Coral Reef Management in the Arabian Seas

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Abstract Coral reefs in the Arabian Seas exist in and are resilient to a harsh environment with extremes of temperature and salinity. Temperatures range from 16° C in the winter to 37° C in the summer and salinity may reach 40 ‰. These coral assemblages and their associated biota and fisheries are under threat from a wide variety of impacts, including global climate change and associated ocean warming, coral disease, heavy tourism pressure, sedimentation and physical habitat destruction from intense, widespread coastal development, overfishing, industrial pollution, heated, hypersaline brine effluent from desalination, and shipping. Coral reef management is primarily accomplished through the implementation of MPAs, with unknown success due to the lack of MPA management effectiveness assessments. Fisheries are the most important renewable resource in the Arabian seas and the second most important natural resource after oil and gas, but reef fisheries management in the region is poorly developed and needs to move toward a precautionary, ecosystem-based management approach. There has been increasing interest in coral reef research in the Arabian Seas, primarily to understand the resilience of corals to global environmental change. Recent advances in GIS and remote sensing provide useful tools for managing marine ecosystems.

Keywords Oman · Indian Ocean watercraft · Arabian Sea · Sewn boats · Reed boats · Boatbuilding technology

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1 Introduction: Biogeography of the Arabian Seas Region

The Arabian Seas comprise the marine basins surrounding the Arabian Peninsula, including the Red Sea and its northernmost extensions, the Gulf of Suez and Gulf of Aqaba, the Gulf of Aden, the Arabian Sea proper, and the Gulf of Oman and Persian Gulf. Of these basins, the Red Sea and Persian Gulf are of particular interest for the coral reefs they support. Both the Red Sea and the Persian Gulf are located at high latitudes (up to 29° North) within a desert belt, and both are shallow, resulting in extremes of seawater temperature and salinity. Sea surface temperatures in the region can range from 16 °C in the winter to 37 °C in the summer, with a typical range of 20 °C to 25 °C (Burt et al. 2014). Salinity may reach 40‰ (Edwards 1987). The Red Sea and Persian Gulf are the warmest and most saline waters in which coral reefs form. Genetic and physical adaptations allow coral reefs to grow and show remarkable resilience to this extreme environment (Bento et al. 2015).

The Red Sea is 1900 km north to south and just over 500 km wide at its widest point. The average depth is 500 m, with the deepest point being 2500 m (Behairy et al. 1992). Over 300 species of scleractinian corals and 1400 species of fish have been recorded from the Red Sea (Kotb et al. 2008). Despite its size and diversity, Red Sea coral reefs remain poorly studied compared to Caribbean reefs and the Australian Great Barrier Reef. Berumen et al. (2013) assessed the number of publications as a measure of the amount of research conducted on Red Sea coral reefs vs Caribbean reefs and the Australian Great Barrier Reef (GBR). Research on Red Sea reefs amounted to about 1/6 of the research conducted on the GBR and 1/8 of the research done on Caribbean reefs. More than half of the Red Sea research was from a small area in the Gulf of Aqaba. As a result, critical data for informing coral reef management is limited in most Red Sea countries (Berumen et al. 2013). The same is likely true of the Persian Gulf.

Both the Red Sea and the Persian Gulf receive relatively little freshwater input and as a result have relatively high coastal water clarity and extensive seagrass and algal meadows, mangroves and coral reefs (Porter and Tougas 2001). In the Red Sea narrow but well-developed fringing coral reefs are found nearly the length of entire coastline from the Gulf of Aqaba to the Arabian Sea (Porter and Tougas 2001). In contrast, the Persian Gulf has an average depth of only 50 m and a maximum depth of only 90 m (Reigl and Purkiss 2012). Much of the Persian Gulf basin is therefore in the photic zone, but because the substrate is primarily unconsolidated sediment rather than hard bottom, it is not conducive to coral reef formation. Coral reefs in the Persian Gulf are therefore not typical high-relief reef structures but are more like an encrusting carpet of corals (Sheppard and Salm 1998). Because of its extreme environment, unusual coral assemblages and heavy human impacts from coastal industrialization, the Persian Gulf has been the target of extensive research in recent years (Burt et al. 2014).

Similar to the Caribbean, Acroporid corals once dominated Persian Gulf coral reefs and were the major reef framework builders. Mass bleaching of corals, particularly *Acropora* species, occurred in 1996 and 1998 as a result of increased sea surface temperatures (Burt et al. 2012, 2014; Riegl 2002; Riegl and Purkiss

2012). Bleaching events recurred in 2002, 2007, 2010 and 2011 limiting and in some cases reversing the recovery of coral reefs (Buchanan et al. 2016; Burt et al. 2012, 2014; Riegl and Purkiss 2012). Intense coastal development beginning in the 1960s further accelerated the degradation of Persian Gulf coral reefs (Burt 2014; Burt et al. 2014; Sheppard et al. 1992). This chapter examines the natural and human impact impacts on coral reefs of the Arabian Seas and their current management needs.

2 Role of the Natural Environment in Shaping Coral Reef Communities

2.1 Temperature

The Persian Gulf and Arabian Sea have been reported to support 34 and 103 coral species (respectively), covering 16 families (Al Cibahy 2012). The corals are unique as they experience not only a wide seasonal sea temperature variation (14–36 °C), but they also experience one of the highest mean daily summer temperatures of 34–35 °C (Schoepf et al. 2015). Compare this region's thermal threshold of 35 °C (Wellington et al. 2001; Riegl 2003), to other regions such as the Caribbean, where thermal thresholds for bleaching and subsequent mortality occurs between ~28 °C and 30 °C (Coles and Brown 2003). On a global scale, there have been three major bleaching events (1998, 2010, 2015) where more than 40 pantropical locations reported mass bleaching (Hughes et al. 2018). Given their comparatively low thermal threshold, it is of no surprise that the Western Atlantic experienced more than double the bleaching events than that reported from Australasia and Indian Ocean (7 vs. 3, respectively) (Hughes et al. 2018), leading to more than 50% mortality in some locations.

Given that some corals recover from bleaching, it is important to distinguish the levels of stress (sub-lethal) that these corals experience from those that perish (lethal), as this has implications toward understanding thermal tolerance in corals, and by extension the management of reef systems in the face of climate change. Reefs such as those in the Gulf and near geographic regions, which undergo such varied annual thermal ranges, are of particular interest for advancing knowledge on climate change impacts of coral reefs. They (1) allow clearer physiological adaptations and molecular expression of patterns to be ascertained (e.g., Oliver and Palumbi 2011; Bellantuono et al. 2012; Schoepf et al. 2015), and (2) they do not seem to physiologically behave as other corals around the world (e.g., Seyfabadi et al. 2011).

2.2 Bleaching

For the Persian Gulf, there have been several reported mass coral bleaching and mortalities events. These events were associated with not only very high

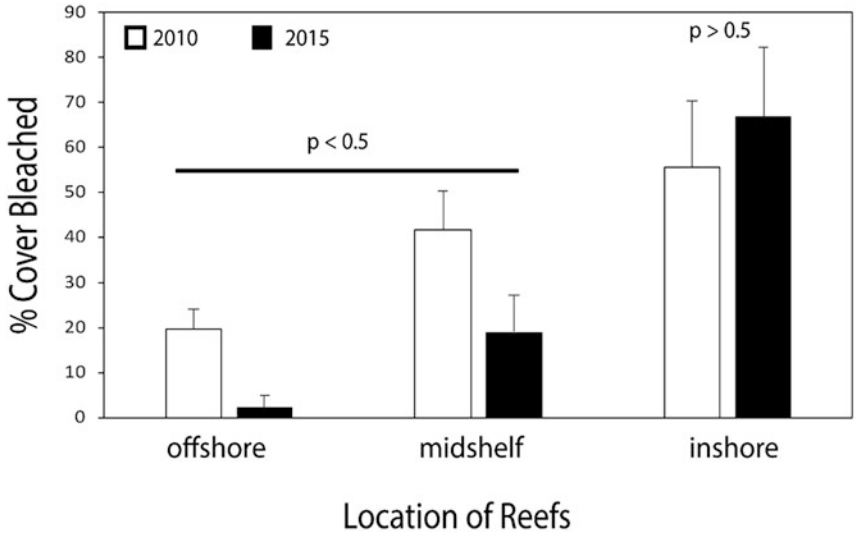

Fig. 1 Difference in % observed coral cover bleached at three reef locations in Central Saudi Arabian Red Sea between 2010 and 2015. There is a significant difference between 2010 and 2015 at the offshore and mid-shelf locations. Shallow inshore reefs experienced similar bleaching. Data from Monroe et al. (2018)

temperatures (Al Cibahy 2012; Monroe et al. 2018) but also cooling temperatures (Fadlallah et al. 1995; Al Cibahy 2012).

With sea temperatures reaching 33.7 °C in the central Saudi Arabian Red Sea (Osman et al. 2017), the identity of those corals susceptible to bleaching or more importantly those that resist bleaching can be used to understand those phenotypic and genotypic traits that allow these corals to propagate in extreme sea water temperatures. Furby et al. (2013) reported that the bleaching in 2015 was less severe than in 2010, with the inshore reefs being the most affected (Fig. 1). Moreso, it was the rarer coral species (Agariciidae and Fungiidae, and the genus *Galaxea*) that bleached more than the dominant species (Pocilloporidae, Acroporidae, Poritidae, and Merulinidae) (Monroe et al. 2018). While the most abundant corals such *Acropora, Porites*, and *Pocillopora* were the least affected corals during this time, in the 1996 mortality event, over 98% of *Acropora* spp. died (Riegl 2002). This drastic shift is a clear example of the impact and necessity of acclimatization and adaptation and the role these play in thermal tolerance of corals.

2.3 Thermal Tolerance

The Gulf reefs experience wide temperature regimes and are as such instrumental in the study and understanding of thermal thresholds. Such thermal thresholds can be

Table 1 Compiled list of known stress-causing factors for corals related to bleaching events, and typical phenotypic characteristics observed of corals that experienced repeated sub-lethal levels of stress

Stress factor		Phenotypic counter-acting characteristic	
Description	References	Description	References
Decreased/ increased salinity	Jokiel and Coles (1992)	Regulation of Na+ pump	van der Merwe et al. (2014)
Competition with algae	Quan-Young and Espinoza-Avalos (2006)	Variation of host tissue thickness; zooxanthellae density; *Symbiodinium* clade; increased capacity for heterotrophic feeding	Thornhill et al. (2011), Grottoli et al. (2014), Quan-Young and Espinoza-Avalos (2006), Jones and Yellowlees (1997), Fitt et al. (2001), Fagoonee et al. (1999), Berkelmans and van Oppen (2006), Stat et al. (2011), Grottoli et al. (2006), Schoepf et al. (2015), Bessell-Browne et al. (2014)
Depth, exposure to low tide	Vaughan (1914), Yonge and Nicholls (1931), Monroe et al. (2018)		
High (or low) temperatures relative to ambient (exposure and duration)	Steen and Muscatine (1987), Jokiel and Coles (1990), Gates et al. (1992), Fitt et al. (2001)		
High radiance, solar radiation	Brown et al. (1994)	Smaller zooxanthellae; *Symbiodinium* clade	Seyfabadi et al. (2011), Schoepf et al. (2015), Berkelmans and van Oppen (2006), Stat et al. (2011)
Low light	Yonge and Nicholls (1931)	Increased density of zooxanthellae; morphology (e.g., branching, plate, boulder); increased capacity for heterotrophic feeding	Jones and Yellowlees (1997), Grottoli et al. (2006), Schoepf et al. (2015), Bessell-Browne et al. (2014)
(Elevated) nutrient levels	Jones and Yellowlees (1997)	Increased density of zooxanthellae	
Sedimentation	Bak (1978), Dollar and Grigg (1981)		

used to predict not only possible bleaching events but also their rate of occurrences (frequency) and severity (Fitt et al. 2001). Although coral bleaching is often coupled with elevated sea temperatures, any environmental stress factor affecting the host coral (e.g., Thomas et al. 2019), the algal symbiont (e.g., Fitt et al. 2001), and/or the microbial assemblage (e.g., Guppy and Bythell 2006) could elicit a bleaching response. Overall, there is growing evidence (e.g., Bellantuono et al. 2012), to suggest that corals that survive a mass bleaching event appear to be more tolerant of subsequent thermal stress, such as the offshore and midshelf reefs in the Red Sea (Fig. 1). Interestingly, corals that experience repeated sub-lethal levels of stress typically share specific characteristics (Table 1); this does not appear to be the case of Gulf corals.

Interestingly, Persian Gulf *Acropora* appear to be able to cope with these extreme water temperatures, even though as a fast-growing species, it was earmarked to fail as global warming increased (Loya et al. 2001). This may be because Persian Gulf corals have increased symbiont densities. Unlike previous research (e.g., Gates et al. 1992; Fagoonee et al. 1999), symbiont densities in Gulf corals, depending on species and geography of reef, have shown increases in *Symbiodinium* densities in shallow corals (up to 2.75–5.34 $\times$ 10^6 cells) compared to deeper sites (3.07–4.39 $\times$ 10^6 cells) (Seyfabadi et al. 2011). Most studies, that experience less thermal variance, typically demonstrate a decrease in symbionts with increased temperature and/or solar radiation. It is possible that the surviving Gulf corals have acclimatized to the varied and high thermal ranges that resulted in their 1996 sub-lethal experience. This was previously demonstrated by Bellantuono et al. (2012) to be possible in *Acropora.*

This in turn may have activated genotypic thermal adaptation of both corals and symbionts (Thomas et al. 2019). Some of these adaptations can include increased host tissue thickness, which allows for greater space for increased symbiont numbers. It is generally accepted that zooxanthellae of clade D is thermal resistant; however this clade is not common in these Gulf corals (Burt et al. 2014), providing further support that Persian Gulf organisms are especially adapted to the high water temperatures experienced. In fact, corals in this region were found with an increased production of heat shock proteins (Bellantuono et al. 2012) and with the ability to repair the photosystem II (Howells et al. 2011). Further, Persian Gulf *Porites* demonstrated “symbiont flexibility” (Monroe et al. 2018) compared to most coral species, regardless of location, that harbor similar symbiont clades; this may also contribute to its thermal resistivity. In addition, a unique thermotolerant symbiont (*Symbiodinium thermophilum*) is only found in the hyperthermal waters of the Persian Gulf (Hume et al. 2015). Other adaptations are compiled in Table 1.

2.4 Salinity

Acclimation and adaptation is not applicable to thermal tolerance alone. Salinity within the lower water masses within the Persian Gulf regularly exceeds 42 psu (Coles 2003; Riegl and Purkiss 2012) due to a combination of several factors: restricted flows, high evaporation, low rainfall, and hypersaline inputs from desalinization plants. In the summer months, these values have been recorded as high as 60–70 psu (John et al. 1990), nearly twice that found in the Caribbean. Comparatively, the Gulf of Oman is considered as well-mixed, with salinity up to 37 psu (Bento et al. 2015), and the northern Arabian Sea is eutrophic for nearly half of the year, but experiences a salinity as high as 35 psu (Rezai et al. 2004). These hypersaline conditions, besides thermal stress, are arguably another major contributing factor for coral distribution and survival in the Persian Gulf. At such hypersaline conditions, in tandem with hyperthermal conditions, the Persian Gulf corals survive at perhaps the uppermost thresholds at most extreme conditions.

Previous studies have shown that corals could be stenohaline osmoconformers (Hoegh-Guldberg and Smith 1989; Ferrier-Pages et al. 1999; Kerswell and Jones

2003) or stenohaline regulators (Chartrand et al. 2009). However, it appears that corals surviving in extreme saline conditions may display genetic plasticity, where they are both osmoregulators such as the Red Sea *Fungia granulosa* (van der Merwe et al. 2014) and osmoconformers in less extreme and variable conditions.

Tolerance and survival of corals in extreme saline environments is also dependent on the survival of the *Symbiodinium* symbiont in these conditions. Na+ regulation affected symbiont growth at both low (25 psu) and high salinities (55 psu) (van der Merwe et al. 2014). This possible deterministic relationship between genetically plastic host coral and choice of harboring similarly plastic *Symbiodinium* has yet to be fully explored.

2.5 Coral Diseases

Coral diseases have been of concern since the 1970s, where both the prevalence and virulence of an array of diseases are apparent particularly in areas such as the Caribbean, especially during the warmer summer months. There are much fewer reported incidences of coral diseases in the Gulf (see review in Green and Bruckner 2000), quite possibly due to the extreme thermal and saline conditions. Only four coral diseases are recorded in the Gulf (Riegl et al. 2012), where black band, white band and the Arabian yellow band disease (AYBD) are the most recorded (Green and Bruckner 2000; Bruckner and Riegl 2015). By comparison, there are 30 or so reported diseases in the Caribbean. Although not discussed here, abnormal pigmentation (Benzoni et al. 2010) and tumors (Green and Bruckner 2000) have also been described within the Gulf region.

Black band disease (BBD) is perhaps considered to be the most widespread of coral diseases, having been first observed in the Caribbean in the 1970s, but recorded on reefs globally (Antonius 1985). In cooler months, BBD has been observed to arrest, becoming active with increasing temperatures (Bruckner 2002). Acroporids within the Gulf are the most affected by this disease, described with similar etiology as other corals around the world (Riegl et al. 2015).

White band disease (WBD), first reported in the Red Sea in 1981 (Antonius 1985), affected more than 30 coral species, of which one third were *Acropora* (Riegl et al. 2015). By 2003, nearly 90% of the reefs were infected (Willis et al. 2004), attributed to the corals' compromised immunity from the 2010 mass bleaching event (Riegl et al. 2015), similar the pattern observed in both Caribbean and Pacific corals (Bruno et al. 2007; Brandt and McManus 2009; Eakin et al. 2010; Bruckner and Hill 2009).

Yellow band disease (YBD) has been reported in the Caribbean (CYBD), Indo-Pacific PYBD), and Arabian Gulf (AYBD), and Bruckner and Riegl (2015) present a comprehensive review of variation of this disease. It should be noted that the behavior of AYBD appears to differ from the other types of YBD based on its overall manifestation, spread, and host susceptibility (Bruckner and Riegl 2015).

So far, AYBD has been reported within the Arabian Gulf on six species of *Acropora*, five *Porites* spp. *Turbinaria reniformis*, and *Cyphastrea microphthalma* (Korrubel and Riegl 1997). Of these, AYBD is most aggressive with faster rates of spread on *Acropora* spp., with slower though more persistent infectivity on *Porites*. Thus far AYBD has only been reported within the region of the Gulf (Riegl et al. 2012). Tissue loss resulting from AYBD is most devastating during the summer months, with average tissue loss of 1–2 cm/wk., compared to that of CYBD with a rate of 1 cm/mth (Bruckner and Riegl 2015). Interestingly, rates of AYBD infection and virulence is neither temporal nor thermally driven (Riegl et al. 2015); however it is highly contagious.

The strong link between coral diseases prevalence and climate change may also be linked the adaptation battles for survival that organisms must undergo. It is inconceivable that the genotypic plasticity that corals have demonstrated for both hyperthermal and hypersaline conditions is only from these Scleractinia. Microbes have been shown to express different genes in hyperthermal conditions that allow them to become better established in host tissues. *Vibrio shilo,* for example, affects the *Symbiodinium* photosynthetic process via activated adhesion genes (Ben Haim et al. 1999), causing the production of extracellular substances.

2.6 Harmful Algal Blooms (HABs)

The overall health of the Gulf's unique ecosystem is dependent on, among other factors, nutrient levels. It is well accepted that corals tend to thrive in oligotrophic (low nutrient) conditions. However, similar to the extraordinary thermal and saline conditions, the Gulf is also hypereutrophic.

Nutrients enter the Gulf from a variety of sources (Al-Yamani et al. 2006; Gilbert 2007): sewage and industrial outfalls, agricultural and husbandry waste including aquaculture, air and oil pollution, and ship discharges such as ballast. Due to high nutrient loading, these normally hypereutrophic waters experience seasonal algal blooms (Al-Yamani et al. 2000; Subba Rao et al. 1999, 2003). Some of the algae are non-harmful (n-HABs, e.g., *Myrionecta rubra*), but others are harmful (HABs) such as *Karenia brevis* (formerly *Gymnodinium breve* and *Ptychodiscus brevis*), *Ceratium furca*, *Gymnodinium catenatum*, *Gyrodinium impudicum*, *Pyrodinium bahamense* var. *compressum* (Manche 2014), and *Cochlodinium polykrikoides* (Al-Omar). Regardless, these algal blooms HABs have affected: (1) tourism due to the discoloration of the water, (2) loss of revenue when the filters from the desalinization plants clog, and (3) loss of fisheries due to clogged gills and/or toxins. HABs (sometimes called red tides) are estimated to occur when cell counts exceed 1 million per liter of seawater. Within the Gulf, e.g., Iran, these cell counts has been reported as high as 27 million cells/l (Al-Omar 2002).

The HABs occur in the summer months, where light is maximal. This therefore also adds further stress to the Gulf's coral reefs, forming yet another extreme condition that these corals must and do survive in. Major HAB events in the Gulf have been reported as early as 1988 in the Oman region (Al-Omar 2002), 1997 in Kuwait's waters (e.g., Subba Rao et al. 1999), and two in 1999 (Al-Yamani et al. 2012). Massive fish kills (up to 2500 metric tons of dead fish) were also recorded in Oman and Kuwait in 2001, 2002, 2008, and 2009 where more than one HAB occurred in Oman in 2008 (Al-Omar 2002). The most widespread HAB event in the Gulf occurred in 2009 (Al-Omar 2002), affecting the UAE, Diba, Fujairah, and Qeshm Island.

3 Human Impacts on Coral Reefs in the Arabian Seas

Coral reefs in the Arabian seas are being rapidly degraded by a number of human and natural factors. These include eutrophication from sewage and agricultural runoff, sedimentation from land reclamation, dredging, mining and other industrial activities, habitat alteration or destruction due to coastal development, overfishing, coral disease and predation, and recurrent coral bleaching due to increasing seawater temperatures (Bento et al. 2015). Pollution from oil and natural gas production and desalination plants also pose serious threats to coral reefs of the Persian Gulf (Wilson et al. 2002). Here we review the major human impacts on coral reefs of the Arabian Seas.

3.1 Coastal Development

Persian Gulf nations have undergone dramatic economic development since the oil boom of the 1970s. Several Gulf nations now rank among the richest and fastest-growing economies in the world. This economic growth has supported population increases of more than 300% in the past 40 years, with an average annual growth rate (2.1%) that is nearly double the global average (1.1%) (van Lavieren et al. 2011). This rapid growth has led to extensive urbanization of coastal areas in the Gulf region. Over 40% of the Persian Gulf coastline had been modified in some way by the 1990s (Al-Ghadban and Price 2002) and that number is likely to be much higher in 2019 (Fig. 2). More recently, massive development projects such as Palm Jumeirah and other artificial islands (Fig. 3) have become common, resulting in mass land reclamation, dredging, and infilling of coastal habitats (Burt 2014; Burt et al. 2012, 2014; Cavalcante et al. 2012). These developments have particularly impacted nearshore coral reefs. Burt et al. (2014) recorded local declines of greater than 90% of live coral cover in some areas, resulting in reduced coastal productivity and biodiversity. Despite the overall negative impacts of coastal development and land reclamation, other built structures such as submerged breakwaters, jetties, and seawalls provide hard substrate for the recruitment of corals. In some areas of the Persian Gulf, this has allowed coral growth in areas where corals did not previously grow on unconsolidated sediments (Burt et al. 2009a, b).

Fig. 2 Comparison of coastal development in the UAE in 2004 (top) and 2018 (bottom). Images courtesy of Google Earth

3.2 *Hydrocarbon and Wastewater Pollution*

The rapid population growth and urbanization in the Persian Gulf region is supported by a petroleum industry that produces roughly 30% of the world's current supply of oil and gas. The Gulf countries hold the largest oil and gas reserves in the world

Fig. 3 Comparison of coastal development in Dubai in 1984 (top) and 2018 (bottom), showing the Palm Jebel Ali, Palm Jumeirah and The World offshore developments in addition to coastal reclamation and urban sprawl. Images courtesy of Google Earth

(Haapkylai et al. 2007). Oil is extracted from around 800 offshore platforms and transported by 25,000 tanker shipments annually (van Lavieren et al. 2011). Chronic contamination from harbors, ballast water, terminals, and atmospheric fallout of burning hydrocarbons have occurred as a result of oil and gas activities (Madany et al. 1998). The most dramatic impacts of oil on marine ecosystems occurred during the 1991 Gulf War when Iraqi troops deliberately spilled approximately 10.8 million barrels of oil from abandoned tankers and terminals. The resulting spill covered thousands of square kilometers of the Persian Gulf coast from Kuwait to northern Saudi Arabia and was second in size only to the Deepwater Horizon blowout of 2010 in the Gulf of Mexico (Price 1998).

Although coral reefs in the Persian Gulf are seriously impacted by chronic oil pollution, they have shown remarkable resilience (Price 1998). The Persian Gulf region has naturally high levels of hydrocarbon which could potentially provide a selective pressure for bacterial assemblages on reefs that are capable of mineralizing crude oils (Al-Saleh et al. 2009). Moreover, the high temperatures and nutrient levels in the Persian Gulf may increase the mineralization rates of these bacteria (Sale et al. 2011). The Persian Gulf region also supports industries that produce chemicals, minerals, plastics, and fertilizers (Gevao et al. 2006). Economic development and a concomitant demand for fresh produce have also encouraged increased agriculture. Effluent from industrial and agricultural activities deposits heavy metals, petroleum-based compounds, nutrients, and halogenated organics into coastal sediments (Gevao et al. 2006). Although high standards for wastewater treatment are implemented throughout the Persian Gulf region (Sheppard et al. 2010), domestic and industrial wastewater still enter coastal waters in large volumes. Sewage in Persian Gulf countries is typically subjected secondary or tertiary treatment before discharge (Sale et al. 2011). However, large quantities of nutrients and other pollutants also enter Gulf waters from inland agriculture and industry (Sale et al. 2011).

3.3 Desalination

Desalination of seawater accounts for a global production of 5 billion m^3/year of fresh water, along with 10 billion m^3/year of heated, hypersaline brine effluent (Dahwoud and Mullah 2012). The coast of the Arabian Peninsula, particularly the Red Sea and Persian Gulf, is an area of intense desalination activity. Limited available surface water, high population growth, and urbanization, along with poor management practices, have led to a situation in which water demand far outstrips supply (Dahwoud and Mullah 2012). This increasing demand for water in the domestic sector has shifted attention to the role of desalination in alleviating water shortages.

Modern desalination technology can serve as a reliable source of water at a price comparable to water from conventional sources. Desalination plants are thus the most feasible alternative to meet future water supply requirements for the Arabian peninsula (Sale et al. 2011). Unfortunately, desalination has the potential to negatively impact the marine environment, primarily through the release of brine concentrate and chemicals into seawater but also as a result of air pollution from fossil fuels used to power the desalination process. Desalination effluent is hypersaline and typically 7–8 Celsius degrees warmer than ambient seawater (Dahwoud and Mullah

2012). Given that corals in the Arabian seas exist at or near their upper limits of temperature and salinity, desalination effluent will inevitably lead to local coral bleaching and mortality.

3.4 Reef Fisheries

Prior to the discovery of oil, fisheries, pearl diving and maritime trade were major economic activities in the Arabian seas for the past 8000 years (Beech 2002). The industrial boom of the 1970s brought rapid and extensive development to the Persian Gulf region, with major environmental impacts to marine ecosystems (Khan et al. 2002). Fisheries are the most important renewable resource in the Arabian seas and the second most important natural resource after oil and gas (Carpenter et al. 1997; Grandcourt 2012). Fisheries provide a source of food security, income, cultural heritage, and recreational opportunities to the coastal populations of the Arabian Peninsula.

Commonly used fishing gears in the Gulf region include traps and bottom trawling to target demersal and reef fishes (Grandcourt 2012). Overfishing and habitat degradation have led to severe declines in fish and shrimp populations. Shrimp trawling in particular has led to the destruction of important nursery habitats. This has prompted fisheries managers to reduce fishing effort by limiting entry to reduce the size of the trawl fleet and by reducing the length of the fishing season. There has been a move to further develop commercial fisheries throughout the region, especially in Saudi Arabia (Bruckner et al. 2011). The UAE, however, has recently banned trawling within its waters.

Nearshore, artisanal fisheries in the Gulf region employ steel wire basket traps, spearfishing and hook and line along rocky shores, and seine nets, gill nets, cast nets, and barrier traps along beaches and in intertidal zones. In the Red Sea, traditional fishing with handlines and gill nets and hand lines account for around 89% of total landings. Traps and nets catch about 240 fish species in the Red Sea or about 25% of all species reported from the region (Bruckner et al. 2011). The bulk of the landings from trammel and gill nets set over sandy bottoms adjacent to reefs consists of the parrotfishes (*Hipposcarus harid*, *Scarus ghobban*, and *S. psittacus*). Bottom nets also catch transient reef predators such as trevally (Carangidae) and dogfin tunas (Scombridae).

“Ghost fishing” due to loss of fishing gears in rocky and coral reef areas is a serious problem contributing to overfishing. Tawfik (2000a) estimates that artisanal fishers may lose 7–12 traps per month, while larger commercial fishing boats that carry 150 to 200 traps may lose 2–25 traps per month. There have been recent attempts to introduce biodegradable escape panels to fish traps, allowing fish to escape after a period of time. Traps were not traditionally used by Saudi fishermen in the Red Sea, but their use is increasing (Bruckner et al. 2011). Spearfishing is illegal in Saudi Arabia.

Another issue leading to overfishing is the subsidy of fisheries by national governments, which give money to fishers for boats, fuel, and equipment, increasing the effort directed at fish stocks in the Arabian seas.

Artificial reefs have been created as a measure to offset habitat degradation. In the UAE, manmade reef structures include cement cones and a form of "cave" made with palm leaves woven together and lashed to iron frames (Tawfik 2000b). The impact of these artificial reefs is unknown. Unless they are placed within regularly patrolled, protected areas, they may simply concentrate fish biomass, making it easier for fishermen to harvest the fish.

3.5 Tourism

The Red Sea has a several unique marine habitats, including coral reefs, mangroves, and sea grass beds. They provide key resources for coastal populations: food, shoreline protection, and stabilization as well as economic benefits from tourism. Coral reefs are therefore considered a natural capital providing valuable ecosystem services. Tourism is generating increasing pressures on coral reefs in Egypt, Israel, and Jordan by coastal construction, sewage, solid waste, and recreational activities, such as swimming, snorkeling, and diving. In Eilat, 250,000 to 300,000 dives are carried out each year in a small area, resulting in severe damage to coral reefs. According to global estimates (World Bank 2002), the cost of destroying 1 km^2 of coral reef area is estimated at between USD 137,000 and USD 1,200,000 over a 25-year period, based on the economic value of coral reef fisheries, tourism, and shoreline protection. Sustainably managed coral reefs can yield an annual average of 15 tons of fish and other seafood per 1 km^2. Egypt's Red Sea reefs yield about 1400 tons of seafood, and their total economic value is estimated at USD 205.5 million to USD 1.8 billion (Cesar 2003; Hilmi et al. 2012).

Hilmi et al. (2012) list two steps to estimate the cost of coral reef degradation. First, physical losses of coral reef habitats and the goods and services generated by coral reef ecosystems as a result of tourism activities must be quantified. Second, the monetary valuation of such physical losses must be estimated (Hilmi et al. 2012). These losses include the loss of natural capital, the loss of income from marine recreational activities, the cost of shoreline protection from erosion, and the loss of fisheries resources. The cost of coral reefs degradation and associated fisheries decline resulting from unregulated tourism activities in the Red Sea was estimated at about USD 12 billion (Cesar 2003). In 2007, Egypt lost an estimated 60 tons of fish production valued at USD 556 million as a result of coral reef degradation. The cost of shoreline protection to replace damaged reefs along the Egyptian coast was valued at USD 12.5 million per km of coast or USD 1.3 billion for the Egyptian Red Sea coast (Hilmi et al. 2012).

4 Management Options for Coral Reefs in the Arabian Seas

Of the existing marine conservation initiatives in the Arabian Seas, perhaps the most important is the Regional Action Plan for the Conservation of Coral Reefs in the Red Sea and Gulf of Aden (PERSGA), which is based in Jeddah, Saudi Arabia, and involves all Red Sea countries except Eritrea (PERSGA 2003). PERSGA is responsible for the development and implementation of regional programs for the protection and conservation of the marine environment and defines six priority actions for the conservation and sustainable development of marine resources, particularly coral reefs:

1. Integrated coastal zone management
2. Education and awareness
3. Marine protected areas (MPAs)
4. Ecologically sustainable reef fisheries
5. Impacts of shipping and marine pollution
6. Research, monitoring, and economic valuation

In the Persian Gulf, the primary instrument governing the marine environment is the Kuwait Regional Convention on Cooperation for Protection of the Marine Environment from Pollution (ROPME). All eight countries bordering the Persian Gulf are signatories to ROPME. However, while PERSGA specifically mentions coral reefs, the word coral does not appear in the ROPME Convention.

In the Persian Gulf, ROPME is primarily aimed at reducing pollution from coastal development and oil and gas exploration, extraction, and processing. Specific management measures appear to focus more on oysters than on coral reefs. In the Red Sea, PERSGA takes a more integrated approach to coast and ocean management, education, and awareness. Current PERSGA capacity-building programs (PERSGA 2018) include national and regional training workshops on:

- Economic Valuation of Damage by Ship/Boat Grounding on Coral reefs
- The Importance of Environmental Impact Assessment (EIA) in Protecting the Marine Environment and Achieving Sustainable Development
- Marine Protected Areas Governance in the PERSGA Region
- Negotiation Skills for Multilateral Environmental Agreements
- Economic valuation of environmental resources of the Red Sea and Gulf of Aden
- Ocean Acidification in the Red Sea and Gulf of Aden
- Ecosystem Approach in Nationally Determined Contributions “NDCs” for Climate Change in Coastal Areas
- Management of Marine Protected Areas
- Management Effectiveness Evaluation of Marine Protected Areas

4.1 Marine Protected Areas (MPAs)

The establishment of a regional network of marine protected areas (MPAs) is perhaps the most important coral reef conservation measure for the Arabian Seas. Marine protected areas are areas set aside for conservation but generally allow non-extractive tourism uses such as snorkeling, diving, and, in some cases, limited subsistence fishing. MPAs vary greatly in their effectiveness, with well-enforced MPAs often showing rapid increases in biomass of commercially valuable reef fish and invertebrates following the cessation of fishing activities, while poorly planned and enforced MPAs show little benefit (Tupper 2002). However, MPAs have been less successful at protecting corals, as their boundaries are porous to a wide range of impacts, including global warming, marine pollution, agricultural and industrial runoff, atmospheric fallout of dust and hydrocarbons, harmful algal blooms, and other impacts that cannot be mitigated simply by excluding humans from an area (Jameson et al. 2002).

Coral reef MPAs have been declared or proposed in all eight countries bordering the Red Sea. Table 2 lists the current declared and proposed coral reef MPAs in the Red Sea, Arabian Sea, and Persian Gulf, together with their size, the habitat protected, and the major impacts affecting the coral reefs. In contrast, only Saudi Arabia and Oman have declared or proposed MPAs in the Persian Gulf. In the Red Sea, roughly half of Egypt's coral reefs are inside MPAs. MPAs in the Red Sea are considered at least partially effective in terms of maintaining healthy reefs and reducing the impact of the rapidly expanding tourism industry. The effectiveness of MPAs in the Persian Gulf is not clear. Throughout the region, proper assessments of MPA management effectiveness (e.g., Garces et al. 2013; Tupper et al. 2015) are urgently needed.

4.2 Reef Fisheries Management

Fisheries management in the Persian Gulf remains poorly developed. There are no regional fisheries management plans or policy instruments currently implemented (De Young 2006; Grandcourt 2012). Management is further constrained by a lack of basic catch and effort data needed for stock assessment and socioeconomic data to determine the value of fisheries to local and national economies. Limited current management measures focus on controlling fishing effort (e.g., the trawl ban and trap mesh regulations in the UAE) rather than on output controls such as minimum size limits or catch quotas (Grandcourt et al. 2011). While the trawl ban has reduced the amount of damage to corals in the UAE, trap mesh and escape panel regulations have not been successful in protecting juvenile fishes nor in preventing overfishing and reef fish stock decline in the UAE (Grandcourt et al. 2011).

High levels of illegal, unregulated, and unreported (IUU) fishing result from weak monitoring and enforcement of fisheries regulations and a lack of legal frameworks

Table 2 List of coral reef marine protected areas in the Red Sea, Arabian Sea, and Persian Gulf, showing their status, size, habitats protected, and the threats impacting them

Name	Status	Size	Habitats	Impacts
Djibouti				
Moucha Territorial Park	Declared	3 km^2	Coral reefs, mangroves	Reef trampling, souvenir collection, spearfishing
South Masgali Islands	Declared	10 km^2	Coral reefs	Reef trampling, souvenir collection, spearfishing
Iles des Sept Frères and Ras Siyan	Proposed	Undefined	Coral reefs, mangroves	Tourism pressure, diving-related damage, sedimentation from shipping activities
Egypt				
Ras Mohammed national park	Declared	750 km^2	Coral reefs, mangroves, seagrass, mudflats, turtle nesting beaches	Heavy tourism use (diving, snorkeling); illegal fishing
Nabq	Declared	600 km^2	Coral reefs, mangroves, mudflats	Diving-related damage, shrimp farm effluent
Abu Galum	Declared	500 km^2	Coral reefs, seagrass beds, sand dunes	Diving-related damage
Elba	Declared	35,000 km^2	Coral reefs, mangroves	Illegal fishing
Giftun Islands and Straits of Gubal	Proposed	Undefined	Coral reefs, turtle nesting beaches, seabird nesting sites	Tourism pressure, diving-related and anchor damage, illegal fishing
Safaga Island	Proposed	Undefined	Coral patch reefs, turtle nesting beaches	Shipping, illegal fishing
Sharm al-Lalu	Proposed	Undefined	Coral reefs	Tourism pressure
Dedalus Island	Proposed	Undefined	Coral reefs	Diving-related and anchor damage
Zabareged Island	Proposed	Undefined	Coral reefs, turtle nesting beaches	Diving-related and anchor damage
Brother Islands	Proposed	Undefined	Coral reefs	Diving-related and anchor damage
Al-Qusair reef complex	Proposed	Undefined	Coral reefs	Diving-related and anchor damage
Eritrea				
Dahlac Marine National Park	Proposed	Undefined	Coral reefs	Diving-related and anchor damage
Israel				
HaYam HaDeromi Be Elat	Declared	0.33 km^2	Coral reefs	Diving-related damage, illegal fishing

(continued)

Table 2 (continued)

Name	Status	Size	Habitats	Impacts
Jordan				
Aqaba	Declared	40 km^2	Coral reefs	Diving-related damage, illegal fishing
Oman				
Daymaniyat Islands	Declared	1 km^2	Coral reefs	Tourism and diving-related impacts
Saudi Arabia (Red Sea)				
Yanbu protected area	Declared	5 km^2	Coral reefs, mangroves, seabird nesting areas	Tourism and diving-related impacts
Umm al Qamari Islands	Declared	2000 km^2	Coral reefs, seabird nesting sites	Tourism and diving-related impacts
Farasan Islands	Declared	3310 km^2	Coral reefs, mangroves, seagrass, turtle nesting beaches, seabird nesting sites	Illegal fishing, coastal development, tourism and diving-related impacts
Straits of Tiran	Proposed	Undefined	Coral reefs, seagrass beds, turtle nesting beaches, dugong habitat	Tourism-related impacts
Ras Suwayhil	Proposed	267 km^2	Coral reefs, seabird nesting sites, dugong habitat	Undefined
Sharm Zubayr	Proposed	80 km^2	Coral reefs, mangroves	Coastal development (causeway construction)
Ghubbat Bal'aksh	Proposed	33 km^2	Coral reefs, seagrass, seabird nesting sites	Unregulated tourism-related impacts
Sharm Dumagyh/ Sharm Antar	Proposed	70 km^2	Coral reefs, mangroves, seagrass beds, turtle nesting beaches	Fishing and tourism-related impacts
Al-Wedj bank	Proposed	2840 km^2	Coral reefs, mangroves, seagrass beds, seabird and turtle nesting sites, dugong habitat	Undefined
Al-Hasani and Libana Islands	Proposed	Undefined	Coral reefs, seabird nesting sites, and turtle nesting beaches	Fishing
Ras Biridi/ Sharm Al-Khawr	Proposed	Undefined	Coral reefs, seagrass beds, turtle nesting beaches	Coastal development (cement factory)
Sharm Yanbu	Proposed	50 km^2	Coral reefs, mangroves, seabird nesting areas	Tourism and diving-related impacts
Shi'b al-Qirin	Proposed	30 km^2	Coral reefs, seabird nesting sites	Undefined
Marsa as-Sarraj	Proposed	200 km^2	Coral reefs, mangroves, seagrass beds, halophytes	Agricultural development and fishing

(continued)

Table 2 (continued)

Name	Status	Size	Habitats	Impacts
Ras Hatiba	Proposed	450 km^2	Coral reefs, mangroves, extensive sand areas	Unregulated tourism and coastal development
Ash-Shu'aybah and Mastaba	Proposed	100 km^2	Coral reefs, mangroves	Unregulated development, highway construction, illegal mangrove deforestation
Qishran	Proposed	Undefined	Coral reefs, mangroves, seagrass beds, seabird nesting sites, dugong habitat	Undefined
Khawr Nahoud	Proposed	33 km^2	Coral reefs, mangroves, seagrass beds, seabird nesting sites, dugong habitat	Undefined
Khawr Itwad	Proposed	70 km^2	Coral reefs, mangroves, seagrass beds	Undefined
Shi'b Abu al-Liqa and Shi'b al-Kabir	Proposed	140 km^2	Coral reefs, mangroves	Undefined
Saudi Arabia (Persian Gulf)				
Dawad al-Dafl & Coral Islands	Declared	2100 km^2	Coral reefs	Coastal development, shipping
Jubail Wildlife Sanctuary	Proposed	2300 km^2	Coral reefs, wetlands for bird migration, bird nesting sites, turtle nesting beaches	Coastal development, shipping
Sudan				
Sanganeb Marine Natl Park	Declared	12 km^2	Coral reefs, only true atoll in Red Sea	Illegal fishing
Shuab Rami	Proposed	4 km^2	Coral reefs	Undefined
Mukkawar Island and Dungonab Bay	Proposed	300 km^2	Coral reefs	Fishing and tourism-related impacts
Suakin Archipelago	Proposed	Undefined	Coral reefs, seabird nesting sites, turtle nesting beaches	Fishing and tourism-related impacts
Abu Hashish	Proposed	5 km^2	Coral reefs	Undefined
United Arab Emirates				
Bazm al Gharbi and Murawwa	Declared	Undefined	Coral reefs	Coastal development, illegal fishing

(continued)

Table 2 (continued)

Name	Status	Size	Habitats	Impacts
Yemen				
Socotra Islands	Declared	362,500 km^2	Coral reefs, seagrass beds, turtle nesting beaches	Illegal fishing
Belhaf and Bir Ali Area	Proposed	Undefined	Coral reefs, seabird and turtle nesting sites	Fishing
Khor Umaira	Proposed	Undefined	Mixed seagrass and small patch reefs	Undefined

to support long-term fisheries sustainability (De Young 2006; Grandcourt 2012). The rapid population growth and IUU fishing practices, coupled with a lack of alternative livelihoods, have resulted in rapid overexploitation of fishery resources throughout the region. The wide-scale destruction of fish habitat by land reclamation for coastal development and by navigational dredging activities further exacerbates the decline of fisheries (Sheppard et al. 2010). Management of fish habitat, which forms the basis of fisheries management in countries like Canada and the United States, is not addressed in any national policy frameworks. Little attention is paid to the concepts of precautionary management or to the ecosystem approach to fisheries management (EAFM), other than the creation of MPAs (PERSGA 2018).

The lack of effective monitoring, control and surveillance systems results in widespread poaching and habitat destruction by both foreign and national fishing fleets. IUU fishing is particularly common in the Gulf of Aden, off the coasts of Somalia and Yemen, where foreign industrial trawling causes extensive damage to coral reefs and seagrass beds (Bruckner et al. 2011). Conflicts between industrial trawlers and artisanal fishers are common and often lead to artisanal fishers' gear being damaged. Fish stocks in the northern Red Sea, particularly in the Gulf of Suez and the upper Gulf of Aqaba, are fully exploited or overexploited, with reported reductions in the biomass and species richness of catches in Jordan (Bruckner et al. 2011).

In order to ensure the sustainability of reef fisheries in the Arabian seas, a precautionary, ecosystem approach to fisheries management must be adopted (Sale et al. 2011; van Lavieren et al. 2011). Management decisions should be data-driven and participatory in nature. If sufficient data are not available, reef fisheries management should focus on developing data-limited assessment and management strategies. There are methods for assessing stock status and identifying management reference points (i.e., thresholds, indicators) for fisheries that are data-limited (Apel et al. 2013; Babcock and MacCall 2011; Babcock et al. 2013; McDonald et al. 2018). Honey et al. (2010, p. 161) define a data-limited method as "a method for fisheries data analysis and/or for informing a control rule or management action, which can be a qualitative or quantitative method, but is not a full, stage-structured stock assessment that requires data-rich or data-moderate conditions." Data-limited assessment methods allow managers to prioritize fisheries for research and management, as well as estimate biological reference points, indicators of stock status, or catch or effort limits with limited information (Apel et al. 2013; Smith et al. 2009).

4.3 Remote Sensing and Geographic Information Systems (GIS) for Coral Reef Management

The Arabian Seas region includes the Persian Gulf, the Gulf of Oman, the Strait of Hormuz, the Gulf of Aden, and the Red Sea (Krupp et al. 2006). Extensive coral reef communities comprising a wide variety of flora and fauna exist within each of these zones (Burt et al. 2015). Although these individual coral communities occur in distinct environmental conditions, one commonality among the reefs of the Arabian Seas region is the types of stressors that they face (Ben-Romdhane et al. 2016). The many adverse impacts caused by these stressors make it critical that sustainable and effective monitoring and management policies be implemented to ensure the healthy proliferation of these vital ecosystems (Owfi et al. 2014). Remotely sensed data provides current information that is both reliable and accurate, over spatially extensive areas (Jensen 2007).

Significant advancements in technology within the last decade have greatly improved the remote sensing systems available to the earth science, research, and resource management communities. Remote sensing tools offer insights into the current status and long-term trends occurring within coral reefs (Awak et al. 2016). This is achieved by merging the ability to capture sensor data for visual and computer interpretation of coral community distribution with their biophysical properties and associated processes (Purkis 2018). Remote sensing has progressed into of a vast array of technologies that include sensors on board manned aircrafts, unmanned aerial systems (UAS), autonomous underwater vehicles (AUV), high-resolution satellite imagery, and boat-based systems (Goodman et al. 2013). The capabilities of these methods can be used to resolve many of the monitoring and management objectives for coral reefs within the Arabian Seas.

Remote sensing tools offer faster and cheaper methods that can be used to delineate reef boundaries, conduct bathymetric surveys, and map benthic coverage and rugosity while simultaneously collecting data on sea surface temperature, exposure, light, and carbonate chemistry (Hedley et al. 2016; Burt et al. 2015). These technologies are highly valued as they capture information from hard to reach areas in a synoptic, cost-effective, and noninvasive manner (Hedley et al. 2016). With advancements in recent decades, the ability to obtain larger quantities of higher quality remotely sensed data on coral communities is rapidly increasing. This allows for a more complete approach to the study of these complex marine ecosystems (Selgrath et al. 2016) and the relationships between their temporal and spatial distribution patterns (Hedley et al. 2016).

Global environmental organizations such as Coral Reef Watch of the National Oceanic and Atmospheric Administration (NOAA), ReefTemp, and the IMaRS observing system have been effectively utilizing remotely sensed data from satellites for monitoring reef systems for several years (Hedley et al. 2016). Through the use of remotely sensed satellite data, NOAA's Coral Reef Watch program focuses on monitoring coral bleaching-level heat stress globally, enabling the prediction of the inception of mass bleaching events (Skirving et al. 2018).

In Colombia, the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor was used to observe the impacts that river discharge had on watershed regions and nearby coral reefs (Moreno-Madrinan et al. 2017). Additionally, in Mexico, Contreras-Silva et al. (2012) studied different satellite uses for mapping reefs with a specific emphasis on mapping the benthic substrate. Remote sensing technologies have been utilized for acquiring datasets on coral ecosystems and their surrounding properties worldwide. Collectively these systems can be implemented or adapted for monitoring reefs within the Arabian Seas to develop integrated management systems for sustainable conservation.

With wide fluctuations of temperature being one of the more problematic issues that impact Arabian Seas reefs (Ziegler et al. 2018), the use of high-resolution, multispectral satellite imagery offers the ability to monitor sea surface temperatures for predicting anomalies at much smaller scales. With Red Sea experiencing temperatures exceeding the normal range for the reef communities in the Atlantic, Indian, and Pacific Oceans (Monroe et al. 2018), there is a persistently high probability therefore that coral bleaching will occur in this region. The enhanced functionalities of the latest remote sensing technologies can not only detect where bleaching has occurred but can also collect hyperspectral data to help identify the rapid increases of ocean temperatures beforehand. This capacity enables resource managers to develop proactive strategies based on the remotely sensed data. Enhanced remotely sensed data can also be used to update and define improved habitat extent and distribution maps.

Ben-Romdhane et al. (2016) evaluated the ability of high spatial resolution DubaiSat-2 to map benthic communities within the region. The results illustrated that when published habitat maps were compared to the results from the satellite imagery, the spectral-spatial technique produced a 96.41% mapping accuracy. The Jebel Ali Marine Sanctuary and Marawah Marine Protected Area (MPA) along the mainland coast of Dubai are within a sustained coral reef monitoring program that is heavily supported by remotely sensed data. Temporal multi-spectral data acquired from the Indian Remote Sensing Satellite: Resourcesat-1 (IRS-P6) has been utilized for the development of a monitoring approach for change analysis in United Arab Emirates (UAE) coral reefs (Sanghvi et al. 2013). Sub-meter resolution satellite data has also been applied for coral reef mapping and monitoring in the Arabian Seas region.

Grizzle et al. (2016) utilized data from the GeoEye-1 satellite to generate the most up to date maps of live coral distribution in UAE, whereas coral habitats in the northern Persian Gulf region close to Hendorabi Island were mapped using Worldview-2 satellite imagery (Kabiri et al. 2018). The European space agency's

(ESA) twin satellite Sentinel-2 multispectral imager (MSI) is capable of delivering multispectral imagery with ground pixel sizes as small as 10 m. NASA's Landsat–8 operational land imager (OLI) has similar capabilities albeit with a larger minimum ground pixel size of 30 m. Both Sentinel-2 and Landsat-8 are fairly recent additions to the earth observation system (EOS) community and have been utilized for monitoring coral bleaching, reef surveying, and habitat mapping at small spatial scales (Ramsewak et al. 2018; ESA 2017; Duan et al. 2016).

The immediate predecessors of Landsat-8 (i.e., Landsat-5 TM and Landsat-7 ETM+) have been utilized effectively in the Red Sea for local coral reef monitoring. In Hurghada, Egypt, classifications of coral reef bottom type derived from satellite imagery were combined with geomorphological data to generate baseline data for marine protected area (MPA) management (Vanderstraete et al. 2003, 2004, 2005). The Sentinel-2 and Landsat-8 satellite data from ESA and NASA occurs at no cost and in most instances can now be seamlessly incorporated into geographic information systems (GIS) via web mapping services (WMS). This is a significant development as satellite data traditionally required large amounts of storage space (Tanimura et al. 2008) for effective utility.

Drone technology is also becoming ubiquitous for coral reef and coastal ecosystem applications (Ramsewak et al. 2012; Abbey 2017), as it offers much more versatility for data capture with regard to achieving higher ground resolutions and avoiding atmospheric disturbance. It is anticipated that the primary causes of coral declination in the Arabian Seas region within the next few decades will be due to anthropogenic and natural elements. It is critical therefore to develop and maintain effective management strategies to help preserve these natural resources. Mapping and monitoring of the reef communities remain key elements of any decisive management strategy. Data from advanced remote sensing systems, which are becoming more and more cost-effective and widely available, should be integrated into such strategies if the thriving coral communities are to be sustained. A broad range of existing remote sensing capabilities can be implemented, from moderate resolution to very high-resolution satellites and drones. The right combination of technologies and sensors used, however, will inevitably be based on several factors including the objectives of the management plan, scale, local conditions, and available funding.

5 Conclusions

In conclusion, coral reefs in the Arabian Seas exist in and are resilient to a harsh environment with extremes of temperature and salinity. These coral assemblages and their associated biota and fisheries are under threat from a wide variety of impacts, including global climate change and associated ocean warming, heavy tourism pressure, sedimentation, and physical habitat destruction from intense, widespread coastal development, overfishing, industrial pollution, and shipping. Coral reef management is primarily accomplished through the implementation of MPAs, with unknown success due to the lack of MPA management effectiveness assessments. Reef fisheries management in the region is poorly developed and needs to move toward a precautionary, ecosystem-based management approach. There has been increasing interest in coral reef research in the Arabian Seas, primarily to understand the resilience of corals to global environmental change. Recent advances in GIS and remote sensing provide useful tools for managing marine ecosystems.

References

Abbey E (2017) Great Barrier Reef monitoring is for the drones. Spatial Source, 4 September [online]. Available from https://www.spatialsource.com.au/remote-sensing/great-barrier-reef-monitoring-drones-work

Al Cibahy A Coral reefs of Arabian Gulf, the hottest sea on earth. Environment Agency - a brief to the IUCN, 2nd SSC Chairs Meeting, 23–27 Feb, 2012, Abu Dhabi, United Arab Emirates

Al-Ghadban A, Price ARG (2002) Dredging and infilling. In: Khan NY, Munwar M, Price ARG (eds) The Gulf ecosystem health and sustainability. Backhuys Publishers, Leiden, pp 207–218

Al-Omar MA (2002) Red tide: a new threat to water resources in the Arabian Gulf region. Abu Dhabi Water and Electricity Authority and National Energy and Water Research Center. Available from https://www.riob.org/IMG/pdf/Muthanna_Alomar.pdf. Accessed 13 June 2018

Al-Saleh E, Drobiovaa H, Obuekwea C (2009) Predominant culturable crude oil-degrading bacteria in the coast of Kuwait. Int Biodeterior Biodegradation 63:400–406

Al-Yamani F, Al-Ghunaim A, Subba Rao DV, Khan NY, Al-Ghool M, Murupped M, Al-Qatma S, Luis M (2000) Fish Kills, Red Tides, Kuwait's Marine Environment. Kuwait Institute for Scientific Research, Kuwait. Available from www.kisr.edu.kw/Data/Site1/images/kisr_publications/978–99906-41–90-5.pdf

Al-Yamani F, Saburova M, Polikarpov I (2012) A preliminary assessment of harmful algal blooms in Kuwait's marine environment. Aquat Ecosys Health 15(Suppl 1):64–72

Al-Yamani F, Subba Rao DV, Mharzi A, Ismail W, Al-Rifaie K (2006) Primary production off Kuwait, an arid zone. Environment, Arabian Gulf. Int J Oceans Oceanogr 1:67–85

Antonius A (1985) Coral diseases in the Indo-Pacific: a first record. Mar Ecol 6:197–218

Apel AM, Fujita R, Karr K (2013) Science-based management of data-poor fisheries: a supplement to the catch share design manual. Environmental Defense Fund

Awak DSHLMK, Gaol JL, Subhan B, Madduppa HH, Arafat D (2016) Coral reef ecosystem monitoring using remote sensing data: case study in Owi Island, Biak, Papua. Procedia Environ Sci 33:600–606

Babcock EA, MacCall AD (2011) How useful is the ratio of fish density outside versus inside no-take marine reserves as a metric for fishery management control rules? Can J Fish Aquat Sci 68(2):343–359

Babcock EA, Coleman R, Karnauskas M, Gibson J (2013) Length-based indicators of fishery and ecosystem status: Glover's reef marine reserve Belize. Fish Res 147:434–445

Bak RPM (1978) Lethal and sublethal effects of dredging on reef corals. Mar Poll Bull 9:14–16

Beech MJ (2002) Fishing in the 'Ubaid: a review of fish-bone assemblages from early prehistoric coastal settlements in the Arabian Gulf. J Oman Stud 12:25–40

Behairy AKA, Sheppard CRC, El-Sayed MK (1992) A review of geology of the geology of coral reefs in the Red Sea. UNEP Regional Reports and Studies, No. 152, UNEP

Bellantuono AJ, Granados-Cifuentes C, Miller DJ, Hoegh-Guldberg O, Rodriquez-Lanetty M (2012) Coral thermal tolerance: tuning gene expression to resist thermal stress. PLoS One 7 (11):e50685

Ben Haim Y, Banim E, Kushmaro A, Lyoa Y, Rosenberg E (1999) Inhibition of photosynthesis and bleaching of zooxanthellae by the coral pathogen *Vibrio shilo*. Environ Microbiol 1:223–229

Ben-Romdhane H, Marpu PR, Ghedira H, Ouarda TBM (2016) Mapping of coral reef environment in the Arabian Gulf using multispectral remote sensing. ISPRS XLI-B8:1111–1113

Bento R, Hoey AS, Bauman AG, Feary DA, Burt FA (2015) The implications of recurrent disturbances within the world's hottest coral reef. Mar Poll Bull 105(2):466–472

Benzoni F, Galli P, Pichon M (2010) Pink spots on *Porites*: not always a coral disease. Coral Reefs 29:153

Berkelmans R, Van Oppen MJ (2006) The role of zooxanthellae in the thermal tolerance of corals: a 'nugget of hope' for coral reefs in an era of climate change. Proc R Soc Biol Sci Ser 273:2305–2312

Berumen M, Hoey AS, Bass WH, Bouwmeester J, Catania D, Cochran JEM, Khalil MT, Miyake S, Mughal MR, Spaet JLY, Saenz-Agudelo P (2013) The status of coral reef ecology research in the Red Sea. Coral Reefs 32:738–748

Bessell-Browne P, Stat M, Thomson D, Clode PL (2014) *Coscinaraea marshae* corals that have survived prolonged bleaching exhibit signs of increased heterotrophic feeding. Coral Reefs 33:795–804

Brandt ME, McManus JW (2009) Disease incidence is related to bleaching extent in reef-building corals. Ecology 90:2859–2867

Brown BE, Dunne RP, Scoffin TP, Le Tissier MDA (1994) Solar damage in intertidal corals. Mar Ecol Prog Ser 105:219–230

Bruckner AW (2002) Priorities for the effective management of coral diseases. NOAA Technical Memorandum NMFS-OPR-22. U.S. Department of Commerce/National Oceanic and Atmospheric Administration/National Marine Fisheries Service, Silver Spring, 54 pp

Bruckner AW, Alnazry HH, Faisal M (2011) A paradigm shift for fisheries management to enhance recovery, resilience and sustainability of coral reef ecosystems in the Red Sea. In: Taylor WW, Lynch AJ, Schechter MG (eds) Sustainable fisheries: multi-level approaches to a global problem. AFS, Bethesda, pp 85–111

Bruckner AW, Hill R (2009) Ten years of change to coral communities off Mona and Desecheo Islands, Puerto Rico from disease and bleaching. Dis Aquat Org 87:19–31

Bruckner AW, Riegl B (2015) Yellow-band diseases. In: Woodley CM, Downs CA, Bruckner AW, Porter JW, Galloway SB (eds) Diseases of coral, 1st edn. Wiley, Hoboken, NJ, pp 376–386

Bruno JF, Selig ER, Casey KS, Page CA, Willis BL, Harvell D, Sweatman H, Melendy AM (2007) Thermal stress and coral cover as drivers of coral disease outbreaks. PLoS Biol 5:1220–1227

Buchanan JR, Krupp F, Burt JA, Feary DA, Ralph GM, Carpenter KE (2016) Living on the edge: vulnerability of coral-dependent fishes in the gulf. Mar Pollut Bull 105:480–488

Burt JA (2014) The environmental costs of urbanization in the Arabian Gulf. City 18(6):760–770

Burt J, Bartholomew A, Bauman A, Saif A, Sale PF (2009a) Coral recruitment and early benthic community development on several materials used in the construction of artificial reefs and breakwaters. J Exp Mar Biol Ecol 373:72–78

Burt J, Bartholomew A, Usseglio P, Bauman A, Sale PF (2009b) Are artificial reefs surrogates of natural habitats for corals and fish in Dubai, United Arab Emirates? Coral Reefs 28:663–675

Burt J, Bartholomew A, Feary D (2012) Man-made structures as artificial reefs in the Gulf. In: Riegl B, Purkis S (eds) Coral reefs of the Gulf: adaptation to climatic extremes. Springer, New York, pp 171–186

Burt JA, van Lavieren H, Feary DA (2014) Persian Gulf reefs: an important asset for climate science in urgent need of protection. Ocean Challenge 20:49–56

Burt JA, Coles S, Lavieren HV, Taylor O, Looker E, Samimi-Manin K (2015) Oma's coral reefs: a unique ecosystem challenged by natural and man-related stresses and in need of conservation. Mar Pollut Bull 105(2). https://doi.org/10.1016/j.marpolbul.2015.11.010

Carpenter KE, Krupp F, Jones DA, Zajonz U (1997) FAO species identification field guide for fishery purposes: the living marine resources of Kuwait, Eastern Saudi Arabia, Bahrain, Qatar, and the United Arab Emirates. Food and Agriculture Organization of the United Nations, Rome

Cavalcante GH, Kjerfve B, Feary DA (2012) Examination of residence time and its relevance to water quality within a coastal mega-structure: the Palm Jumeirah Lagoon. J Hydrol 468-469:111–119

Cesar H (2003) Economic valuation of the Egyptian Red Sea coral reefs. USAID Egypt Contract No. LAG I-00-99-00014-00

Chartrand K, Durako M, Blum J (2009) Effect of hyposalinity on the photophysiology of *Siderastrea radians*. Mar Biol 156:1691–1702

Coles SL (2003) Coral species diversity and environmental factors in the Arabian Gulf and the Gulf of Oman: a comparison to the Indo-Pacific region. National Museum of Natural History, Smithsonian Institution

Coles SR, Brown BE (2003) Coral bleaching - capacity for acclimatization and adaptation. Adv Mar Biol 46:183–223

Contreras-Silva AI, Lopez-Calcoa AA, Tapia-Silva FO, Cerdeira-Estrada S (2012) Satellite remote sensing of coral reef habitats mapping in shallow waters at banco chinchorro reefs, México: a classification approach, Chapter 14. In: Escalante-Ramirez B (ed) Remote sensing - applications. Intech, Mexico, pp 331–354

Dahwoud MA, Mullah MM (2012) Environmental impacts of seawater desalination: Arabian Gulf case study. Int J Environ Sustain 1(3):22–37

De Young C (2006) Review of the state of world marine capture fisheries management: Indian Ocean. Food and Agriculture Organization of the United Nations, Rome

Dollar SJ, Grigg RW (1981) Impact of a kaolin clay spill on a coral reef in Hawaii. Mar Biol 65:269–276

Duan Y, Liu Y, Li M, Zhou M, Yang Y (2016) Survey of reefs based on Landsat 8 operational land imager (OLI) images in the Nansha Islands, South China Sea. Acta Ocean Sin 35:11–19. https://doi.org/10.1007/s13131-016-0898-6

Eakin CM, Morgan JA, Heron SF, Smith TB, Liu G, Alvarez-Filip L, Bart B, Bartels E, Bastidas C, Bouchon C, Brandt M, Bruckner AW et al (2010) Caribbean corals in crisis: record thermal stress, bleaching, and mortality in 2005. PLoS One 5(11):e13969

Edwards FJ (1987) Climate and oceanography. In: Edwards AJ, Head S (eds) Key environments: Red Sea. Pergamon Press, Oxford, pp 45–68

European Space Agency (ESA) (2017) Sentinel-2 captures coral bleaching of Great Barrier Reef [Online]. Available from http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Sentinel-2/Sentinel-2_captures_coral_bleaching_of_Great_Barrier_Reef/. Accessed 25 May 2018

Fadlallah YH, Allen KW, Estudillo RA (1995) Damage to shallow reef corals in the Gulf caused by periodic exposures to air during extreme low tides and low water temperatures (Tarut Bay, eastern Saudi Arabia). In: Ginsburg RN (ed) Proceedings of the colloquial global aspects of Coral Reefs, health, hazards, and history. RSMAS Univ. of Miami, Miami, pp 371–377

Fagoonee I, Wilson HB, Hassell MP, Turner JR (1999) The dynamics of zooxanthellae populations: a long-term study in the field. Science 283:843–845

Ferrier-Pages C, Gattuso JP, Jaubert J (1999) Effect of small variations in salinity on the rates of photosynthesis and respiration of the zooxanthellate coral *Stylophora pistillata*. Mar Ecol Prog Ser 181:309–314

Fitt WK, Brown BE, Warner ME, Dunne RP (2001) Coral bleaching: interpretation of thermal tolerance limits and thermal thresholds in tropical corals. Coral Reefs 20:51–65

Furby KA, Bouwmeester J, Berumen ML (2013) Susceptibility of Central Red Sea corals during a major bleaching event. Coral Reefs 32:505–513

Garces L, Pido M, Tupper M, Silvestre G (2013) Evaluating the management effectiveness of three marine protected areas in the Calamianes Islands, Palawan Province, Philippines: process, selected results and their implications for planning and management. Ocean Coast Manag 81:49–57

Gates RD, Baghdasarian G, Muscatine L (1992) Temperature stress causes host cell detachment in symbiotic cnidarians: implications for coral bleaching. Biol Bull 182:324–332

Gevao B, Beg MU, Al-Omair A, Helaleh M, Zafar J (2006) Spatial distribution of polychlorinated biphenyls in coastal marine sediments receiving industrial effluents in Kuwait. Arch Environ Contam Toxicol 50:166–174

Gilbert PM (2007) Eutrophication and harmful algal blooms: a complex global issue, examples from the Arabian seas including Kuwait Bay, and an introduction to the global ecology and oceanography of harmful algal blooms (GEOHAB) programme. Int J Ocean Oceanogr 2:157–169

Goodman JA, Purkis SJ, Phinn SR (2013) Coral reef remote sensing: a guide for mapping, monitoring and management. Springer, New York

Grandcourt EA (2012) Reef fish and fisheries in the Gulf. In: Riegl BM, Purkis S (eds) Coral reefs of the Gulf: adaptation to climatic extremes. Springer, Dordrecht, Netherlands, pp 127–161

Grandcourt EA, Al Abdessalaam TA, Hartmann SA, Francis F, Al -Shamsi AT (2011) An evaluation of the management effectiveness of a stock re-building strategy for a multi-species Demersal trap fishery in Abu Dhabi, United Arab Emirates. Open J Mar Sci 3:82–97

Green EP, Bruckner AW (2000) The significance of coral disease epizootiology for coral reef conservation. Biol Conserv 96:347–361

Grizzle ER, Ward KM, AlShihi RMS, Burt JA (2016) Current status of coral reefs in the United Arab Emirates: distribution, extent, and community structure with implications for management. Mar Pollut Bull. 105(2):515–523

Grottoli AG, Rodrigues LJ, Palardy JE (2006) Heterotrophic plasticity and resilience in bleached corals. Nature 440:1186–1189

Grottoli AG, Warner ME, Levas SJ, Aschaffenburg MD, Schoepf V, McGinley M, Baumann J, Matsui Y (2014) The cumulative impact of annual coral bleaching can turn some coral species winners into losers. Glob Chang Biol 20:3823–3833

Guppy R, Bythell JC (2006) Environmental effects on bacterial diversity in the surface mucus layer of the reef coral *Montastraea faveolata*. Mar Ecol Prog Ser 328:133–142

Haapkylai J, Ramade F, Salvat B (2007) Oil pollution on coral reefs: a review of the state of knowledge and management needs. Vie Milieu 57:95–111

Hedley JD, Roelfsema CM, Chollett I, Harborne AR, Heron SF, Weeks SJ, Skirving WJ, Strong AE, Eakin M, Christensen TRL, Ticzon V, Bejerano S, Mumby PJ (2016) Remote sensing of coral reefs for monitoring and management: a review 2015 – 2018. Remote Sens 8:118. https://doi.org/10.3390/rs8020118

Hilmi N, Safa A, Reynaud S, Allemand D (2012) Coral reefs and tourism in Egypt's Red Sea. Topics Middle East Afr Econ 14:416–434

Hoegh-Guldberg O, Smith GJ (1989) The effect of sudden changes in temperature, light and salinity on the population density and export of zooxanthellae from the reef corals *Stylophora pistillata* Esper and *Seriatopora hystrix* Dana. J Exp Mar Biol Ecol 129:279–303

Honey KT, Moxley JH, Fujita RM (2010) From rags to fishes: data-poor methods for fishery managers. Managing data-poor fisheries: case studies. Models Solutions 1:159–184

Howells EJ, Beltran VH, Larsen NW, Bay LK, Willis BL, van Oppen MJH (2011) Coral thermal tolerance shaped by local adaptation of photosynthesis. Nat Clim Chang 2:116–120

Hughes TP, Anderson KD, Connolly SR, Heron SF, Kerry JT, Lough JM, Baird AH, Baum JK, Berumen ML, Bridge TC, Claar DC, Eakin CM, Gilmour JP, Graham NAJ, Harrison H, Hobbs JPA, Hoey AS, Hoogenboom M, Lowe RJ, McCulloch MT, Pandolfi JM, Pratchett M, Schoepf V, Torda G, Wilson SK (2018) Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. Science 359:80–83

Hume BCC, D'Angelo C, Smith EG, Stevens JR, Burt J, Wiedenmann J (2015) *Symbiodinium thermophilum* sp. nov., a thermotolerant symbiotic alga prevalent in corals of the world's hottest sea, the Persian/Arabian Gulf. Sci Rep 8562(5):1–8

Jameson DC, Tupper MH, Ridley JM (2002) The three screen doors: can marine "protected" areas be effective? Mar Pollut Bull 44:1177–1183

Jensen JR (2007) Remote sensing of the environment: an earth resource perspective. Pearson Prentice Hall, Upper Saddle River, NJ

John VC, Coles SL, Abozed AI (1990) Seasonal cycles of temperature, salinity and water masses of the Western Arabian Gulf. Oceanol Acta 13(3):273–281
Jokiel PL, Coles SL (1990) Response to Hawaiian and other Indo-Pacific reef corals to elevated temperature. Coral Reefs 8:155–162
Jokiel PL, Coles SL. Effects of salinity on coral reefs(1992) In: Connell DW, Hawker DW (eds) Pollution in tropical aquatic systems. CRC Press, Boca Raton, FL, pp 147–166
Jones RJ, Yellowlees D (1997) Regulation and control of intracellular algae (= zooxanthellae) in hard corals. Philos Trans R Soc B 352:457–468
Kabiri K, Rezai H, Moradi M (2018) Mapping of the corals around Hendorabi Island (Persian Gulf), using WorldView-2 standard imagery coupled with field observations. Mar Pollut Bull 129. https://doi.org/10.1016/j.marpolbul.2018.02.045
Kerswell AP, Jones RJ (2003) Effects of hypo-osmosis on the coral *Stylophora pistillata*: nature and cause of 'low-salinity bleaching'. Mar Ecol Prog Ser 253:145–154
Khan NY, Munawar M, Price ARG (eds) (2002) The gulf ecosystem: health and sustainability. Backhuys Publishers, Leiden
Korrubel J, Riegl B (1997) A new coral disease from the southern Arabian Gulf. Coral Reefs 17:22
Kotb MA, Hanafy MM, Rirache H, Matsumura S, Al-Sofyani AA, Ahmed AG, Bawazir G, Al-Horani FA (2008) Status of coral reefs in the Red Sea and Gulf of Aden region. AIMS, Townsville
Krupp F, Al-Muftah A, Jones DA, Hoolihan JA (2006) Marine and coastal ecosystem management requirements in the Arabian Peninsula with special regard to water resources. In: Amer KM et al (eds) Policy perspectives for ecosystem and water management in the Arabian Peninsula. UNESCO and United Nations University, Doha and Hamilton, pp 73–87
Loya Y, Sakai K, Yamazato K, Nakano Y, Sambali H, van Woesik R (2001) Coral bleaching: the winners and the losers. Ecol Lett 4:122–131
Madany IM, Jaffar A, AI-Shirbini ES (1998) Variations in the concentrations of aromatic petroleum hydrocarbons in Bahraini coastal waters during the period October 1993 to December 1995. Environ Int 24:61–66
Manche C (2014) A remote sensing based early warning system for algal blooms in Kuwait Bay and Coastal Waters. Master's Thesis, Western Michigan University, 546 p
McDonald G, Campbell SJ, Karr K, Clemence M, Granados-Dieseldorff P, Jakub R, Kartawijayae T, Mueller JC, Prihatinningsih P, Siegel K, Syaifudin Y (2018) An adaptive assessment and management toolkit for data-limited fisheries. Ocean Coast Manag 52:100–119
Monroe AA, Ziegler M, Roik A, Hardenstine RS, Emmss MA, Jensen T, Voolstra CR, Berumen ML (2018) In situ observations of coral bleaching in the central Saudi Arabian Red Sea during the 2015/2016 global coral bleaching event. PLoS One. https://doi.org/10.1371/journal.pone.0195814
Moreno-Madrinan MJ, Rickman DL, Ogashwara I, Irwi DE, Jun Ye I, Al-Hamdam M (2017) Using remote sensing to monitor the influence of river discharge on watershed outlets and adjacent coral reefs: Magdalena River and Rosario Islands, Colombia. Int J Appl Earth Obs 38:204–215
Oliver TA, Palumbi SR (2011) Do fluctuating temperature environments elevate coral thermal tolerance? Coral Reefs 30(2):429–440
Osman EO, Smith DJ, Ziegler M, Kürten B, Conrad C, El-Haddad KM, Voolstra CR, Suggett DJ (2017) Thermal refugia against coral bleaching throughout the northern Red Sea. Glob Chang Biol 24:e474–e484
Owfi F, Rabbaniha M, Al-Obeid Mehana S, Mahichi F (2014) Biodiversity and distribution patterns of coral reef ecosystems in ROPME Sea Area (Inner part: Persian Gulf-Iranian waters). J Surv Fish Sci 1(2):21–26
PERSGA (2003) Regional action plan for the conservation of coral reefs in the Red Sea and Gulf of Aden. PERSGA technical series no. 3. PERSGA, Jeddah
PERSGA (2018) PERSGA training and capacity building program 2018. Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden, Jeddah, p 43

Porter JW, Tougas JI (2001) Reef ecosystems: threats to their biodiversity. In: Levin SA (ed) Encyclopedia of biodiversity, vol 5. Academic Press, San Diego, pp 73–95

Price ARG (1998) Impact of the 1991 Gulf war on the coastal environment and ecosystems: current status and future prospects. Environ Int 24:91–96

Purkis SJ (2018) Remote sensing tropical coral reefs: a view from above. Annu Rev Mar Sci 10:149–168

Quan-Young LI, Espinoza-Avalos J (2006) Reduction in zooxanthellae density, chlorophyll a concentration, and tissue thickness of the coral *Montastraea faveolata* (Scleractinia) when competing with mixed turf algae. Limnol Oceanogr 51(2):1159–1166

Ramsewak D, Herwitz S, Muller-Karger F, Hu C, Toro-Farmer G, Vega-Rodriguez M, Carlson P, Yates K, Berthold MN (2012) The application of UAV technology for coral reef and seagrass monitoring: a multi-agency project "high resolution assessment of carbon dynamics in Seagrass and coral reef Biomes". In: Proceedings of the 6th URISA Caribbean GIS Conference, Montego Bay, Jamaica

Ramsewak D, Douglas E, Kingon K, Phillip D (2018) Mapping a marginal coral habitat in north-east, Trinidad using passive and active remote sensing techniques. University of Trinidad and Tobago Annual Research Symposium

Rezai H, Wilson S, Claereboudt M, Riegl B (2004) Coral reef status in the ROPME Sea area: Arabian/Persian Gulf, Gulf of Oman and Arabian Sea. In: Wilkinson C (ed) Status of Coral Reefs of the World: 2004, vol 1 Australian Institute of Marine Science, Townsville, QLD, Australia, pp 155–170, 301 p

Riegl B (2002) Effects of the 1996 and 1998 SST anomalies on corals, coral diseases and fish in the Arabian Gulf (Dubai, UAE). Mar Biol 140:29–40

Riegl B (2003) Climate change and coral reefs: different effects in two high-latitude areas (Arabian Gulf, South Africa). Coral Reefs 22:433–446

Riegl B, Glynn PW, Wieters E, Purkis S, d'Angelo C, Wiedenmann J (2015) Water column productivity and temperature predict coral reef regeneration across the Indo-Pacific Scientific Reports, vol 5, pp 1–7

Riegl BM, Purkiss S (2012) Environmental constraints for reef building in the Gulf. In: Riegl BM, Purkis SJ (eds) Coral reefs of the Gulf: adaptation to climatic extremes. Springer, New York, pp 5–32

Riegl BM, Bruckner AW, Samimi-Namin K, Purkis SJ (2012) Diseases, harmful algae blooms (HABs) and their effects on gulf coral populations and communities. In: Riegl BM, Purkis SJ (eds) Coral reefs of the Gulf: adaptation to climatic extremes, coral reefs of the world 3. Springer, Dordrecht, pp 107–125

Sale PF, Feary D, Burt JA, Bauman A, Cavalcante G, Drouillard K, Kjerfve B, Marquis E, Trick C, Usseglio P, van Lavieren H (2011) The growing need for sustainable ecological management of marine communities of the Persian Gulf. Ambio 40:4–17

Sanghvi D, Tiwari R, Chaudhury NR, Shukla A, Ajai (2013) Inventory and monitoring of coral reefs of United Arab Emirates (UAE), Arabian Gulf, using remote sensing techniques. In: Sundaresan J, Sreekesh S, Ramanathan A, Sonnenschein L, Boojh R (eds) Climate change and island and coastal vulnerability. Springer, Dordrecht

Schoepf V, Stat M, Falter JL, McCulloch MT (2015) Limits to the thermal tolerance of corals adapted to a highly fluctuating, naturally extreme temperature environment. Nat Sci Rep 5:17639

Selgrath JC, Roelfsema C, Gergel SE, Vincent ACJ (2016) Mapping for coral reef conservation: comparing the value of participatory and remote sensing approaches. Ecosphere 7(5):e01235

Seyfabadi J, Shokri N, Fatemi MR (2011) Spatial variation of symbiotic dinoflagellates on coral reefs of the norther Persian Gulf. Iran J Fish Sci 10(3):475–486

Sheppard C, Price A, Roberts C (1992) Marine ecology of the Arabian region. Academic Press, London, p 359

Sheppard CRC, Salm RV (1998) Reef and coral communities of Oman, with a description of a new coral species (order Scleractinia, genus *Acanthastrea*). J Nat Hist 22:263–279

Sheppard CRC, Al-Husiani M, Al-Jamali F, Al-Yamani F, Baldwin R, Bishop J, Benzoni F, Dutrieux E et al (2010) The Gulf: a young sea in decline. Mar Pollut Bull 60:13–38
Skirving W, Enriquez S, Hedley JD, Dove S, Eakin M, Mason RAB, De La Cour JL, Liu G, Hoegh-Guldberg O, Strong AE, Mumby PJ, Iglesias-Prieto I (2018) Remote sensing of coral bleaching using temperature and light: progress towards an operational algorithm. Remote Sens 10(1):18. https://doi.org/10.3390/rs10010018
Smith D, Punt A, Dowling N, Smith A, Tuck G, Knuckey I (2009) Reconciling approaches to the assessment and management of data-poor species and fisheries with Australia's harvest strategy policy. Mar Coast Fish 1:244–254
Stat M, Gates RD, Clade D (2011) *Symbiodinium* in scleractinian corals: a "nugget" of hope, a selfish opportunist, an ominous sign, or all of the above? J Mar Biol. https://doi.org/10.1155/2011/730715
Steen GR, Muscatine L (1987) Low temperature evokes rapid exocytosis of symbiotic algae by a sea anemone. Biol Bull 172:246–263
Subba Rao DV, Al-Yamani F, Lennox A, Pan Y, Al-Said TFO (1999) Biomass and production characteristics of the first red tide noticed in Kuwait Bay, Arabian Gulf. J Plankton Res 21 (4):805–810
Subba Rao DV, Al-Hassan JM, Al-Yamani F, Al-Rafaie K, Ismail W, Nageswara Rao CV, Al-Hassan M (2003) Elusive red tides in Kuwait coastal waters. Harmful Algae News 24:10–13
Tanimura Y, Yamamoto N, Tanaka Y, Iwao K, Kojima I, Nakamura R, Tsuchida S, Sekiguchi S (2008) Evaluation of large-scale storage systems for satellite data in GEO GRID. In: The international archives of the photogrammetry, remote sensing and spatial information sciences, XXXVII, Part B4, pp 1567–1574
Tawfik F (2000a) 'Ghost fishing' blamed for death of coral, marine creatures. Gulf News, 3 July 2000
Tawfik F (2000b) Third reef to boost fish stocks. Gulf News, 25 July 2000
Thomas L, Lopez EH, Morikawa MK, Palumbi SJ (2019) Transcriptomic resilience, symbiont shuffling, and vulnerability to recurrent bleaching in reef-building corals. Mol Ecol 28:3371–3382
Thornhill DJ, Rotjan RD, Todd BD, Chilcoat GC, Iglesias-Prieto R, Kemp DW, LaJeunesse TC, McCabe Reynolds J, Schmidt GW, Shannon T, Warner ME, Fitt WK (2011) A connection between colony biomass and death in Caribbean reef-building corals. PLoS One 6:e29535
Tupper M (2002) Marine reserves and fisheries management. Science 295:1233
Tupper M, Asif F, Garces L, Pido M (2015) Evaluating the management of marine protected areas at seven sites in the Philippines. Mar Policy 56:33–42
van der Merwe R, Röthig T, Voolstra CR, Ochsenkühn LS, Amy GL (2014) High salinity tolerance of the Red Sea coral *Fungia granulosa* under desalination concentration discharge conditions: an *in situ* photophysiology experiment. Front Mar Sci 1(58):1–8
van Lavieren H, Burt J, Feary DA, Cavalcante G, Marquis E, Benedetti L, Trick C, Kjerfve B, Sale PF (2011) Managing the growing impacts of development on fragile coastal and marine ecosystems: lessons from the Gulf. UNU-INWEH, p 82
Vanderstraete T, Goossens R, Ghabour TK (2003) Bathymetric mapping of coral reefs in the Red Sea (Hurghada, Egypt) using Landsat7 ETM+ data. Belgeo 3:257–268
Vanderstraete T, Goossens R, Ghabour TK (2004) Coral reef bottom-type mapping in the Red Sea (Hurghada, Egypt) based on remote sensing. EARSeL eProc 3(2):191–207
Vanderstraete T, Goossens R, Ghabour TK (2005) Realization of a local coral reef monitoring system in the Red Sea using Landsat7 ETM+ data. In: Oluic M (ed) Proceedings of the 24th EARSeL Symposium 'New Strategies for European Remote Sensing', Dubrovnik (Croatia), pp 479–488
Vaughan TW (1914) Reef corals of the Bahamas and South Florida. Carnegie Inst Washington Yearbook 13:222–226
Wellington G, Glynn P, Strong A, Navarrete S, Wieters E, Hubbard D (2001) Crisis on coral reefs linked to climate change. EOS Trans Am Geo Union 82:1–3

Willis BL, Page CA, Dinsdale EA (2004) Coral disease on the Great Barrier Reef. In: Rosenberg E, Loya Y (eds) Coral health and diseases. Springer, Berlin, pp 69–104
Wilson S, Fatemi SMR, Shokri MR, Claereboudt M (2002) Status of coral reefs of the Persian Gulf and Arabian Sea region. In: Status of coral reefs of the world. AIMS, Townsville, pp 53–62
World Bank (2002) Arab Republic of Egypt, Cost Assessment of Environment Degradation Report, Rural Development. Water and Environment Department of Middle East and North Africa Region
Yonge CM, Nicholls AG (1931) Studies on the physiology of corals. IV. The structure, distribution and physiology of the zooxanthellae. Science Report from the Great Barrier Reef Expedition 1928-1929 1:135–176
Ziegler M, Arif C, Burt JA, Dobretsov S, Roder C, La Jeunesse TC, Voolstra CR (2018) Biogeography and molecular diversity of coral symbionts in the genus *Symbiodinium* around the Arabian Peninsula. J Biogeogr 44(3):674–686