview. *IEEE Trans. Geosci. Remote Sensing* **3**, 675–685.

Zinke, J., Pfeiffer, M., Timm, O., Dullo, W.-C. & Davies, G. R. 2005 Atmosphere–ocean dynamics in the Western Indian Ocean recorded in corals. *Phil. Trans. R. Soc. Lond.* **363**, 121–142.

This content downloaded from 137.189.171.235 on Mon, 25 Sep 2017 13:23:32 UTC
All use subject to http://about.jstor.org/terms