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RESEARCH ARTICLE

Recovery of corals a decade after a bleaching event in Dubai, United Arab Emirates

J. Burt · A. Bartholomew · P. Usseglio

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Abstract Elevated sea surface temperatures in the late 1990s were associated with widespread coral mortality in the Arabian Gulf, particularly in *Acropora* dominated areas. This study investigates the composition, condition, and recruitment patterns of coral communities in Saih Al-Shaib, Dubai, United Arab Emirates, a decade after mass bleaching. Five statistically distinct communities were identified by cluster analysis, with grouping optimized from 17 significant indicator species. Overall, 25 species of scleractinian coral were observed, representing 35 ± 1.6% coral cover. Densities of recruits were low ($0.8 \pm 0.2\ \text{m}^{-2}$), and composition generally reflected that of the surrounding adult community. Ten years after mass mortality, *Acropora* dominated assemblages were observed in three of the six sites examined and coral cover (41.9 ± 2.5%) was double post-bleaching cover. One shallow near-shore site appears to have had recovery of *Acropora* reset by a further bleaching event in 2002. However, the prevalence of young *Acropora* colonies here indicates that recovery may recur in several years. One area formerly dominated by *Acropora* is now dominated by faviids and poritids, with adult and juvenile composition suggesting this dominance shift is likely to persist. *Porites lutea* and *Porites harrisoni* dominated communities were negligibly impacted by the bleaching events, and the limited change in coral cover and composition in intervening years likely results from slow growth and low recruitment. Despite strong recovery of several dominant *Acropora* species, five formerly common species from this area were not observed suggesting local extinction. Dubai coral communities exhibit both resistance and resilience to elevated sea temperatures. The conservation of these patch reefs is warranted given the predicted increase in bleaching events, and the role that these communities may play in regional recovery.

Introduction

Elevated sea surface temperatures (SSTs) resulting from El Ninõ events in the late 1990s were associated with mass coral bleaching throughout the world (Bruno et al. 2001; Mumby et al. 2001; Carriquiry et al. 2001; Aronson et al. 2002; Bena and van Woesik 2004). Indian Ocean reefs were the most severely impacted, with bleaching resulting in regional loss of 50–90% of coral cover (Obura 2001; Stobart et al. 2005; Sheppard and Obura 2005; Arthur et al. 2006). As a biogeographic subset of the Indian Ocean, the Arabian Gulf was also impacted by these increased SSTs.

The Arabian Gulf is characterized by environmental extremes. Salinity regularly exceeds 45 ppt, and SSTs can annually fluctuate from winter lows less than 12°C to

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J. Burt
Department of Biological Sciences, University of Windsor,
401 Sunset Avenue, N9B3P4 Windsor, ON, Canada

A. Bartholomew
Department of Biology and Chemistry,
American University of Sharjah, PO Box 26666,
Sharjah, United Arab Emirates

P. Usseglio
International Network on Water, Environment and Health,
United Nations University, 50 Main Street East, Hamilton,
ON, L8N1E9, Canada

J. Burt (✉)
Natural Science and Public Health, Zayed University,
Zayed University, PO Box 19282, Dubai, United Arab Emirates
e-mail: John.Burt@zu.ac.ae

summer highs above 36°C (Coles and Fadlallah 1991; Sheppard et al. 1992). These environmental conditions are selective for corals adapted to these extremes, with corals surviving in temperatures that would normally cause mortality in other areas (Coles 2003). As a result, dominant taxa in Arabian Gulf reefs differ from those in the Indo-Pacific, where Gulf fauna are represented by more tolerant taxa such as faviids and siderastreids while more sensitive acroporids are under-represented (Coles 2003). Despite housing a relatively tolerant sub-set of the Indo-Pacific fauna, extreme thermal events do occasionally result in bleaching and mortality. These events generally result in differential mortality of *Acropora* species, while faviids and poritids are often negligibly impacted (Coles and Fadlallah 1991; Riegl 2002a; Sheppard and Loughland 2002).

Coral reefs in the Arabian Gulf were severely affected by thermal bleaching in both 1996 and 1998 (Riegl 2002a). Summer conditions are most extreme in the shallow southern basin of the Arabian Gulf (Sheppard et al. 1992), where SSTs reached 37.7°C during the 1998 bleaching event (Sheppard and Loughland 2002), a 4–8°C increase over temperatures associated with bleaching elsewhere (Bruno et al. 2001; Mumby et al. 2001; Aronson et al. 2002; Sheppard 2003). These high temperatures caused extensive loss of coral cover from patch reefs located along the coastline in the United Arab Emirates (Riegl 1999; George and John 1999; Sheppard and Loughland 2002; Sheppard and Loughland 2002). Dense coral patch reefs in the Saih Al-Shaib and Jebel Ali areas of Dubai, UAE, were heavily impacted by a 2°C positive SST anomaly in the summer of both 1996 and 1998 (Riegl 2002a). Bleaching virtually eliminated *Acropora* species that had constituted over 98.7% of the reef building coral in the area (Riegl 1999), and resulted in a complete loss of corals from a 7.8-km^2 area in Jebel Ali alone (Riegl 2002a).

Recovery from mass bleaching events can take a number of years to occur, if it happens at all. Recruitment levels are typically depressed for several years following bleaching (Aronson et al. 2002; Tamelander 2002; Sheppard and Obura 2005), due to the high mortality in the reproductive population and the reduced fecundity of partially bleached survivors (Baird and Marshall 2002). Following bleaching events, a shift in dominance can occur as a result of space preemption by opportunistic algal and invertebrate competitors (Carriquiry et al. 2001; Aronson et al. 2002; McClanahan et al. 2002), or the coral community composition can change due to differential reproductive success in species less affected by bleaching (Tamelander 2002; Sheppard and Loughland 2002; Sheppard and Obura 2005). Alternatively, assemblages may progressively recover to their pre-bleaching state due to the rapid growth rates of taxa that were most affected by bleaching (Baird and Marshall 2002; Arthur et al. 2005). Coral recovery can be highly site specific as a result of differences in proximity to seeding reefs, hydrodynamic conditions, and the extent of damage (Arthur et al. 2006), making it difficult to predict the extent and direction of recovery.

This study describes the coral assemblages in Saih Al-Shaib nearly a decade after mass coral bleaching, and compares the present coral communities with those described in the area both before and soon after the mass mortality event to determine the extent to which these assemblages have changed since bleaching. Surveys performed through 2002 indicated that coral cover remained low compared with pre-bleaching levels and was composed mainly of bleaching resistant *Porites* and faviid species (Riegl 1999; Purkis and Riegl 2005). However, recruitment of rapidly growing *Acropora* juveniles was also observed in the 2 years after the bleaching event (Riegl 2002a, b). This indicates a potential return to *Acropora* dominance in the area and associated recovery of coral cover to pre-bleaching levels within a matter of years. This study examines both the adult assemblage and patterns of juvenile recruitment to determine whether community composition is stable or if species dominance appears to be shifting. Coral communities in the Arabian Gulf are exposed to rapid and extreme SST elevations. It is important to understand whether the composition and condition of coral assemblages here are resilient to the bleaching that is likely to occur with increasing frequency in the coming decades. Information on these assemblages and their recovery from bleaching may be useful in predicting changes to coral community composition and potential recovery processes in other regions that are likely to be impacted by future increases in SST.

Materials and methods

The Dubai reef is composed of discontinuous coral patches associated with areas of exposed cap-rock approximately 0.5–1 km from shore, and are interspersed between areas of unconsolidated sands and mixed algal assemblages. The size of coral patches differs, but each generally exceeded 1,000 m^2. This series of patch reefs extends approximately 12 km along western Dubai from the Saih Al-Shaib through Jebel Ali areas (Fig. 1). Pre-bleaching communities have been described for the entire area by Riegl (1999). Following the elevated SSTs of 1998, extensive loss of *Acropora* was reported on patch reefs sampled in the Jebel Ali area, while massive corals were negligibly impacted (Purkis and Riegl 2005; Riegl 2002a, b). Similar bleaching response was observed in patch reefs in Saih Al-Shaib (B. Riegl, pers. comm.). To compare current communities with those that had been described for Dubai before and after the 1998 bleaching event, six sites in Saih Al-Shaib were selected for detailed evaluation of coral communities (Fig. 1), and were

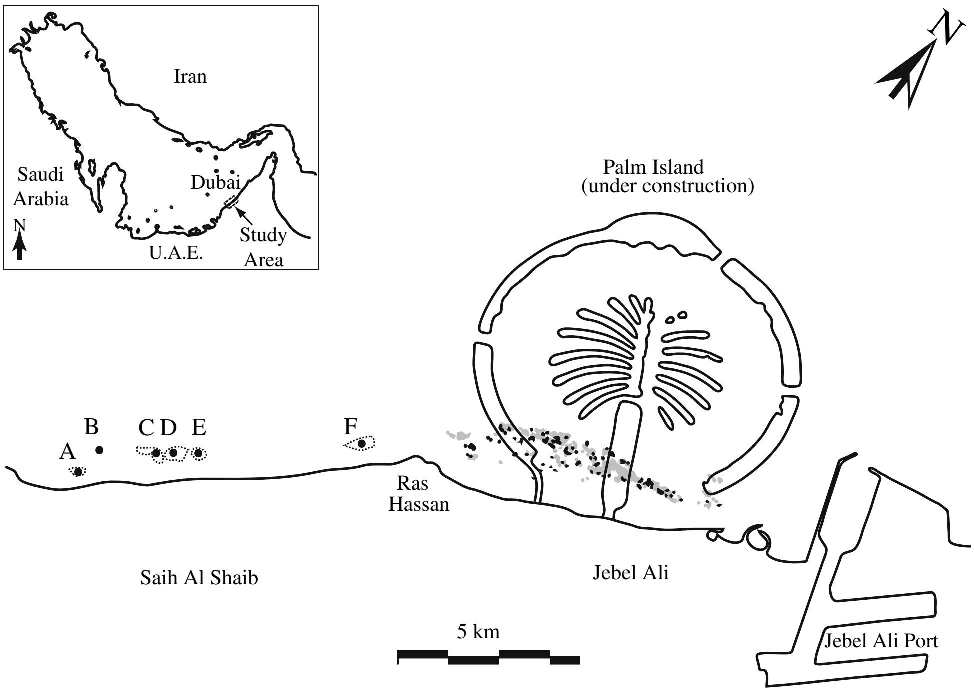

Fig. 1 Map of study area in Dubai, United Arab Emirates. Sampling sites are marked with a *black circle* and labeled. Areas containing dense live coral in Saih Al-Shaib are enclosed by a *dashed line*, but should not be considered exhaustive. In Jebel Ali, areas containing dense live corals (*black*) and dense dead corals (*gray*) following 1996/1998 bleaching are indicated (adapted from Purkis and Riegl 2005). Palm Island construction began in 2002 and is in progress

sampled between 04 September and 23 October 2006. The patch reefs described by Riegl (2002a, b) for the Jebel Ali area could not be re-sampled as they lie in a restricted area that is the site of extensive land reclamation activities.

Within each site six 30 m fibreglass tapes were placed approximately 5 m apart and laid parallel to the coastline. This length is representative of the scale of coral patches in these discontinuous habitats, and is appropriate based upon patch descriptions from earlier studies in the area (Riegl 1999). Depth varied negligibly (<0.5 m) among transects due to the low substrate relief in this area. A total of 21 quadrats were photographed on each transect at 1.5-m intervals, resulting in a total of 126 quadrats per site. Each quadrat enclosed an area of 0.25 m^2. Photographs were taken digitally using a SeaLife DC500 5.0 mega-pixel camera mounted on a PVC frame demarcating the photoquadrat area.

Photoquadrats were analyzed using CPCe software, version 3.4 (Kohler and Gill 2006). Each 0.25-m^2 quadrat was examined using 50 randomly placed points, and the fauna underlying each point were identified to the lowest possible taxa (Veron 2000). Identification from photographs was confirmed visually in the field on subsequent surveys, and microscopically in the laboratory through examination of corallite structure from specimens cleaned using 5% sodium hypochlorite for 4 h at 30°C (Clode and Marshall 2003). Juvenile corals were categorized as those with a maximum diameter of $\leq$4 cm, and were identified to the lowest taxonomic level possible.

Quadrat data were pooled within each transect. Coral percent cover data was transformed using arcsine square root prior to analysis to normalize the data. Preliminary analysis indicated that one transect was an outlier (Transect B6: Ave Sørensen distance = 0.797, SD = 3.98), and was excluded from subsequent analysis (Tabachnick and Fidell 2001). Species occurring in less than 5% of samples were removed prior to multivariate analyses as recommended by McCune and Grace (2002).

Transects were grouped using hierarchical agglomerative cluster analysis. The flexible beta linkage method ($\beta = -0.25$) was applied, using a Sørensen (i.e., Bray–Curtis) distance matrix. Sørensen distance is generally preferred for analysis of community data, and is compatible with this linkage method (McCune and Grace 2002). The resulting dendrogram was scaled by Wishart's objective function converted to a percentage of information remaining (McCune and Mefford 1999).

Indicator species analysis was used to determine the number of ecologically meaningful groups resulting from cluster analysis (Dufrene and Legendre 1997). This method combines information on both the fidelity and the relative abundance of species in a group, such that a species' indicator value is maximum (IV = 100%) when all transects in a group are occupied by that species and it is only found in that group. Indicator values for each species were calculated for 2–20 possible groups resulting from the cluster analysis using PC-ORD (McCune and Mefford 1999), and statistical significance was evaluated using a randomly seeded Monte Carlo test with 1,000 iterations. The optimum number of groups was selected as that which provided the maximum number of significant indicator species, as well as the lowest average *P*-value (Dufrene and Legendre

1997). The species with significant indicator values were also subsequently used to characterize the coral communities in these groups.

Univariate comparisons of substrate coverage employed non-parametric Kruskal–Wallis ANOVA and post hoc Mann–Whitney *U*-tests. The diversity of each group identified from cluster analysis was examined by calculating the Shannon–Wiener diversity index, inclusive of rare species. Pair-wise comparisons between group indices were performed using the Shannon *t*-test (Zar 1996). To assess the adequacy of sampling, species-area curves were generated in PC-ORD (McCune and Mefford 1999), where the curve represents the mean number of species from 500 sub-samples for each possible sample size and associated estimates of standard deviation. The abundance of juvenile corals was compared among assemblages using a Kruskal–Wallis ANOVA and post hoc Mann–Whitney *U*-tests.

Results

A total of 25 coral species were found in Saih Al-Shaib, with a mean richness of 12.8 ± 2.1 species per transect (mean ± SD). The most common species were *Porites harrisoni* (23.5% of living coral), *Porites lutea* (22.2%), *Cyphastrea microphthalma* (13.4%), *Acropora downingi* (9.1%), *Acropora clathrata* (7.9%), and *Platygyra daedalea* (5.7%), with remaining species each representing less than 5% of coral cover. Overall coral cover in Saih Al-Shaib was 35.0 ± 1.6 % (mean ± SE). A species area curve was generated to assess the adequacy of sampling. Species accumulation was asymptotic with ten transects capturing 90% of the maximum richness, indicating that the sampling design was sufficient to catalogue diversity in this area.

Cluster analysis was used to group transects, and species indicator analysis was applied to optimize the number of biologically meaningful groups from cluster analysis. Five groups (clusters) yielded the lowest average *P*-value from Monte Carlo significance tests (average $P = 0.091$ for all species) and maximized the number of significant indicator species (17 of the 26 species) compared with all other grouping combinations examined. Trimming the dendrogram from cluster analysis at five groups provided a good compromise between information loss (approximately 53% retained) and summarizing affinities among groups (Fig. 2). The biological characteristics of the five community groups are summarized in Table 1 and described below.

> Group 1: This community was characterized by small massive corals and extensive *Acropora* rubble. Live coral cover in this group was 26.0 ± 1.6%, mainly dominated by *Porites lutea* (42.1 ± 5.4% of living coral cover), *Cyphastrea microphthalma* (16.8 ± 0.8%), and *Platygyra daedalea* (7.7 ± 1.1%). One species, *Acanthastraea echinata*, was characteristic of this assemblage having a species indicator value of 50 in this group, and was absent from all other groups (Table 1). This assemblage was distinct to Site A, a shallow (approx. 4 m depth) near-shore site where *Acropora* rubble was significantly more frequent

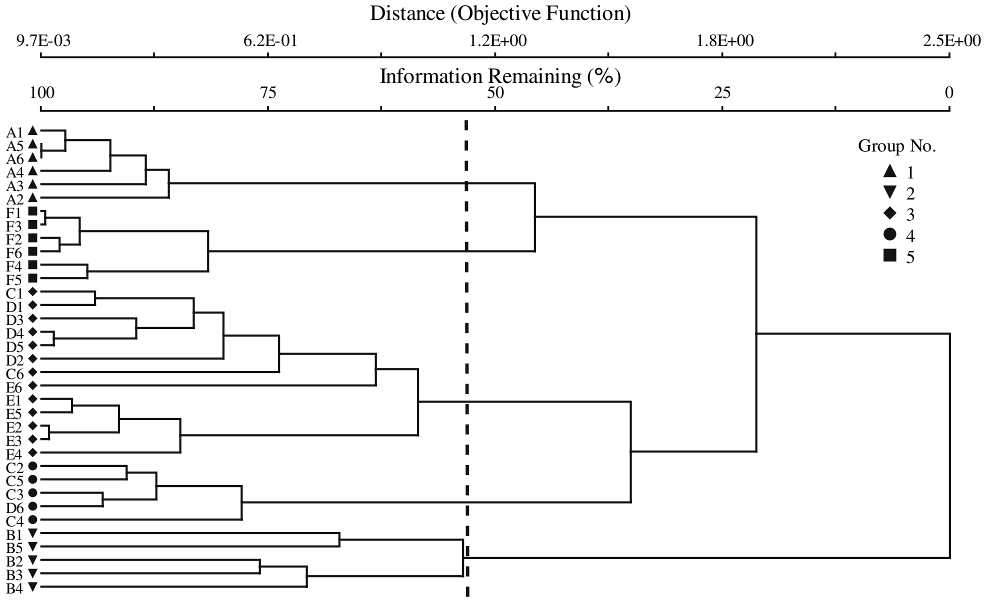

Fig. 2 Dendrogram of transect groups generated from cluster analysis. *Symbols* correspond with community groups described in Table 1. The cut point is indicated by the *dashed line*, which represents the grouping combination with the highest number of significant species and lowest average *P*-value from indicator species analysis. Transects are indicated by the *letter-number code* (site-replicate)

Table 1 Biological characteristics of coral community groups identified from cluster analysis (Fig. 3)

Group	Coral cover (% ± SE)	Assemblage description	Indicator species	Richness	Shannon–Wiener *H*
Group 1	26.0 ± 1.6	Small massive *Porites* with extensive *Acropora* rubble	*Acanthastraea echinata* (50)	16	1.83
Group 2	7.6 ± 0.6	Sparse small massive *Porites lutea*	None	16	1.69
Group 3	41.9 ± 2.5	Dense tabular *Acropora*	*Acropora valenciennesi* (60) *Acropora clathrata* (57) *Acropora downingi* (40) *Leptastrea transversa* (38) *Platygyra daedalea* (35)	24	2.34
Group 4	37.3 ± 2.4	Dense columnar *Porites harrisoni*	*Porites harrisoni* (49)	19	1.51
Group 5	34.7 ± 2.1	Small massive faviids and *Porites*	*Coscinaraea monile* (57) *Favia pallida* (56) *Cyphastrea serailia* (51) *Platygyra lamellina* (41) *Psammocora contigua* (41) *Favia rotumana* (38) *Pseudosiderastrea tayamai* (35) *Turbinaria reniformis* (32) *Porites lutea* (31)	18	1.91

Assemblage description summarizes the ecologically and spatially dominant taxa associated with each group, along with their growth form. Indicator species are those which had significant indicator values (given in parentheses) compared with randomized values from Monte Carlo tests ($P < 0.05$). Indicator species are listed in descending order of each species' indicator value to a group, not taxonomic affinity

(20.4 ± 0.7% of space) than at any other site (overall mean: 4.6 ± 0.6%) (Kruskal–Wallis ANOVA: $H_{(4,N=35)} = 23.1$, $P < 0.001$; Post hoc Mann–Whitney *U*-tests: $P < 0.001$ for each).

Group 2: This assemblage is characterized by sparse massive corals separated by large areas of pavement and sand. Overall coral cover was significantly lower in this group (7.6 ± 0.8% of substratum) than in any other groups (overall mean: 36.5 ± 1.7%; Kruskal–Wallis ANOVA: $H_{(4,N=35)} = 23.0$, $P < 0.001$; Post hoc Mann–Whitney *U*-tests: $P < 0.01$ for each.). *Porites lutea* made up almost half of the live coral observed in this site (48.7 ± 5.2% of live coral cover). No species had significant indicator values in this group (Table 1), indicating that no species had high fidelity for this assemblage and/or none were common among transects representing this group. Bare pavement was significantly more common here (40.1 ± 5.7% of total substratum) than in other groups (overall mean: 5.9 ± 1.5%; Kruskal–Wallis ANOVA: $H_{(5,N=35)} = 22.4$, $P < 0.001$; Post hoc Mann–Whitney *U*-tests: $P < 0.001$ for each). Although this group included only transects from Site B, this community was observed to be the most widespread in the area.

Group 3: Large tabular *Acropora* dominated this community, making up 32% of the 41.9 ± 2.5% live coral cover in this assemblage. Coral cover was significantly more abundant in this group than in groups 1 and 2 (Mann–Whitney *U*-tests: $Z = -3.24$, $P < 0.01$ and $Z = -3.20$, $P < 0.01$, respectively). Tabular *Acropora* dominated this assemblage, with significantly higher coverage here than in any other group (Overall mean of other groups: 2.1 ± 0.6; Kruskal–Wallis ANOVA: $H_{(4,N=35)} = 30.1$, $P < 0.001$; Post hoc Mann–Whitney *U*-tests: $P < 0.01$ for each). *Acropora* colonies were generally larger than 1–1.5 m in maximum diameter. Three *Acropora* species were significant indicators of Group 3 (Table 1), including *Acropora clathrata* (IV = 57), *Acropora downingi* (40), *Acropora valenciennesi* (60). In addition *Platygyra daedalea* (IV = 35), and *Leptastrea transversa* (38) were also common to this assemblage. This community included 24 of the 25 species observed in this study, with a Shannon–Wiener diversity index significantly higher than any other group (Table 1; Pair-wise Shannon *t*-tests, $P < 0.05$ for each). This assemblage was generally associated with low relief areas of sand covered limestone found at sites C, D, and E, and it graded into the group 2 and group 4 assemblages. Coral rubble occupied 6.0 ± 1.1% of total space in this assemblage.

Group 4: The columnar *Porites harrisoni* dominated the Group 4 assemblage, making up two-thirds of live coral cover (24.6 ± 1.2 of 37.3 ± 2.4%). This species had an indicator value of 49%, and was significantly more abundant in this group than in any other group (Overall mean of other groups: 3.8 ± 0.7%; Kruskal–Wallis ANOVA: $H_{(4,N=35)} = 27.7$, $P < 0.001$; Post hoc Mann–Whitney U-tests: $P < 0.01$ for each). Despite having 19 of the 25 species observed in this study, Shannon–Wiener diversity was significantly lower in this group than in any other group (Table 1; Pair-wise Shannon t-tests, $P < 0.05$ for each), reflecting low species evenness because of the dominance of *Porites harrisoni* in this assemblage. This assemblage was generally associated with elevated limestone ridges found at Site C and Site D, and was usually located at the periphery of the *Acropora* dominated Group 3 assemblage. Surrounding substrate was mainly coarse sand with occasional limestone pavement outcrops. Coral rubble occupied 4.5 ± 1.0% of space.

Group 5: This assemblage was characterized by shared dominance of faviids and poritids. Ten significant indicator species characterized this community: *Coscinaraea monile* (IV = 57), *Cyphastrea microphthalma* (31), *Cyphastrea serailia* (51), *Favia pallida* (56), *Favia rotumana* (38), *Platygyra lamellina* (41*), Porites lutea* (31), *Psammocora contigua* (41), *Pseudosiderastrea tayamai* (35), and *Turbinaria reniformis* (32) (Table 1). *Acropora* comprised 0.3 ± 0.1% of substrate cover. This assemblage was spatially distinct, with representation occurring only at Site F, where corals were associated with low relief limestone outcrops surrounded by pockets of sand. Although this assemblage was observed to be widely distributed in the area immediately surrounding Site F, it was not observed elsewhere in the survey area. Here, coral rubble occupied 5.5 ± 0.6% of substrates.

Mean density of juvenile corals across all assemblages was 0.8 ± 0.2 recruits m^{-2}, and differed significantly among the assemblages described above (Kruskal–Wallis ANOVA: $H_{(4,N=35)} = 21.1$, $P < 0.001$). Groups 2 and 5 had the highest juvenile density, and did not differ significantly from each other (Mann–Whitney U-test). Group 1 had significantly fewer juveniles than Group 5, while Groups 3 and 4 had significantly lower density than all other groups based on post hoc Mann–Whitney U-tests ($P < 0.05$; Fig. 3a). Most juveniles were either *Porites* or faviids (59.4 and 16.7% of recruits, respectively). *Acropora* made up less than 2% of all juvenile corals observed. The relative composition of coral recruits generally reflected that of the current adult composition within each assemblage, with the exception of the *Acropora* dominated group 3 (Fig. 3b). Here, *Acropora* recruits represented 12.5% of juvenile corals despite representing almost a third of the live coral cover, and *Porites* represented 62.5% of juveniles compared with an adult population representing just over a third of live cover.

Discussion and conclusions

Elevated SSTs during the summers of 1996 and 1998 resulted in extensive loss of corals from patch reefs along hundreds of kilometres of coastline of the United Arab Emirates (Riegl 1999; George and John 1999; Sheppard and Loughland 2002). Similar to bleached reefs in other regions (Loya et al. 2001; Sheppard and Obura 2005; Arthur et al. 2006), some coral species were more vulnerable to bleaching than others. In the Arabian Gulf, dominant *Acropora* species were virtually eliminated, resulting in stands of dead coral skeletons extending over large areas of patch reefs (Sheppard and Loughland 2002; Riegl 2002a, b). Faviids and *Porites* were less affected by mortality (Riegl 1999; Sheppard and Loughland 2002), and recovery of partially bleached colonies was common (George and John 1999). In the decade since the mass bleaching event, there are signs of extensive recovery of *Acropora* cover in parts of Saih Al-Shaib, and there is little evidence of a

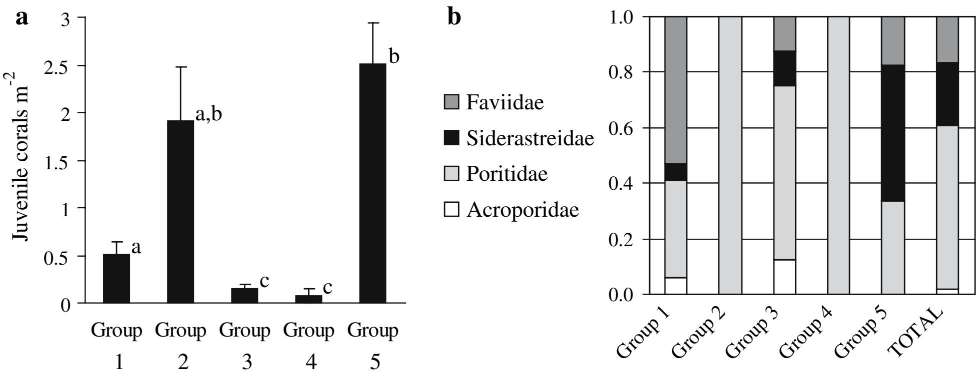

Fig. 3 Density and composition of coral juveniles in the five assemblages identified from cluster analysis. **a** Density of coral juveniles for each group (mean ± SE m^{-2}). *Letters* indicate significant differences based on Mann–Whitney U-tests ($P < 0.05$). **b** Relative abundance of juveniles by family for each assemblage group, and the overall total

phase-shift in coral dominance to species less affected by bleaching, except at site F (see below).

Prior to the mass mortality event, coral cover in *Acropora* dominated assemblages in the Saih Al-Shaib area was 62 ± 24%, and *Acropora* was represented by six species (Riegl 2002a). Following the 1998 bleaching event, live coral cover fell to 22 ± 10% (Riegl 2002a), and *Acropora* was virtually eliminated with only five partially bleached colonies observed in the entire 37.7 km^2 study area (Riegl 1999). Overall species richness fell from 34 to 27 species (Riegl 2002a). In the current study *Acropora* were observed in five of the six sites examined and dominated assemblages at three of these sites. Coral cover in the *Acropora* dominated assemblage (Group 3) is now 41.9 ± 2.5%, nearly double that observed after the mass mortality event. This *Acropora* dominated assemblage is found in sites C, D, and E, areas formerly dominated by *Acropora* that had suffered substantial loss during the bleaching event (Riegl 1999). Although coral cover remains lower than pre-bleaching levels it is likely that recovery will continue barring any additional disturbances. Many *Acropora* colonies in this assemblage are approximately 1 m in diameter, supporting earlier growth rate estimates of 10 cm year^{-1} for this genus in the Arabian Gulf (Coles and Fadlallah 1991). Coral cover will likely continue to increase for the next few years as the common *Acropora clathrata* and *Acropora downingi* colonies approach the 1.5 m size typical of these species (Fadlallah 1996). Similar recovery of coral cover through rapid re-growth of new *Acropora* colonies has been observed on bleached reefs elsewhere (Loya et al. 2001; Arthur et al. 2005, 2006), even in cases where juvenile recruitment is depressed (Tamelander 2002). Rapid *Acropora* growth rates appear to compensate for the low recruitment levels observed in this assemblage in Saih Al-Shaib, allowing coral cover to recover quickly. Although coral cover is increasing, species richness remains depressed in this assemblage. Several *Acropora* species previously reported as common to Dubai (Riegl 1999) were absent from the present study, including *Acropora arabensis*, *Acropora horrida*, *Acropora florida*, *Acropora valida* and *Acropora tenuis*, and *Acropora pharaonis* is now uncommon. Similar diversity loss has followed bleaching in other areas (Loya et al. 2001; Sheppard and Loughland 2002; Tamelander 2002), with richness remaining depressed for years afterwards despite improvements in coral cover (Sheppard and Obura 2005; Lambo and Ormond 2006). Despite the loss of several species, over 85% of the *Acropora* cover is composed of the same species that had dominated *Acropora* assemblages in the Arabian Gulf prior to the bleaching event, *Acropora clathrata* and *Acropora downingi* (Fadlallah 1996; Riegl 2002a). The recovery of these dominant species indicates that although there has been a loss of species richness, long-term ecosystem function may not be substantially impaired as a result of bleaching.

In this study the faviid/*Porites* dominated assemblage (Group 5) occupies an area that was dominated by *Acropora* before the mass bleaching events of the late 1990s (Site F; see map in Riegl 2002a, b). *Acropora* now contributes less than 1% of coral cover in this area. Faviids and *Porites* have been widely reported to be among the most resistant taxa on reefs affected by thermal bleaching throughout the world (Loya et al. 2001; Obura 2001; Baird and Marshall 2002; Sheppard and Obura 2005). This was also true in Dubai, where the elevated SSTs in both 1996 and 1998 had negligible impact on the live coral coverage and species richness of faviids and *Porites* (Riegl 1999, 2002a). The differential survival and subsequent reproductive success of such bleaching resistant taxa has been suggested to contribute to shifts in coral dominance (Tamelander 2002; Sheppard and Loughland 2002). This appears to be occurring at site F. This site is now dominated by bleaching resistant taxa, and current coral cover of these taxa (34.7 ± 2.1%) is double that observed following the bleaching event in areas that were formerly *Acropora* dominated (mean: 17%, Riegl 1999), and in compositionally similar faviid dominated assemblages in the area both before and after the bleaching event (16 ± 4%, Riegl 1999). This site also contained the highest densities of coral juveniles in all of Saih Al-Shaib, and the composition of juveniles reflected the composition of adults with faviids, siderastreids, and poritids dominating recruitment. *Acropora* juveniles were not observed. These patterns of recruitment coupled with the increased coral cover compared with similar assemblages in 1998 indicate that there has been a shift in coral dominance at this site in the decade following the mass bleaching event, and that it is unlikely that *Acropora* will regain dominance in the near future.

The assemblage dominated by small massive corals and *Acropora* rubble (Group 1) appears to have experienced *Acropora* bleaching in recent years. Similar to the *Acropora* dominated Group 3 assemblage, the presence of several large (1–1.5 m) *Acropora* colonies indicate that this assemblage was recovering from the 1996 and 1998 bleaching event. However, extensive *Acropora* rubble covering approximately a fifth of the substratum compared with less than 5% in other assemblages, and the lack of standing dead *Acropora* skeletons known to persist for several years after bleaching (Riegl 1999, 2002a; Sheppard and Loughland 2002) suggest that many *Acropora* were killed in the years since the 1998 bleaching event, most likely in 2002. Elevated SSTs in the summer of 2002 were associated with coral bleaching events in the Arabian Gulf and surroundings (Dodge 2002; Wilkinson 2004), and coral bleaching was also observed on near-shore reefs in the Jebel Ali area, 10 km west of Saih Al-Shaib (Dodge 2002; B. Riegl, pers.

comm.). It is likely that this 2002 bleaching event also reset recovery of *Acropora* on the patch reef at site A due to its shallow depth. This assemblage occurs at a 3- to 4-m depth, while intact *Acropora* assemblages elsewhere in Saih Al-Shaib (Group 3) occur at approximately 6 m depth. Shallow depth has been related to increased levels of coral bleaching (Mumby et al. 2001; Sheppard and Loughland 2002; Bena and van Woesik 2004; Stobart et al. 2005), and this assemblage lies within the 3–5 m 'critical depth' associated with severe bleaching in the Arabian Gulf (Sheppard and Obura 2005), making it more susceptible to elevated SST. This assemblage may recover *Acropora* dominance over time unless interrupted by future bleaching events or anthropogenic disturbance. Currently, there are several large *Acropora* colonies that appear to have survived the 2002 bleaching event, as well as a number of young colonies 30–40 cm in diameter which have likely recruited in the years since. Although *Acropora* juveniles are currently a minor component of the recruiting assemblage, we predict that *Acropora* recruitment will increase in the next few years as young colonies become reproductive, generally occurring at approximately 50 cm (Hall and Hughes 1996). The rapid growth rates and increasing fecundity with size should contribute to the rapid recovery of *Acropora* in this assemblage, provided that there are no further disturbances.

The recovery of the formerly dominant *Acropora* is highly site specific. In general, recovery is highest in western Saih Al-Shaib. This may be a reflection of either natural settlement processes or the influence of coastal development in the area. Early post-bleaching *Acropora* recruitment in 1999 was observed to decline from west to east in Dubai (Riegl 2002a). This pattern of recruitment follows the direction of prevailing coastal currents in the area (Wilkinson 2004; Smit et al. 2005), and suggests that this area is being seeded by reefs 30 km upstream which had *Acropora* survive the 1998 bleaching event (Riegl 2002a). However, it is also possible that large scale coastal development extending several kilometers east of Saih Al-Shaib may have affected recovery. The patch reef closest to this development is currently dominated by sediment tolerant faviids and poritids, and the more sensitive *Acropora* now account for less than 1% of the live coral cover a that site. Because this area was not sampled between 2002 and 2006, it is unknown to what extent either propogule supply or human influence has affected this recovery. Continued monitoring of the area is warranted.

The remaining assemblages in Saih Al-Shaib are dominated by *Porites*. *Porites* are generally tolerant of elevated SSTs (Obura 2001; Loya et al. 2001; Baird and Marshall 2002; Sheppard and Loughland 2002; Sheppard and Obura 2005), and the sparse *Porites lutea* and the dense *Porites harrisoni* dominated assemblages in the Saih Al-Shaib area were negligibly impacted by the 1996 and 1998 bleaching event (Riegl 1999, 2002a). In the intervening years, these assemblages have changed little in Saih Al-Shaib. Coral cover has not increased in either of the *Porites* dominated assemblages (Groups 2 and 4) compared with pre-bleaching coverage. It is also unlikely that there will be substantial increases in coral cover for these assemblages in the near future due to the slow growth rate known for both *Porites* adults (Yap et al. 1998; Baird and Marshall 2002; Flora and Ely 2003) and juveniles (Tamelander 2002). This is particularly true in the dense *Porites harrisoni* assemblage which had the lowest recruit density of all assemblages, indicating that any increases in coral cover will result mainly from vegetative growth of adult colonies. Like coral cover, composition and diversity in these *Porites* dominated assemblages remains comparable to that observed prior to the bleaching event (Riegl 1999, 2002a). Because the current juvenile composition in each assemblage reflects that of the adult population it is likely that the community composition is stable. Thus, coral coverage and composition in the sparse *Porites lutea* assemblage (Group 2) and the dense *Porites harrisoni* (Group 4) assemblages remain comparable to pre-bleaching levels.

In the first 5 years following the 1998 bleaching event most impacted reefs worldwide showed little recovery of coral cover compared with pre-bleaching levels (Aronson et al. 2002; Riegl 2002a; McClanahan et al. 2005; Stobart et al. 2005; Sheppard and Obura 2005). However, the presence of abundant juvenile recruits (Tamelander 2002; Stobart et al. 2005; Sheppard and Obura 2005), with densities increasing through time (Aronson et al. 2002; Sheppard and Obura 2005), suggested that recovery was beginning in many areas. Ten years after the 1996 mass mortality of *Acropora* in Dubai (Riegl 1999, 2002a), *Acropora* cover shows strong signs of recovery in parts of Saih Al-Shaib, and despite the loss of several species *Acropora clathrata* and *Acropora downingi* have recovered their former dominance. The resilience of this assemblage appears due, in part, to the rapid growth rates of these species. Other assemblages in Saih Al-Shaib, dominated by more temperature-tolerant taxa such as faviids, *Porites harrisoni*, and *Porites lutea*, were negligibly impacted by the bleaching events of the late 1990s (Riegl 1999, 2002a). The differential survival of taxa in these assemblages has not resulted in the predicted phase-shift in coral dominance in the area (Sheppard and Loughland 2002; Sheppard and Obura 2005), most likely because localized coral recruitment has resulted in self-seeding assemblages and because the slow growth rates of most bleaching resistant taxa inhibits competitive overgrowth of available substrates. There has also not been a phase-shift to dominance by macro-algae. Similar observations have been made in other areas recovering from bleaching (Arthur et al. 2005, 2006; Stobart et al. 2005), and macro-algae cannot achieve long-term dominance in this region due to seasonal die-offs (Ateweberhan et al. 2006).

The patterns of resilience and resistance observed in Saih Al-Shaib have important implications both regionally and globally. The southern Arabian Gulf experiences repeated mass coral mortality on a 10–15-year cycle due to recurrent thermal anomalies (Riegl 1999, 2001, 2002b; Purkis and Riegl 2005). This has resulted in corals which are acclimatized and adapted to extreme environmental conditions (Coles and Fadlallah 1991; Coles and Brown 2003; Coles 2003), capable of both enhanced survival through both high and low temperature extremes as well as relatively rapid recovery from bleaching events. The comparatively minimal loss of species richness in the Saih Al-Shaib (11%) compared with other areas (>50%; Loya et al. 2001; Sheppard and Obura 2005; Lambo and Ormond 2006), during the most extreme bleaching event on record (West and Salm 2003; McClanahan et al. 2005) provides further evidence of tolerance to temperature extremes. This is particularly true given that temperatures here were 4–10°C higher than associated with bleaching elsewhere (Bruno et al. 2001; Wellington et al. 2001; Mumby et al. 2001; Aronson et al. 2002; Sheppard 2003). Given that elevated SSTs are predicted to continue increase in both magnitude and frequency in the coming decades (Sheppard 2003; Coles and Brown 2003), such patterns of resistance and resilience may approximate what will occur in more stable reef environments in the tropics in the future. Those taxa more tolerant of high temperatures or more capable of rapid re-colonization and growth may come to dominate in areas affected by increasing SSTs, while those less tolerant and slower growing species may eventually become regionally extinct. Like Saih Al-Shaib, reefs experiencing repeated bleaching may recover coral cover to pre-bleaching levels, but diversity will likely decline through time eventually becoming dominated by a low-diversity subset of the original fauna which is more adapted to extreme conditions. The ability of species to acclimatize to increasing temperatures will also be important (Coles and Brown 2003). The predicted 5-year cycle of bleaching events expected to affect low latitude reefs may be too frequent to allow many populations to adapt (Sheppard 2003). However, the rapid recovery of corals following major stress events 2–4 years apart observed in this study does indicate that regional pockets of resilient taxa can withstand these perturbations.

Coral patch reefs in the Saih Al-Shaib area exhibit both resistance and resilience to the impacts of high SSTs, and are among the richest assemblages in the Arabian Gulf (Riegl 1999; Coles 2003). Such areas are considered a priority for coral reef conservation and management efforts because they are likely to support recovery of regional reefs predicted to be affected by bleaching in the coming decades (West and Salm 2003). However, large-scale coastal development, land reclamation projects, and development of desalination facilities throughout Dubai are a threat to these patch reefs (Wilkinson 2004). A number of these current and proposed developments are within several hundred meters of reefs surveyed in this study and are likely to directly affect these coral communities through burial or sedimentation, or indirectly through modification of nearshore water movement and large-scale changes in coastal currents. It is possible that these direct and indirect impacts may inhibit or even eliminate the natural recovery and resilience capacity of even these hardy corals and coral reef communities. The immediate protection and conservation of surviving coral communities in this area is warranted.

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