2.1.2. CORAL

2.1.2.1. Introduction

1. Study region

The near-continuous reef tract of the central and northern Saudi Arabian Red Sea covers some 10,000 km^2, from the city of Jeddah in the south to the Gulf of Aqaba in the north (Fig. 2, page 9). This region includes a range of coastal and marine habitats, related largely to oceanographic regime, degree of exposure, and topographic features (particularly the distribution of suitable antecedent topography for development of coral reefs, mangrove stands and seagrass beds). The area has a complex tectonic history of uplift and subsidence, related to the rift development of the Red Sea from the movements of the Arabian and African tectonic plates. The present series of living coral reefs are the latest in a chronological sequence of raised (uplifted) and submerged reefs that have developed at various times over the past several hundred thousand years. In many cases the present reefs are developed on earlier reef structures. Detailed descriptions of the geology, physical environment, climate, hydrology, oceanography and habitats of the Red Sea and wider Arabian region are presented by FISHELSON (1971), IUCN (1984), EDWARDS & HEAD (1987), BENTHOUX (1988), SHEPPARD & SHEPPARD (1991), BEHAIRY et al. (1992) and SHEPPARD et al. (1992).

2. Zoogeography and evolution

Previous studies of the coral reef communities of the Arabian region have centered on the Gulf of Aqaba (e.g. FISHELSON 1971, 1973, LOYA 1972, 1976), central and southern Red Sea (e.g. SHEPPARD & SHEPPARD 1985, 1987, 1991), Arabian Gulf (e.g. COLES 1988, COLES & FADLALLAH 1991) and Gulf of Oman (e.g. SHEPPARD & SALM 1988, GLYNN 1993, SALM 1993, COLES 1997). These studies (and studies of other reef taxa, notably fishes and echinoderms) have demonstrated that the marine biota of Arabia has a complex zoogeography and evolutionary history, related to the effects of eustatic sea-level fluctuations and the tectonic activity.

Because of the relatively high levels of endemism among its coral reef fauna (reviewed in KLAUSEWITZ 1989, SHEPPARD et al. 1992), the region has been regarded as a 'centre of evolution', and separate Indo-Pacific coral reef zoogeographic province or sub-province (BRIGGS 1974, KLAUSEWITZ 1989, SHEPPARD & SHEPPARD 1991). In the case of reef-building corals, there are presently reported to be nine endemic species in eight genera of six families (Table 3) from a total of approximately 190 species in 68 genera from 16 families known from the Red Sea (SHEPPARD & SHEPPARD 1991, SHEPPARD & JOHNSTONE 1997).

Table 3. Endemic coral taxa of the Red Sea (from SHEPPARD & SHEPPARD 1991, SHEPPARD & JOHNSTONE 1997).

Family	***Genus and species* (scientific name)**
Pocilloporidae	*Stylophora mamillata* SCHEER & PILLAI (1983)
	Stylophora wellsi SCHEER (1964)
	Madracis interjecta VON MARENZELLER (1907)
Poritidae	*Alveopora ocellata* WELLS (1954)
Mussidae	*Symphyllia erythraea* (KLUNZINGER, 1879)
Fungiidae	*Cantharellus doerderleini* (VON MARENZELLER 1907)
Merulinidae	*Merulina scheeri* Head (1983)
Faviidae	*Erythrastrea flabellata* PICHON, SCHEER & PILLAI (1983)
	Echinopora fruticulosa KLUNZINGER (1879)

The high level of endemism raises interesting questions regarding rates of speciation. A variety of hypotheses have been proposed to explain this endemism in corals, fishes, echinoderms and other biota (see e.g. BRIGGS 1974, KLAUSEWITZ 1989, SHEPPARD et al. 1992). These hypotheses are based on different interpretations of the degree of isolation of the Red Sea during the Pleistocene Ice Age glaciations and inter-glacial transgressions, and related assumptions about changes in sea level, temperature and salinity. At present, there remains considerable controversy surrounding these questions (e.g. see KLAUSEWITZ 1989, SHEPPARD & SHEPPARD 1991). Nonetheless, the presence of the endemic species clearly affords the coral reefs of the Red Sea and Arabian region special significance in terms of coral reef zoogeography and evolution.

3. Reef and community types

Of the four biogeographic sub-zones described for the Saudi Arabian Red Sea by IUCN (1984), two are in the region of the present study:

- The Gulf of Aqaba, 'characterized by its geographic isolation and the relatively high number of species restricted to or excluded from it'; and
- south of the Gulf of Aqaba to an area between Yanbu' and Jeddah.

Previous studies have identified a range of different coral reef types (defined by different species composition, relative abundance of reef-building versus non-reef building taxa and degree of reef framework development) within the region (SHEPPARD & SHEPPARD 1985, 1991). The predominant reef types are fringing reefs along the mainland coast and occasionally extending across or into coastal bays (sharms), patch reefs and barrier reefs situated further offshore, particularly in the region of Al-Wajh Bank. Additionally, fringing reefs have developed around most offshore islands.

Cross-sectional profiles of the various reef types found around Yanbu' are provided by SHEPPARD & SHEPPARD (1985). These authors identified 116 coral species or species groups in thirteen coral assemblages, the most distinctive being those from exposed locations dominated by species of *Acropora* Oken, 1815, and those from sheltered locations dominated by species of *Porites* Link, 1807. The Yanbu' area was notable in supporting both a higher coral diversity and number of assemblage types than had previously been reported from the

Red Sea. Within the larger central - northern Red Sea region , an even greater variety of coral assemblage types were described (SHEPPARD & SHEPPARD 1991, Table 4). Whilst differentiating these assemblage types, the latter authors also noted the high degree of similarity in species composition within the region, where species at most individual reefs were a subset of the larger regional species-pool.

Table 4. Major coral communities of northern - central Red Sea (from SHEPPARD & SHEPPARD 1991).

Community	Reef type, exposure and habitat	Dominant coral species	Location in Red Sea	Characteristic Assemblages
1	Shallow patch reef, exposed in sandy plain	*Acropora horrida, A. formosa*	Suez	None
2	Shallow exposed fore-reef slopes	*Acropora hyacinthus, A. humulis*	North - central	None
3	Shallow - mid-depths, moderate exposure	None	North	None
4	Sheltered fringing reefs, backs of patch reefs	**Porites lutea**	North - central	None
5	Shallow – mid-depths in north, mid-deep in central region, moderate exposure	None	North - central	A) *Millepora* B) None C) *Goniopora*
6	Moderately turbid and exposed mid-depths	None	North - south	None
7	Mid-depths, patch-reefs in sand	*Pocillopora damicornis, Acropora eurystoma, A. clathrata*	Central	None
8	Patch- and barrier reefs, mid-depths	*Pocillopora verrucosa, Acropora hemprichi*	Central	None
9	Barrier and exposed fringing reefs, shallow	*Acropora spp.: A. hyacinthus, A. digitifera, A. humilis A. danai, A. hemprichi, Pocillopora verrucosa*	Central	A) *A. hyacinthus* B) *A. danai* C) *P. verrucosa*
10	Barrier, patch- and fringing reefs, mid-depths	*Porites*	Central - south	A) *Montipora circumvallata* B) *Goniastrea pectinata*

4. Objectives and rationale

The present survey formed part of the National Commission for Wildlife Conservation and Development - Japan International Cooperation Agency (NCWCD-JICA) study of the habitats and biota of the central and northern Red Sea coast of Saudi Arabia. It aimed to assess the present status and 'conservation values' of reefs of the region, useful for future NCWCD management planning.

From an ecological standpoint, 'conservation value' should embrace concepts of representativeness and quality, in line with similar efforts to define indicators of ecological integrity in other aquatic ecosystems (e.g. LEVY et al. 1996). Interpretations of quality are based on both human and ecological values and human perceptions. Interpretations of quality also vary within and among biogeographic regions, in response to different regional conditions and local patterns of zonation and diversity (DEVANTIER et al. 1998). We consider high quality reefs in this region of the Red Sea as having high diversity and a strong reef-building capacity, usually represented by high living cover and species abundance of corals. These criteria provide for the maintenance and replenishment of biodiversity, through reproduction and dispersal locally and throughout the Red Sea reef tract.

Thus the main objectives of the present study were to assess:

i. Distribution of coral habitats, and amount of reef development,

ii. levels of coral cover,

iii. species richness (diversity) and community types, including preparation of a reference collection,

iv. present status – effects of natural disturbances and human impacts,

v. conservation value of individual reefs and larger areas,

vi. management implications - sites and areas of local / regional / global significance, in terms of representativeness / uniqueness,

and to provide

vii. recommendations for future management, and

viii. training and technology transfer to Saudi Arabian counterpart personnel.

There is growing recognition of the need for effective management to ensure the long-term ecological sustainability of coral reefs. This has led to increased communication between coral reef managers and researchers, fostering development of new ecological and biodiversity indices for assessing the conservation values of reefs (e.g. DONE 1995, DEVANTIER et al. 1998, MANTHACHITRA 1998). In this study, we apply indices incorporating attributes by which coral reefs are commonly compared:

- benthic cover,

- coral species diversity and abundance,
- representativeness - uniqueness,
- rarity (based on the regional composition and distribution of the coral fauna).

This approach reflects a similar terrestrial trend in assessment of land units for inclusion in protected areas.

5. Red Sea protected areas proposed in Saudi Arabia

Prior to the formation of NCWCD in 1986, the Meteorological and Environment Protection Agency (MEPA) took initial steps towards recommending a system of nature protectorates. Subsequent recommendations for a 'System Plan of Protected Areas', prepared by NCWCD and the World Conservation Union (IUCN), identified 46 'Environmentally Sensitive Areas' (ESA) along the Red Sea coast and offshore islands.

Of the 46 ESA's proposed by NCWCD and IUCN, 24 are in the region of the present study (Table 5), of which most have important coral reef areas. Since listing of the ESA's, some have been amalgamated into proposals for larger Marine Protected Areas. Present proposals include the future designation of approximately 20 MPAs in the Red Sea.

Table 5. Environmentally Sensitive Areas (ESAs) in the Study Area, as defined by NCWCD and IUCN (CHILD & GRAINGER 1990). Areas in the vicinity of these ESAs that were visited during the present study are **bolded**. Sh. – Sharm.

ESA No.	Name	Nearest Town	Latitude	Longitude	Important coral reefs
1	**Humaydah Beach**	**Haql**	**29 15' N**	**34 35' E**	**Northern reefs, KSA**
2	**Ra's Suwahil**	**Maqna**	**28 50' N**	**34 50' E**	**Fringing reefs**
3	**Maqna N Beach**	**Magna**	**28 25' N**	**34 45' E**	**Fringing reefs**
4	**Tiran Is. area**	**Al Khuraybah**	**27 55' N**	**34 10' E**	**Rich reef sections**
5	Al Muwailih	Duba	27 35' N	35 30' E	Fringing reef
6	**Sh. Yahar – Sh. Jubba**	**Duba**	**27 30' N**	**35 30' E**	**Fringing reef**
7	**Sh. Zubayrr**	**Duba**	**27 25' N**	**35 35' E**	**Fringing reef**
8	**Coast S Sh. Zubayr**	**Duba**	**27 20' N**	**35 35' E**	**Important reef sites**
9	Ghubbet Bal'aksh	Al –Wajh	26 45' N	35 20' E	Fringing reefs
10	**Sh. Dumagha; Sh. Antar**	**Al –Wajh**	**26 40' N**	**35 20' E**	**Fringing reefs**
11	**Sh. Habban - Sh. Munaybirah**	**Al –Wajh**	**25 35' N**	**37 15' E**	**Reef and seagrass area**
12	**Al-Wajh Bank**	**Al –Wajh**	**25 35' N**	**37 15' E**	**Reef and seagrass area**
13	**Qalib Is. Chain**	**Umluj**	**25 12' N**	**37 15' E**	**Reef and seagrass area**
14	Umluj	Umluj	25 05' N	37 15' E	Fringing reef
15	**Al Hasini, Libana Is.**	**Umluj**	**25 00' N**	**37 15' E**	**Island reef**
16	**Ra's Abu Madd - Sh. Hasi**	**Umluj**	**24 30' N**	**37 15' E**	**High quality reefs**
17	**Ra's Baridi -Sh. al Khaur**	**Yanbu' al-Bahr**	**24 15' N**	**37 40' E**	**High quality reefs**
18	Sh. Yanbu'	Yanbu' al- Bahr	24 15' N	37 55' E	Fringing reefs
19	Yanbu' Conservation Area	Yanbu' al- Bahr	24 05' N	38 10' E	Quality fringing reef
20	Shi'b al-Qirin Reef	Yanbu' al- Bahr	24 00' N	38 15' E	Inshore – offshore reefs
21	Marsa al Usalla	Masturah	23 15' N	38 40' E	Seagrass beds
22	Marsa Tarwil	Masturah	23 15' N	38 40' E	Seagrass beds
23	Masturah Beach	Masturah	23 10' N	38 40' E	Seagrass beds
24	Mersa as Sarraj	Rabigh	23 05' N	38 40' E	

A detailed analysis of the objectives, goals and proposed methods of establishment of Protected Areas was developed between NCWCD and IUCN (CHILD & GRAINGER 1990), identifying five main criteria for establishment of the national system plan for protected areas:

- Adequate representation of all major biotopes,
- Protection of specific sites for conservation of particular species in suitable habitats, (including endemic, rare or globally endangered species, economically important

species, and species of aesthetic interest),

- Protection of key biological sites,
- Protection of areas for promotion of environmental awareness, improved forms of resource use and maintenance of biological productivity, and
- Protection of areas of special interest (culture or history, geology or geomorphology, outstanding natural beauty).

These criteria form the basis of the reserve system, which incorporates in increasing order of protection:

- Resource Use Reserves (RUR - with minimal limits on human use)
- Natural Reserves (NR - with higher level of protection than RURs)
- Special Natural Reserves (SNR - with no extractive activities)
- Biological Reserves (BR - with no entry except with express permission of the management agency).

The IUCN-NCWCD report (CHILD & GRAINGER 1990, p191) further noted that 'ideally the design of a representative system plan would require a specially prepared prior classification and inventory of natural biological communities'. Initial steps toward this goal were made with extensive surveys along the Red Sea coast in the mid-1980's. These surveys identified three types of marine protected areas:

- Mainland sites with creeks or bays, mangrove stands, seagrass beds or coral reefs,
- Mainland sites of special scenic and recreational value, and
- Offshore islands with seabird and turtle colonies, lagoons and fringing reefs or reef complexes.

In the Saudi Arabian Red Sea, two Marine Protected Areas (MPA) have been proclaimed to date, one in the southern-central region at the Jazirat (island) Farasan and one at

Jazirat Umm Al Gumari, two islands near the coastal city of Al Gumfuda, about 300 km north of the Farasan Islands. A brief history of nature conservation in Arabia is provided by JUNGIUS (1988).

Following from the earlier work, and with consideration of the above criteria, th e present report identifies reefs of high conservation significance in the central – northern Red Sea study region, and provides recommendations re future MPA management options, monitoring, research and development projects.

2.1.2.2. Methods

During initial reconnaissance surveys in February 1998, the study region was inspected and potential candidate sites for more detailed study were selected. For ease of interpretation, the Study Area is divided into different areas, from N to S:

- the Gulf of Aqaba,
- the Tiran area (entrance to the Gulf of Aqaba at Ash Shaykh Humayd to Duba),
- Duba - Al-Wajh,
- Al-Wajh Bank (Model Area),
- Umluj – Ra's Baridi,
- Yanbu' - Rabigh.

Within these areas, 145 spots on 86 reefs were surveyed in 1998-99 (Fig. 2, Appendix 5). The surveys were undertaken at a representative range of habitats, including mainland fringing reefs, sharms, island fringing reefs, patch reefs and barrier reefs. The sites were accessed by car (mainland) or boat. At each site, the coral communities were surveyed using SCUBA.

Where the reef slope descended to > 5 m depth, deep (6 - 15 m) and shallow (1 - 5

m) sites were surveyed separately. Two types of information were assimilated and recorded on water-proof data-sheets during the ~ 40 min. survey swims: 1) a detailed inventory of sessile benthic taxa; and 2) an assessment of the relative percent cover of the substrate by the major benthic groups and amount of reef development (DONE 1982, SHEPPARD & SHEPPARD 1985, 1991, DEVANTIER et al. 1998).

1. Taxonomic inventories

A detailed inventory of benthic taxa was compiled during each survey swim. Taxa were identified *in situ* to the following levels:

hard corals

- species wherever possible, (Veron & Pichon 1976, 1980, 1982, Veron, Pichon & Wijsman-Best 1977, Veron & Wallace 1984, Veron 1986, 1993, Scheer & Pillai 1983, Hoeksema 1989, Sheppard & Sheppard 1991, Sheppard & Johnstone 1997, Wallace & Wolstenholme 1998), otherwise genus and growth form (e.g. *Porites* spp. of massive growth-form). Hard corals that could not be readily identified in the field were labeled with a sequentially numbered tag, photographed (Nikonos V with 28 mm lens for colony morphology, and with close-up kit and strobe flash unit for corallite morphology), collected and bleached for detailed study. The bleached corals are stored as a permanent reference collection with the NCWCD. Specimens for which expert confirmation of identity was required were shipped for assessment by Dr. J.E.N. Veron (Australian Institute of Marine Science) and Dr. C.C. Wallace (for *Acropora* spp., Museum of Tropical Queensland). This approach facilitated comparison of specimens and photographs from the present collection with the most comprehensive compilations of extant Scleractinia to date. Corals for which taxonomic status remain unresolved at time of reporting are listed as '*genus cf. species*';

Soft corals, zoanthids, corallimorpharians, anemones and some macro-algae

- genus (VINE 1986, ALLEN & STEEN 1995, COLIN & ARNESON 1995, GOSLINGER et al. 1996, REINECKE 1998);

Other sessile macro-benthos, such as sponges, ascidians and most algae

- higher taxonomic level, usually phylum plus growth-form (VINE 1986, ALLEN & STEEN 1995, COLIN & ARNESON 1995, GOSLINGER et al. 1996).

At the end of each swim, the inventory was reviewed, and each taxon was categorized in terms of its relative abundance in the community (Table 6). The categories reflect relative numbers of individuals in each taxon, rather than its contribution to benthic cover (DEVANTIER et al. 1998). These ordinal ranks are similar to those long employed in vegetation analysis (BARKMAN et al. 1964, BRAUN-BLANQUET 1964). For each coral taxon present, a visual estimate of the total amount of injury present on colonies at each site was made, in increments of 0.1, where 0 = no injury and 1 = all colonies in the site dead. The approximate proportion of colonies of each taxon in each of three size classes was also estimated. The size classes were 1 - 10 cm diameter, 11 - 50 cm diameter and > 50 cm diameter (Table 6).

Table 6. Categories of relative abundance, injury and sizes (maximum diameter) of each benthic taxon in the biological inventories.

Rank	Relative abundance	Injury – damage	Size frequency distribution
0	absent	0 - 1 in increments of 0.1	proportion of corals in each of 3 size classes: 1) 1 - 10 cm 2) 11 - 50 cm 3) > 50 cm
1	rare		
2	uncommon		
3	common		
4	abundant		
5	dominant		

2. Categorization of benthic cover and reef development

At completion of each swim, six ecological and six substratum attributes (Table 7) were assigned to 1 of 6 standard categories, based on an assessment integrated over the length of the swim. These broad categories have been shown to be relatively insensitive to biases among different observers (MILLER & DE'ATH 1995) and capable of discriminating among contrasting benthic assemblages (DONE 1982, DEVANTIER et al. 1998). The reef itself was also classified into one of four categories based on the amount of reef development (after HOPLEY 1982, HOPLEY et al. 1989, SHEPPARD & SHEPPARD 1991), where:

1) reefs with extensive reef flats (> 50m wide);

2) reefs with moderate flats (< 50m wide);

3) reefs with no flats but with some carbonate accretion (incipient reefs); and

4) coral communities developed on rock, sand or rubble.

Table 7. Categories of benthic attributes and % cover categories.

Attribute		**% cover category**	
ecological:	**physical:**	**Rank**	**%**
Hard coral	Hard substrate	0)	Not recorded
Dead standing coral	Continuous pavement	1)	1 - 10 %
Soft coral	Large blocks (diam. > 1 m)	2)	11 - 30 %
Coralline algae	Small blocks (diam. < 1 m)	3)	31 - 50 %
Turf algae	Rubble	4)	51 - 75 %
Macro-algae	Sand	5)	76 – 100 %

The sites were also classified into one of four categories based on the degree of exposure to wave energy, where:

1) Sheltered;

2) Semi-sheltered;

3) Semi-exposed;

4) Exposed.

Sea temperatures were recorded in °C with a thermometer mounted on a SCUBA regulator (accuracy +/- 0.5 °C). The depths of the sites (maximum and minimum), average angle of reef slope to the horizontal, and underwater visibility were also recorded. The presence of any unique or outstanding biological features, such as particularly large corals or unusual community compositions, bleached corals (partial or total loss of pigments on living corals), coral predators, other cause(s) of coral mortality were also recorded.

All data were input to EXCEL for preliminary storage and analysis, and transferred to the NCWCD-JICA Study ACCESS database and GIS unit for long-term storage.

3. Coral bleaching

Extensive coral bleaching, the whitening of corals from expulsion of endo-symbiotic micro-algae (zooxanthellae) and pigments following stress, occurred on many reefs of the Indian Ocean in 1998 (WILKINSON et al. 1999). To assess the effects of bleaching in the study region, additional data were collected during the field survey periods of May-June (pre-bleaching) and September-October (post-bleaching) 1998 (Sites C1 - C52). For scleractinian hard corals, fire-corals *Millepora* spp. and alcyonarian soft corals, the absolute percent covers that appeared unbleached, partially-bleached (patchily bleached, blanched or 'fluorescent'), totally-bleached (completely white) or recently dead (dead standing skeletons) were estimated (as < 1 %, or to the nearest 5 % for higher values). Anecdotal reports of bleaching were sought from other marine scientists and dive operators working in Saudi Arabia during the survey period.

4. Data Analysis

The following statistical methods and data sets were used to define groups of sites according to quality and community type.

4-1. Site description

Principal components (Redundancy) analysis was used to illustrate relationships between the benthic cover: hard coral, dead standing coral, coral rubble, soft corals, macro-algae, turf algae, coralline algae and sand (all as the rank scores) and environmental variables: water clarity (underwater visibility, m), degree of exposure (1-4), slope angle and amount of reef development (1-4). Preliminary analysis of the remaining substratum site-descriptor variables (other than coral rubble and sand) did not prove useful and these were discarded.

4-2. Community types

Site groups defined by community type were generated by hierarchical cluster analysis using rank abundance of all coral taxa in the inventories. The data were analyzed using the Euclidian metric and complete linkage, plotted using PCA, and the groups defined by K-means clustering were outlined. The 'community type' groups so produced were then plotted on the site descriptor PCA biplot to illustrate relationships between coral community types and the site descriptor (cover and environment) variables.

The species that best characterized each community group (key indicator taxa) were determined, based on relative abundance and fidelity (percentage occurrence of sites in each group) using the method of DUFRENE & LEGENDRE (1997). Differences among the community groups in terms of their physical (reef development, exposure, depth) and ecological (benthic cover) attributes were examined using ANOVA.

4-3. Ecological and Biodiversity Indices

1). Evenness

Evenness of the hard coral communities in each site was calculated using Shannon-

Weaver's index H' for hard corals.

2). Rarity

The presence of rare species may afford some sites greater importance than others in terms of the conservation of regional biodiversity of corals. Two indices, *RI* and *VI*, to indicate the relative importance of rare versus common hard coral species were calculated for each site:

$$RI = \sum a_i / P_i$$

$$VI = \sum A_i / P_i$$

where a_i = 1 for the *i*th coral taxon (all sessile cnidarians) present at a given site, A_i = abundance rank for the *i*th coral taxon at a given site (1-5, as in Table 6), and P_i = the proportion of all sites in which the taxon was present. The indices weight species on a continuum according to their frequency in the data set. *RI*, based on presence - absence of each taxon, takes no account of local abundance. The indices give highest values to sites which are least representative or most unusual faunistically (ie. with taxa which are rare in the data set).

3). Coral replenishment

The presence of high species diversity, abundance and cover of corals may afford some sites greater importance than others in terms of their role as reproductive sources for replenishment of populations. Two coral indices, *CI* and *HCI*, which rate sites based on a combination of their coral cover and individual taxon rank abundance scores was calculated for each site:

$$CI = \sum A_i H_i / 100$$

where A_i = abundance rank for the *i*th coral taxon (all sessile cnidarians) at a given site (1-5, as in Table 6), and H_i = sum of the rank values of hard and soft coral cover at the site

(1-5, as in Table 7). The index give highest scores to sites which have high species abundance and cover of all corals.

$$HCI = \sum a_i h_i / 100$$

where a_i = abundance rank for the *i*th scleractinian coral taxon at a given site (1-5, as in Table 6), and h_i = rank of hard coral cover category at the site (1-5, as in Table 7). The index give highest scores to sites which have high species diversity, abundance and cover of hard corals.

All data analyses were conducted using S-PLUS ver. 3.3 (STATISTICAL SCIENCES 1995).

2.1.2.3. Results

Results are presented under the major objectives listed in the Introduction.

1. Reef distribution and development

The study region supports a near-continuous coral reef tract composed of a wide range of reef types of generally high ecological integrity. These include mainland fringing reefs, island fringing reefs, platform and 'reticulate' patch reefs, 'pinnacles' and barrier reefs. Reefs were often developed in sharms along the mainland coast, a characteristic reef-form largely restricted to the Red Sea.

Distribution of various reef types varied among different areas as detailed in the Habitat Maps section of this report.. Well-developed reefs and extensive coral growth occurred in all major sub-regions, particularly in the Tiran area, Duba - Al-Wajh, Al-Wajh Bank, Umluj – Ra's Baridi and Yanbu' - Rabigh. These areas each support relatively complex reef geomorphology, being comprised of:

- Mainland fringing reefs, distributed along much of the coast-line,

- Island fringing reefs, particularly in the Tiran area and between Duba and Al-Wajh Bank,
- circular - elongate patch reefs developed in offshore waters < 50 m depth, some of which support sand-coral islands (cays), the latter form being common in Al-Wajh Bank,
- 'reticulate' patch reefs composed of interconnected networks of reef matrix separated by sand, and forming intricate reticulate patterns, usually in shallow waters (< 10 m depth),
- pinnacles – individual corals and coral 'bommies' developed on sand, usually in shallow waters (< 10 m depth),
- barrier reefs composed of patch and 'ribbon' reefs developed on the edge of the 'continental' slope, where water depths increase from < 50 m to > 200 m.

The best-developed barrier reef system in the study region was distributed along the seaward margin of Al-Wajh Bank, forming a near-continuous line of reefs stretching for ~ 100 km and separated by several narrow (< 200 m width) channels. The Bank also supports a large number of patch reefs, some of which support sand-coral islands, occasionally hosting mangrove habitats.

Well developed mainland fringing reefs occur around Ra's Baridi, Umluj, Al-Wajh-Duba and in the Gulf of Aqaba. Parts of the Gulf of Aqaba support fringing reefs that were narrow 'contours' developed on the relatively steep sub-littoral topography. Water temperatures in parts of the Gulf are cool (< 27° C), because of the high latitude and upwelling of cool waters from the deep (> 1,000 m) central portion of the Gulf.

Levels of reef development within the various reef types varied widely, from subsurface patch reefs with no reef flat (mostly in Al-Wajh Bank), to narrow 'contour' fringing reefs with reef flats < 30 m wide (in the Gulf of Aqaba) to large platform and barrier reefs with reef flats often > 100 m wide (Appendix 6).

There were extensive (67 % of sites) or moderate (18 % of sites) levels of reef development at most sites. Reefs with no reef flats but some carbonate reef accretion (incipient reefs) were represented in ~ 15 % of sites. All sites exhibited some carbonate accretion and there were no non-accretional coral communities developed on non-reefal rock in the survey locations. At most sites, reef flats were at sea level, and supported few corals. Flourishing coral growth was limited largely to the outer edges of the flats, reef crests and slopes below low tide level. In sub-tidal areas, vigorous reef growth was apparent at most sites, by scleractinian hard corals and hydrozoan fire corals (*Millepora* spp.) and a large species of the alcyonarian soft coral *Sinularia*. Growth of crustose coralline algae further contributed to reef cementation and accretion. There was little evidence of high rates of bio-erosion, such that in general, most reefs in this region of the Red Sea appear to be strongly accretional at the present time.

2. Coral cover

Cover of reef-building hard corals, including the hydrozoan fire corals *Millepora* spp., ranged from < 10 % to > 75 % (Appendix 6), with a regional average of ~ 35 % (Fig. 10). Reefs with high living coral cover were distributed widely, from the Gulf of Aqaba in the north to Rabigh in the south (Table 8). Approximately 17 % of total sites had living hard coral cover of > 50 %. Reefs with high cover represented all major reef types, from reefs fringing sharms, reefs fringing the exposed mainland coast and islands, to patch reefs and barrier reefs. Overall, cover was higher on the shallow reef slopes (mean ~ 42 %) than deep slopes (mean ~ 27 %), on well-developed reefs of moderate - high exposure. However, some sheltered and semi-sheltered sites with little reef development did exhibit high living coral over, notably on

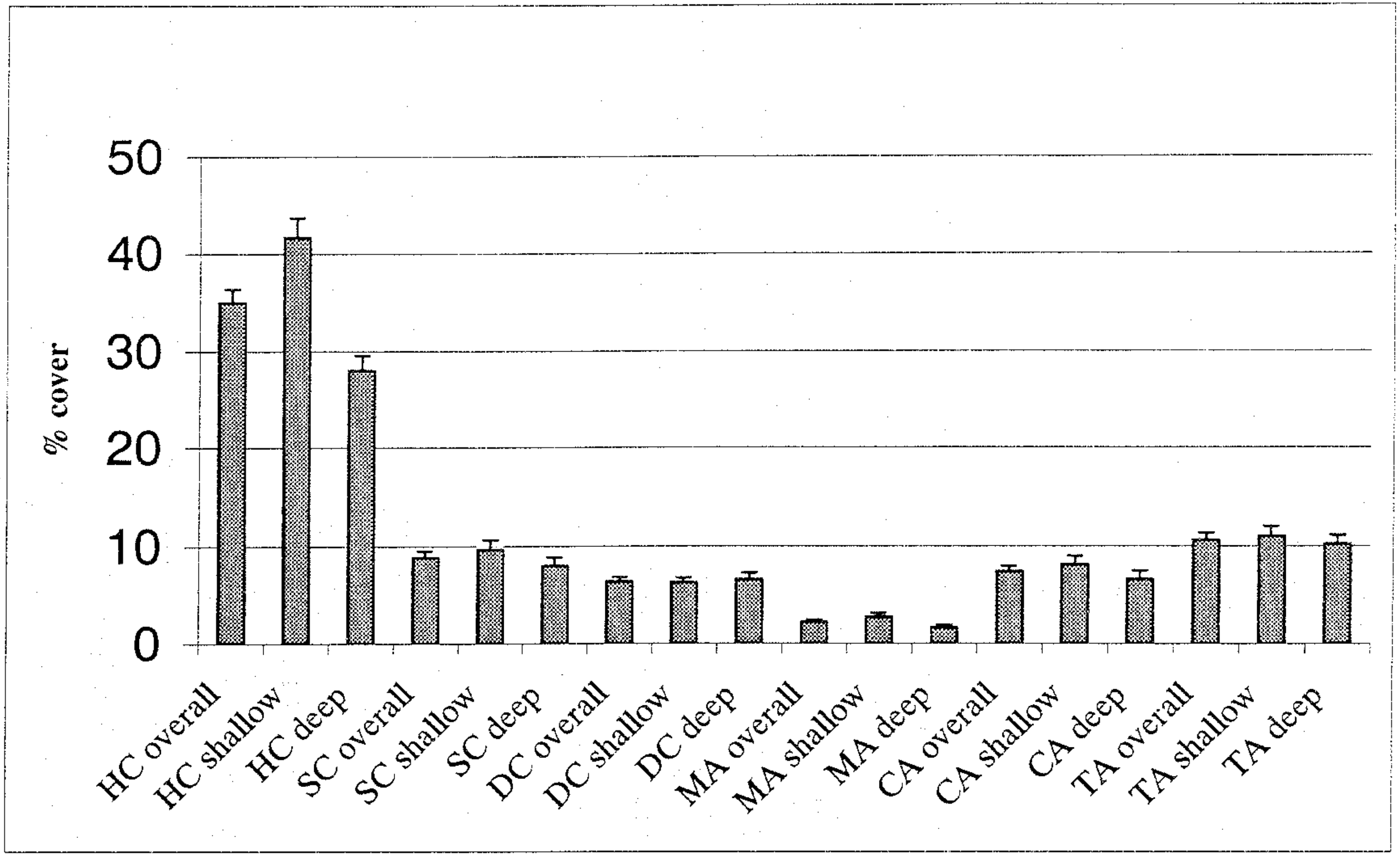


Fig. 10. % cover (+ 1 s.e.) of corals and algae, Study Area, 1998-99.

some sub-surface patch reefs in Al-Wajh Bank (Table 8). The overall average hard coral cover of ~ 35 % indicates the region is in relatively good condition in comparison with many other reef areas (HODGSON in press).

Table 8. Sites with highest cover (> 50 %) of living hard corals in the Study Area, 1998-99. J. – Jazirat (island), Sh. – Sharm (coastal inlet), a - deep slope, b - shallow slope. Reef types: MF - Mainland Fringing, IF - Island Fringing, SF - Sharm Fringing, P - patch, B - Barrier. Site 24b had cover > 75 %. GPS locations of sites are listed in Appendix 5. Ratings for reef development and exposure are also listed.

Site No.	Reef type	Reef name	Location	Reef devel.	Exposure
C24b	MF	Marsa (Sh.) Hawwaz	Duba - Al-Wajh	4	3
C6b	MF	S of Sh. Habban	Al-Wajh Bank	4	4
C8b	B	N Al-Wajh Bank	Al-Wajh Bank	4	4
C26a	MF	adjacent J. Al-Wassl, S of Haql	Gulf of Aqaba	4	1
C26b	MF	adjacent J. Al-Wassl, S of Haql	Gulf of Aqaba	4	3
C28b	MF	Ash Shaykh Humayd	Tiran Area	4	3
C30b	MF	'contour' reef, N of Maqna	Gulf of Aqaba	3	3
C31b	IF	J. Al-Farshah	Tiran Area	4	1
C32b	IF	J. Baraqan	Tiran Area	4	3
C37b	SF	Sh. Jazzah	Duba - Al-Wajh	4	1
C40b	SF	Sh. Ar Rayis	Yanbu' - Rabigh	4	2
C41b	MF	Ra's Baridi	Umluj - Yanbu'	4	4
C47b	IF	J. Malihah	Umluj - Yanbu'	4	3
C49b	P	S of J. Shaybarah	Al-Wajh Bank	4	4
C50b	P	SE of J. Shaybarah	Al-Wajh Bank	4	3
C67b	P	W J. Qumma'an	Al-Wajh Bank	2	1
C71b	B	W of J. Qumma'an	Al-Wajh Bank	4	4
C75b	B	J. Hassan N side	Al-Wajh Bank	4	4
C77a	P	N of Umluj	S of Al-Wajh Bank	2	3
C77b	P	N of Umluj	S of Al-Wajh Bank	2	3
C78b	P	N of Umluj	S of Al-Wajh Bank	4	2
C80a	P	S J. Qumma'an	Al-Wajh Bank	2	2
C82b	P	S of J. Juzur Shurayrat	Al-Wajh Bank	2	2
C86b	P	W of Al Khuraybah, N of Duba	Tiran area	4	2

Dead standing corals were relatively minor components of cover (< 10 %) of the substrate at most sites (Appendix 6), with a regional average of ~ 7 % (Fig. 10). There was little overall difference in dead coral cover between deep and shallow sites. Highest levels of dead coral cover (~ 20 %) occurred in sites around Rabigh following intense coral bleaching in August-September 1998 and on patch reefs in Al-Wajh Bank following predation by crown-of-thorns starfish *Acanthaster planci* (LINNAEUS, 1746) (see later). Cover of coral rubble was also low (< 10 %) at most sites.

Cover of soft corals ranged up to ~ 50 % at several sites (Appendix 6), but usually was < 30 %, with a regional average of ~ 9 % (Fig. 10). Cover of turf, coralline and macro-algae was usually low (< 10 %) in these coral dominated areas (Appendix 6). Cover of algae usually increased on the inner reef flats (see Algae and Seagrasses section of this report).

Although some reefs with high living coral cover occurred in sheltered habitats (Table 8), high cover of hard corals, soft corals and crustose coralline algae were positively associated with the degree of exposure, amount of reef development and water clarity (Fig. 11).

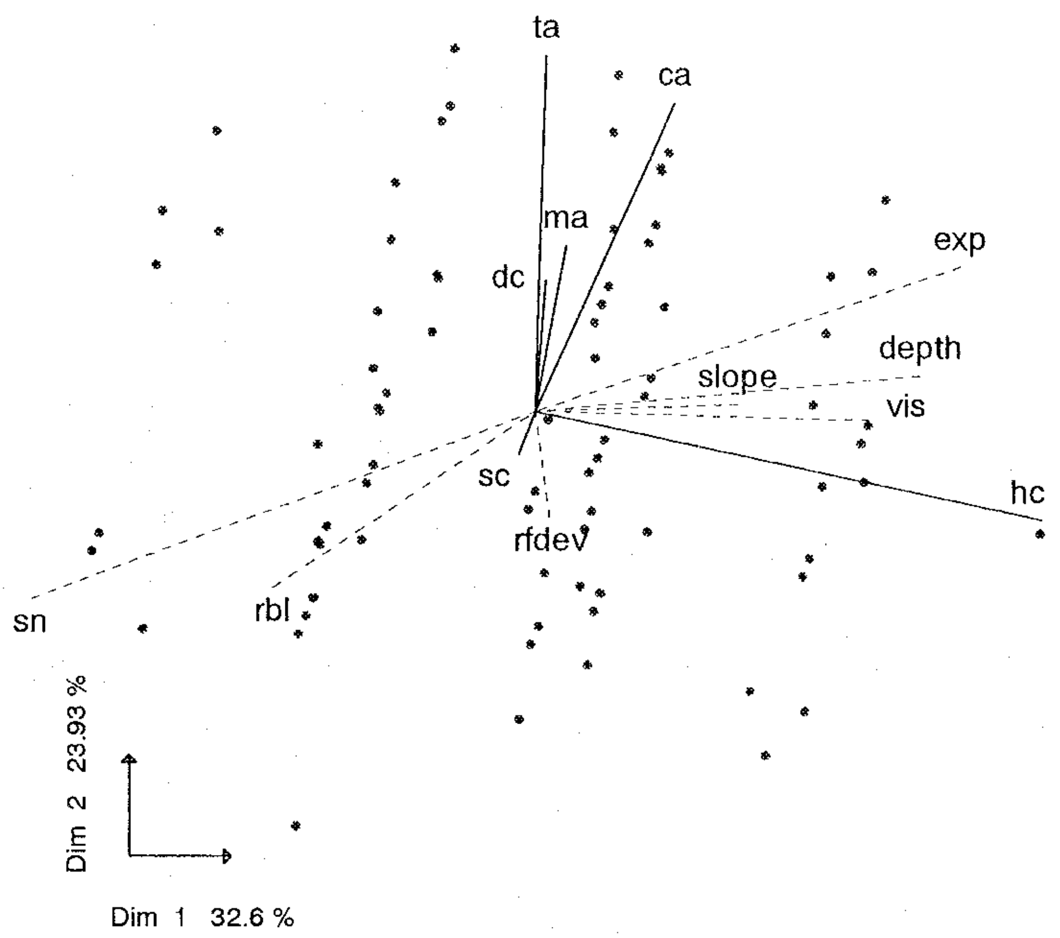
3. Coral species diversity

Coral diversity is considered under the three headings of within-habitat (individual sites - *alpha*), between habitat (among sites within the study region – *beta*) and regional (Red Sea – Arabia) diversity (Red Sea – *gamma*, after WHITTAKER 1972, also see PAULAY 1997). Herein diversity is considered simply as the number of species present (richness). Evenness-dominance of corals among sites was calculated using the Shannon-Weaver index H'. The following section is concerned primarily with the scleractinian hard corals.

3-1. Alpha Diversity (individual sites)

Diversity at individual sites ranged from a minimum of 21 to a maximum of 98 scleractinian taxa, with a further ~ 5 – 15 taxa of soft corals and other sessile cnidarians.

Fig. 11. Redundancy analysis biplot of relationship between cover and environmental variables in 145 sites, Study Area, 1998-99. Dimensions 1 and 2 account for ~ 56 % of the observed variance. The vectors point in the direction of the highest scores for the indicated variables, where hc - hard coral, dc - dead coral, sc - soft coral, ta - turf algae, ca - coralline algae, ma - macro-algae, rbl – rubble, sn – sand, exp - exposure, vis - water clarity, rfdev - reef development.



Average site diversity for hard corals was 61 species, with deep sites slightly more rich on average than shallow sites (Fig. 12). Given that highest level of site (alpha) diversity was ~ 100 spp., sites with > 75 spp. were considered as important reservoirs of high diversity. Approximately 17 % of all sites had diversity > 75 spp. (Table 9), and these were widely distributed throughout the study region, from near Rabigh in the south (site C40a, Sharm Ar Rayis), near Yanbu' (site C41a, b, Ra's Baridi), near Umluj (C44a, C45b, C77a, C78b), in Al-Wajh Bank (C58a, C73a,b, C74a), near Duba (C34a, C37a), the Tiran area (C32b, C86a,b) and in the Gulf of Aqaba (sites C26b, C30a, C83a, C84b). Thus, there were no clear latitudinal or longitudinal trends, although reefs in the northern Gulf of Aqaba were surprisingly rich, given their location at the extreme north-west of reef development in the entire Indo-Pacific region.

Individual sites of high diversity occurred on all major reef types, from fringing to barrier (Table 9). In contrast to sites with high coral cover, sites of high diversity were more commonly located on sheltered - semi-exposed reefs (exposure ranks 1 - 3) than on those of maximum exposure (4). There was no relation between high diversity per se and eveness (H'), reflecting the high variability in relative abundance (dominance - rarity) of species among sites (Table 9).

3-2. Beta Diversity (central-northern Red Sea)

Approximately 250 species from 58 genera of 14 families of reef-building scleractinian corals and ~ 30 taxa of soft corals, fire corals, zoanthids and gorgonians were recorded during the surveys. At species level, this is an approximate total, because of continuing taxonomic revision.

Most of the known Red Sea endemic coral species (Table 3) were well represented and widely distributed within the study region. Key community types for each species are

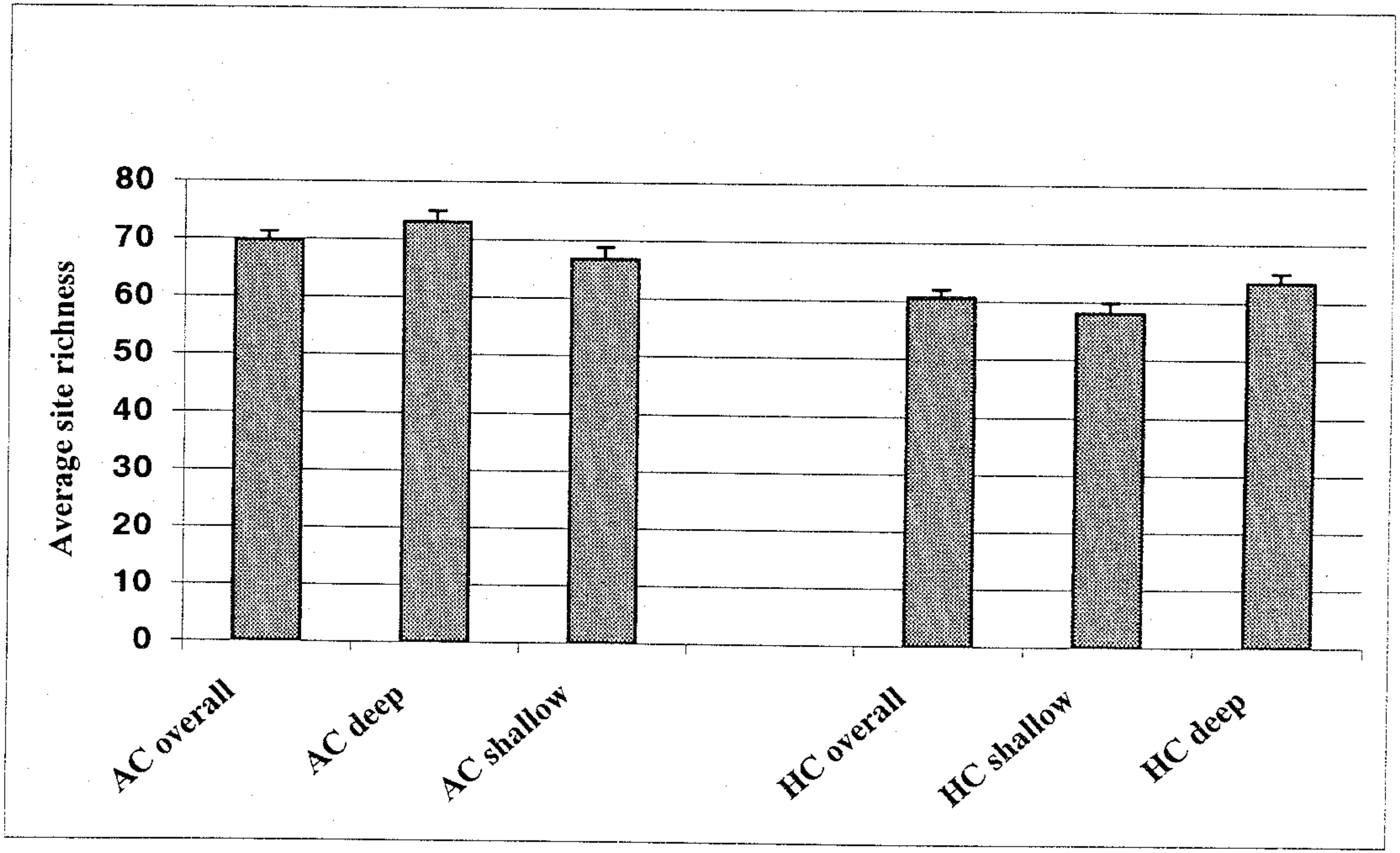


Fig. 12. Species diversity (+ 1 s.e.) of all corals (AC) and hard corals (HC), Study Area, 1998-99.

listed (see later for Community type descriptions):

- *Stylophora mamillata* SCHEER & PILLAI (1983) - Community types A, C and D,
- *Stylophora wellsi* SCHEER (1964) - Community type B,
- *Alveopora ocellata* WELLS (1954) - Community types C and D,
- *Symphyllia erythraea* (KLUNZINGER 1879) - Community types A, C and D,
- *Erythrastrea flabellata* PICHON, SCHEER & PILLAI (1983) - Community types C and D,
- *Echinopora fruticulosa* KLUNZINGER (1879) - Community types C and D,
- *Merulina scheeri* HEAD (1983) - Community types C and D.

Table 9. Sites with highest hard coral diversity (> 75 spp.) and ranking (1 - 145) on evenness (Shannon-Weaver H'), Study Area, 1998-99. J. – Jazirat (island), Sh. – Sharm (coastal inlet), a - deep slope, b - shallow slope. Reef types: MF - mainland fringing, IF - island fringing, SF - Sharm fringing, P - patch, B - Barrier.GPS locations of sites are listed in Appendix 5. Rank scores for cover of hard corals and ratings for reef development and exposure are also listed.

Site No.	Reef type	Reef name	Location	H'	HC cover	Reef devel.	Expo-sure
C74a	B	W of J. Qumma'an	Al-Wajh Bank	62	3	2	2
C85a	P	W of Al-Khuraybah	Tiran Area	5	2	2	2
C78b	P	N of Umluj	Al-Wajh Bank	92	4	4	2
C32b	IF	Jazirat Baraqan	Tiran Area	18	4	4	3
C77a	P	Nof Umluj	Al-Wajh Bank	20	4	2	3
C83a	MF	'contour' reef, N of Maqna	Gulf of Aqaba	7	2	3	3
C86b	P	W of Al-Khuraybah	Tiran Area	97	4	4	2
C44a	SF	Sh. Al-Hisay	Umluj - Yanbu'	63	2	3	1
C40a	SF	Sh. Ar Rayis	Yanbu' - Rabigh	42	2	4	1
C86a	P	W of Al-Khuraybah	Tiran Area	14	3	4	1
C84b	MF	'contour' reef, N of Maqna	Gulf of Aqaba	69	3	3	4
C63a	SF	Sh. Habban	Al-Wajh Bank	4	2	4	2
C37a	SF	Sh. Jazzah	Duba - Al-Wajh	79	3	4	1
C45b	SF	Sh. Al-Hisay	Umluj - Yanbu'	53	3	3	1
C30a	MF	'contour' reef, N of Maqna	Gulf of Aqaba	24	2	3	1
C73a	B-P	W of J. Qumma'an	Al-Wajh Bank	39	3	4	1
C46b	SF	Sh. Al-Hisay	Umluj - Yanbu'	10	3	4	3
C41b	MF	Ra's Baridi	Umluj -Yanbu'	72	4	4	4
C58a	P	J. Shaybarah	Al-Wajh Bank	60	2	4	2
C41a	MF	Ra's Baridi	Umluj -Yanbu'	16	3	4	2
C26b	MF	S of Haql	Gulf of Aqaba	85	4	4	3
C73b	B-P	W of J. Qumma'an	Al-Wajh Bank	12	2	4	3
C26a	MF	S of Haql	Gulf of Aqaba	98	4	4	1
C34a	IF	J. Al-Naman	Duba - Al-Wajh	25	2	4	1

By contrast, the endemic fungiid *Cantharellus doerderleini* (VON MARENZELLER 1907) appears largely restricted to the Gulf of Aqaba, and the deep water pocilloporid *Madracis interjecta* VON MARENZELLER (1907) was not recorded during the present shallow water surveys.

Of the samples forwarded for expert appraisal, six were unknown to science:

- *Montipora sp. nov.* (Family Acroporidae),
- *Anacropora sp. nov.* (Family Acroporidae),
- *Goniopora sp. nov.* (Family Poritidae),
- *Cyphastrea sp. nov.* (Family Faviidae),
- *Echinopora sp. nov. 1* (Family Faviidae),
- *Echinopora sp. nov. 2* (Family Faviidae).

Key sub-regions for the undescribed species were the Tiran area, Al-Wajh Bank and south to Umjuj, and Umluj-Yanbu'. Presently, distribution ranges for these species are highly restricted (Table 10), however, further work in the region is likely to extend their distribution ranges. Each of the undescribed species is morphologically distinctive, and unlikely to be confused with other congeneric taxa. However, where present, most of these species were uncommon or rare (Table C8), a possible reason for their remaining undescribed.

Further species recorded during this study are also presently undescribed, having recently been found in Egypt (by J.E.N. VERON) or Socotra Archipelago (by L.M. DEVANTIER). These include:

- *Acropora sp. nov. 1* (Family Acroporidae) - Community types A, C,
- *Acropora sp. nov. 2* (Family Acroporidae) - Community types C, D,
- *Acanthastrea sp. nov. 1* (Family Mussidae) - Community types A, C and D,
- *Acanthastrea sp. nov. 2* (Family Mussidae) - Community types A, C, and D,
- *Mycedium sp. nov.* (Family Pectiniidae) - Community types C and D,
- *Podabacia sp. nov.* (Family Fungidae) - Community types A, C and D,
- *Sandalolitha sp. nov.* (Family Fungiidae) - Community types C and D,
- *Favia sp. nov.* (Family Faviidae) - Community types A, C and D,
- *Favites sp. nov.* (Family Faviidae) - Community types B and D,

- *Platygyra sp. nov.* (Family Faviidae) – Community types B and D.

Additional species recorded during the present study that were previously described (but omitted in recent Red Sea taxonomic lists) have been reinstated as valid by WALLACE (1999) and VERON (IN PRESS). These include:

- *Acropora variolosa* ( ) - Community types A-C,
- *Echinopora forskaliana* (MILNE EDWARDS & HAIME 1850) - Community types A, C, D,
- *Acanthastrea hemprichii* (EHRENBERG 1834) - Community types B - D.

Table 10. Sites supporting undescribed species of Scleractinia, where *Mo. sp. - Montipora sp. nov., An. sp. - Anacropora sp. nov., Go. sp. - Goniopora sp. nov., Cy. sp. - Cyphastrea sp. nov.* (Family Faviidae), *Ec. sp. 1 - Echinopora sp. nov. 1, Ec. sp. 2 -Echinopora sp. nov. 2.* Rank abundance score (1-5, Table 6) of each species in each site is given.

Site	Reef type	Reef name	Location	*Mo. sp.*	*An. sp.*	*Go. sp.*	*Cy. sp.*	*Ec. Sp.1*	*Ec. Sp.2*
C12a	SF	Sh. Shabaan	Umluj - Yanbu'			1			
C14b	IF	J. Jabal Hassan	Umluj			1			
C31a	P	J. Al Farshah	Tiran area					1	
C31b	P	J. Al Farshah	Tiran area	1					
C49a	P	S. of J. Shaybarah	S of Al-Wajh Bank				1		
C62a	P	J. Ummahat Shaykh	Al-Wajh Bank		2				
C67a	P	W J. Qumma'an	Al-Wajh Bank		1				
C70b	P	J. Umm Rumah	Al-Wajh Bank					1	
C73b	P-B	W of J.	Al-Wajh Bank					1	
C74a	P-B	W of J.	Al-Wajh Bank			1			
C77b	P	N of Umluj	S of Al-Wajh Bank				1		
C78b	P	N of Umluj	S of Al-Wajh Bank				1		
C79a	P	SW J. Qumma'an	Al-Wajh Bank					1	
C82b	P	S of J. Juzur Shurayrat	Al-Wajh Bank						1
C86a	P	W of Al Khuraybah	Tiran area				1		
C86b	P	W of Al Khuraybah	Tiran area				1		

3-3. Gamma (regional) Diversity

Comparison with the recent Red Sea species lists of SCHEER & PILLAI (1983), SHEPPARD & SHEPPARD (1991) and SHEPPARD & JOHNSTONE (1997) indicates that the present study has recorded most of the common scleractinian coral taxa known previously from the Red Sea, and further taxa previously unreported from the region (Table 11). The distribution ranges of ~ 40 hard coral species are extended into the Red Sea.

Conversely, some scleractinian taxa that were previously reported from the Red Sea are missing from the present list. These include the fungiids *Diaseris* spp., trachyphylliid *Trachyphyllia geoffroyi* (AUDOUIN, 1826), and deep water and inter-reefal species (eg. the pocilloporid *Madracis interjecta* VON MARENZELLER (1907), the siderastreid *Craterastrea laevis* HEAD (1983), caryophylliids and rhizangiids, Table 11).

The species inventory of this study has increased the total scleractinian diversity of the Region substantially. This is in small part related to differences in taxonomic interpretation among different workers (see e.g. VERON 1986, HOEKSEMA 1989 and SHEPPARD & SHEPPARD 1991 for some different classifications of the same corals). The present species list, and the other lists cited above, are based largely on the traditional taxonomic approach. This is based on assessing differences in bleached skeletal (corallum and corallite) morphologies and comparing these with type specimens and other published records, combined with field observations and photographs of living corals.

This approach has several difficulties, related to:

- Synonymy – different workers in different regions naming the same species several times,
- Morphological 'plasticity' – the tendency of the same species to grow in different ways in different environments (phenotypes), or to have different genotypic morphotypes,

- Lack of reliable and consistent morphological characters in certain taxa,
- Hybridization - some previously well-defined 'separate' species interbreed successfully, whereas certain 'single' species have morphotypes that appear reproductively isolated (WILLIS et al. 1997).

Table 11. Taxonomic composition of Red Sea scleractinian coral fauna, based on SHEPPARD & SHEPPARD (1991) and SHEPPARD & JOHNSTONE (1997) and the present study *. Continuing taxonomic revision makes this an approximate comparison only.

Family	Genus			Species		
	N – C Red Sea	Red Sea	N – C Red Sea *	N – C Red Sea	Red Sea	N – C Red Sea *
Astrocoeniidae	1	1	1	2	2	2
Pocilloporidae	4	4	3	8	8	9
Acroporidae	4	4	4	32	32	61
Poritidae	4	4	3	10	10	26
Siderastreidae	4	4	4	6	7	10
Agariciidae	4	4	4	16	16	18
Fungiidae	6	6	6	21	21	26
Oculinidae	1	1	1	1	1	2
Pectinidae	3	3	3	3	3	7
Mussidae	5	5	6	8	8	17
Merulinidae	2	2	2	3	3	3
Faviidae	15	15	16	40	41	58
Caryophylliidae	6	8	2	6	9	2
Dendrophylliidae	4	4	3	6	7	12
Trachyphylliidae	1	1	0	1	1	0
Rhizangiidae	2	2	0	2	2	0
Total	**66**	**68**	**58**	**174**	**180**	**253**

For these reasons, corals of uncertain taxonomic status were referred to acknowledged world authorities (Drs. J.E.N. VERON and C.C. WALLACE). Both these workers were in the process of major revisions (WALLACE 1999, VERON in press) and their assistance has proven invaluable in sorting out some of the confusion introduced by synoymy, morphological plasticity and hybridization. However, considerable further work needs to be undertaken before scleractinian taxonomy of the region is in a well defined state, contrary to some earlier claims. Recent advances in coral reproductive studies, combined with chemical and molecular taxonomy, should improve taxonomic understanding substantially over the next several decades (also see ZIEGLER & KRUPP 1996).

4. Coral communities

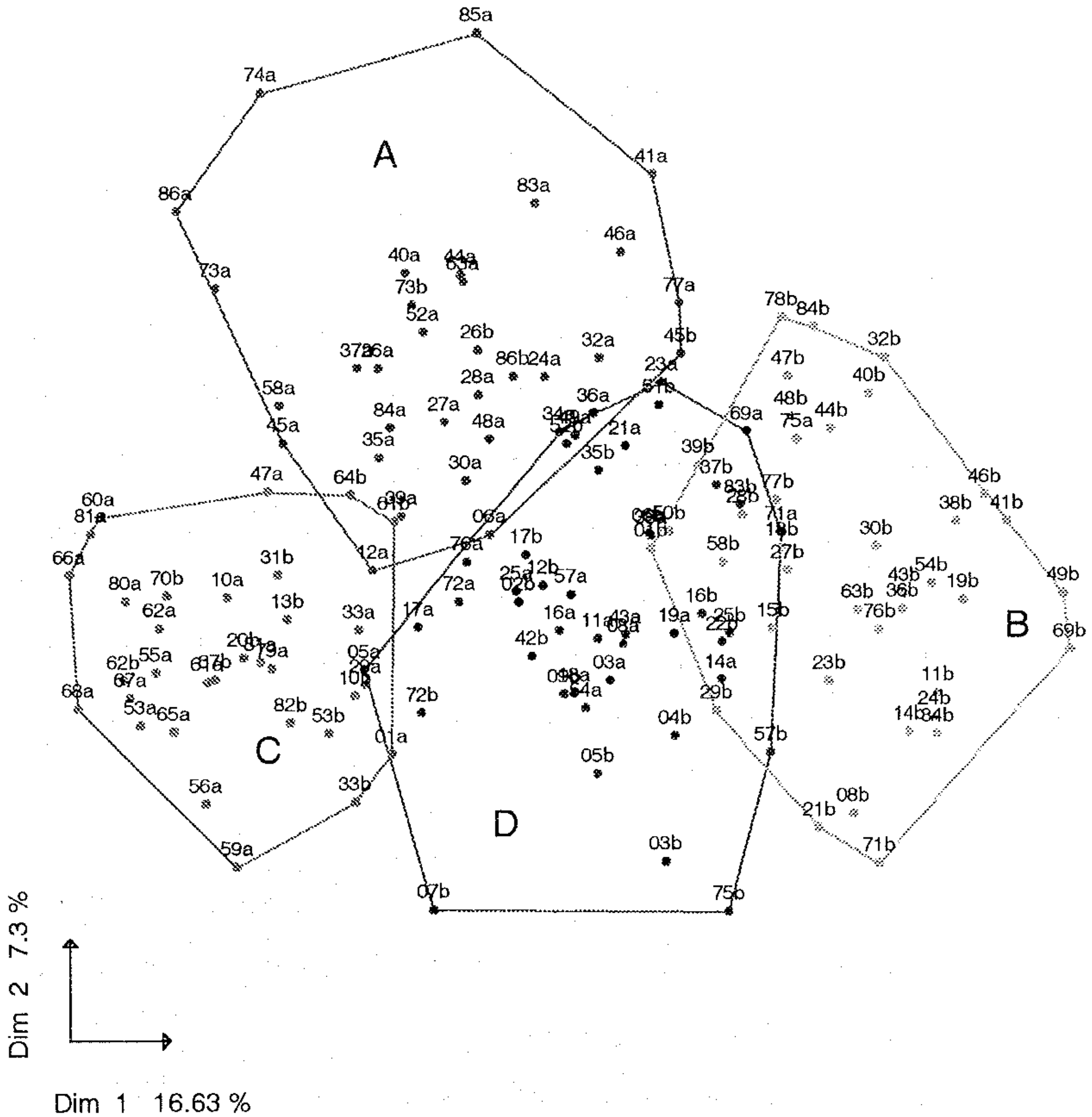
Overall, there was a high degree of homogeneity in species composition within the region, with most sites having a subset of the same species-pool (see also SHEPPARD & SHEPPARD 1985, 1991). There were however, major differences in abundance of particular taxa in certain biotopes, and thus clear zonation patterns in the structure of coral communities. These were related largely to degree of physical exposure, water clarity-irradiance, depth and steepness of reef slope (DONE 1982, SHEPPARD 1983).

Most of the assemblage types previously described for the central - northern Red Sea (SHEPPARD & SHEPPARD 1985, 1991, and see Table 4) were present in the study region, as represented in the four major community types described below (Fig. 13). These community types form part of a continuum, with particular species exhibiting differences in occurrence and abundance related to site-specific habitat characteristics and disturbance-histories.

4-1. Species distribution ranges

Some species in the assemblages have very widespread Indo-Pacific distributions, others are widespread in the Indo-west Pacific, others in the central Indo-west Pacific, others only in the Indian Ocean or W Indian Ocean (SHEPPARD & SHEPPARD 1991, VERON 1986, 1993, SHEPPARD & JOHNSTONE 1997, WALLACE & WOLSTENHOLME 1998, WALLACE 1999). Thus the northern-central Red Sea supports a unique composite coral fauna composed of species known from the following faunal provinces or sub-provinces:

Fig. 13. Principal components biplot of sites defined by hierarchical clustering (Euclidian metric, complete linkage) of species-abundance in the bio-inventories of 145 sites, Study Area, 1998-99. Convex hulls show the four community types A - D. Dimensions 1 and 2 account for ~ 24 % of the observed variance.



- Widespread across the entire Indo-Pacific - e.g. *Pocillopora damicornis* (LINNEAUS 1758), *Gardineroseris planulata* (DANA 1846),
- Widespread in the Indo-west Pacific - e.g. *Stylophora pistillata* (Esper 1797), *Acropora muricata* (LAMARCK 1816),
- Widespread in the Indian Ocean - e.g. *Coscinaraea monile* (Forskal 1775), *Siderastrea savignyana* MILNE EDWARDS & HAIME (1850),
- Widespread in the western Indian Ocean - e.g. *Acropora hemprichi* (EHRENBERG 1834),
- Red Sea 'endemics' - e.g. *Stylophora wellsi* SCHEER (1964), *S. mamillata* SCHEER & PILLAI (1983), *Symphyllia erythraea* (KLUNZINGER 1879), *Echinopora forskaliana* (MILNE EDWARDS & HAIME 1850), *Merulina scheeri* Head (1983), *Cantharellus doerderleini* (VON MARENZELLER 1907),
- Presently undescribed (e.g. *Montipora sp. nov., Anacropora sp. nov., Goniopora sp. nov., Cyphastrea sp. nov., Echinopora spp. nov.*).

Based on the geographic distribution ranges of SHEPPARD & JOHNSTONE (1997), the present study extends or reinstates the known distributions of ~ 40 species into the Red Sea, including:

- Family Acroporidae: *Acropora acuminata* (VERRILL, 1864), *A. anthocercis* (BROOK, 1893), *A. austera* (DANA 1846), *A. gemmifera* (BROOK 1892), *A. listeri* (BROOK 1893), *A. lutkeni* CROSSLAND (1952), *A. secale* (STUDER 1878), and *Astreopora gracilis* BERNARD (1896);
- Family Poritidae: *Goniopora djiboutiensis* VAUGHAN (1907), *Alveopora fenestrata* (LAMARCK 1816);
- Family Agaricidae: *Pavona clavus* (DANA 1846), *P. frondifera* LAMARCK (1816), *Leptoseris incrustans* (QUELCH 1886);

- Family Fungiidae: *Cycloseris vaughani* (BOSCHMA 1923), *Cantharellus noumeae* HOEKSEMA & BEST (1984), *Herpolitha weberi* ();
- Family Oculinidae: *Galaxea astreata* (LAMARCK 1816);
- Family Pectiniidae: *Echinophyllia orpheensis* VERON & PICHON (1979), *Oxypora glabra* NEMENZO (1959) and *O. crassispinosa* NEMENZO (1980);
- Family Mussidae: *Acanthastrea amakusensis* VERON (1990), *Symphyllia agaricia* MILNE EDWARDS & HAIME (1849) and *S. valenciennesi* MILNE EDWARDS & HAIME (1849);
- Family Faviidae: *Caulastrea (Astreosmilia) connata* (ORTMANN 1892), *Favia maxima* VERON, PICHON & WIJSMAN-BEST (1977), *Platygyra pini* CHEVALIER (1975), *Leptastrea pruinosa* CROSSLAND (1952) and *Echinopora mammiformis* (NEMENZO 1959);
- Family Dendrophylliidae: *Turbinaria frondens* (DANA 1846), *T. irregularis* BERNARD (1896) and *T. stellulata* (LAMARCK 1816).

Recent studies have indicated that populations of some of the Red Sea 'endemics' (Table 3) occur outside the Red Sea, in other parts of the Arabian Region (L. DEVANTIER, pers. obs.) or further afield in E. Africa and the central Indian Ocean (VERON, in press). However, the present study and those of VERON (loc. cit.) have identified another suite of presently undescribed species with distribution ranges presently restricted to the northern-central Red Sea, such that the overall level of endemism within the Red Sea may remain relatively high.

The composite species composition of the study region was distributed in four major coral community 'types' as defined by the heirarchical cluster analysis.

4-2. Exposed - semi-exposed biotopes

1). Community A, characteristic of mid - lower reef slopes

Mid - lower slope communities were composed of mixed assemblages of encrusting and massive taxa (faviids, agariciids, siderastreids, pectiniids, poritids, merulinids and acroporids – notably:

- Encrusting *Stylophora mamillata* SCHEER & PILLAI, 1983 and *Montipora* spp. and 'tree-like' to open tabular colonies of *Acropora,* mostly *Acropora pharaonis* (MILNE EDWARDS & HAIME 1860), *A. clathrata* (BROOK 1891), *A. downingi* WALLACE (1999) and *A. valenciennesi* (MILNE EDWARDS & HAIME 1860).
- Soft corals, notably xeniids, gorgonions, antipatharian 'black corals' and 'sea whips' also occurred.

Vertical to overhanging sections and occasional caves were dominated by encrusting corals, notably

- agariciids *Gardineroseris planulata* (DANA 1846), *Pachyseris speciosa* (DANA 1846) *Leptoseris mycetoceroides* WELLS (1954), *L. hawaiiensis* VAUGHAN (1907), *Pavona varians* VERRILL (1864) and *P. explanulata* (LAMARCK 1816),
- faviids *Echinopora lamellosa* (ESPER 1795),
- pectiniids *Echinophyllia aspera* (ELLIS & SOLANDER 1786), *Oxypora lacera* (VERRILL, 1864) and *O. crassispinosa* NEMENZO (1980),
- siderastreids *Coscinaraea monile* (FORSKAL 1775) and *Psammocora haimeana* MILNE EWDWARDS & HAIME (1851),
- and merulinids *Hydnophora exesa* (PALLAS 1766).

The agariciids, adapted to low levels of irradiance, more commonly occur on deeper reef slopes, but also occupy shallower areas where topographic steepness provides habitats of low irradiance.

Growing commonly on less-steep substrates:

- branching and tabular *Acropora* spp., including *Acropora hemprichi* (EHRENBERG 1834), *A. valida* (DANA 1846) and *A. eurystoma* (KLUNZINGER 1879),
- massive poritids (*Porites* spp.) and faviids (*Favia* and *Favites* spp.),
- and the alcyonarian soft corals *Xenia* spp. and large 'tree-like' colonies of *Sinularia* sp. The latter species was a major reef-builder at some sites, forming large (~ 2 m high) pillar-like colonies covering 100's of m^3 along the slopes.

Coral cover was usually moderate, mostly ranging between 20 and 50 % (average ~ 25 %). Mid - lower slopes receive no direct wave energy and also lower levels of irradiance, in comparison with the shallower biotopes. Thus, differences between deep communities at exposed sites and those of more sheltered locations were less marked than their shallow counterparts. Key indicator coral species included *Montipora danae* (MILNE EDWARDS & HAIME 1851), *Fungia* spp., *Astreopora myriophthalma* (LAMARCK 1816) and *A. gracilis* BERNARD (1896), *Pachyseris speciosa* (DANA 1846), *Stylocoeniella guentheri* BASSETT-SMITH (1890) and *Leptoseris mycetoseroides* WELLS (1954).

This community type encompasses Communities 6, 8 and 10 of SHEPPARD & SHEPPARD (1991, see Table 4).

2). Community B, characteristic of reef crests – upper reef slopes

Coral communities of exposed reef crests were dominated by stout taxa of low growth-form, adapted to high wave energy environments:

- digitate-branching acroporids notably *Acropora humilis* (DANA 1846), *A. digitifera*

(DANA 1846), *A. gemmifera* (BROOK 1892), *A. lutkeni* CROSSLAND (1952), *A. acuminata* (VERRILL 1864), *A. polystoma* (BROOK 1891) and *A. secale* (STUDER 1878),

- pociloporids *Stylophora wellsi* SCHEER (1964), *S. pistillata* (ESPER 1797), *Pocillopora verrucosa* (ELLIS & SOLANDER 1786),
- encrusting – massive faviids *Favia stelligera* (DANA 1846), *Favites pentagona* (ESPER, 1794), *Echinopora gemmacea* (LAMARCK 1816) and *Leptoria phrygia* (ELLIS & SOLANDER 1786)
- and merulinids *Hydnophora microconos* (LAMARCK 1816).

Because of minimal tidal exchange (< 1 m), and shallowness of the crests, rich coral assemblages were generally limited to the outer 5 – 10 m of reef crest and reef flat. Further inshore, corals tended to become both less species-rich and more sparse, as turf and short macro-algae predominated (see Algae - Seagrass section of the Report).

These communities are physically-structured by wind-driven waves (generally from the north-west and < two m in height) and episodic exposure during 'catastrophic' low tides (e.g. FISHELSON 1973), and are also most-affected by changes in irradiance and sea surface temperature that can induce coral bleaching and death. Water clarity is generally high, with underwater visibility of 30 – 40 m not uncommon.

Slightly deeper (~2 – 6 m depth) on exposed - semi-exposed reefs, assemblages were dominated by:

- fire corals (*Millepora* spp.),
- by tabular and branching species of *Acropora cytherea* (DANA 1846), *A. cf. hyacinthus* (DANA 1846), *A. muricata* (LAMARCK 1816), *A. hemprichi* (EHRENBERG, 1834), *A. eurystoma* (KLUNZINGER 1879) and *A. valida* (DANA

1846),

- branched pocilloporids,
- massive faviids (*Goniastrea*, *Favia*, *Favites* and *Platygyra* spp.) and poritids (*Porites* spp.).

In areas of moderate exposure, these assemblages occurred on the reef crest, interspersed with or replacing the former high-exposure taxa.

Coral cover was usually moderate to high, ranging between ~ 30 and 75 % (mean ~ 55 %). Key indicator corals included *Acropora gemmifera* (BROOK 1892), *Leptoria phrygia* (ELLIS & SOLANDER 1786), *Hydnophora microconos* (LAMARCK 1816), *Stylophora wellsi* SCHEER (1964), *Favia stelligera* (DANA 1846), *Favites pentagona* (ESPER 1794), *Pocillopora verrucosa* (ELLIS & SOLANDER 1786) and *Millepora* spp.

This community type encompasses Communities 2, 3, 5 and 9 of SHEPPARD & SHEPPARD (1991, see Table 4).

4-3. Sheltered biotopes

Community C, characteristic of turbid areas

Coral communities of sheltered biotopes were developed on the protected sides of patch reefs, in lagoons behind barrier reefs and inside sharms. These communities experience little wave energy (< 0.5 m) and resuspension of fine sandy – silty sediments can reduce water clarity. Often, the depth range of these communities was restricted by shallow waters and turbidity to < 10 m depth. Below ~ 5 m depth, the reefs often sloped steeply onto sand at ~ 6 - 8 m depth. The sides of these reef patches supported coral taxa characteristically occurring in deeper assemblages in waters of greater clarity further offshore.

These communities were composed of mixed assemblages:

- digitate, encrusting, branching and tabular acroporids *Acropora, Montipora* and *Astreopora* spp.,
- encrusting and massive faviids (*Favia, Favites, Erythrastrea flabellata* PICHON, SCHEER & PILLAI (1983), and *Echinopora* spp.), agariciids (*Pavona* spp.), poritids (*Porites, Goniopora* and *Alveopora* spp.) and mussids (*Lobophyllia* spp.),
- encrusting pectiniids (*Echinophyllia* and *Mycedium* spp.), oculinids *Galaxea fascicularis* (LINNEAUS 1767), 'mushroom' fungiids (*Fungia* spp.) and soft corals (*Xenia, Sarcophyton, Paraerthropodium* and *Sinularia* spp).

Where coral growth had partially or completely closed the entrances of sharms, coral assemblages of limited species diversity were sometimes developed inside the sharm, in areas of limited water influx across the reef top. These communities were composed mostly of massive poritids, siderastreids and faviids. Adjacent sand areas supported sea grasses and algae.

Key indicator species included *Montipora* spp., *Pavona decussata* (DANA 1846), *Fungia concinna* VERRILL (1864), *Cantharellus noumeae* HOEKSEMA & BEST (1984), *Echinopora fruticulosa* KLUNZINGER (1879) and *E. forskaliana* (MILNE EDWARDS & HAIME 1850), *Platygyra lamellina* (EHRENBERG 1834) and *Acropora* spp. Coral cover was usually low to moderate (average ~ 25 %).

This community type encompasses Communities 1, 4 and 7 of SHEPPARD & SHEPPARD (1991, see Table 4).

4-4. Biotopes of moderate exposure

Community type D, characteristic of reef 'cusps'

This community occurred in a wide range of habitats and depth ranges, but was commonest on moderately-exposed reef corners ('cusps'). This community had relatively low fidelity among indicator taxa. Key indicator species included:

- branching-table colonies of *Acropora pharaonis* (MILNE EDWARDS & HAIME 1850),
- massive colonies of the faviids *Oulophyllia crispa* (LAMARCK 1816), *Favia rotundata* VERON et al. (1977), *Diploastrea heliopora* (LAMARCK 1816) and *Barabattoia amicorum* (MILNE EDWARDS & HAIME 1850),
- and mushroom fungiids *Ctenactis echinata* (PALLAS 1766).

Coral cover was usually moderate (mean ~ 20 %), but ranged up to 75 % at some sites. This community type encompasses Communities 3 and 5 of SHEPPARD & SHEPPARD (1991, see Table 4).

The distribution of each site in the community type groups is listed in Appendix 6. There were significant differences among the four coral community types in terms of the distribution of sites at different depths and exposures, and in terms of the levels of reef development and species diversity (Table 12, Figs. 14-16, Appendix 6):

- Community type A occurred commonly on deeper sites of well developed reefs of low - moderate exposure. These communities were on average the most species rich,
- Community type B occurred mostly in shallow sites of well developed reefs subject to high exposure,
- Community type C was more commonly found on incipient reefs of low exposure and higher turbidity (low water clarity - visibility), notably on patch reefs of Al-Wajh Bank,
- Community type D occurred commonly in both shallow and deep sites, on well-

developed reefs of moderate exposure.

Table 12. ANOVA of differences among the four coral community types in terms of environmental attributes (depth, exposure, reef development, analysed as ranks), species diversity and benthic cover.

Source	Sum of Squares	df	Mean Square	F	P
Depth	13.3	3	4.43	27.25	< 0.0001
Reef develop.	25.75	3	8.58	22.22	< 0.0001
Exposure	57.19	3	19.07	33.83	< 0.0001
Spp. diversity	17283	3	5761	35.66	< 0.0001
HC	20.05	3	6.68	12.43	< 0.0001
DC	1.72	3	0.57	3.89	0.01
SC	6.37	3	2.12	9.46	< 0.0001
TA	2.92	3	0.97	2.79	0.04
MA	2.44	3	0.81	3.41	0.02
CA	4.28	3	1.43	3.69	0.01

There also were significant differences among the four community types in terms of the cover of hard corals, soft corals, dead corals, turf algae, macro-algae, and crustose coralline algae (Table 12). Average cover of living hard corals, turf algae, crustose coralline algae and macro-algae were all highest in Community B, characteristic of shallow exposed biotopes. By contrast, highest average cover of dead corals and soft corals occurred in Communities C and D respectively (Fig. 16).

6. Present Status - disturbances

Overall, most reefs of the region were in good to excellent condition in 1998-99. There was little to no direct human impact (e.g. destructive fishing, anchor damage, coral mining or pollution) on the great majority of reefs, other than some reefs in urban areas subject to land reclamation or littering. At most sites, levels of injury and death of corals were low (< 10 % cover of dead corals, Fig. 10), with < 20 % of species present exibiting injury,

Fig. 14. PCA biplot of relations among coral community types and site descriptor variables. Dimensions 1 and 2 account for ~ 55 % of the observed variance. The vectors point in the direction of the highest scores for the indicated variables, where hc - hard coral, dc - dead coral, sc - soft coral, ta - turf algae, ca - coralline algae, ma - macro-algae, sn - sand, rb - rubble, exp - exposure, rfdev - reef development, vis - water clarity, slope - reef slope. The symbols represent sites in each of the 4 coral community type groups A - D.

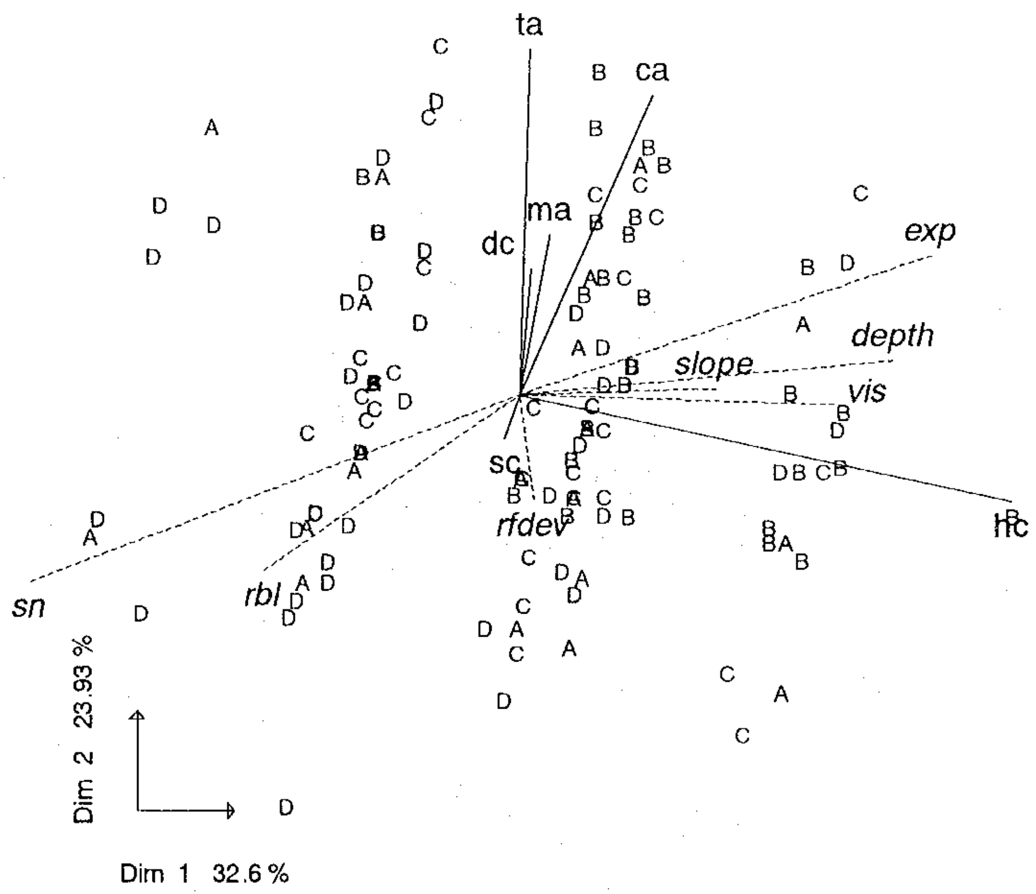


Fig. 15. Principal components biplot of four coral community site groups defined by hierarchical clustering (Euclidian metric, complete linkage) of species-abundance in the bio-inventories of 145 sites, Study Area, 1998-99. Convex hulls show the four community types A - D. Dimensions 1 and 2 account for ~ 24 % of the observed variance. The amount of fill in the bars indicates depth of sites (empty bars – deep slope, filled bars – shallow slope).

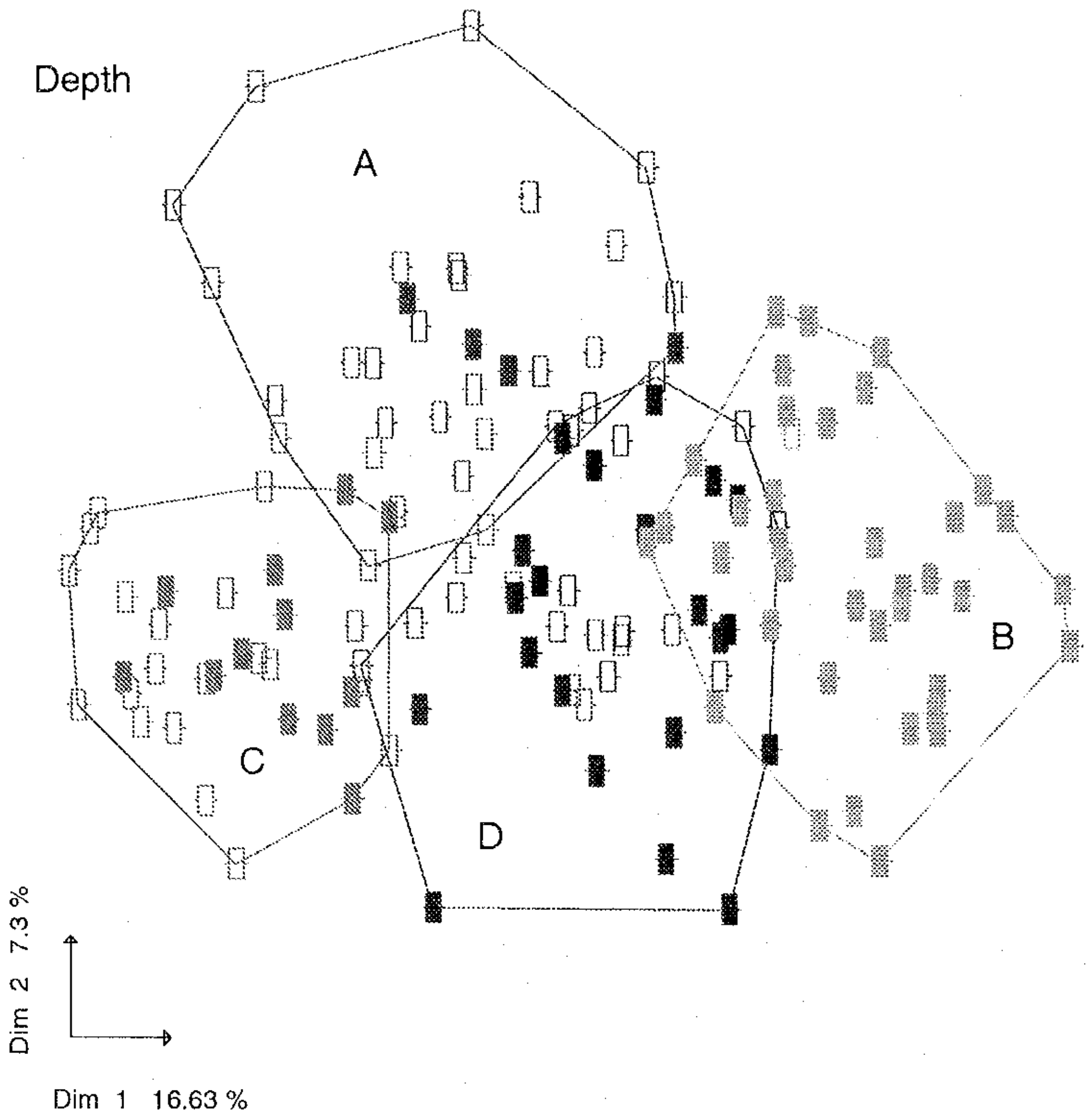
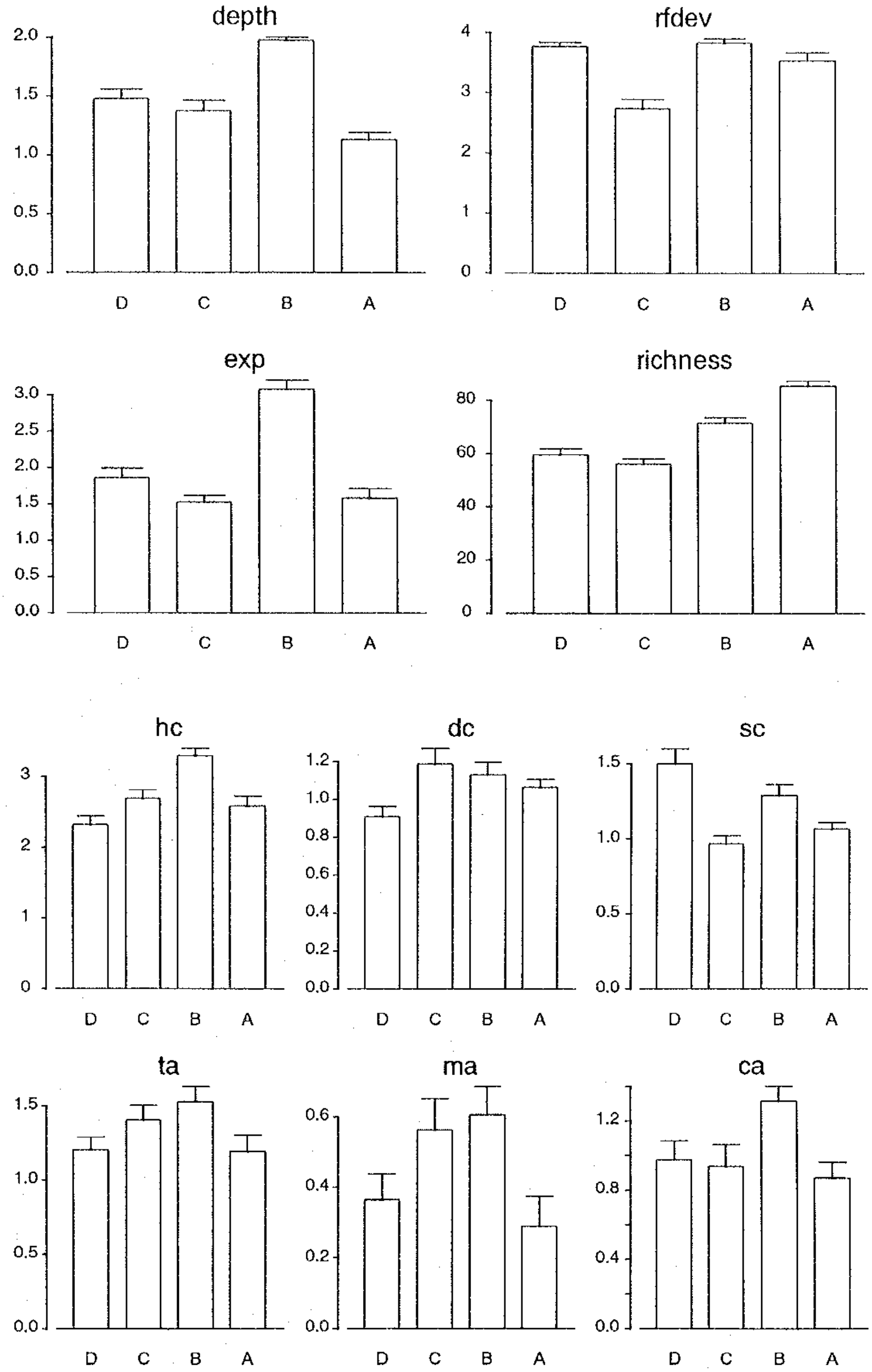


Fig. 16. Bar graphs of differences among the community types for environmental and cover variables.



and < 20 % average injury to those species (Fig. 17). However, coral communities on some reefs had been adversely affected to greater or lesser extent by bleaching (the expulsion of symbiotic microalgae – zooxanthellae, and pigments by the corals when stressed), by coral predation (mostly by crown-of-thorns starfish *Acanthaster planci*) or by sedimentation (Tables 13, 14).

Sites with highest levels of injury, in terms of the proportion of species present that were injured (Table 13), included sites C38 - C40 (Yanbu' - Rabigh, affected by coral bleaching), and sites C53 - C81 (Al-Wajh Bank patch reefs affected by *A. planci*). Sites in these areas were also among the highest scoring in terms of average levels of injury per species present (Table 14). Species in sites affected by sedimentation also had high levels of injury (e.g. C16a - Rabigh, C7b - S of Al-Wajh). In other sites, the likely cause(s) of the injury were unknown (e.g. C14b - J. Jabal Hassan). The predominance of patch reefs in Al-Wajh Bank with high levels of injury reflect the impact of predation by *A. planci* on corals on these reefs (see later, Model Study).

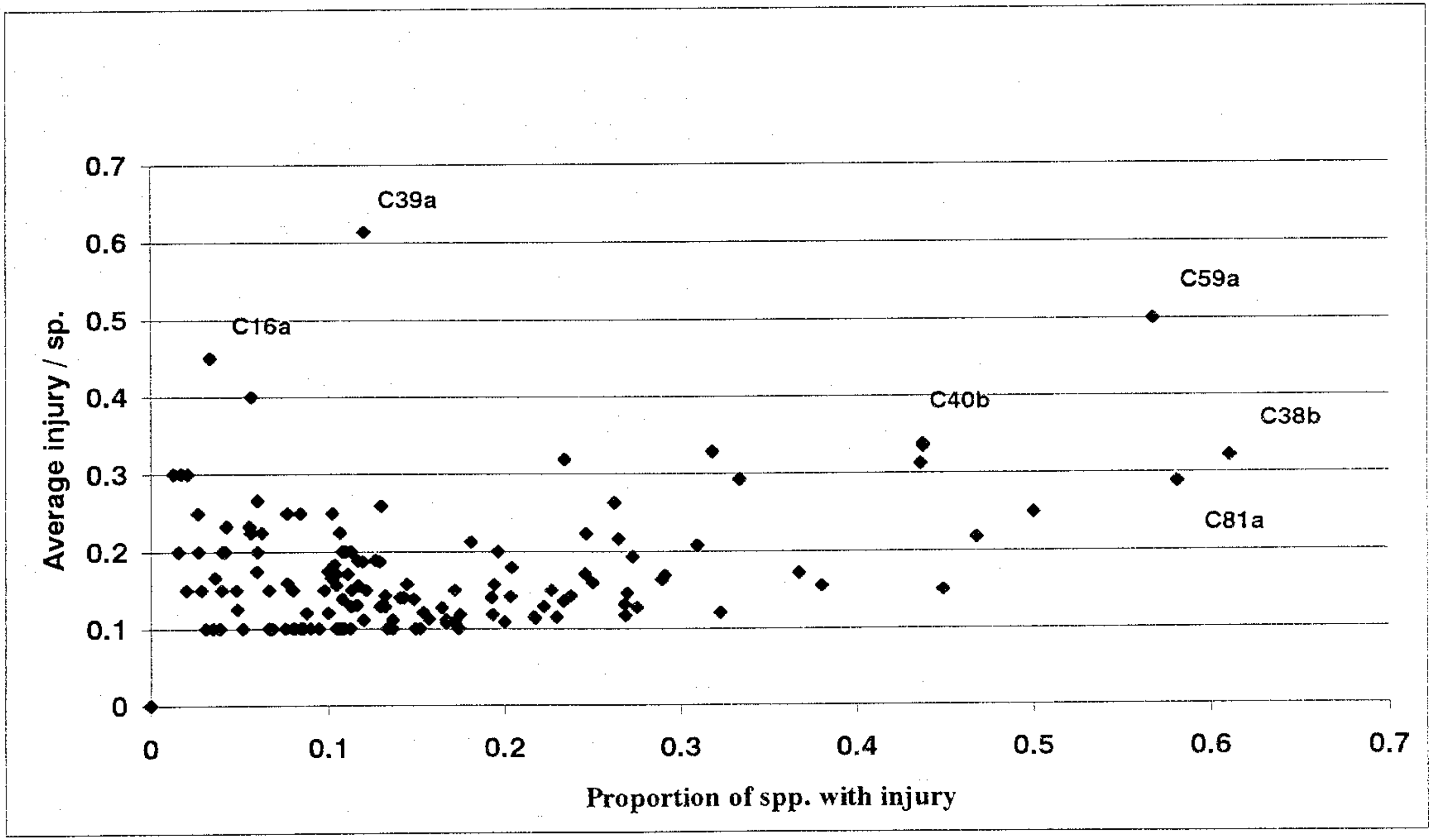


Fig. 17. Proportion of injured spp. versus average injury / sp. at each sites, Study Area, 1998-99.

Table 13. Sites with highest proportion of species that exhibited injury and the average level of injury per species at those sites. Probable cause(s) of injury are also listed, where predation - p, bleaching - b, sedimentation - s, unknown - u. Reef types: B – Barrier, P – Patch, MF – Mainland Fringing, SF – Sharm Fringing. GPS locations of sites are listed in Appendix 5.

Site No.	Reef name	Location	Reef type	Prop. Spp.	Ave. injury	Cause
C38b	Patch W of Marsa al Qadyah	Yanbu' - Rabigh	P-B	0.61	0.32	b
C81a	SW of J. Juzur Shurayrat	Al-Wajh Bank	P	0.58	0.29	p
C59a	SW J. Qumma'an	Al-Wajh Bank	P	0.57	0.50	p
C66a	SW J. Abu Lahij	Al-Wajh Bank	P	0.50	0.25	p
C53a	N of J. Qumma'an	Al-Wajh Bank	P	0.47	0.22	p
C55a	NW of J. Qumma'an	Al-Wajh Bank	P	0.45	0.15	p
C40b	Sh. Ar Rayis	Yanbu'-Rabigh	SF	0.44	0.34	b
C68a	S. J.Qumma'an	Al-Wajh Bank	P	0.44	0.33	p
C79a	SW J. Qumma'an	Al-Wajh Bank	P	0.44	0.31	p
C60a	SE J. Qumma'an	Al-Wajh Bank	P	0.38	0.16	p
C39b	Patch W of Marsa al Qadyah	SW of Rabigh	P-B	0.37	0.17	b
C56a	NW of J. Qumma'an	Al-Wajh Bank	P	0.33	0.29	p
C42b	Ra's Al-Mukharraf	Umluj - Yanbu'	MF	0.32	0.12	b-s
C7b	S of Sh. Habban	N of Al-Wajh Bank	SF	0.32	0.33	s
C1a	Sh. Al-Muraybirah	N of Al-Wajh Bank	SF	0.31	0.21	s
C13b	Sh. Shabaan	Umluj - Yanbu'	SF	0.29	0.17	s
C53b	N of J. Qumma'an	Al-Wajh Bank	P	0.29	0.16	p
C4b	J. Shawyk Murbat	Al-Wajh Bank	P	0.28	0.13	s
C69b	J. Mizab	Al-Wajh Bank	B	0.27	0.19	u
C86b	W of Al Khuraybah	Tiran area	P	0.27	0.15	u
C1b	Sh. Al-Muraybirah	N of Al-Wajh Bank	SF	0.27	0.12	s
C85a	W of Al Khuraybah	Tiran area	P	0.27	0.13	u
C6b	S of Sh. Habban	N of Al-Wajh Bank	SF	0.26	0.22	u
C67a	W J. Qumma'an	Al-Wajh Bank	P	0.26	0.26	p
C57b	W of J. Shaybarah	Al-Wajh Bank	B	0.25	0.16	u

Table 14. Sites with highest average level of injury per species and proportion of species with injury at those sites. Probable cause(s) of injury are also listed, where predation - p, bleaching - b, sedimentation -s, unknown - u. Reef types: B – Barrier, P - Patch, MF - Mainland Fringing, IF - Island Fringing, SF - Sharm Fringing. GPS locations of sites are listed in Appendix 5.

Site No.	Reef name	Location	Reef type	Ave. injury	Prop. Spp.	Cause
C39a	Patch W of Marsa al Qadyah	SW of Rabigh	P-B	0.61	0.12	b
C59a	SW J. Qumma'an	Al-Wajh Bank	p	0.5	0.57	p
C16a	Sh. Abu Aduli	Yanbu' - Rabigh	SF	0.45	0.03	s
C14b	J. Jabal Hassan	Umluj - Yanbu'	IF	0.4	0.06	-
C40b	Sh. Ar Rayis	Yanbu' - Rabigh	SF	0.34	0.44	b
C68a	S. J.Qumma'an	Al-Wajh Bank	P	0.33	0.44	p
C7b	S of Sh. Habban	N of Al-Wajh Bank	SF	0.33	0.32	s
C38b	Patch W of Marsa al Qadyah	Yanbu' - Rabigh	P-B	0.32	0.61	b
C65a	NE of J. Qumma'an	Al-Wajh Bank	P	0.32	0.23	p
C79a	SW J. Qumma'an	Al-Wajh Bank	P	0.31	0.44	p
C43a	Ra's Al-Mukharraf	Umluj - Yanbu'	MF	0.3	0.02	b
C9b	N. Al-Wajh Bank	Al-Wajh Bank	B	0.3	0.02	s
C27a	J. Al Wassl	Gulf of Aqaba	IF	0.3	0.01	u
C56a	NW of J. Qumma'an	Al-Wajh Bank	P	0.29	0.33	p
C81a	SW of J. Juzur Shurayrat	Al-Wajh Bank	P	0.29	0.58	p
C25b	Marsa Hawwaz	Duba – Al-Wajh	SF	0.27	0.06	u
C67a	W J. Qumma'an	Al-Wajh Bank	P	0.26	0.26	p
C48b	J. Malihah, Jabal Hassan	Umluj - Yanbu'	P	0.26	0.13	u
C66a	SW J. Abu Lahij	Al-Wajh Bank	P	0.25	0.5	p
C33b	J. Al Fasima	Tiran area	P	0.25	0.1	s
C44b	Sh. Ar Hisay	Umluj - Yanbu'	SF	0.25	0.08	b
C20b	Sh. Al Khwar, Ra's Baridi	Umluj - Yanbu'	SF	0.25	0.08	s
C18b	Masturah	Yanbu' - Rabigh	B	0.25	0.03	u

6-1. Coral bleaching

1). Red Sea overview

No evidence of mass bleaching or other forms of major coral mortality were found during surveys in May – June 1998. Most reefs in the study region appeared to be in good condition, with little evidence of major human or natural impacts. No bleaching was reported from other areas of Saudi Arabia at this time, although reefs further to the south in the Arabian Sea and greater Indian Ocean had already bleached extensively (WILKINSON et al. 1999).

By October 1998, bleaching was patchily distributed throughout the Saudi Arabian Red Sea, extending north from the Farasan Islands (S. Saudi Arabia, NCWCD pers. comm.) to reefs around Jeddah and Yanbu' (central Saudi Arabia). In the study region, some reefs offshore from Rabigh and north to Yanbu' experienced intense bleaching, causing high levels of coral mortality, while others (Ra's Baridi, Al-Wajh Bank, Gulf of Aqaba) were little affected or unaffected. Minor bleaching occurred at some locations near Haql in the Gulf of Aqaba, and minor - moderate bleaching occurred in the Tiran area near J. Muksoor. Bleaching was most widespread and intense in the shallower coral communities (depths < 6 m), although corals on the deeper slopes (> 20 m depth) had also been affected. Bleaching had little overall effect on cover of living corals in the region, but did cause an increase in cover of dead corals (Fig. 18).

The bleaching on reefs around Rabigh (Sites C38 – C40) resulting in increased levels of injury and mortality, particularly in the shallower communities (depths < 6 m, Sites C38b – C40b). At these sites, bleaching had killed many reef crest and shallow water corals, and recently dead and bleached corals accounted for up to 90 % of the total cover of hard corals, soft corals and fire-corals *Millepora* spp. (Figs. 19 a - c). Deeper communities had also been affected, with some coral mortality (notably site C39a with injury and mortality to ~ 15 % of

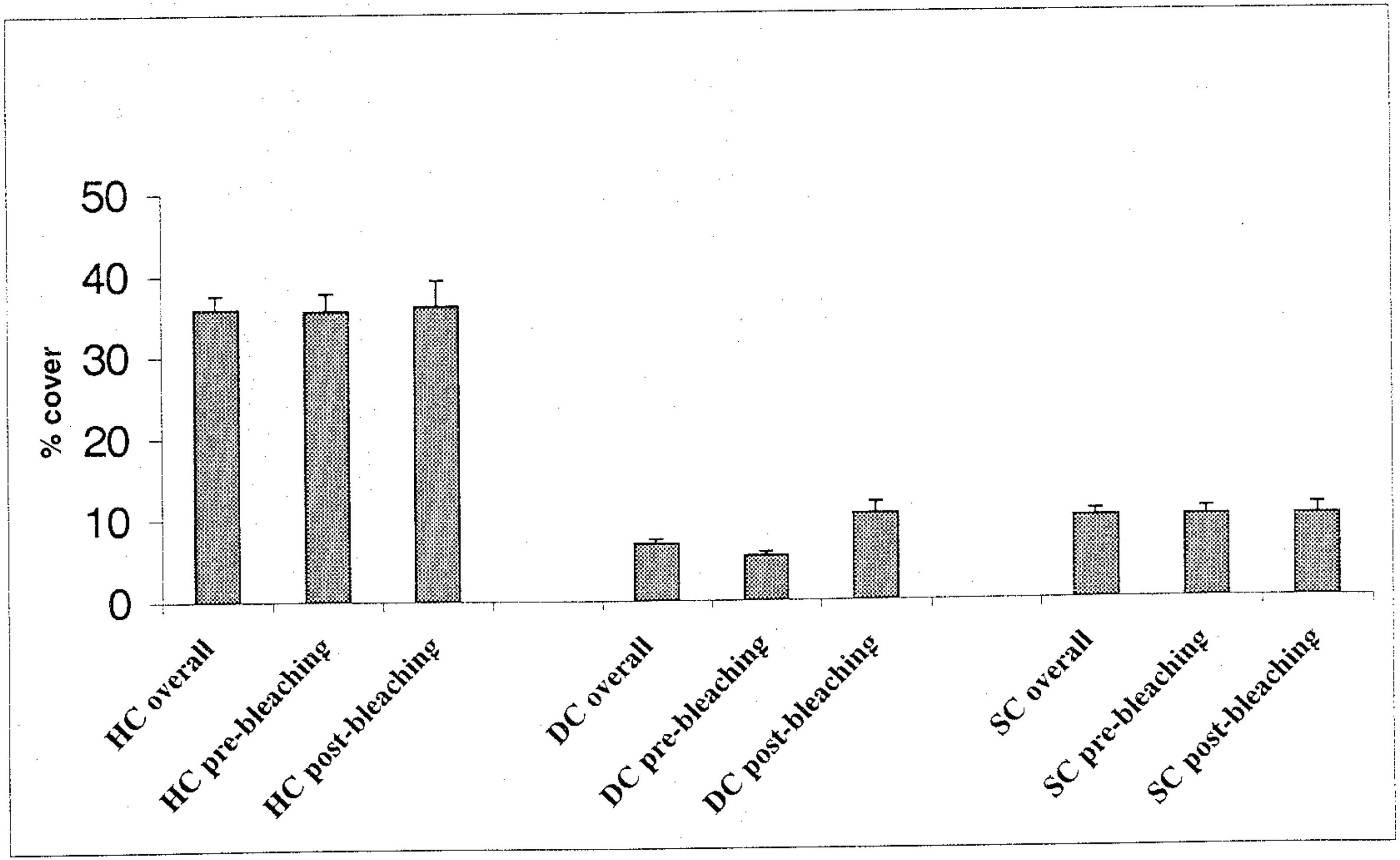
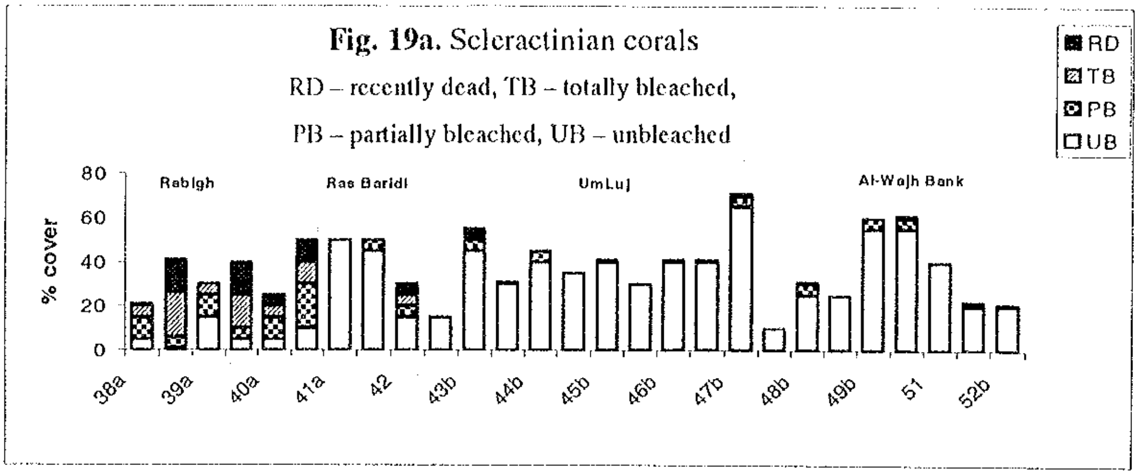
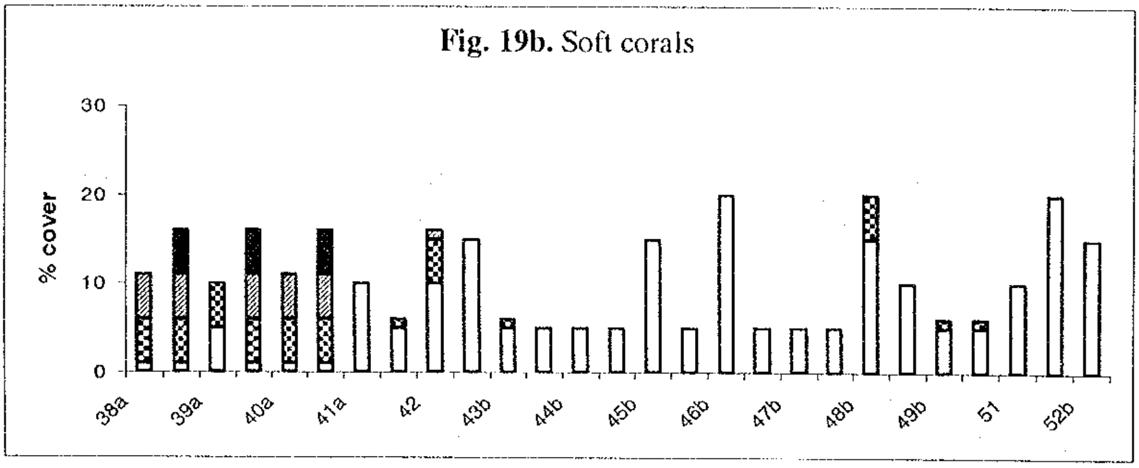


Fig. 18. % cover of hard corals, dead corals and soft corals (+ 1 s.e.), Study Area, 1998-99.





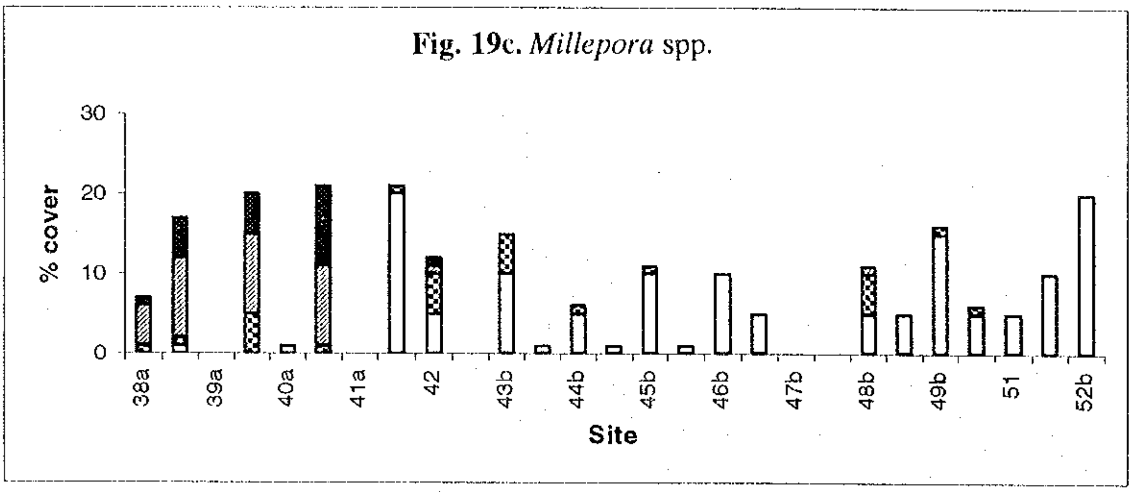


Fig. 19. % cover of bleached and unbleached corals, Study Area, 9-10 / 1998.

species present).

2). Bleaching effects on coral species

Of the 325 anthozoan taxa recorded during the pre- and post-bleaching surveys in May-June and September-October 1998, 124 taxa exhibited injury at one or more of the sites (84 species pre-bleaching, 101 species post-bleaching). Both the proportion of coral species with injury and also the level of average injury per species increased from the pre- to post-bleaching surveys (Fig. 20). As with coral cover, levels of injury to individual species were most intense on reefs around Rabigh, where over half of all species had been affected (Fig. 17), with coincident high mortality (~ 90 %) to worst-affected taxa. Coral species that were worst affected by bleaching-related injury represented a wide range of genera and growth forms (Table 15).

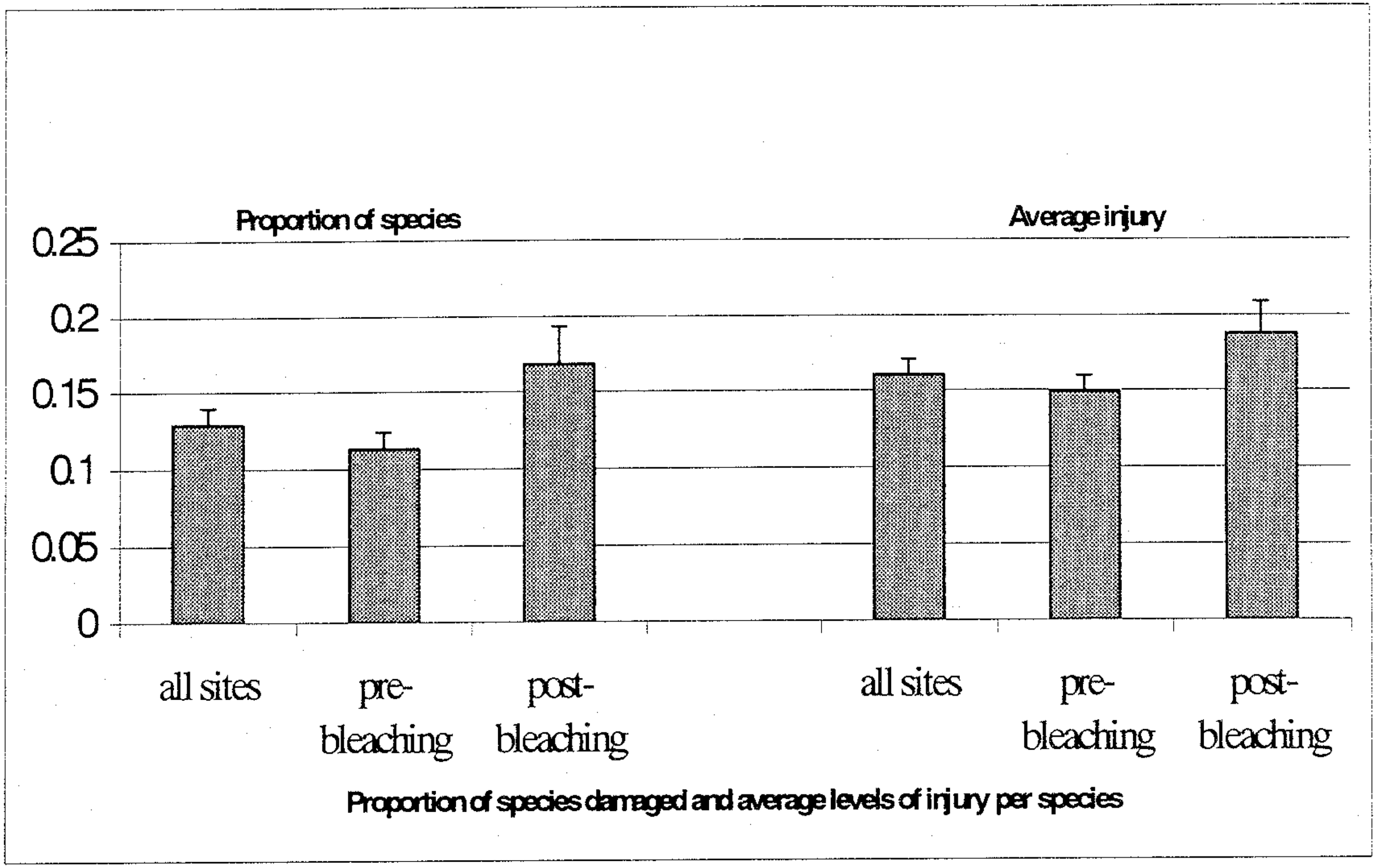


Fig. 20. Injury to stony corals, Study Area, 5-10 / 1998.

Table 15. Coral species that exhibited highest levels of injury following bleaching (Sites C38 – C52, September – October 1998), with maximum and average levels of injury, average rank abundance and % of sites at which the species occurred.

Species	Max. injury	Ave. injury	Ave. abundance	% sites
Podabacia crustacea	0.9	0.90	1	26
Tubastraea micrantha	0.9	0.90	2.5	15
Pavona duerdeni	0.8	0.80	1.25	15
Pachyseris speciosa	0.9	0.60	1.59	26
Leptoseris foliosa	0.9	0.60	1.5	7
Montipora venosa	0.5	0.50	1.11	33
Acropora cytherea	0.9	0.48	1.83	44
Pavona explanulata	0.8	0.40	1.33	33
Millepora dichotoma	0.6	0.40	2.56	93
Millepora platyphylla	0.7	0.40	2.47	70
Acropora acuminata	0.4	0.40	1.75	26
Turbinaria frondens	0.4	0.40	1	11
Acropora austera	0.4	0.35	1.86	48
Favia favus	0.6	0.35	1.74	85
Sinularia cf. capitalis	0.5	0.35	2.7	37
Gardineroseris planulata	0.7	0.30	1.7	70
Acropora gemmifera	0.3	0.30	2.6	41
Acropora intermedia	0.3	0.30	2.3	15
Merulina scheeri	0.3	0.30	1.9	52
Favia pallida	0.3	0.30	1.6	78
Stylophora welsii	0.4	0.28	1.9	67
Favites peresi	0.9	0.27	2	63
Acropora hemprichi	0.8	0.27	2.3	85
Leptastrea purpurea	0.5	0.27	1.8	96
Lobophyllia corymbosa	0.4	0.26	1.3	37
Favia stelligera	0.7	0.26	2.1	59
Acropora listeri	0.3	0.25	1.4	30
Acanthastrea echinata	0.4	0.25	1.7	85
Favia lizardensis	0.4	0.25	1	7
Sinularia sp.	0.3	0.25	2.4	96
Goniasatrea retiformis	0.6	0.20	2.3	67
Galaxea fasicularis	0.5	0.15	2	100
Acropora hyacinthus	0.4	0.17	2.2	74
Porites massive spp.	0.4	0.20	2.8	100
Pocillopora damicornis	0.3	0.16	2.5	89

Many of the worst-affected taxa were uncommon, occurring at low abundance (ranks 1 or 2) in few sites. Such species may be particularly susceptible to local extinction following such catastrophic mortality. Of those species that were relatively common and widespread (i.e. mean rank abundance of > 2 and occurring in > one-third of sites), ~ 15 species were conspicuous in sustaining high levels of injury (Table 15). Most of the latter taxa, particularly the fire corals and *Acropora* spp., exhibit preferences for shallow water habitats.

6-2. Anecdotal reports of bleaching in Red Sea

Farasan Islands

Extensive coral bleaching is reported to have occurred on reefs of the Farasan Islands, although the level of subsequent mortality and species affected are not known at present (NCWCD, pers. comm.). Precise timing of the bleaching at the Farasan Islands is not known.

6-3. Coral predation

Predation by Crown-of-thorns Starfish *Acanthaster planci* (Linneaus 1758) and muricid snails *Drupella* spp. had no noticable effect on coral cover or community composition on most reefs in the study region, where starfish and snail populations were at low levels. However, coral cover and community structure had been adversely affected by larger populations of the starfish (~ 100 *A. planci* ha^{-1}) on patch reefs in Al-Wajh Bank (Table 16). At the patch reef sites in Al-Wajh Bank, the starfish had caused substantial reductions in living coral cover and coincident increases in dead coral cover and shifts in relative abundance and community structure (see later, Model Study).

Table 16. Distribution and abundance of Crown-of-thorns Starfish *Acanthaster planci* in the Study Area, 1998-99. Abundance is expressed as approximate number of *A. planci* ~ $500m^{-2}$. Reef types: MF - Mainland Fringing, P - Patch. GPS locations of sites are listed in Appendix 5.

Site No.	Reef name	Location	Reef type	*A. planci* ~ $500m^{-2}$
C10a	N of J. Shaybarah	Al-Wajh Bank	P	2
C19a	Ra's Baridi	Umluj – Yanbu'	MF	1
C53a	N of J. Qumma'an	Al-Wajh Bank	P	5
C53b	N of J. Qumma'an	Al-Wajh Bank	P	7
C55a	NW of J. Qumma'an	Al-Wajh Bank	P	3
C56a	NW of J. Qumma'an	Al-Wajh Bank	P	3
C59a	SW J. Qumma'an	Al-Wajh Bank	P	6
C60a	SE J. Qumma'an	Al-Wajh Bank	P	4
C61a	J. Ummahat Shaykh	Al-Wajh Bank	P	1
C65a	NE of J. Qumma'an	Al-Wajh Bank	P	5
C66a	SW J. Abu Lahij	Al-Wajh Bank	P	6
C67a	W J. Qumma'an	Al-Wajh Bank	P	2
C67b	W J. Qumma'an	Al-Wajh Bank	P	2
C68a	S J. Qumma'an	Al-Wajh Bank	P	2
C78a	N of Umluj	S of Al-Wajh Bank	P	2
C79a	SW J. Qumma'an	Al-Wajh Bank	P	11
RC 33	E J. Qumma'an	Al-Wajh Bank	P	1
RC 34	J. Abu Lahij	Al-Wajh Bank	P	5
C81a	N of J. Shaybarah	Al-Wajh Bank	P	23

7. Management Implications - Sites of special conservation significance

7-1. Coral Replenishment

Sites likely to be important in replenishment of populations, having high abundance and cover of corals, were distributed widely throughout the study region, with key sites located in the Gulf of Aqaba, the Tiran area, Duba - Al-Wajh, Al-Wajh Bank, Umluj - Yanbu' and Yanbu' - Rabigh (Table 17). There was strong concordance between the two coral indices (*CI* and *HCI*), illustrating the strong contribution made to community composition and relative abundance by the scleractinian hard corals. Sites from community types A and B were particularly well represented, reflecting the generally high coral cover and species abundance of these communities.

Table 17. Sites likely to be of special importance for coral replenishment, in terms of coral cover and species abundance (*CI*, *HCI*). Community types are also listed. Reef types: MF - Mainland Fringing, IF - Island Fringing, SF - Sharm Fringing, P - Patch, B - Barrier. GPS locations of sites are listed in Appendix 5.

Site	Reef name – location	Reef Type	CI value	HCI ranking	Total spp. diversity	Hard coral diversity	Community type
C74a	W of J. Qumma'an, Al-Wajh Bank	B-P	10.7	6	111	98	A
C32b	J. Baraqan, Tiran area	IF	9.6	1	107	94	B
C78b	S of Al-Wajh Bank	P	9.55	2	108	97	B
C77a	S of Al-Wajh Bank	B	8.95	4	110	91	A
C40b	Sh. Ar Rayis, Yanbu'-Rabigh	SF	8.75	5	85	73	B
C86b	W Al Khuraybah, Tiran area	P	8.55	3	97	89	A
C77b	S of Al-Wajh Bank	P	8.28	18	70	60	B
C26b	N J. Al-Wassl, G. of Aqaba	MF	8.15	7	90	77	A
C41b	Ra's Baridi, Umluj-Yanbu'	MF	8.05	9	93	78	B
C48b	J. Malihah, Umluj-Yanbu'	IF	7.95	25	79	70	B
C49b	S. J. Shaybarah, Al-Wajh Bank	P	7.9	10	82	69	B
C47b	J. Malihah, Umluj	P	7.65	8	83	74	B
C86a	W Al Khuraybah, Tiran area	P	7.44	13	94	83	A
C44b	N Sh. al Hisay, Umluj-Yanbu'	SF	7.3	42	76	64	B
C24b	Marsa Hawwaz, Duba-Al-Wajh	SF	7.26	12	66	56	B
C19b	Ra's Baridi, Umluj-Yanbu'	MF	7.2	34	82	70	B
C84b	N of Maqna, G. of Aqaba	MF	7.2	15	94	83	B
C46b	S Sh. al Hisay, Umluj-Yanbu'	SF	7.15	39	74	62	B
C23a	J. Raykhah, Al-Wajh	IF	7.05	47	76	63	A
C69b	J. Mizab, Al-Wajh Bank	B	7.05	45	68	55	B
C26a	N J. Al Wassl, G. of Aqaba	MF	7.0	11	86	76	A
C50b	S Al-Wajh Bank	P	6.95	14	74	63	B
C28b	Ash Shaykh Humayd, Tiran area	MF	6.85	20	82	70	B
C41a	Ra's Baridi, Umluj-Yanbu'	MF	6.76	24	90	77	A
C30b	N of Maqna, G. of Aqaba	MF	6.75	17	76	64	B
C85a	W Al Khuraybah, Tiran area	P	6.63	30	109	97	A

7-2. Rarity Indices

Important sites in terms of the conservation of coral taxa that were uncommon or rare in the study region were also widely distributed, with key sites located in the Gulf of Aqaba, the Tiran area, Duba - Al-Wajh, Al-Wajh Bank, Umluj - Yanbu' and Yanbu' - Rabigh (Table 18).

Table 18. Sites of special importance in terms of presence or abundance of species rare in the Study Area (RI, VI). Community types are also listed. Reef types: MF - Mainland Fringing, IF - Island Fringing, SF - Sharm Fringing, P - Patch, B - Barrier. GPS locations of sites are listed in Appendix 5.

Site	Reef name	Location	Reef Type	RI value	VI rank	Total coral diversity	Hard coral diversity	Community type
70b	J. Umm Rumah	Al-Wajh Bank	P	9.978	1	67	64	C
10a	S of J. Qumma'an	Al-Wajh Bank	P	7.514	10	68	63	C
73a	W of J. Qumma'an,	Al-Wajh Bank	B-P	7.079	8	89	79	A
77a	S of Al-Wajh Bank	Al-Wajh Bank	B	7.077	6	110	91	A
82b	S Al-Wajh Bank	Al-Wajh Bank	P	6.935	2	53	50	C
31a	J. Al-Farshah	Tiran area	P	6.898	3	52	48	C
30a	N of Maqna	G. of Aqaba	MF	6.536	5	90	81	A
67a	W J. Qumma'an	Al-Wajh Bank	P	5.879	19	65	61	C
32b	J. Baraqan	Tiran area	IF	5.718	9	107	94	B
83a	N of Maqna	G. of Aqaba	MF	5.39	7	104	89	A
27a	J. Al-Wassl	G. of Aqaba	IF	5.379	21	90	73	A
86b	W of Al Khuraybah	Tiran area	P	5.209	18	97	89	A
74a	W of J. Qumma'an	Al-Wajh Bank	B-P	4.974	11	111	98	A
69a	J. Mizab	Al-Wajh Bank	B	4.671	15	76	64	D
16b	Sh. Abu Aduli	Yanbu' - Rabigh	SF	4.606	26	61	50	D
86a	W of Al Khuraybah	Tiran area	P	4.586	14	94	83	A
84b	N of Maqna	G. of Aqaba	MF	4.554	17	94	83	B
81a	S of J. Juzur Shurayrat	Al-Wajh Bank	P	4.553	12	84	74	C
8a	N Al-Wajh Bank	Al-Wajh Bank	B	4.434	25	62	54	D
85a	W of Al Khuraybah	Tiran area	P	4.419	13	109	97	A
54b	W of J. Qumma'an	Al-Wajh Bank	B	4.378	16	77	66	B
84a	N of Maqna	G. of Aqaba	MF	4.335	29	80	71	A
60a	J. Qumma'an	Al-Wajh Bank	P	4.324	28	79	71	C
31b	J. Al-Farshah	Tiran area	P	4.175	4	56	52	C
78b	S of Al-Wajh Bank	Al-Wajh Bank	P	4.076	22	108	97	B
37a	Sh. Jazzah	Duba – Al-Wajh	SF	4.012	34	92	83	A

There was strong concordance between the two rarity indices (RI and VI). The four coral community types were well represented among the sites. Notably, most of the important sites rich in species otherwise uncommon in the study region were located in the vicinity of Al-Wajh Bank, in the Gulf of Aqaba and in the Tiran Area.

2.1.2.4. Discussion and conclusions

Most reefs supported rich coral communities with moderate to high living coral cover (mean ~ 35 %), composed of a subset of the region's ~ 250 species of reef-building corals. There was a high degree of homogeneity in the species composition of communities within the study region, and little latitudinal or longitudinal effect on composition. There were however differences in relative abundances of different taxa, producing characteristic zonation patterns and four major coral community types with key indicator taxa, related largely to degree of exposure, depth, and water clarity.

The communities were generally in good condition, with little injury to corals at most locations. However, coral reef bleaching and predation by the Crown-of-thorns Starfish produced high levels of coral mortality on some reefs. Bleaching was patchily distributed and highly variable in intensity, and there was little overall effect on living coral cover in the study region. Worst affected were reefs around Rabigh, where bleaching had caused major mortality and high levels of dead coral cover on shallow coral communities (depths < 6 m). On these reefs, recent mortality accounted for over half the total coral cover, and over half of the coral species present had been affected to greater or lesser degree.

1. Cause(s) of coral bleaching

Bleaching followed the development of a warm pool of surface waters in the area in August-September 1998, with high sea surface temperatures (SSTs > 31° C). At some reefs, fluctuations in photosynthetically-active radiation (PAR) may also have played a contributing role. Conversely, areas under the direct influence of cool water upwelling (e.g. Ra's Baridi, barrier reefs in Al-Wajh Bank and reefs in the Gulf of Aqaba) showed little evidence of bleaching, probably related to the influx of cooler waters (23° – 28° C). The cool waters may provide a natural buffer against the worst effects of coral bleaching. Coral communities in these upwelling areas are likely to play a very important future role in maintenance of coral populations and conservation of biodiversity, and also as 'source' populations for restocking of areas affected by bleaching.

The Red Sea bleaching formed part of a global phenomenon on reefs stretching across the three tropical oceans. Reefs further south in the Indian Ocean bleached in the earlier part of 1998 (from February - July), when extremely high ocean SSTs migrated from south to north in the Indian Ocean. A similar episode of elevated SSTs occurred following the 1987 ENSO, however SSTs moderated in 1988 as the Sun moved into the Northern Hemisphere, and Indian Ocean reefs were little affected (P. Viets, NOAA, pers. comm.). In 1998, this moderation did not occur, and reefs from as far afield as South Africa, Madagascar, Tanzania, Kenya, Somalia, Reunion, Mauritius, The Seychelles, Maldives, Sri Lanka, Andaman Islands, Cambodia, Thailand, Malaysia, Indonesia, NW Australia, Oman and Yemen have been adversely affected.

Although the proximate cause of the bleaching has been attributed to high sea surface temperatures, in some areas associated with the exceptionally-strong 1997-98 El Nino – Southern Oscillation (ENSO), the possibility exists that ultimately the high SSTs may be linked with global warming (WILKINSON et al. 1999). At present the potential influence of global warming remains uncertain and is an area of intense research interest.

The other major form of disturbance to coral communities in the study region occurred on Al-Wajh Bank, and was caused by predation by crown-of-thorns starfish *Acanthaster planci*. The *A. planci* populations in Al-Wajh Bank (density on individual reefs ~ 100 starfish ha^{-1}) may be incipient outbreak populations. Predation has caused an increase in dead coral cover to > 20 % on worst-affected reefs, with coincident decline in living coral cover (see later, Model Study). Predation has also caused apparent shifts in coral community structure, with non-preferred prey coral species (notably *Porites* spp.) forming major components of the communities. Reproduction by the starfish during the summers of 1999 and 2000 may initiate major outbreaks on other Saudi Arabian reefs in the future. Outbreaks of the starfish have also occurred recently on Egyptian reefs around Ra's Muhammad on the tip of the Sinai Peninsula and at Hurgada.

2. Cause(s) of starfish outbreaks

A variety of factors have been implicated in the initiation of starfish outbreaks (see MORAN 1986, BIRKELAND & LUCAS 1990 for reviews). These include factors associated with the metabolic requirements of the starfish (larval nutrition and development, settlement sites, food, shelter), factors associated with larval dispersal, factors associated with its behavior (cues that induce feeding and/or spawning aggregations) and factors associated with the regulation of its population numbers, chiefly release from predation. Changes in water quality and abundance of food for starfish larvae are likely to be the most important factors influencing the metabolic requirements of the starfish (BIRKELAND 1982), and with predation at all stages of the starfish life-cycle, are likely to be the most important regulatory mechanisms affecting starfish population fluctuations (ENDEAN & STABLUM 1975, CAMERON & ENDEAN 1982, GLYNN 1982, ORMOND et al. 1988, MACCALLUM et al. 1989).

It is unlikely that starfish outbreaks arise from a single cause in all areas, but rather result from the influence of a variety of factors (ORMOND et al. 1990). Like other ecological phenomena, there may be both positive and negative feedback mechanisms involved in initiation, propagation and ultimate ceasation of outbreaks. Within Al-Wajh Bank, nutrient enrichment from human inputs is unlikely to be a factor, and the moderate - high starfish population levels may be related to fishing of predatory fishes in the families Lethrinidae, Balistidae, Serranidae and Lutjanidae.

Within the study region, bleaching and predation were restricted largely to the area between Rabigh andYanbu' (bleaching) and to patch reefs in Al-Wajh Bank (predation). Most reefs of the region were little affected by bleaching, predation or local human impact, other than in the vicinity of larger towns where reef fishing, land reclamation and some coastal littering has occurred. Thus the study region, from Rabigh in the south to Haql in the Gulf of Aqaba in the north, is one of the most important coral reef areas globally for marine protected area management.

3. Sites of Special Importance for MPA Management

The preceding analyses have identified reefs and larger sub-regions of special conservation significance, based on a range of ecological and biodiversity criteria. Reefs of special conservation significance in terms of representativeness-uniqueness and 'quality' (i.e. high coral cover, species diversity and importance as reservoirs of biodiversity and replenishment) were widely distributed, from the Gulf of Aqaba and Tiran areas in the north, Duba - Al-Wajh, Al-Wajh Bank, Umluj - Yanbu' and Yanbu'-Rabigh in the south (Tables 8-10, 17-18, Fig. 21).

Sites in Al-Wajh Bank and Tiran area were particularly important in terms of supporting presently undescribed coral species (Table C8). Sites in the Tiran area and Al-Wajh Bank and south to Umluj were also likely to be important in terms of replenishment (Table 17). Individual sites that scored highly on several of the above criteria are listed in Table 19. These sites are of major importance for future marine protected areas management.

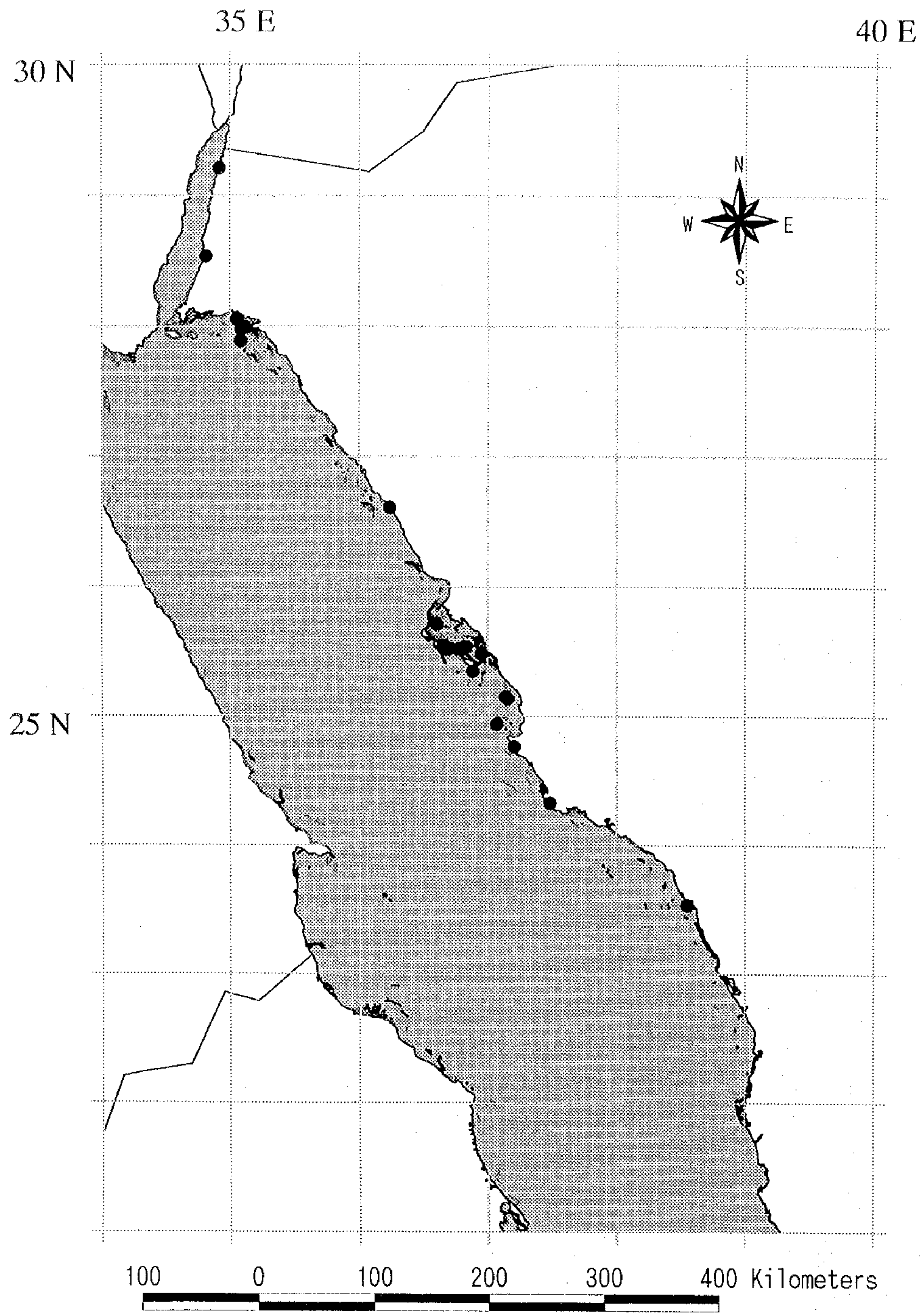


Fig. 21. Map of the Study Area showing appropriate locations of sites of special conservation value.

Table 19. Sites of special management significance in terms of high conservation values. Reef names and GPS locations are listed in Appendix 5. Reef types: B – Barrier, P – Patch, IF – Island Fringing, MF – Mainland Fringing, SF – Sharm Fringing. Hard coral cover ranks: 2 = 11-30 %, 3 = 31-50 %, 4 = 51-75 %. Coral species diversity, ratings (1-145) within the study region for indices of replenishment potential (CI) and rarity (VI), the presence of undescribed species and coral community type are listed for each site.

Site	Location	Reef Type	Hard coral cover	Species diversity - all corals	Repleni-shment (CI)	Rarity (VI)	Undes-cribed spp.	Comm-unity Type
C32b	Tiran area	IF	4	107	2	9		B
C77a	S of Al-Wajh Bank	P	4	110	4	6		A
C74a	Al-Wajh Bank	B-P	3	111	1	11	y	A
C78b	S of Al-Wajh Bank	P	4	108	3	22		B
C86b	Tiran area	P	4	97	6	18	y	A
C77b	S of Al-Wajh Bank	P	4	70	7	33	y	B
C85a	Tiran area	P	3	109	26	13		A
C40b	Yanbu' - Rabigh	SF	4	85	5	36		B
C26b	Gulf of Aqaba	MF	4	90	8	53		A
C41b	Umjuj - Yanbu'	MF	4	93	9	46		B
C70b	Al-Wajh Bank	P	3	67	65	1	y	C
C82b	Al-Wajh Bank	P	4	53	92	2	y	C
C31b	Tiran area	P	4	56	37	4	y	C
C31a	Tiran area	P	2	52	121	3	y	C
C30a	Gulf of Aqaba	MF	2	90	91	5		A
C86a	Tiran area	P	3	94	13	14	y	A
C24b	Duba - Al-Wajh	MF	5	66	15	73		B
C12a	Umluj - Yanbu'	SF	3	63	82	57	y	A
C14b	Umluj - Yanbu'	IF	3	56	85	114	y	B
C49a	S of Al-Wajh Bank	P	2	69	110	111	y	D
C62a	Al-Wajh Bank	P	2	65	108	51	y	C
C67a	Al-Wajh Bank	P	3	65	88	19	y	C
C73b	Al-Wajh Bank	B-P	2	87	74	35	y	A
C79a	Al-Wajh Bank	P	2	62	112	55	y	C