Chapter 11
Coral Reefs of the Emirates

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11.1 UAE Coral Reefs in a Global and Regional Context

Coral reefs extend across the tropics from the Tropic of Cancer to the Tropic of Capricorn (30 °N to 30 °S), mainly in shallow coastal areas. They are among the most diverse ecosystems on earth, covering less than 0.1% of the ocean yet containing over a quarter of all marine species—a level of diversity comparable to tropical rainforests (Hoegh-Guldberg et al. 2017). They are also important for humanity, providing coastal protection, food, and livelihoods to over 850 million people, nearly a tenth of the global population (Burke et al. 2011). They are also economically important and are classified as the most valuable ecosystem on earth on a per unit area basis (over US $35 million/km^2/year), each year providing over US $9 trillion in goods and services globally, equating to nearly 8% of annual global GDP (de Groot et al. 2012; 2007 dollars; Costanza et al. 2014).

Over 6% of the world's coral reefs (15,000 km^2) occur in the Arabian region, largely made up by the extensive reef systems of the Red Sea and Gulf of Aden (Souter et al. 2021). Northeastern Arabia is broken into two marine biogeographic provinces with very distinct environmental conditions: the Sea of Oman and the Arabian Gulf (see Chap. 4; Sheppard et al. 1992; Briggs and Bowen 2012). While environmental conditions in the Sea of Oman are more benign and therefore more suitable for coral growth, the sharp increase in depth near the coast and the generally sandy sea-bottom make much of the Sea of Oman coastline unsuitable for coral growth (Burt et al. 2016). As a result, while the environment supports high coral diversity (ca. 120 species), only a modest area (196 km^2) is occupied by coral reefs across the Sea of Oman's entire coast (Claereboudt 2019; Burt et al. 2021b). In

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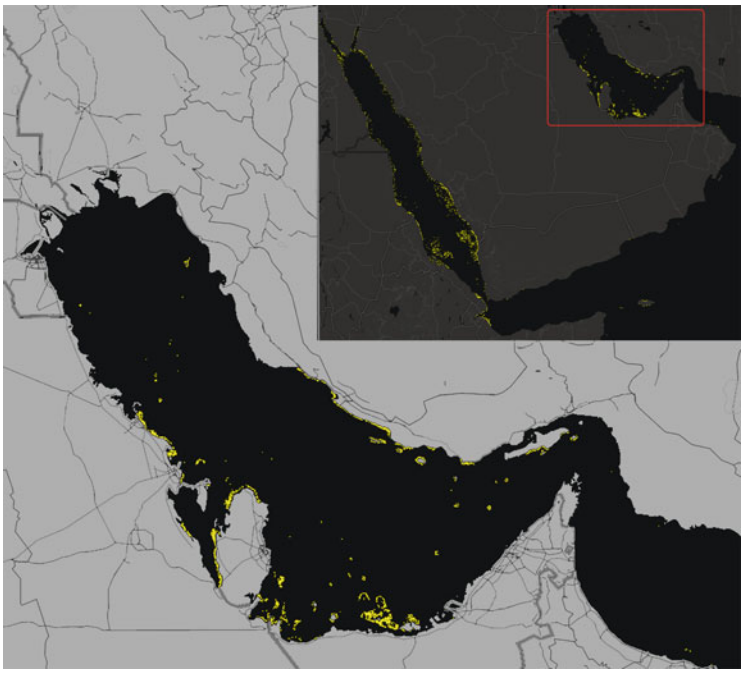

Fig. 11.1 Map illustrating the location of mapped coral reefs across the Arabian region, including the Arabian Gulf. In total, 6% of the world's coral reefs occur in Arabia, and corals occur in all eight nations bordering the Arabian Gulf. Map source: Modified from Allen Coral Atlas (2022) and shared under Creative Commons license (CC BY 4.0)

contrast, coral reefs have far greater area of coverage in the Arabian Gulf, where shallow water (mean depth <30 m) and widespread availability of hard-bottom support 1482 km^2 of reef habitat (Fig. 11.1) (Vaughan et al. 2019; Burt et al. 2021b). However, the shallow, semi-enclosed nature of the Gulf results in a marine environment that is characterized by extremes in salinity and temperature, particularly towards the southwest (see Chap. 4; Vaughan et al. 2019). As a result, while reefs are widespread, the diversity and complexity of reefs drops markedly with distance from the entrance of the Gulf. Approximately 70 coral species occur at the Strait of Hormuz (a third lower than in the wider Sea of Oman), dropping to around 50 species in the northwestern Gulf near Kuwait and Saudi Arabia, with the lowest diversity occurring in the southern basin along the coast of the United Arab Emirates (UAE) where 34 species have been reported (Sheppard and Sheppard 1991; Riegl et al. 2012; Bouwmeester et al. 2022). As a result of its young age, small size, high latitude (27–30 °N) and extreme environmental conditions, the Gulf contains only about a tenth of the coral diversity occurring in the wider Indo-Pacific, with only two regionally endemic coral species (*Acropora downingi* and *Porites harrisoni*) (Coles 2003). Reef complexity also varies with environmental conditions. True reefs, where corals grow on top of skeletal remains of older corals, only occur around the entrance

of the Gulf at the Strait of Hormuz and around the offshore islands of Kuwait and Saudi Arabia, while reefs of the southern Gulf near the UAE are best described as 'coral carpets', where individual coral colonies grow as a single layer directly on rocky substrates (Sheppard and Sheppard 1991; Carpenter 1997; Riegl et al. 2012).

11.2 Coral Distribution and Diversity in the Emirates

Corals reefs in the Emirates fall into several distinct assemblage types that are largely structured by the prevailing environmental conditions in the local marine systems. Each of these are discussed separately below.

11.2.1 East Coast Reefs

In the UAE corals only occur where rocky habitats emerge from the sands that dominate the sea-bottom on both coasts. On the Sea of Oman coast, these occur mainly as headlands and nearshore islands that push out past the gravel plains at the base of the Hajar mountains (Fig. 11.2). Areas with the most extensive coral growth occur at rocky promontories around Dibba, Al Aqah, Mirbah, and Khor Fakkan; no reefs occur south of Khor Fakkan due to the absence of rocky substrate on this sandy coast. Virtually all corals on the East Coast occur in a narrow band of just a few tens of meters from the shoreline due to the steep slope, with corals largely restricted to $<$15 m depth. The relatively benign environmental conditions here are more typical of the Indian Ocean and support the highest diversity of corals in the UAE, estimated at approximately 60 species, although this is likely an underestimate as

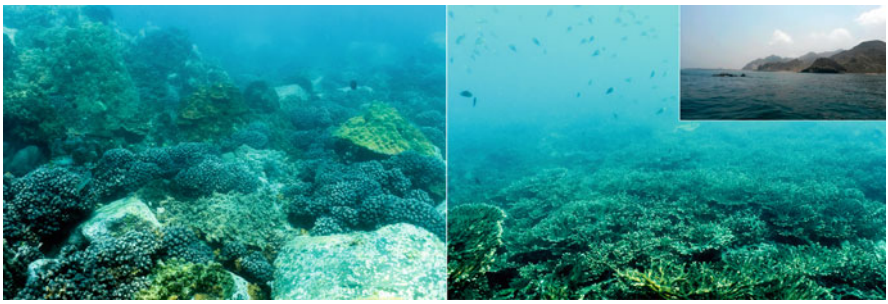

Fig. 11.2 Diverse coral reefs occur on the UAE's east coast wherever the Hajar Mountain headlands extend into the Sea of Oman (right inset), providing rocky bottom that supports coral growth. A mixed coral assemblage at Martini Wall (left) is mainly made up of mound corals (*Porites*, background) and cauliflower coral (*Pocillopora*, foreground), while table corals (*Acropora*) dominate Shark Island (right), both in Khor Fakkan. Photographer: John Burt

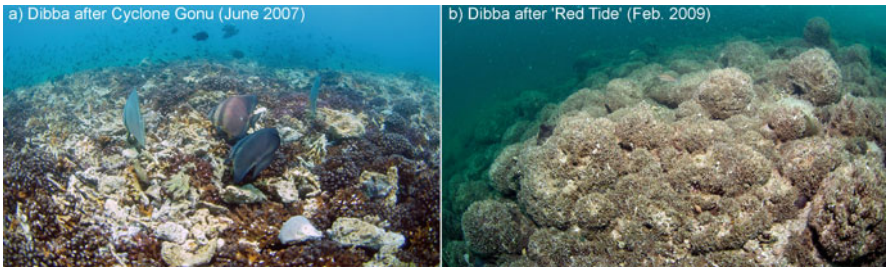

Fig. 11.3 A dense stand of cauliflower coral (*Pocillopora damicornis*) at Dibba Rock was impacted by (**a**) wave action during supercyclone Gonu in 2007 and by (**b**) low oxygen during a harmful algal bloom (HAB) in 2008/9, after which the corals were colonized by algae. Such impacts extended across most UAE east coast reefs. Images: Maral Chreiki (**a**) and Rita Bento (**b**)

comprehensive surveys (particularly of the large corals stands around Khor Fakkan) have not yet been published.

Coral reefs on the UAE's east coast have largely escaped the impacts of coastal development that have affected many nearshore reefs on the Arabian Gulf coast (see below), and the deeper adjacent waters have historically buffered corals against marine heat waves. However, two major back-to-back disturbances in the late 2000s resulted in the first record of wide-scale coral loss in this area.

In 2007 Supercyclone Gonu struck reefs across the Sea of Oman with sustained winds of over 270 km/h and waves reaching 5 m height (Fritz et al. 2010). The resulting storm surge heavily impacted the UAE's east coast, causing the loss of over half of coral from many reefs, with breakage and dislodgement particularly acute for the fragile branching corals (e.g. *Acropora* table corals and *Pocillopora* cauliflower corals) that had dominated these reefs (Fig. 11.3a) (Foster et al. 2008, 2011). Unfortunately, this was followed the next year by a severe harmful algal bloom (HAB) which caused oxygen-deprivation in waters across the northern portion of the UAE's east coast (Dibba to Mirbah) that persisted for several months (Bauman et al. 2010). This long-term exposure to hypoxia caused mortality of >80% of corals in many areas (Fig. 11.3b), and the local extirpation of particularly sensitive coral species (Bauman et al. 2010; Foster et al. 2011).

Despite the dramatic impacts to the UAE's northern east coast reefs in the late 2000s, recovery was underway within several years. Although there was only modest improvement in the total amount of coral on Sea of Oman reefs between 2009 and 2011 (Bento et al. 2016), juvenile colonies of table corals (*Acropora*), cauliflower corals (*Pocillopora*) and smooth cauliflower corals (*Stylophora*)—groups that had been particularly heavily impacted by earlier events—were observed in reef surveys performed in 2012 (Pratchett et al. 2017), indicating that recovery was underway. It generally takes 10–15 years for coral reefs to recover from a severe disturbance (Burt et al. 2008; Gilmour et al. 2013), suggesting that follow-up surveys of the coral reefs at these sites are warranted to determine the extent of recovery.

Fig. 11.4 Soft corals such as this colorful *Dendronephytha* sp. are common on the east coast (here, Khor Fakkan), but are absent on the UAE's Arabian Gulf coastal reefs south of Ras Al Khaimah, presumably due to environmental differences. They can be observed on far offshore islands in the Gulf, such as Sir Bu Nair, where conditions are more less extreme due to deeper water, but are uncommon. Photographer: John Burt

While the extensive coral reefs of Khor Fakkan, further to the south, were also impacted by Cyclone Gonu, they escaped most of the impact of the HAB event that afflicted reefs to the north near Dibba and Mirbah. Although Cyclone Gonu did cause breakage and fragmentation of much of the complex table corals (*Acropora*) that dominated these reefs down to ~7 m depth (Maghsoudlou et al. 2008), this did not lead to local extirpation. Because each fragment is capable of adhering to the bottom and growing into a new individual, within several years many of the fragments had grown into new colonies. Given the rapid growth rates (10–15 cm/year) of table corals, anecdotal observations suggested that much of the table coral community had recovered across Khor Fakkan within several years.

More delicate soft corals such as *Sinularia* and *Sarcophyton* generally only occur on the UAE's coast (Fig. 11.4), mainly around Khor Fakkan, and are largely absent on the UAE's Arabian Gulf nearshore reefs, presumably due to the more severe environment there. Soft corals were also heavily impacted by Cyclone Gonu, with large areas heavily denuded by the storm surge. However, recovery of soft corals was rapid, with significant regrowth observed within 6 months (Maghsoudlou et al. 2008). Unfortunately, there has been no comprehensive monitoring program for Khor Fakkan's reefs in the past, and quantitative data on trends in reef health are unavailable for these important reefs; development of such a program is highly warranted.

11.2.2 Reefs of the Gulf's Northern Emirates

The distribution of corals along the UAE's Arabian Gulf coast varies as a function of depth and availability of rocky bottom. Corals here are typically restricted to <10 m depth as a result of light limitation from the moderate turbidity of Gulf waters (Fig. 11.5) (Chap. 4; Grizzle et al. 2016). Where the sea-bottom slope is steep, as in Ras Al Khaimah, this restricts coral growth to the immediate coastline in areas where hard-bottom occurs (e.g. Ghalilah), although occasional coral colonies can be found on rocky outcrops offshore at depths exceeding 40 m (so-called mesophotic coral reefs (Fig. 11.6), about which little is known in the Gulf; Pyle and Copus 2019).

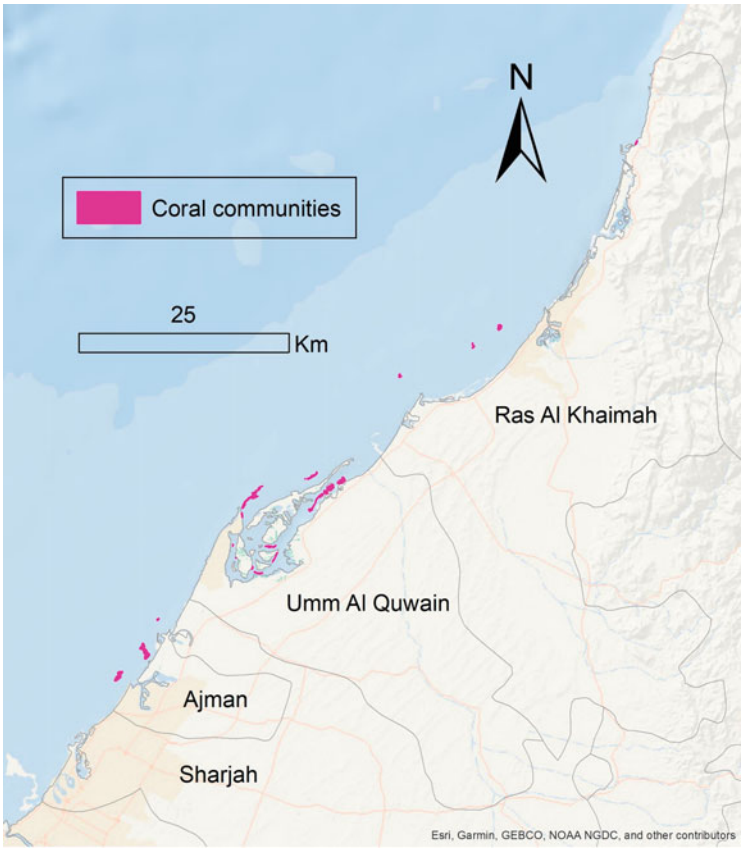

Fig. 11.5 Although often underappreciated by the general public, coral reefs do occur in nearshore areas and in lagoons across the northern Emirates, some quite extensive in area (e.g. around Umm Al Quwain). Not shown are unique 'mesophotic' offshore reefs that occur at >40 m depth and remain largely unmapped and unstudied. Modified from Fig. 4 in Mateos-Molina et al. (2020), reprinted under Elsevier license 5514050185453

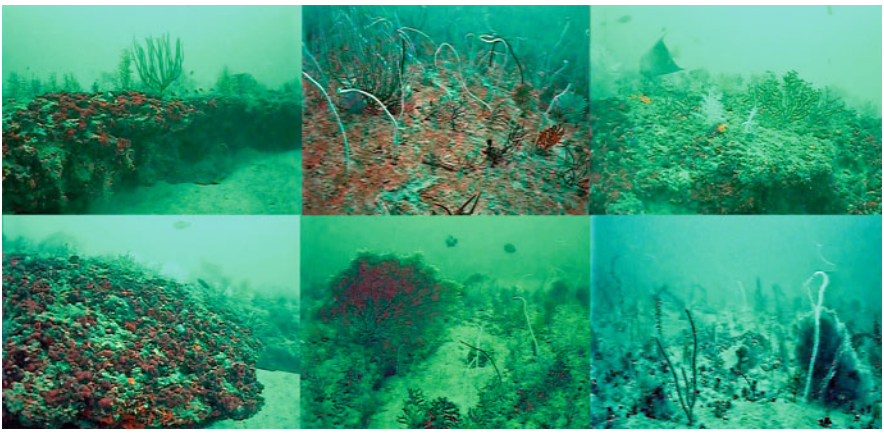

Fig. 11.6 A variety of fan corals, whip corals, and other soft and hard corals occur on a rocky outcrop that makes up the Sheikh Salim reef, a deep (ca. 40 m) mesophotic (low light) reef that occurs approximately 37 km offshore from Ras Al Khaimah, occupying an area of over 3 km^2. Image credit: Samantha Allyson

Fig. 11.7 Corals are a major building material of the >500 buildings that make up the historic village of Jezirat Al Hamra, Ras Al Khaimah, as well as various other historic buildings across the Emirates. The local coral construction trade seems to have peaked in the 1800s before being supplanted by concrete in the 1920s. Members of the Emirates Natural History Group have catalogued the diversity and abundance of these corals (right). Photographer: John Burt

Coral reefs had previously occurred in a discontinuous narrow band approximately 500–1000 m from shore in each of the Gulf Emirates, and new reefs are still occasionally being documented today (e.g. a recently described nearshore reef in Umm Al Quwain; Grizzle et al. 2016). Historically, corals from these reefs had served as a major source of building materials in a unique trade industry that originated in the 1400s and continued through the early twentieth century before being supplanted by concrete (King 1997; Hawker 2006; Petersen 2012). Historic sites such as the Qasr Al Hosn in Abu Dhabi, the Al Hisn fort in Sharjah, and the >500 buildings that made up the village of Jezirat Al Hamra in Ras Al Khaimah (Fig. 11.7) all incorporated corals into their walls (Lorimer 1908; Fox et al. 2006;

Petersen 2012), an ingenious solution to the lack of stone along the sandy coast of the early Emirates. Together, an estimated 45 km^2 of reef was historically estimated to have occurred in this nearshore strip from Dubai through the northern Emirates (Grizzle et al. 2016).

Unfortunately, coastal dredging and reclamation since the 1980s have decimated the once extensive reefs in Dubai and the Northern Emirates, and the large reefs once documented adjacent to Jebel Ali, the Sharjah corniche and Jezirat Al Hamra have all been lost (Riegl 1999; Goudie et al. 2000; Burt et al. 2008; Sheppard et al. 2010). Any remaining reefs in the northern Emirates should be recognized as vestiges of what were much more widespread ecosystems just 50 years ago (Fig. 11.8).

11.2.3 Corals of the Capital and Western Region

Nearshore coral reefs were quite extensive in the capital area and western region up until the 1970s (Fig. 11.9), and even today the most extensive reef areas in the UAE occur across Abu Dhabi (79.5 km^2, representing 60% of all coral reefs in the UAE) (Grizzle et al. 2016). Geologists supporting the nascent petroleum industry during the 1970s 'oil boom' have provided vivid descriptions and detailed aerial photographs of extensive coral reefs dominating the nearshore areas and tidal channels next to many of the familiar barrier islands surrounding the capital, including Saadiyat, Halat Al Bahraini, Dhabiya, Abu Al Abyad islands and in front of Abu Dhabi city itself (Evans et al. 1964; Kinsman 1964b; Kendall and Skipwith 1969; Murray 1970; Purser and Evans 1973). Descriptions of complex and extensive table coral reefs are common in the 1960s literature, with Kinsman (1964a) stating that, "...Trucial Coast reefs are composed dominantly of *Acropora* [table corals], even in very shoal areas which suffer maximum temperature changes", while Evans et al. (1964) writes of the capital area that "...directly fronting the islands are coral reefs, predominantly of *Acropora* [table corals] with subordinate *Platygyra* [brain corals] and other massive corals.... The coral here is diffuse and occurs in patches, whereas on the steep walls of the ebb [tidal] channels the growth of the dominant coral, *Acropora*, is extremely prolific".

Unfortunately, many of these once extensive reefs have been lost or heavily degraded as a result of channel dredging and land reclamation to support the early oil and port industries in the 1970s (Murray 1970; Carp 1976; Crisp 1976). Today the large nearshore reef that provided food to local communities on Abu Dhabi island for millennia sits under the footprint of the man-made Lulu Island and Mina Zayed, while navigation channel dredging led to complete loss of the table-coral (*Acropora*) dominated reefs that had fringed the shallow tidal areas around Reem and Mariyah Islands (Murray 1970).

Today, coral reefs do continue to exist in some nearshore locations in the Abu Dhabi emirate, with large reefs still occurring in front of Ras Ghanada, Saadiyat and Dhabiya (Burt et al. 2011; Grizzle et al. 2016), but the current coral communities are degraded relative to historic descriptions (e.g. the virtual extirpation of the *Acropora*

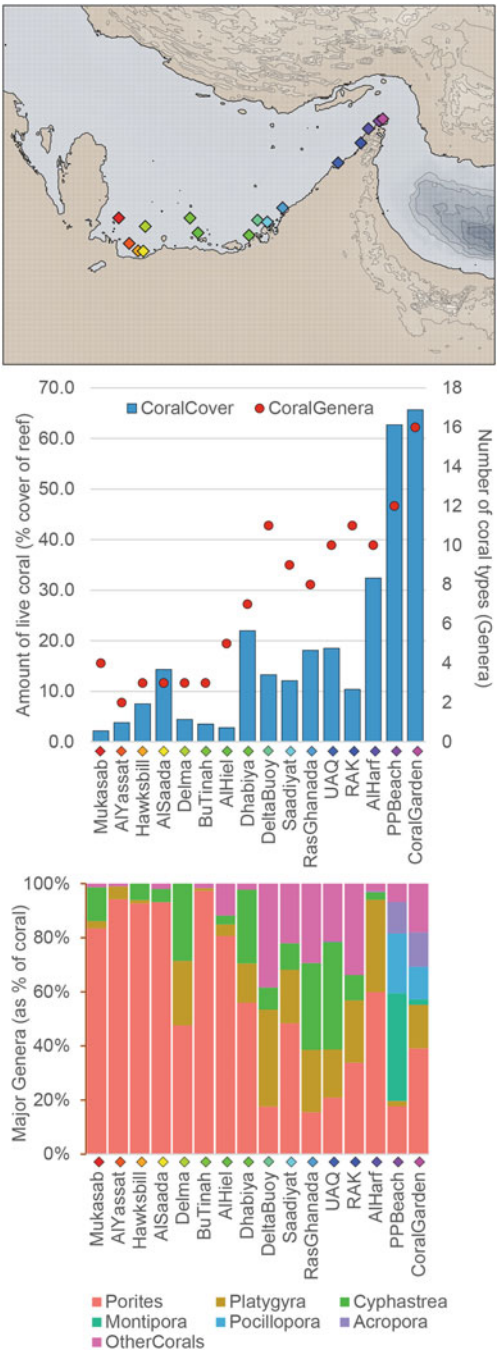

Fig. 11.8 Changes in coral communities across the Arabian Gulf coast of the UAE and Oman as a result of a gradient of environmental conditions. (**a**) Map of survey sites. (**b**) Coral abundance (bars) and diversity (dots) are highest near the entrance of the Gulf and decline towards the west. (**c**) Broad shifts in coral composition from west (where *Porites* dominates) to east (where a number of other groups are common, including *Acropora* and other sensitive groups not seen at western sites). Data are from 2019 surveys; all site names are color-coded under charts. Source: John Burt, unpubl. data

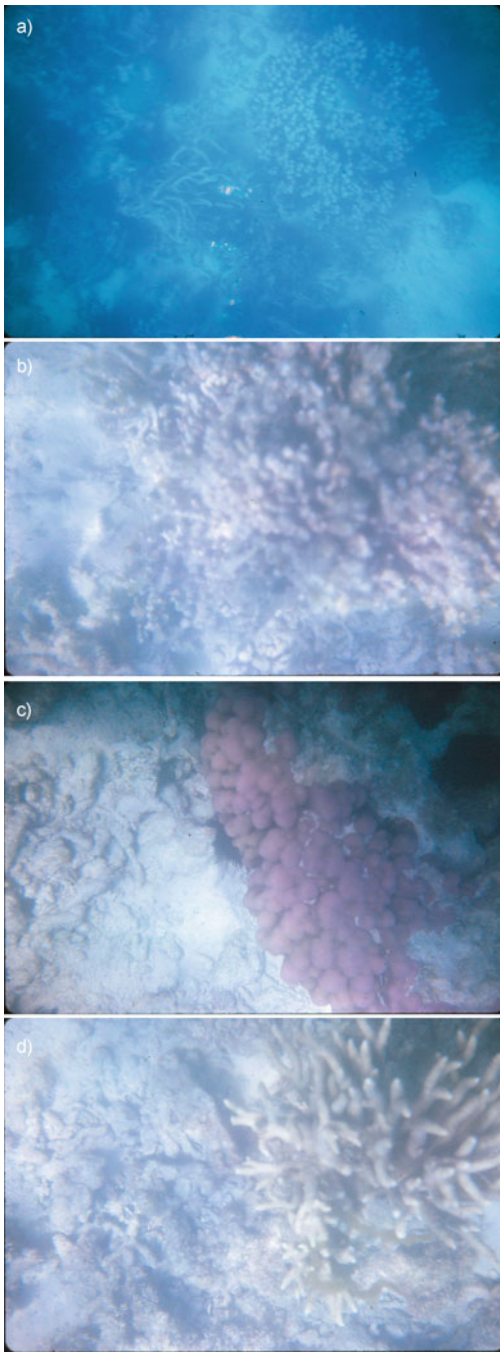

Fig. 11.9 Corals photographed over a half-century ago in 1965 in Abu Dhabi. (**a**) Table coral (*Acropora*) and finger coral (*Porites harrisoni*) in the Abu Dhabi lagoon, (**b**) dead coral (*P. harrisoni*) encrusted with turf algae and (**c**) live *Porites* mound coral (likely *P. lobata*) in the Abu Dhabi lagoon, and (**d**) live table coral (*Acropora*) on the reef in front of Abu Dhabi city. Photographer: John Murray

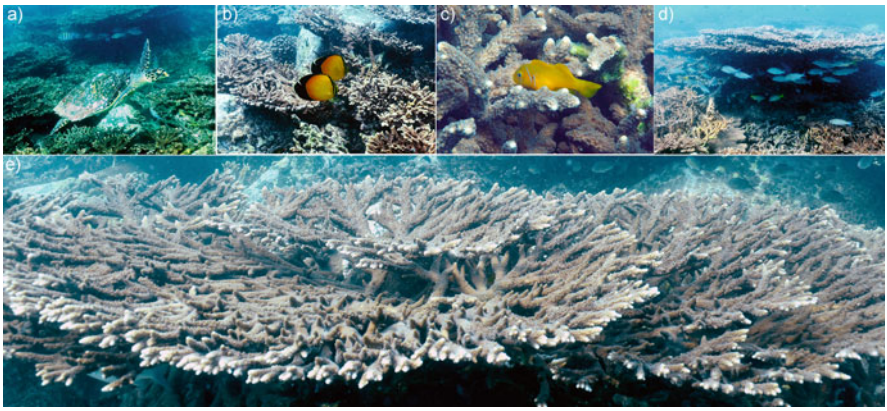

Fig. 11.10 Table corals (*Acropora* spp.) have historically dominated reefs across the UAE. They are an important reef building coral that provides (**a**) foraging habitat for the critically endangered hawksbill turtle (*Eretmochelys imbricate*), (**b**) a food source for coral-feeding fish such as the Arabian butterflyfish (*Chaetodon melapterus*), (**c**) obligate habitat for table coral-dwelling organisms such as the lemon goby (*Gobiodon citrinus*), and (**d**) shelter from predators for many other species. (**e**) Table corals such as the regional endemic *Acropora downingi* are common to the East Coast of the UAE and offshore islands such as Sir Bu Nair, but have largely been lost on coastal reefs along the Arabian Gulf coast of the Emirates due to marine heat waves. Photographer: John Burt

table corals that had once been common (see Box 11.1) (Burt et al. 2011). Continuing pressure from coastal urbanization and industrialization represent a threat to their long-term persistence (Burt 2014).

Box 11.1 Table Corals (*Acropora*) as Bellwethers of Environmental Change

When the general public sees videos or photographs of coral reefs anywhere in the world, they are most likely looking at images of a shoal of bright and colorful reef fishes surrounding a stand of table corals—a group of corals belonging to the genus *Acropora* (Fig. 11.10). At least 12 species of table corals have been described for the UAE, although taxonomic uncertainty remains (Riegl et al. 2012), which includes the regionally endemic species *Acropora downingi* that once dominated reefs across the southern Gulf (Evans et al. 1964). Table corals represent one of the primary reef-building corals in the Emirates, with their long horizontal branches fusing into 'tables' that can reach over 3 m in diameter, with the fastest growth rates of any corals in the Emirates, estimated at 10 cm per year (Riegl 2002).

Table corals provide considerable three-dimensional complexity that support a diverse array of fishes using the colonies as shelter from predators, or even as a home (e.g. the coral-dwelling citron goby); they also provide shade

(continued)

Box 11.1 (continued)
to an understory of sub-dominant species such as brain and mound corals that are typically found in deeper low-light environments (Riegl 1999,2002).

Unfortunately table corals are highly sensitive to environmental stress, and are widely known to be among the first corals to suffer under pressures such as sedimentation, extreme temperatures and disease, which can decimate local populations (Loya et al. 2001; Dana and Margaret 2005; Burt et al. 2011; Clark et al. 2017; Riegl et al. 2018). If conditions remain benign for a period of 10–15 years after a mass die-off, their rapid growth rates can provide a capacity to recover (Burt et al. 2008; Gilmour et al. 2013). However, if recovery is 'reset' by more frequent disturbances, for example by recurrent bleaching events associated with marine heat waves that are becoming all-too-common under climate change, then the stock of remaining adults on reefs can crash or be so physiologically impaired that it affects reproductive output, resulting in loss of larvae to help replenish these reefs (Howells et al. 2016a; Burt and Bauman 2019). If this happens at regional scales, as it has in the Gulf in recent decades (Bauman et al. 2014; Bento et al. 2017; Pratchett et al. 2017), then this can result in a region-wide collapse of these species, with little hope for their return without active restoration interventions.

11.2.4 Offshore Reefs of the Southern Gulf

The southern basin of the Gulf is the only area of the UAE where substantial offshore coral reefs occur. These reefs mainly surround islands and shoals in Abu Dhabi waters, although the most diverse and extensive reefs occur at Sir Bu Nair island, which is governed by Sharjah but geographically sits 70 km offshore from the Abu Dhabi-Dubai border towards the center of the Gulf. The prevalence of offshore reefs in the southern basin is due to the shallow, low sloping bathymetry in the area which keeps much of the bottom in the well-lit photic zone, as well as the presence of large hard-bottomed shoals and offshore islands that occur where salt domes push up rocky substrate through the largely sand bottom (Riegl and Purkis 2012). This combination of features provides corals with hard substrate suitable for growth at a depth where sunlight can readily penetrate, and the offshore nature of these locations protects these reefs from the influence of urban-related pressures that typically affect nearshore areas (e.g. dredging, nutrient pollution; Riegl and Purkis 2012; Aeby et al. 2020). The presence of deeper waters surrounding many of the offshore islands has also been suggested to buffer these reefs during summer, as tidal currents push cool, deeper waters up into the shallows where corals occur, providing temporary respite from summer heat (Cavalcante et al. 2020; Bento et al. 2021).

Extensive fringing reefs occur adjacent to islands such as Sir Bu Nair, Delma and Arzanah (Burt et al. 2011; Riegl and Purkis 2012; Bento et al. 2021), and were known to have occurred at Sir Bani Yas island prior to widespread dredging and

Fig. 11.11 The most diverse coral reefs on the UAE's Arabian Gulf coast occur at Sir Bu Nair, an island situated ca. 70 km offshore from the mainland. The deeper surrounding water is thought to buffer coral communities from the prolonged extreme temperatures that affect inshore reefs, allowing existence of sprawling stands of table corals (*Acropora downingi*, left) and environmentally sensitive species such as the smooth cauliflower coral (*Stylophora pistillata*, right), corals that are now functionally extinct on nearshore reefs. Photographer: John Burt

reclamation in the 1980s (Purser and Evans 1973). Sharjah's Sir Bu Nair island, lying farthest out from land and surrounded by deep (>30 m) waters, today represents the best developed and most extensive coral reef ecosystem in the UAE's Arabian Gulf waters (Fig. 11.11), in part because of its isolation but also because of its strictly enforced 'no go' protected area supported by the presence of military infrastructure on the island. Reefs here are dominated by table corals (*Acropora*) which makes up over half of all coral, with large stands typically occurring in shallow (<6 m) depths to the northwest and south of the island; with increasing depth these shallow-water specialists become less common and the community grades to one dominated by brain corals and mound corals (Merulinids and Poritids) that are more resilient to lower light (Bejarano et al. 2022). The coral reefs of Sir Bu Nair are considered to be extremely important as one of the only remaining source of table coral (*Acropora*) larvae that have potential to colonize and replenish the nearshore reefs along the Gulf coast of the UAE and, as such, their continued conservation is considered a high priority for the nation (Cavalcante et al. 2016; Riegl et al. 2018; Bento et al. 2021).

11.3 UAE Coral Reefs: A Globally Important Scientific Asset

Coral reefs are the most biodiverse ecosystem in the Emirates, and are also highly economically valuable, supporting fisheries productivity that is comparable to the most productive coral reefs on earth (Grandcourt et al. 2011). In addition to these local benefits, coral reefs of the UAE are also increasingly regarded as an important asset for global science, particularly around the implications of future climate change across the tropics (Burt et al. 2014, 2020).

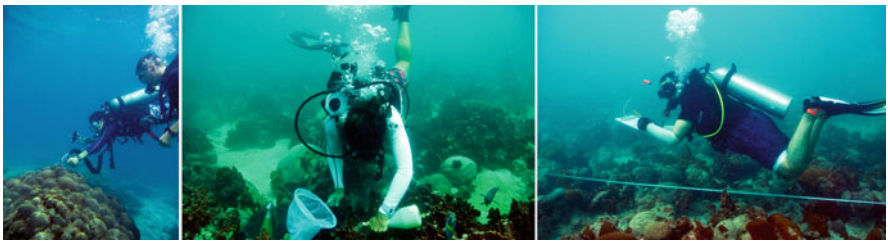

Fig. 11.12 Research on the Emirates' coral reefs has grown dramatically in the past decade as scientists are increasingly using reefs in the Arabian Gulf—the world's hottest sea—to understand how corals and other organisms cope with and respond to extreme temperatures. Photographer: John Burt

Each summer the Arabian Gulf becomes the world's hottest sea, and this is particularly true of the southern Gulf basin along the UAE's Abu Dhabi coast where sea temperatures regularly exceed 36 °C (Coles 2003; Riegl and Purkis 2012). Such temperatures are upwards of 5 °C warmer than temperatures that would be lethal to corals in tropical regions such as the Caribbean and the Great Barrier Reef (Riegl et al. 2011), and represent conditions that are predicted to occur across much of the tropics by the end of the century as a result of climate change (Burt et al. 2020). As such, there has been dramatic growth of research on the UAE's coral reefs in the past decade as scientists race to understand how local corals are able to cope with such extreme temperatures, and what the implications of these responses are for corals elsewhere in the world (Fig. 11.12) (Burt 2013; Vaughan and Burt 2016).

While the extreme summer temperatures in the southern Gulf have drawn the most attention, reefs here are also exposed to extreme cold in winter (<18 °C), high salinity (>44 PSU), high turbidity, and recurrent low oxygen exposure, each of which represent major stressors for coral (Coles 2003; Bauman et al. 2012; de Verneil et al. 2021). These extreme conditions do have costs for corals, as only a hardy subset of regional species is capable of surviving in the southern Gulf, where coral diversity is approximately half of that occurring in the Gulf of Oman and <10% of the diversity of the wider Indo-Pacific (Coles 2003; Bauman et al. 2012; Bento et al. 2016; Claereboudt 2019; Bouwmeester et al. 2021). Yet those species that are able to survive can be highly abundant in the southern Gulf, with dense coral communities often having coverage of live coral that rivals reefs of the east coast (Sheppard et al. 2000; Bento et al. 2016; Grizzle et al. 2016; Riegl et al. 2018).

Recent research has shown that a number of different mechanisms permit coral survival under the extreme environmental stress of the southern Gulf. Population genetics analyses on a locally abundant brain coral (*Platygyra daedalea*) has shown that corals rapidly colonized the Gulf following the flooding of the basin after the last glacial period, and in the final stages corals had colonized the modern UAE's Gulf coast approximately 8000–6000 years ago (Smith et al. 2022). In the intervening millennia, the environment has acted a 'filter' for natural selection, resulting a preponderance of genes related to temperature and stress tolerance being fixed in

the genome of local populations, such that they are now genetically distinct from populations outside of the Gulf (Smith et al. 2022). In addition to the coral animal itself, the UAE's Gulf corals also host a unique species of thermally tolerant symbiotic algae (*Cladocopium thermophilum*) that dominates virtually all corals in the southern Gulf and is functionally absent in corals east of Ras Al Khaimah where conditions are less extreme (Hume et al. 2013, 2016, 2018). This coral-algae association is even retained across extreme seasonal cycles of temperature and through severe bleaching events, suggesting that this symbiosis is critical for coral survival in the southern Gulf (Hume et al. 2015; Smith et al. 2017; Howells et al. 2020). Together, the unique genetic adaptations of Gulf corals and their symbionts support the highest thermal tolerance and bleaching thresholds known anywhere on earth (Riegl et al. 2011; Howells et al. 2016b).

11.4 Climate Change and the Future of Coral Reefs in the Emirates

Paradoxically, while the UAE is home to some of the most heat tolerant corals on earth, it may be one of the first nations to experience the functional loss of coral reefs as a result of climate change. This is because while these corals do have adaptations allowing them to exist in the most extreme temperatures known on earth, they already live very close to their physiological limits and, as a result, can be easily pushed across this threshold during bleaching events in unusually warm summers (Fig. 11.13) (Lincoln et al. 2021).

As a whole, the Gulf is warming at over twice the rate of the global oceans, and this is leading to the occurrence of more frequent and severe marine heat waves (Riegl et al. 2018; Lachkar et al. 2021). Historically, coral bleaching events were first reported for the UAE's Gulf reefs in the early 1980s, followed by severe back-to-back events in 1996 and 1998 which resulted in the loss of over 90% of corals from reefs in Abu Dhabi and Dubai (Fig. 11.14) (Riegl 1999, 2002). This was followed by more than a decade of benign temperatures, which allowed corals to recolonize degraded areas and coral coverage to return to mid-1990s levels in many locations by the late 2000s (Sheppard and Loughland 2002; Burt et al. 2008). Recurrent marine heat waves occurred again in 2010, 2011 and 2012, though temperatures were not as extreme as earlier and only a fifth of corals were estimated to have been lost following these three events (Riegl and Purkis 2015). Unfortunately, one of the most severe marine heat waves ever recorded in the Gulf occurred in 2017, when nearly three-quarters (73%) of corals were killed across the southern Gulf (Burt et al. 2019), with the summers of 2020 and 2021 also characterized by unusually extreme periods of elevated temperatures (data on coral losses during this period are still being developed). As a result, coral reefs of the UAE's Gulf coast are now heavily degraded both in terms of the amount of live coral, as well as in terms of the overall

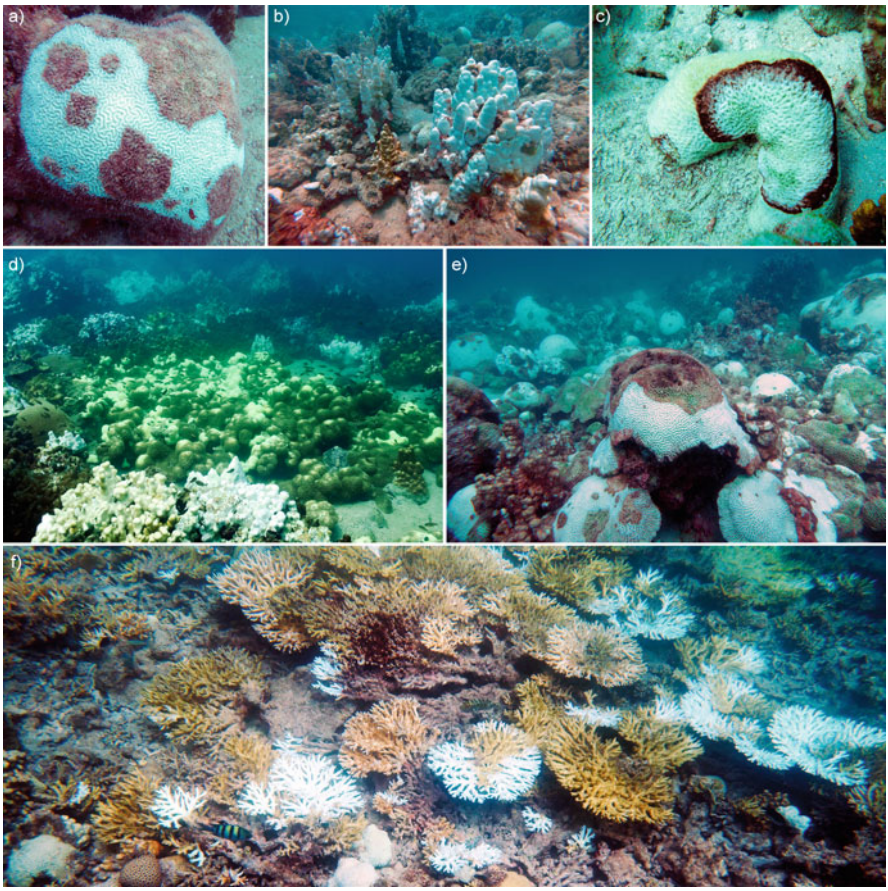

Fig. 11.13 Temperature-induced coral bleaching is occurring with increasing frequency as a result of climate change and has caused considerable loss of corals from UAE reefs in recent years. While colonies may survive bleaching for several days, partial colony mortality will start to occur after several days (**a**, **c**, **e**) with whole colonies dying off within a period of a week or 2 (**e**, top) unless temperatures abate. Bleached colonies of (**a**) *Platygyra daedalea* showing partial colony mortality, (**b**) *Porites* spp., fully bleached, and (**c**) *Coscinaraea monile* showing partial mortality with cyanobacterial overgrowth on the lesion edge, all from Dhabiya, August 2017. (**d**) A bleached cluster of *Goniopora* (center) surrounded by *Porites* at Martini Wall, Khor Fakkan, September 2021. (**e**) Saadiyat reef during mass bleaching in August 2017, which led to the loss of over 70% of corals from Abu Dhabi. (**f**) The large *Acropora* stands at Sir Bu Nair island had escaped the impacts of earlier bleaching events, but heavily bleached in summer 2021 due to a marine heat wave. Photographer: John Burt

community structure, with formerly-dominant table corals (*Acropora*) now largely extirpated from coastal reefs.

The coral reefs of the UAE's east coast and those offshore in the Gulf, such as Sir Bu Nair island, have historically managed to escape the impacts of earlier bleaching events, largely due to the presence of deep, cool water in the surrounding

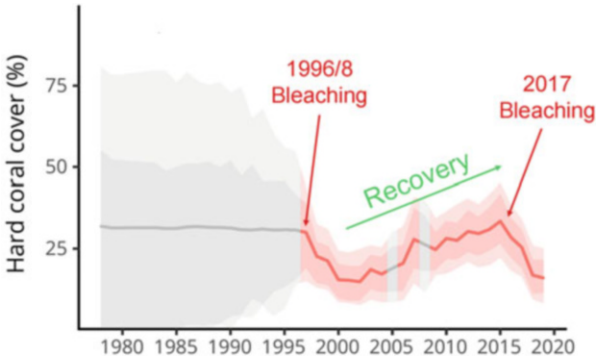

Fig. 11.14 Changes in the amount of live coral over time across the Arabian Gulf based on reef monitoring surveys. Lighter shades represent uncertainty (greater in the past when fewer surveys were performed) while the dark line represents the average; UAE reef surveys make up the majority of this dataset. Between 1995 and 2000 there was a loss of ca. 40% of coral as a result of the back-to-back severe bleaching events in 1996 and 1998. This was followed by 15 years of recovery where the amount of coral returned to pre-1996 levels. However, a severe bleaching event in 2017 again caused substantial coral loss. Whether reefs can again recover will be dependent on the frequency and magnitude of future bleaching events (modified from Burt et al. 2021b)

Fig. 11.15 Algae-covered dead coral framework shortly after bleaching-induced mortality. Although the corals in these images may appear intact, there is virtually no live coral in any of these photos. Instead, algae is overgrowing dead coral skeleton; in the coming year or two this framework will slowly break down (left to right: Martini Wall, Khor Fakkan, 2021; Saadiyat Reef, Abu Dhabi, 2018; Dhabiya Reef, Abu Dhabi, 2019). Photographer: John Burt

environment that buffered these reefs from extreme temperatures. This came to an end in the summer of 2021 when an extended period of low winds resulted in elevated temperatures, particularly at shallow depths. Surveys conducted at Shark Island in Khor Fakkan in early September 2021 showed near complete mortality of table corals down to ca. 6.5 m depth and severe bleaching of most coral species occurring at Martini Wall (Fig. 11.13d); surveys at Sir Bu Nair island several weeks later showed widespread bleaching of this last remaining stand of table corals for the UAE's Gulf waters, although mortality appeared to be less extreme than in Khor Fakkan (Fig. 11.13f). Analyses are currently underway to determine the extent of coral loss and shifts in species that may have occurred as a result of this event, but algal overgrowth has become much more common than in the past (Fig. 11.15).

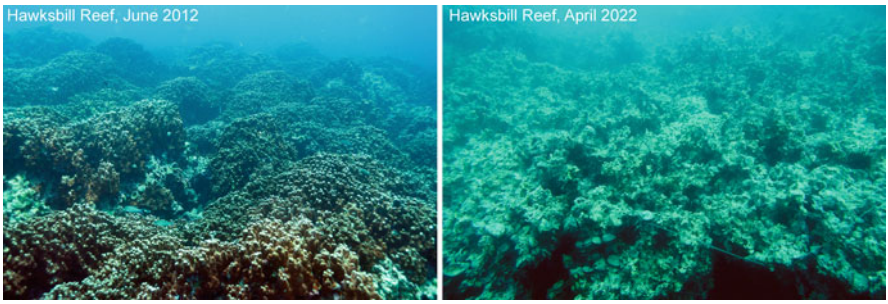

Fig. 11.16 A decade of change at Hawksbill Reef (western Abu Dhabi) between 2012 and 2022. This reef had among the highest abundance of coral in all of Abu Dhabi in 2010 surveys (60% coverage, mainly the finger coral *Porites harrisoni*) (Burt et al. 2011), but is now largely dead (<5% live coral coverage) as a result of recurrent bleaching events due to marine heat waves. Photographer: John Burt

The occurrence of these recent bleaching events across the Emirates represents a profound existential threat to the continued persistence of coral reef ecosystems for the nation (Fig. 11.16). The total amount of coral on most reefs in the UAE has declined by at least half and often over three-quarters since the late 2000s (Bento et al. 2016; Burt et al. 2019).

Recovery of the UAE's coral reefs will be contingent on two processes: vegetative growth and settlement of sexually produced larvae. While vegetative growth from surviving adults is possible, most coral species in the UAE are extremely slow growing (<1 cm/year), meaning that regrowth of pre-2010 coral coverage would take several decades without disturbance—an unlikely scenario given the frequency of recent marine heat waves (Howells et al. 2018; Burt et al. 2019). In addition, several sensitive groups such as table corals (*Acropora*) have been largely extirpated from most reefs (Riegl et al. 2018), meaning vegetative regrowth from surviving colonies will not be possible for these taxa. The news is not much better for the potential of sexually produced larvae to aid the recovery of the UAE's increasingly degraded reefs (Fig. 11.17). The substantial declines in coral abundance in recent years means that the standing stock of adults with reproductive potential has declined considerably and bleaching-induced stress has likely impaired fecundity for at least some species, reducing reef-level reproductive output (Howells et al. 2016a; Burt et al. 2019). Reefs further offshore or in surrounding nations have also been heavily impacted by bleaching events since 2017, suggesting that rescue from larvae produced further afield is also unlikely (Burt et al. 2021b). Recent surveys for recently-settled coral spat and juveniles bear this out, with studies reporting suppressed larval coral settlement after bleaching events (Burt and Bauman 2019), with extremely low levels of juvenile settlement overall compared with reefs in other regions (Bauman et al. 2014; Bento et al. 2017). Worryingly, formerly common coastal species such as table corals (*Acropora*) have all but disappeared from the juvenile communities on the Arabian Gulf coast of the UAE (Bauman et al. 2014; Burt and Bauman 2019), although they have continued to be observed on reefs in

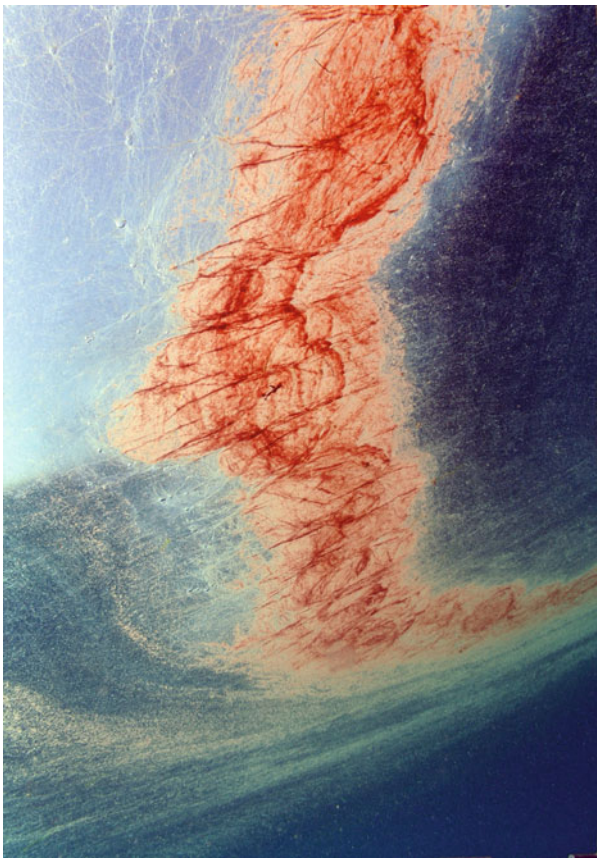

Fig. 11.17 A coral spawn slick floating above Ras Ghanada reef on 20 April, 2011, photographed from below by a diver. The production and dispersal of viable eggs is necessary to ensure the continued persistence of coral reefs in the UAE, but recent studies have demonstrated that egg production is impaired for several common coral species and settlement of new larvae is extremely impaired as a result of recurrent bleaching. Such observations cast doubts on the ability of these reefs to naturally recover from recent marine heat waves, suggesting that more active management intervention approaches are needed. Photographer: John Burt

Fujairah as well as the offshore island of Sir Bu Nair in the Gulf (Pratchett et al. 2017; Bento et al. 2021). Overall, these results suggest that we are witnessing a major transition of coral reef ecosystems in the UAE, particularly on nearshore reefs in the Gulf, where coral communities are characterized by much lower abundance and diversity of corals than in history, with limited capacity for successful natural recovery.

11.5 Improving the Future Trajectory of UAE Reefs

While recent bleaching-induced impacts suggest that the important coral reef ecosystems that line the Emirates' coast are in a vulnerable state, there are actions that can be taken to reverse this trajectory and enhance their recovery going forward.

The UAE has taken increasing steps to conserve various marine ecosystems, including reefs, through the establishment of Marine Protected Areas (MPAs), with

MPAs now covering 12% of the nation's coastal and marine zones (5 in the Sea of Oman and 10 on the Arabian Gulf coast) and two-thirds of this area established in the short period since 2010 (IUCN 2022). In addition, the establishment of new MPAs is being supported by an evolving understanding of the location and nature of marine ecosystems through recent marine habitat mapping efforts (Grizzle et al. 2016; Lamine et al. 2020; Mateos-Molina et al. 2020), allowing identification of gaps in current protection so that future MPAs could prioritize conservation of key reefs (Mateos-Molina et al. 2021). These efforts are laudable and should continue, but should also be enhanced through the development of a national coral reef monitoring program to support such initiatives. While a well-established long-term reef monitoring program exists in Abu Dhabi (e.g. Burt et al. 2011, 2019), only periodic 'snapshot' surveys have occurred in other emirates (e.g. Bento et al. 2016; Grizzle et al. 2016). It is impossible to manage a system which is not understood, nor is it possible to assess the efficacy of any management efforts (e.g. MPA establishment) without detailed monitoring programs. This clearly represents a 'low hanging fruit' that would aid understanding of trends in coral community health, the impact of any intervention measures, and the identification of which areas are most essential for management and conservation efforts (be it based on biodiversity, vulnerability or other factors) at national scales. Such a monitoring program would strongly aid the development of ecosystem-based management and marine spatial planning approaches that are increasingly being promoted in the Emirates and surrounding nations (Fanning et al. 2021; Burt et al. 2017; Ben-Romdhane et al. 2020; Mateos-Molina et al. 2021), and should be considered a priority for adoption.

Reef management and conservation interventions must also be accompanied by active reef restoration efforts. Given the worrying state of larval settlement and the degraded state of many reefs in the Emirates, natural recovery is unlikely to occur in the near-term (Burt et al. 2019). Reef restoration sciences have improved markedly in the past two decades (Bayraktarov et al. 2019; Boström-Einarsson et al. 2020), and development of new approaches such as aquaculture-based nurseries, selection and propagation of thermally-tolerant genotypes, and implementation of techniques to utilize sexually-produced larval out-plants (as opposed to fragments derived from vulnerable and scarce wild colonies) all offer novel approaches that could showcase the UAE as a leader in the reef restoration field on a global stage. The above approaches will not be able to ameliorate the temperature trends resulting from climate change, but they will allow a program to focus on those species and individual genotypes with the highest likelihood of success, particularly when combined with a monitoring program that helps identify those areas where such restoration efforts are likely to have the most success. It should be noted that artificial reefs are not surrogates for natural reefs and often serve to exacerbate the issues they are often designed to resolve (Bartholomew et al. 2022; Burt et al. 2021a), and therefore should not serve as part of the reef management toolkit for the Emirates.

In addition to having local value, the coral reefs of the UAE also represent an important asset for coral reefs on a global stage (Burt et al. 2014, 2020). The local prevalence of corals pre-adapted to temperatures anticipated to occur across most of the tropics by the end of the century cannot be overstated. Currently researchers

across the globe are racing to enhance the thermal tolerance of corals through 'assisted evolution' approaches, where several generations of corals are subject to experimentally induced temperature stress with the goal of enhancing the thermal tolerance of later offspring (van Oppen et al. 2015; Anthony et al. 2017). An alternative approach that side-steps the need for time consuming multi-generational experiments would be through the adoption of cross-breeding approaches that utilize the standing genetic stock of coral populations already adapted to extreme thermal stress such as those in the UAE. Recent work in the Emirates has shown that cross-breeding of heat-tolerant Gulf corals with thermally naïve coral populations in the Indian Ocean resulted in the cross-bred offspring having survival at extreme temperatures that was comparable to pure-bred Gulf corals and that was up to 84% higher than pure-bred offspring from thermally-naïve populations (Howells et al. 2021). These findings highlight the tremendous importance of UAE reefs as a scientific asset and as a resource that could help mitigate against climate change in other regions. The conservation of this unique natural asset should be given high priority.

11.6 Conclusions

Coral reefs represent one of the most important natural assets of the United Arab Emirates, from the perspective of biological diversity, economic value and for their value to global scientific research. While coral reefs are a relatively young ecosystem to a large part of the nation along the Arabian Gulf coast, these corals have experienced a 'trial by fire' that has winnowed out weaker species and individuals, leaving a remarkably robust and thermally tolerance assemblage lining the shores. While the reefs of the east coast and offshore in the Gulf may not exhibit the remarkable stress tolerance of those along the western shores, they contain some of the most diverse and relatively pristine coral communities in the nation. Despite their importance, coral reefs across the Emirates have undergone substantial decline in recent decades, and the reefs today represent just a vestige of what occurred in recent memory. Whether these amazing ecosystems continue on the path they are currently on, or take a new trajectory to recovery towards their former grandeur will largely be depending on UAE government institutions taking bold steps to restore and conserve these ecosystems for the benefit of its future citizenry.

11.7 Recommended Readings

Additional information on the coral reefs of the UAE may be found in Vaughan et al. (2019), Burt et al. (2014) and Riegl and Purkis (2012).

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