Chapter 43. Tropical and Sub-Tropical Coral Reefs

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1. Introduction

Many activities and businesses are judged on three criteria, the triple bottom line: economic evaluation; social responsibility; and environmental conservation. Coral reefs make major contributions towards "people, planet, profit"; they are economically beneficial to many countries, especially small island developing States (SIDS), in the provision of food, materials and income from tourism and fisheries; coastal and island societies are often largely or nearly completely dependent on adjacent coral reefs, with cultures developed around those reefs; and reefs contain the largest reservoirs of biodiversity in the world. Moreover, these reefs constitute a very special ecosystem, forming a link between humans on the land and the ocean around them.

Of the 193 Member States of the United Nations, 79 States (41 per cent) have coral reefs in their maritime zones, including a large number of SIDS. These reefs are estimated to cover 249,713 km^2 (Burke et al., 2011a) to 284,300 km^2 (Spalding et al., 2001), with an additional 600,000 km^2 of sandy lagoons. Reefs and nearby seagrass and mangrove ecosystems are of major importance for 275 million people who depend on associated fisheries as their major source of animal protein (UNSG, 2011) and play a role in social stability, especially within a subsistence economy which is often declining in sustainability. Of these 79 States, more than 30 SIDS have coral reefs that provide the major source of food, coastal protection, and a limited amount of rock and sand; and valuable income from tourism; the continual provision of these ecosystem services is dependent on actions focused on sustaining and conserving healthy, productive coral reef ecosystems.

Coral reefs around the world have been in a state of continual decline over the past 100 years, and especially over the past 50 years. The Global Coral Reef Monitoring Network, which has reported since 1998 in the "Status of Coral Reefs of the World" series assessed that approximately 19 per cent of the world's coral reefs were severely damaged with no immediate prospects of recovery, and 35 per cent of the remaining coral reefs were under imminent risk of degradation from direct human pressures (assessment by the Global Coral Reef Monitoring Network; Wilkinson, 2008; with 372 contributing authors from 96 States and territories). Similar estimates of large-scale degradation have been reported both before and since (Burke et al., 2002; Burke and Maidens, 2004; Bruno and Selig, 2007; Bellwood et al., 2004; Obura et al., 2008). A more recent study by the World Resources Institute in the “Reefs at Risk Revisited” report (Burke et al., 2011a) calculated that more than 60 per cent of the world’s coral reefs are under immediate threat. Indeed the latest Intergovernmental Panel on Climate Change (IPCC (2014)) report suggests that “coral reefs are one of the most vulnerable ecosystem on Earth” and will be functionally extinct by 2050, without adaptation (worst case scenario), or by 2100 with biological adaptation of the whole ecosystem. Presently the level of threats varies considerably in different geographical regions; reefs of the Pacific Ocean are least threatened, but those throughout Asia and the wider Caribbean and Atlantic regions are under greater threats.

Coral reefs developed throughout millions of years under a wide range of “natural” stresses, such as storms, variations in sea level, volcanic and tectonic plate activity. However recent anthropogenic stresses are overwhelming the natural reef resistance/resilience and recovery mechanisms, resulting in major losses and declines in the reefs and their biological resources in many regions. The major threats are: overfishing and destructive fishing practices; pollution and increased sedimentation; habitat destruction; increases in diseases and predation; and especially impacts of climate change and ocean acidification (OA). This chapter highlights the threats to the world’s coral reefs, lists their current status and reports conservation actions that so far have been successful to ensure that reefs continue to provide ecosystem services to several billion people around the world.

Coastal protection and reef fisheries are of utmost socioeconomic importance for coastal communities; and reefs constitute the basis of many cultures. In addition, they are a source of rock and sand aggregate for construction but frequently such exploitation is unsustainable. The economic value of reefs,, only as a source of raw materials, has been estimated at 28 United States dollars per hectare (Costanza et al., 2014; see also Chapter 7). Reefs underpin the reef-based tourism industry and harbour biodiversity as natural capital.

1.1 Cultural

Since humans began to inhabit coral reef areas, they developed strong cultural links with this ecosystem, both with the habitats and also with many species. Such cultural themes associated with reef ecosystems developed through popular beliefs and the ecosystem services essential to their livelihoods. More importantly for many people, the coral reefs constituted and sustained the land on which they lived. Some of the human communities in South East Asia, which had settled near coral reef waters, migrated outwards during the Holocene and progressively colonized islands throughout the Pacific Ocean. Many Pacific communities developed strong cultural affinities towards the reefs and many of these remain active and recognized by local and national governments.

1.2 Coastal protection

Reefs and mangrove forests provide coastal protection for land resources and human infrastructure, especially where large areas of shallow reef flats are adjacent to the shore and reefs have a distinct crest. This is a continual service, which is especially important during storms and cyclones. This service also includes some attenuation of tsunami waves, as was the case during the 2004 Indian Ocean tsunami (Wilkinson et al., 2006). Coastal protection provided by coral reefs is valued at 10.7 billion dollars (Table 1), which can be considered as a natural alternative to the cost of building seawalls along coasts that are otherwise protected from ocean swell and storm waves by offshore barrier reef systems.

Table 1. Annual net global benefits from coral reef-related ecosystem services in dollars assessed in 2010, with two important States included for emphasis. Values are expressed in millions of United States dollars as net benefits, including costs (from Burke et al., 2011b).

Region & Total	**Tourism**	**Reef Fisheries**	**Shoreline Protection**
Global 29 000	11 500	6 800	10 700
Indonesia 2 014	127	1 500	387
Philippines 1 283	133	750	400

1.3 Fisheries and food

About 275 million people worldwide depend directly on ecosystem services provided by coral reefs and associated ecosystems (Newton et al., 2007; Cinner et al., 2008). This is particularly crucial for SIDS and coastal developing countries (Burke et al., 2011a; see also Chapter 15). Estimates of the value of all goods, services, and livelihoods associated with coral reefs (including tourism, fisheries and protection) exceed 30 billion dollars (Cesar et al., 2003). Fisheries in the tropics feed millions of people (Whittingham et al., 2003); but the importance of reefs extends far beyond economically measurable values, as the identity of many coastal peoples is linked to reefs through their socio-cultural practices (Johannes, 1981; Cinner et al., 2008; Kittinger et al., 2012).

1.4 Rock and sand

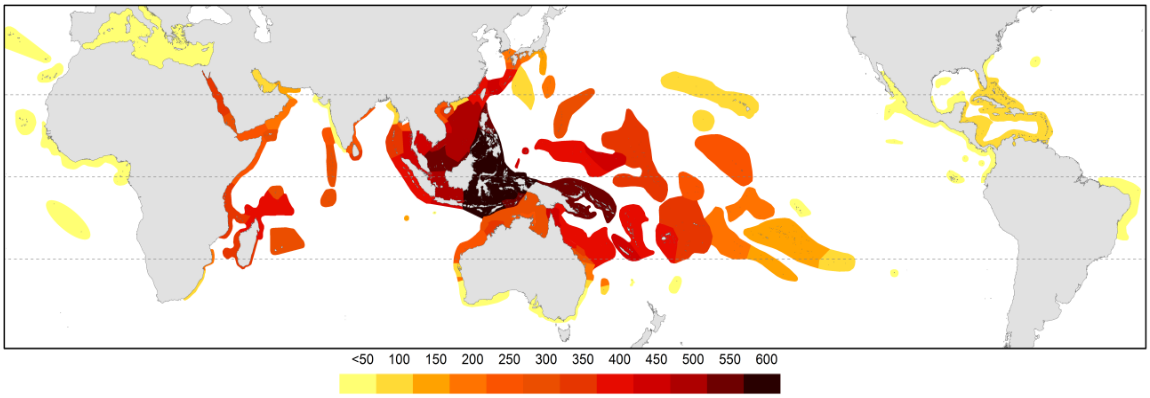
Coral reefs produce large amounts of exploitable sand and rock (Reid et al., 2005), which are valuable for many coastal communities, especially those living on coral islands with no other sources of these materials. The use of coral blocks taken off the reef for building construction was sustainable when human populations were lower. However, with increasing demand from growing populations, the practice became unsustainable in some areas, and excessive harvesting of coral rock and sand exposed shorelines to increased erosion, resulting in damage to adjacent communities. The reef flat around the main island of the Maldives, Malé, was so seriously mined over centuries that the shoreline protection was virtually lost, such that in 1987 storm waves penetrated throughout the city causing massive saltwater damage, including contamination of the groundwater system. Replacement concrete tetrapod seawalls cost more than 10 million dollars per km in the 1990s; the cost would be much higher now (Talbot and Wilkinson, 2001). Such problems create economic dilemmas for governments, as it may be cheaper to mine fringing reefs and sand flats, rather than take the material from land or remote coral structures. This will be exacerbated with climate change-related sea-level rise. Mining also occurs at deeper areas. Large-scale mining projects are predicted for eastern Brazil to explore one of the largest rhodolith beds (i.e., nodules of calcareous coralline algae) in the world (Amado-Filho et al., 2012), aimed at extracting micronutrients and correcting soil acidity for sugar cane plantations.

1.5 Recreation and tourism

Reef-related tourism generates 11.5 billion dollars per year in revenue for the global economy (Table 1). Tourism and recreation in Australia's Great Barrier Reef alone sustain 69,000 jobs and are valued at either 4.4 billion dollars per year (Deloitte Access Economics, 2013) or 11.5 to 15.5 billion dollars (Stoeckl et al. 2014) depending on the methods employed. Reefs contribute about 1 billion dollars per year to the economy of Hawaii, United States of America (Bishop et al., 2011). In 2000-2001, the artificial and natural reefs off southeast Florida supported almost 28 million person-days of recreational diving, fishing and viewing activities. These activities generated about 4.4 billion dollars in local sales, almost 2 billion dollars in local income, and sustained 70,400 full and part-time jobs (Johns, et al., 2001). In Belize, coral reef- and mangrove-associated tourism contributed an estimated 150 - 196 million dollars to the national economy in 2007. Belize is an example of many small developing countries where tourists provide a large proportion of foreign currency earnings. Reef-based tourism is especially sensitive to reef condition, and thus the sector is particularly vulnerable to degradation (Cooper et al., 2008).

1.6 Biodiversity

Coral reefs are the largest reservoirs of biodiversity on earth: they host 32 of 34 recognised phyla and approximately one-third of all marine biodiversity (Spalding et al., 2001; Groombridge and Jenkins, 2002; Roberts et al., 2002; Bouchet, 2006). The centre of global coral reef biodiversity is the "Coral Triangle" (CT), including eastern Indonesia and Malaysia, the Philippines, Timor-Leste, Papua New Guinea and the Solomon Islands (Figure 1). There are more than 550 species of hard corals in the CT area; the diversity decreases away from this focus to the West and to the East, such that less than half this number of species are found in French Polynesia (France), the Hawaiian Islands (United States), and the East African coast. Reef biodiversity in the Caribbean and Atlantic region is also lower; only 65 different coral species are recorded on all these reefs.



The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

Figure 1. The diversity of hard coral species is greatest within Southeast Asia and the West Pacific; declining diversity radiates out from this area, which is called the Coral Triangle. Much lower diversity of corals is found in the Atlantic and wider Caribbean (from Veron et al., (2015).

2. Major threats

Modern coral reefs have developed since the end of the last ice age (the Pleistocene) when global sea level rose approximately 120 m to just above current levels about 6,500 years ago (Woodroffe and Webster, 2014). Coral reef growth has continued throughout this period, especially during relatively stable sea level (the Holocene); until recently the major stressors were local natural damage, e.g., storms, earthquakes, extreme low tides.

The current serious and further deteriorating status of coral reefs around the world is directly due to damaging stresses that arose during the Anthropocene (Bradbury and Seymour, 2009; Hoegh-Guldberg, 2014); effectively since the mid-18th century, and particularly since 1950, when human pressures ramped up to destructive levels. Assessments of coral reefs cited above and anecdotal reports (Sale and Szmant, 2012) indicate that most reefs were largely “pristine” until direct and indirect human pressures and the advent of “new technology” started affecting many reefs, commencing in the 1970s. This “new technology” permitted far more extensive resource exploitation over far greater areas and to greater depths. This technology (discussed below) includes monofilament lines and nets, and boats with motors. Problems with catchment management, in the face of deforestation for agricultural purposes, have also affected coral reefs, especially coastal reefs off Africa, Australia and South America (Wilkinson and Brodie, 2011).

The degradation of many coral reefs around the world is both directly and incidentally due to increasing anthropogenic pressures arising from increasing population pressures on reefs and their resources, especially through increased economic capacity to use these resources. The major threats include extractive activities, pollution, sedimentation, physical destruction, and the effects of anthropogenic climate change. Such stressors often interact synergistically with natural stressors, such as storms (Table 2). Carpenter and 38 other authors (Carpenter et al., 2008) have estimated that 33 per cent of all reef-building corals could become extinct due to damage from local threats combined with climate change impacts.

Table 2. Natural and anthropogenic stresses divided into three direct damage categories and one group of organizational factors [summarised from Wilkinson and Salvat, 2012].

1. Natural factors	***not readily amenable to conservation measures***
i. Catastrophic geological: earthquake, tsunami, volcano, meteors	Potential for rare, but major local damage to coral reefs, especially in Indonesia and South-West Pacific (Papua New Guinea, Solomon Islands, Vanuatu)
ii. Meteorological and climatic: tropical storms, floods, droughts, extremes of heat and cold	Severe storms smash coral reefs or bury them under sediments following floods. Temperature extremes cause coral bleaching and death.
iii. Extreme low tides	Exposes coral reefs leading to widespread mortality e.g., Red Sea
2. Direct human pressures	***major target for conservation measures***
i. Exploitation: overfishing, bomb fishing and trawler damage (exacerbated by global market pressures)	Harvesting of fishes and invertebrates beyond sustainable yields, includes damaging practices (bomb, cyanide fishing); boat scour and anchor damage to reefs
ii. Sedimentation increases: logging, farming, development	Excess sediment and mud on coral reefs from poor land use, deforestation, dredging; reduces photosynthesis; and associated with disease;
iii. Nutrient and chemical pollution	Organic and inorganic chemicals in sediments, untreated sewage, agriculture, animal husbandry and industry wastes; includes complex organics and heavy metals. Turbidity reduces light, promotes growth of competing algae on corals. Herbicides kill algae associated with coral reefs.
iv. Development of coastal areas	Removal or burial of coral reefs for urban, industrial, transport and tourism developments (e.g., airports); mining reef rock and sand beyond sustainable limits
3. Global change threats	***need major global focus; local conservation can assist by increasing reef resilience and raising awareness;***
i. Elevated sea-surface temperatures	Bleaching in corals, i.e., loss of photosynthetic zooxanthellae either temporary or lethal; stimulates algal blooms on reefs; increases disease susceptibility; reduces larval survival.
ii. Increased storms, wider climatic fluctuations	Stronger storms will smash or bury coral reefs; increased rain increases sediment flows; can reduce thermal stress locally.
iii. Rising CO_2 dissolved in seawater with increasing ocean acidification	Increased CO_2 in seawater increases acidity, which decreases calcification in corals and other organisms and reef cementation and increases erosion (including bioerosion); higher CO_2 may increase algal productivity;
iv. Diseases, plagues and invasive species	Intensity and frequency of coral diseases and plagues of predators correlated with global climate change, especially higher temperatures.
4. Governance, awareness, political will	***major target for conservation measures***
i. Rising poverty, increasing populations, alienation from land and sea	More poor, dispossessed people use coral resources for subsistence and habitation.
ii. Poor management capacity and lack of resources	Few trained personnel for coastal management, raising awareness, enforcement and monitoring; lack of funds and logistics for conservation, e.g., smaller countries.

iii. Poor political will and poor oceans governance	Political ignorance, indifference, inertia; corruption and low transparency in governance at global and regional levels all impede decision-making and waste resources.
iv. Uncoordinated global and regional conservation arrangements	Inadequate coordination among multilateral environmental agreements and international donors results in overlapping meeting and reporting requirements which exhaust conservation capacity in smaller countries.

Table 3. A numerical compilation of anthropogenic threats to coral reefs summarized in the graphics in the first map of Burke et al. (2011a), shows that threats are greatest in Southeast and East Asia, with almost 50 percent of reefs at High to Very High threat levels, whereas threats in the wider Pacific and around Australia are much less. Predicted climate change damage, however, will affect all reefs in the world in the next two to three decades. Methodological details are in Burke et al., 2011a.

Region	Low %	Medium %	High %	Very High %
Southeast and East Asia	6	47	28	20
Indian Ocean	34	32	21	13
Caribbean and Atlantic	25	44	18	13
Middle East	35	44	13	8
Pacific	52	28	15	5
Australia	86	13	1	0
World – all areas	**39**	**34**	**17**	**10**

2.1 Overfishing

The major traditional use for coral reefs is extractive exploitation of tropical fisheries resources. For many centuries, these resources, particularly fishes and also turtles, algae, molluscs, crustaceans and echinoids, served as the major animal protein source for many coastal and island communities throughout all oceans. These resources are socially and economically important in sustaining livelihoods of traditional coastal communities, especially through ensuring their food security. However the rate and ease of exploitation has increased, such that in many areas it has reached unsustainable levels and is seriously damaging the ecological integrity of coral reefs. The rate and ease of exploitation has increased in recent decades with the introduction of aluminium boats and motors, monofilament lines and nets, metal hooks, dive masks and spear-guns (now frequently used with underwater lights to catch sleeping fish at night) and use of compressed air (SCUBA and hookah gear). Habitat-damaging practices, such as use of explosives, cyanide or other poisons, also pose a serious threat (Johannes and Riepen, 1995). External markets have driven the increase in the exploitation rate and extension, especially in Asia, to support the tourist demand (see live reef-fish trade below) and also in the wider Caribbean and South America for fresh reef seafood and for export of conch and lobster to the United States. Rapid economic growth throughout Asia has stimulated the lucrative live reef food-fish trade, which is expanding rapidly, with reef fish taken largely through the use of cyanide and other destructive practices. This trade particularly targets large attractive edible fish, such that one species, the humphead wrasse (*Cheilinus undulatus*) is now listed on the International Union for Conservation of Nature (IUCN) Red List as "Endangered" and several groupers, particularly larger species, are listed as "Near Threatened" (Sadovy et al., 2013). This trade is so valuable that industrial-scale fishing across the Indo-West Pacific targets mass fish-spawning aggregations (Sadovy and Domeier, 2005). Reef fish spawning aggregations have also been drastically reduced across the Caribbean by artisanal fishers. A notable example is the Nassau grouper (*Epinephelus striatus*), once of great commercial importance and now listed as "Endangered" and commercially extinct across much of its range in the Caribbean (Sadovy, 1999). More than a quarter of global records of fish aggregations show a declining trend in numbers of fish aggregating, and 4 per cent are documented as having disappeared entirely (Status Report - Worlds Fish Aggregations 2014; Russell et al., 2014).

Another particularly destructive form of industrial scale fishing is via muro ami (drive net) fishing, observed to operate predominantly from the southern Philippines (Jennings and Polunin, 1996). This practice has been banned from many areas; however, illegal fishing with this method still occurs.

A detailed assessment by the Secretariat for the Pacific Community of current and predicted coral reef fisheries resources in 49 island States reported that catch rates in 55 per cent of them are unsustainable and unlikely to be able to provide food security into the future (Figure 2; Bell et al., 2011b in Bell et al., 2011a). The human population of Oceania has increased fourfold since the middle of the last century. A large proportion of this population is still based on a subsistence economy. The extra fish stocks required will have to come from pelagic species, such as tuna, or through aquaculture, as reef fisheries are declining alarmingly due to over-exploitation, especially through the use of "modern" technology (Figure from Bell et al., 2011).

Data from more than 300 coral reefs in the wider Caribbean show a three to six per cent decline in total fish populations per year over a 50-year period (Paddack et al., 2009). This is in parallel to the decline in mean coral cover from 50 per cent to 10 per cent over a 25-year period (Gardner et al., 2003), and a major loss of reef structural complexity over a 30-year period (Jackson et al., 2014). Large-bodied herbivorous fish from the family Scaridae (parrotfish) play key ecological roles and favour coral health and abundance by controlling overgrowth by algae (Bellwood et al., 2004). A recent large-scale synthesis of peer-reviewed and unpublished data indicates that overfishing of coral reef herbivorous fish is a worldwide problem that deserves urgent attention (Edwards et al., 2013).

Similar declines in reef fish stocks in the Indian Ocean due to over-exploitation are documented (McClanahan et al., 2008; McClanahan et al., 2011), matching reports from the Pacific (Dalzell and Adams, 1996; Zeller et al., 2006).

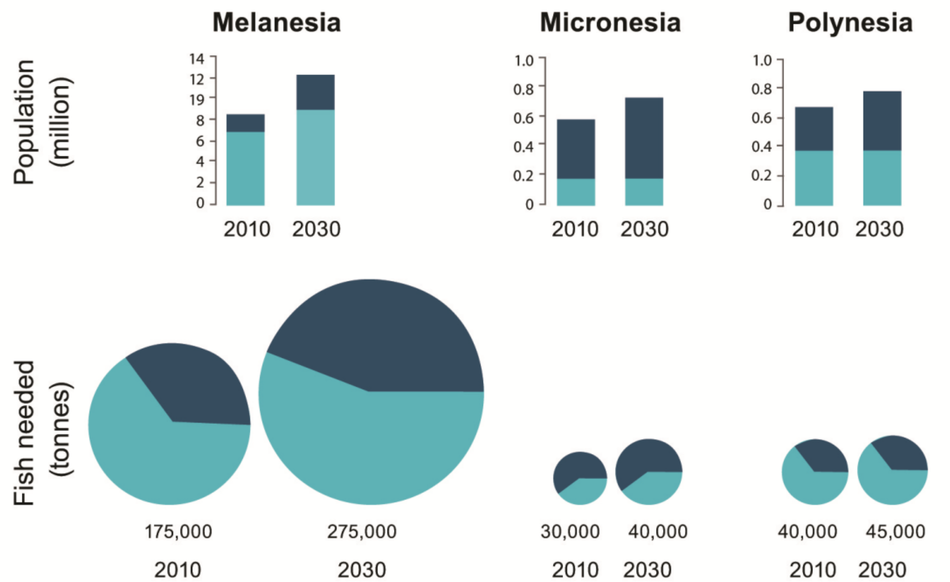


Figure 2. Current and predicted rates of population (upper diagrams), and the fish stocks needed for food security (lower diagrams) in urban (dark colour) and more remote (pale colour) areas of Melanesia, Micronesia and Polynesia between 2010 and 2030. Note that the scale bar for Melanesia is 10 times larger than the other regions (source: SPC and Bell et al., 2011b in Bell et al., 2011a).

Many coral reef fishes periodically and predictably aggregate to spawn, making them vulnerable to fishing. The problem for management of fishing on these aggregations is particularly challenging because little is known about aggregating fish behaviour and the impacts of fishing, although clear evidence exists of serious declines in several species. Although information on the level of management and monitoring is limited, it appears that 35 per cent have some form of management in place such as marine protected areas, seasonal protection from fishing and/or sale, or fisheries harvest controls, and about 25 per cent have some form of monitoring, such as fish counts (Russell et al., 2014). Multiple management measures are needed for those species, however it is clear that whenever uncontrolled exploitation continues it may lead to major depletions for both fish populations and fisheries and livelihoods they support. (De Michelson et al., 2008; Russell et al., 2014)

2.2 Pollution and sedimentation

Water quality (including elevated nutrient, sediment and contaminant concentrations) is a significant environmental driver for the health of coral reefs. Coral reefs are threatened by a wide range of chemical pollution pressures that are likely to increase with further industrial development and land use (see chapter 20 for more detail). Trace metal contaminants are accumulating in fish, with a clear link to coastal contamination from mining in New Caledonia (France), while contamination by persistent organic pollutants (POPs) occurs across the whole lagoon region (Briand et al., 2014). Millions of tons of dust are transported in the atmosphere each year from Africa and Asia to the Caribbean. This is a significant input source of trace metals, organic contaminants and potential microbial pathogens in the reef ecosystem which is likely to adversely affect the health of corals (Garrison et al., 2003).

Excess nutrients result in poor water quality and eutrophication. Reefs exposed to poor water quality show significant increases in macroalgal cover and reduced coral richness and recruitment (De'ath and Fabricius, 2010; Fabricius et al., 2012; Vega Thurber et al., 2014). In the mid-1990s, global models of coral reef pollution estimated that 22 per cent of all reefs were classified as being at high (12 per cent) or medium (10 per cent) risk from pollution and soil erosion (Bryant et al., 1998). On the Great Barrier Reef (GBR), central and southern rivers are reported to deliver five- to nine-fold higher nutrient and sediment loads compared with pre-European settlement, largely due to changes in land-use practices, including land clearing, fertilization and urbanization (Kroon et al., 2012). Flood events that deliver high nutrient and sediment loads via river runoff are now directly affecting up to 15 per cent of GBR reefs (De'ath and Fabricius, 2010; Kroon et al., 2012).

Pressures related to elevated sediments include sedimentation, total suspended solids and light attenuation. All of these can damage coral reef species via smothering, shading and blocking of the filter-feeding systems. Specific assessments of sediment stress have been experimentally examined in only 10 per cent of all known reef-building corals; these studies indicate sediment thresholds and also identify response and adaptation mechanisms that corals employ to cope with excess sediments (Erftemeijer et al., 2012). Reduced coral recruitment success and reef overgrowth by microalgae are significant effects of increased sedimentation on coral reefs. In addition, chronic effects from increased sediment loads include reduced reef calcification, shallower photosynthetic compensation points, changes in the community structure of corals, and reduced species richness. This decreased diversity and increased simplification of reef ecosystems with increasing sediment exposure may compromise their ability to maintain critical ecosystem functions (Fabricius, 2005). The impacts of dredging on coral reefs are primarily linked to the intensity, duration and frequency of exposure to increased total suspended solids and sedimentation (Erftemeijer et al., 2012) and whether the sediments include particulate organic matter or dissolved inorganic nutrients (Fabricius, 2005). Total suspended sediment thresholds reported for coral reef systems range from <10 mg L^{-1} to >100 mg L^{-1} while the maximum sedimentation rates tolerated by corals range from <10 mg cm^{-2} d^{-1} to >400 mg cm^{-2} d^{-1} (Erftemeijer et al., 2012).

Pesticides including herbicides have been widely studied in tropical systems. Most pesticides have no natural sources; concentrations detected in the nearshore lagoon of the GBR are positively correlated with low salinity associated with river runoff. The composition and concentration of pesticides entering the marine environment typically mirror agricultural use in the catchments adjacent to the GBR (Kennedy et al., 2012; Lewis et al., 2009) and on reefs of French Polynesia (France) (Salvat et al., 2012).

Herbicides that inhibit photosystem II in plants are highly persistent in marine environments and are regularly detected in coral reef systems (Schaffelke et al., 2013); with concentrations of herbicides periodically exceeding regulatory guidelines for the GBR during flood plume events (Lewis et al., 2012). These concentrations are known to deleteriously affect corals (Jones and Kerswell, 2003; Negri et al., 2005), microalgae (Bengtson Nash et al., 2005; Magnusson et al., 2008), crustose coralline algae (Negri et al., 2011), foraminifera (van Dam et al., 2012), and seagrass (Haynes et al., 2000; Gao et al., 2011).

The sensitivity of a coral reef to poor water quality largely depends on the pre-existing health of the ecosystem, overall reef resilience and the baseline conditions that the reef normally experiences. For example, the proportion of reefs at risk is highest in countries and entities with widespread land clearing (Burke et al., 2002). It is important that recent research shows that reducing runoff of nutrients, sediments and pesticides from the land will at least partially offset increasing stress and deleterious effects from climate factors for coral reefs (Schaffelke et al., 2013).

2.3 Diseases and predators

Coral disease is reported as one of the most prominent drivers of recent coral reef declines (Aronson and Precht, 2006; Bruckner and Hill, 2009; Rogers, 2009; Sokolow, 2009; Weil and Cróquer, 2009). In particular, the Caribbean has been designated as a “coral disease hotspot” due to the rapid spread, high prevalence, and virulence of diseases associated with corals and other reef organisms (Harvell et al., 2002; Weil et al., 2002). Although the Caribbean is home to only eight per cent of the world’s coral reefs, approximately 66 per cent of all coral diseases are found across 38 Caribbean States and territories (Green and Bruckner, 2000). Disease is also reported as the major factor behind a 25-year decline in Caribbean coral reefs, with mean coral cover declining from 50 per cent to only 10 per cent across the entire Caribbean region (Gardner et al., 2003). Disease has also reshaped the community structure of many Caribbean reefs over the last few decades, including: (i) the virtual elimination of Acroporid corals by White Band Disease in the 1980s (Gladfelter, 1982; Ritchie and Smith, 1998; Aronson and Precht, 2001; Bythell et al. 2001; Kline and Vollmer, 2011); (ii) the loss of many *Acropora palmata* by White Pox in the late 1990s (Sutherland et al., 2011); and (iii) the mass mortality of the keystone grazer species, *Diadema antillarum*, by an unidentified disease in the early 1980s (Hughes et al., 1985). The loss of this sea urchin, coupled with declines in herbivorous fish strongly contributed to overgrowth of reefs by macroalgae (Lessios, 1984; Hunte and Younglao, 1988; Hughes, 1994; Jackson et al., 2001), believed to be a contributing factor to coral disease (Nugues et al., 2004).

Coral diseases have now been documented within all major reef systems and ocean basins (Ruiz-Moreno et al., 2012). Indo-Pacific coral reefs are home to 75 per cent of the world's coral reefs and at least 10 identified coral diseases (~30 per cent of known coral diseases; Willis et al., 2004). It is unclear whether coral disease will have the same impact on Indo-Pacific reefs as it has in the Caribbean due to fundamental differences in their coral reef communities (Wilson et al., 2014). A higher level of diversity and functional redundancy in herbivorous fishes and coral communities, slower macroalgal growth, and less dependence on fragmentation as a reproductive mode, may protect Indo-Pacific reefs from dramatic phase-shifts (Roff and Mumby, 2012).

The recent and rapid increase in disease occurrence worldwide is correlated with increasing environmental stressors that have local and global impacts e.g., elevated seawater temperatures, nutrient enrichment, sedimentation, and fish farming (Sutherland et al., 2004; Sato et al., 2009; Pollock et al., 2014; Vega Thurber et al., 2014; Randall and vanWoesik, 2015). Research is only now starting to determine how diseases are contracted and/or spread from one colony to another. Changes in the coral-associated microbial community and subsequent disease severity are often correlated with bleaching stress in warm summer or winter months (Willis et al., 2004; Bourne et al., 2008; McClanahan et al., 2009, Heron et al., 2010). A significant relationship was shown between the frequency of warm temperature anomalies and white syndrome outbreaks during six years across 48 reefs in the GBR (Bruno et al., 2007). White syndrome was described as either an additional emergent disease, or a group of diseases, among Pacific reef-building corals. Proliferation of disease during the hotter months or during mild winters may be correlated with a greater virulence of coral pathogens at higher temperatures (Miller et al., 2006; Harvell et al., 2007; Heron et al., 2010). Additional anthropogenic factors that are considered to influence disease events include nutrient enrichment from fertilizers (Bruno et al., 2003), sewage pollution (Sutherland et al., 2011), fish farming (Garren et al., 2009), and increased macroalgal abundance as a result of overfishing and disease outbreaks (Nugues et al., 2004).

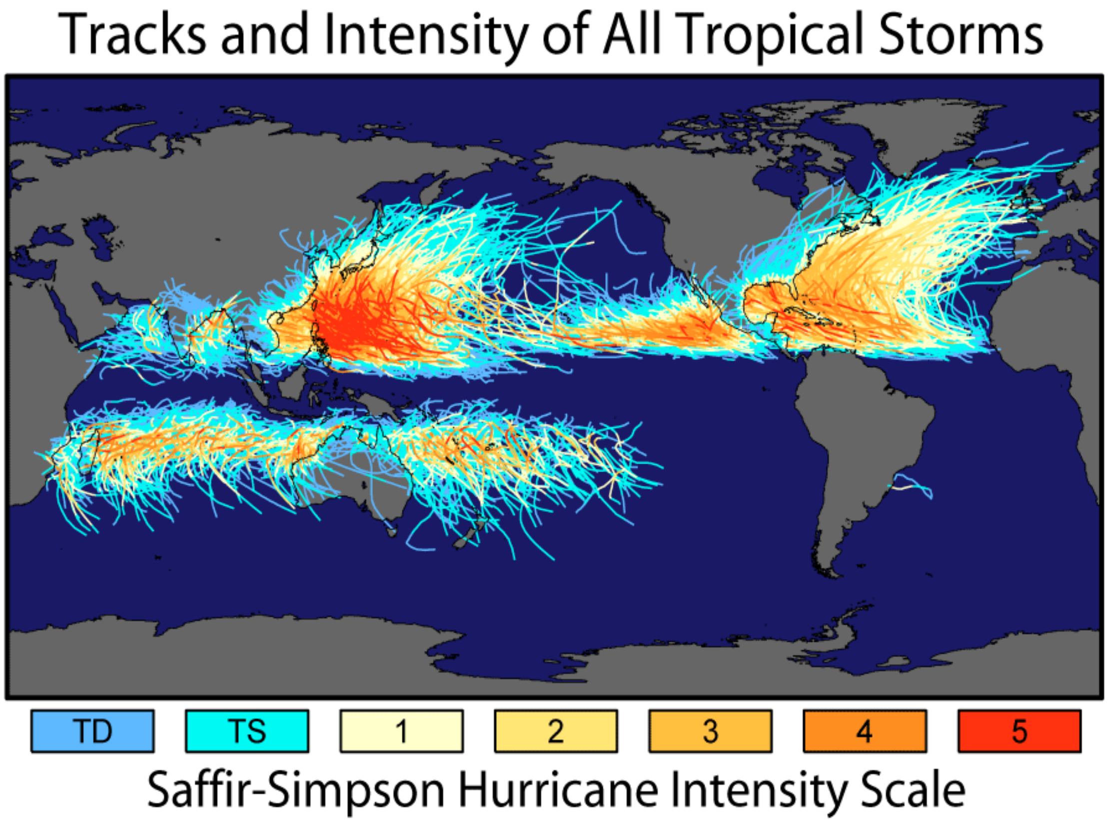
Crown-of-thorns starfish (COTS; *Acanthaster planci*) were not considered a major problem until the last 40 years or so. Population outbreaks in the 1970s devastated large parts of the GBR and similar outbreaks were reported on other reefs of the Indo-Pacific (COTS do not occur in the wider Caribbean). These outbreaks subsided and most reefs recovered their previous coral cover. However, repeated damaging outbreaks have occurred since, such that COTS are reported as the major destructive factors on reefs in French Polynesia (France) (Adjeroud et al., 2009; Kayal et al., 2012), Fiji, Japan, and parts of the Red Sea (Wilkinson, 2008); and COTS contributed 42 per cent of the recent damage to the GBR, alongside storms (48 per cent) and climate change-related damage (10 per cent) (Great Barrier Reef Marine Park Authority 2014; De'ath et al., 2012).

Previous population outbreaks of COTS are reported from the Red Sea around Egypt, in Kenya and the United Republic of Tanzania, and in Southeast and East Asia, especially in China, Japan and the Philippines, and in the Pacific in Fiji, French Polynesia (France), Guam (United States) and Majuro Atoll (Marshall Islands). In the past, these plagues caused massive losses (often in the vicinity of 90 per cent) of the living coral cover (Wilkinson, 2002). Similar outbreaks are reported of the coral-eating mollusc (*Drupella cornus*) on reefs in western Australia and southern China. After apparently abating, major outbreaks have occurred simultaneously with mass coral bleaching in 2005 and 2006.

Four widely supported but not mutually exclusive theories to explain COTS outbreaks are: (a) fluctuations in COTS populations are a natural phenomenon; (b) removal of natural predators (such as large molluscs and some fishes) of the COTS has allowed populations to expand; (c) human-induced increases in the nutrients flowing to the sea have resulted in an increase in planktonic food for larvae of the COTS which leads to an increase in the number of adult starfish causing outbreaks (Fabricius et al., 2010); and (d) increased COTS larval survival as ocean temperatures increase (Uthicke et al., 2014).

2.4 Natural stresses (cyclones, tsunami)

Although many reefs lie outside the zone of frequent tropical cyclones and hurricanes (approximately between 7^{o}N and 7^{o}S latitude), storms regularly damage coral reefs outside this latitudinal zone (Figure 3). Storm damage is exacerbated by storm surge and both reduce the ability of coral reefs to return to their mean pre-disturbance state or condition by slowing coral recruitment, growth, and reducing fitness (Nyström et al., 2000). The combination of tropical storms with other stressors has caused successive and substantial losses of corals worldwide (Harmelin-Vivien, 1994; Done, 1992; Miller et al., 2002; Fabricius et al., 2008; Williams et al., 2008a). However, tropical storms also benefit reefs when the storms are sufficiently distant to not inflict damage, but close enough to cool waters through enhanced wave-induced vertical mixing and to reduce bleaching risk (Szmant and Miller, 2005; Manzello et al., 2007; Carrigan and Puotinen, 2014). A recent modelling study predicted that Caribbean coral reefs with intact herbivore fish and urchin populations would likely maintain their community structure and function under any expected level of tropical cyclone activity, as long as other stressors, such as local pollution and thermal bleaching, are minimal (Edwards et al., 2010).



The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

Figure 3: These plots of tropical cyclones (and typhoons) over the past 100 years illustrate that damaging storms are rare within a band between 7^{o} North and South of the Equator, such that a large proportion of the high biodiversity reefs in Indo-Pacific are rarely damaged by damaging storms (courtesy of NASA, USA, 2008). There are predictions that under increasing climate change, the damaging strength of cyclones will increase with more category 4 and 5 storms, but the number of storms may not change (Wilkinson and Souter, 2008).

2.5 Climate change effects and predictions

The most recent report of the IPCC (2014) stated that "Coral reefs are one of the most vulnerable marine ecosystems (*high confidence*) and more than half of the world's reefs are under medium or high risk of degradation". The effects of anthropogenic climate change on coral reefs include: (a) thermal stress causing coral bleaching; (b) storm damage to reefs; (c) sea-level rise; and (d) acidification causing reduced coral accretion and increased erosion.

2.5.1 Thermal stress and coral bleaching

Coral bleaching was a relatively unknown phenomenon until the early 1980s, when a series of local bleaching events occurred principally in the eastern tropical Pacific and wider Caribbean regions, but was also noticed in the Indo-Pacific. Coral bleaching refers to the expulsion of symbiotic algae, the zooxanthellae, in response to stress. Corals can withstand mild to moderate bleaching but severe, prolonged or repeated bleaching can lead to colony mortality. Corals' physiological processes are optimized to the warmest temperatures they normally experience, so an increase of only 1 -2°C above the normal local seasonal maximum can induce bleaching (Fitt and Warner, 1995). Although most coral species are susceptible to bleaching, thermal tolerance varies amongst taxa and along geographic gradients (Marshall and Baird, 2000; McClanahan et al., 2007). Bleaching is best predicted by using an index of accumulated thermal stress above a locally established threshold (Atwood et al., 1992; Eakin et al., 2009). Many heat-stressed and/or bleached corals subsequently die from coral diseases (reviewed in Burge et al., 2014).

The strong El Niño - La Niña events of 1998 brought a global focus on coral bleaching when approximately 16 per cent of the world's coral reefs in almost all tropical ocean basins were massively damaged and lost most of their corals (Wilkinson, 2000). Rising temperatures have accelerated bleaching and mass mortality during the past 25 years (Brown, 1997a; Eakin et al., 2009), when coral bleaching was documented throughout various parts of the world (Eakin et al., 2009; Eakin et al., 2010; Wilkinson and Souter, 2008; Williams and Bunkley-Williams, 1990). A global analysis of threats to coral reefs shows that this widespread threat has significantly damaged most coral reefs around the world (Burke et al., 2011a).

Although some recovery occurred in the Caribbean from the 1987 (Fitt et al., 1993) and the 1995 bleaching events, bleaching in 1998 and 2005 caused high coral mortality at many reefs with little evidence of recovery (Eakin et al., 2010; Goreau et al., 2000; Wilkinson and Souter, 2008). The subsequent strongest recovery was on reefs that were highly protected from anthropogenic pressure. This led to recognition of the importance of maintaining resilience in coral reef ecosystems (Nyström et al., 2000; Hughes et al., 2007; Anthony et al., 2014). An example of reef resilience was observed on the remote Scott Reef off western Australia, when the reef was severely damaged during the 1997-98 El Niño. However, the herbivore fish population grew rapidly to control algal overgrowth, allowing many new coral recruits to restore most of the lost coral cover after 12 years (Gilmour et al., 2013). Additionally, certain factors such as reef depth and structural complexity were shown to increase reef resilience after the 1998 bleaching in the Seychelles (Graham et al., 2015).

A comparison of the recent and accelerating thermal stress events with the slow recovery rate of most reefs (Baker et al., 2008), suggests the temperature increase has exceeded the balance between event recurrence and recovery rate. It appears that some coral species are less sensitive to short-term temperature anomalies than others, although there are significant geographic variations (McClanahan et al, 2007) and some corals may have already adapted or acclimatised to warming (Guest et al., 2012), albeit not quickly enough to prevent major losses (Logan et al., 2013). Some heritable epigenetic adaptation to frequent heat stress may occur in some species of lagoonal corals (Palumbi et al., 2014; Eakin, 2014). However, adaptation potential may be limited in species where larval survival has been shown to decline at high temperatures (Randall and Szmant, 2009a; 2009b).

Climate models are able to predict the potential consequences of future warming on corals, including the future frequency of thermal events exceeding the bleaching threshold for a given area (map 3.3 in Burke et al., 2011a). In the absence of adaptation, there are predictions that many of the world's coral reefs will experience annual bleaching by mid-century (Donner et al., 2005; Donner, 2009; Logan et al., 2013; van Hooidonk et al., 2013a).

2.5.2 Storm damage to reefs

One consequence of global climate change will be an increase in the frequency of more damaging Category 4 and 5 tropical cyclones; however the number of tropical storms is not predicted to increase. Such intense Category 4 and 5 tropical cyclones (hurricanes) will significantly damage coral reefs and the communities that depend upon them in the wider Caribbean, where evidence is already available (Salvat and Wilkinson, 2011); whereas in other regions, the evidence is less clear (IPCC, 2013).

Corals have withstood and recovered from tropical cyclones for millennia; a seriously damaged reef will normally recover in 15 to 20 years, provided there are no other disturbances during that period (Salvat and Wilkinson, 2011). However, in the last 100 years the combination of natural and anthropogenic stresses (bleaching, sedimentation, eutrophication, ocean acidification) has reduced the ability of many coral reefs to recover from storm damage by slowing coral recruitment and growth, and reducing fitness (Nyström et al., 2000).

2.5.3 Sea-level rise

If CO_2 emissions continue to increase at current rates (exceeding Representative Concentration Pathways RCP 8.5), sea level is predicted to rise 0.5-1.0 m by 2100 (IPCC, 2013), and the impacts on coral reefs will vary depending on local conditions. Corals may be able to colonise reef flats as sea levels rise, and oceanic reefs will not be adversely affected but may benefit from new space to grow upwards. Rates of reef growth at many sites kept up with rising sea levels after the last ice age (about 20 mm yr^{-1} Dullo, 2005, Montaggioni et al., 2005; and up to 40 mm yr^{-1} Camoin et al., 2012) but reefs are now are accreting more slowly (Perry et al., 2013). However, reefs adjacent to coasts may be affected by increased wave action in lagoons, and flooding of polluted coastal plains will increase erosion of coastal sediments (Adey et al., 1977; Lighty et al., 1978), increase sediment transport (Hopley and Kinsey, 1988), and increase turbidity (Storlazzi et al., 2011). This will reduce the ability of corals and reefs to keep up with rising sea level. Simultaneously, increasing ocean acidification will decrease coral reef accretion. Finally, as sea level rises, some coastal systems may undergo landward retreat, and others will experience coastal squeeze as eroding shorelines approach hard, immobile, structures. These may be either natural or man-made; the latter are increasing by coastal hardening to protect human infrastructure. Coastal squeeze may shrink habitats, affecting the survivability of a variety of organisms (Jackson and McIlvenny, 2011).

2.5.4 Ocean acidification

The first detailed prediction of the potential for increasing ocean acidification to damage coral reefs was made in 1992 at the 7th International Coral Reef Symposium (Buddemeier 1993). Experimental studies confirmed these predictions of damage to coral calcification in the 1990s (Gattuso et al., 1998; Gattuso et al., 1999). The IPCC (2014) report determined that under medium- to high-emission scenarios (RCP4.5, 6.0 and 8.5), ocean acidification poses substantial risks to coral reefs through its effects on the physiology, behaviour, and population dynamics of individual species from phytoplankton to animals (*medium* to *high confidence*, IPCC, 2014). Also the lowering of pH will favour the dissolution of the calcareous matrix of coral reefs. These effects will be additive or synergistic with damage from rising sea-surface temperatures. Further experiments with increased concentrations of CO_2 in seawater have shown decreased calcification rates by corals and other calcium carbonate-secreting organisms (Barker and Elderfield, 2002; Doney et al., 2009; Riebesell et al., 2000; see also Chapter 7). A doubling of current atmospheric CO_2 concentrations reduced calcification by 11 per cent to 37 per cent in many corals (Langdon et al., 2003; Marubini et al., 2003; Langdon and Atkinson, 2005). However, some corals show either limited or no response when provided with elevated nutrients (Holcomb et al., 2010; Chauvin et al., 2011). This suggests that nutrient-enriched corals may use more dissolved inorganic carbon to maintain calcification rates.

Ocean acidification also reduces calcification and skeletal growth in post-settlement and juvenile corals (Albright et al., 2008; Albright et al., 2010; Cohen et al., 2009; Kurihara, 2008; Suwa et al., 2010). Fertilization success during spawning and subsequent settlement of *Acropora palmata* were significantly reduced at increased CO_2 levels (Albright et al., 2010); and larvae of *Acropora digitifera* showed reduced metabolism and suppressed metamorphosis (Nakamura et al., 2011). No effect was observed in *Porites astreoides* larvae (Albright et al., 2008).

Reefs found in naturally acidic waters are poorly cemented, unstable, and fragile (Manzello et al., 2008) and show rapid rates of bioerosion (Eakin, 1996; 2001; Glynn, 1988; Reaka-Kudla et al., 1996). Similarly, in “natural experiments” where coral is reduced or absent around volcanic seeps of CO_2 near Papua New Guinea (Fabricius et al., 2011) and Italy (Rudofo-Metalpa et al., 2011), coral calcification is reduced and species composition changes along the pH gradient. Bioerosion by filamentous eroding algae (Tribollet et al., 2009) and boring sponges (Fang et al. 2013; Wisshak et al., 2012) are enhanced under acidified conditions. Other experiments show there may be declines in the growth of crustose coralline algae (Jokiel et al., 2008; Kuffner et al., 2007).

3. Social and economic considerations.

Economic valuation of coral reefs is a relatively recent process (Cesar, 1996; Cesar et al., 2003) to demonstrate the importance of reef ecosystem services and encourage greater conservation efforts. However, there is a potential critical error in that high-value, short-term economic gains that result from development activities can occur at the expense of longer-term benefits. Economic valuation provides more complete information on the economic consequences of decisions that lead to degradation and loss of natural resources, as well as the short- and long-term costs and benefits of environmental protection. Many studies have assessed the value of ecosystem services provided by coral reefs, at local to global scales. The focus is predominantly on tourism and reef-related fisheries; because these are widely studied and direct-use data are more readily available. It is more difficult to estimate indirect-use values, such as shoreline protection, and most difficult with controversial methods to estimate non-use values, such as cultural, biodiversity and heritage values. The annual net global benefits from coral reefs have been estimated at 29 billion dollars

(11.5 billion dollars tourism; 6.8 billion dollars fisheries; 10.7 billion dollars shoreline protection) (Burke et al., 2011a). This emphasizes that tourism and fisheries are especially important as direct money earners for coral-reef communities and their countries. But such an evaluation is for current values and does not take into account all future consequences of changes, such as cultural aspects, community livelihoods, and social and political stability in coral reef communities and their countries, which, if disrupted, will result in other cascading damage. A specific example is the reported value of the GBR to the Australian economy. The total estimated value varies between 4.4 and 15.5 billion dollars, comprising 84 per cent for tourism, 4.6 per cent for other recreational activities, 2.6 per cent for fisheries, and 1.5 per cent for scientific research and management with employment estimated at 69,000 people (Deloitte, 2013; Stoeckl et al. 2014)).

4. Management and conservation.

Calls for increased protection of the marine environment from many organizations and in conventions have specifically addressed the need to protect coral reefs. This includes developing and facilitating the use of diverse approaches and tools, including the ecosystem approach, the elimination of destructive fishing practices, the establishment of marine protected areas (MPAs) consistent with international law and based on scientific information, and the establishment of representative networks and time/area closures. Among the Aichi Biodiversity Targets adopted at the 10th Meeting of the Conference of the Parties to the Convention on Biological Diversity in 2010 was Target 10: “By 2015, the multiple anthropogenic pressures on coral reefs, and other vulnerable ecosystems impacted by climate change or ocean acidification are minimized, so as to maintain their integrity and functioning". The United Nations General Assembly has supported these calls (amongst others) in "The Future We Want" (resolution 66/288) with specific mentions in paragraph 177 and subsequent paragraphs on SIDS.

According to the World Resources Institute, an estimated 2,679 MPAs that coincide with coral reef areas exist worldwide, encompassing approximately 27 per cent of the world's coral reefs (Burke et al., 2011a). Nevertheless global protection of coral reefs is considered by Burke et al. (2011a) to provide effective protection for only 6 per cent of coral reefs, due to shortcomings in planning, management and enforcement of regulations. The benefits of MPAs for achieving targets of conservation of coral reef areas, however, have been reported widely in the scientific literature, in particular when extractive activities are not allowed, as in the no-take areas or marine reserves (Lubchenco et al., 2003; Halpern 2003).

The designs of MPAs range from small units to networks of no-take areas (NTMRs) and large scale marine protected areas (LSMPAs). The first major MPA was the Great Barrier Reef Marine Park in 1975 with 20,679 km^2 of coral reefs. It now has established no-take areas that protect 33.5 per cent of coral reefs (6,928 km^2), to form a network of no-take areas.

Since 2004, ten LSMPAs were established in the Pacific and Indian Oceans in areas within national jurisdiction, and two-thirds of them were declared as marine reserves representing more than 80 per cent of the worldwide MPA coverage (Leenhardt et al., 2013; Table 3).

Table 3. Large Marine Protected Areas that have been established to include significant areas of coral reefs.

Name of Marine Protected Area	**Country**	**Date**	**Area km^2**
Pacific Remote Islands Marine National Monument	United States	2014	2,025,380
Le Parc Naturel de la Mer de Corail (*Natural Park of the Coral Sea*) (New Caledonia)	France	2014	1,291,000
Cook Islands Marine Park	Cook Islands	2012	1,065,000
Coral Sea Commonwealth Marine Reserve	Australia	2011	989,842
Kermadec Benthic Protection Area	New Zealand	2007	620,500
Chagos Marine Protected Area	United Kingdom[1]	2010	545,000

[1] In its award of 18 March 2015 in the matter of the *Chagos Marine Protected Area Arbitration (Mauritius v. United Kingdom)*, the Arbitral Tribunal established under Annex VII to the United Nations Convention on the Law of the Sea, found, *inter alia*, that, as a result of undertakings given by the United Kingdom in 1965 and repeated thereafter, Mauritius holds legally binding rights (i) to fish in the waters surrounding the Chagos Archipelago, (ii) to the eventual return of the Chagos Archipelago to Mauritius when no longer needed for defence purposes, and (iii) to the preservation of the benefit of any minerals or oil discovered in or near the Chagos Archipelago pending its eventual return. The Tribunal held that in declaring the

Phoenix Islands Protected Area	Kiribati	2008	408,250
Papahānaumokuākea (*Northwestern Hawaiian Islands)*	United States	2006	362,100
Great Barrier Reef Marine Park	Australia	1975	344,400

Those areas face major logistical and economic challenges of implementing, managing and monitoring (Leehardt et al., 2103).

Emslie et al. (2015) showed that expanding NTMR networks had clear benefits for fishery target, but not non-target, species. During the study, a cyclone caused widespread degradation, but target species biomass was retained within NTMRs, with greater recovery potential for adjacent areas.

MPAs, even with no-take management, cannot be assured of full protection to reefs. Reefs inside MPAs may still be affected by pollution and sedimentation. In these cases, catchment management has been shown to be effective in promoting reef recovery (many examples in Wilkinson and Brodie, 2011).

Another mechanism targeted at conserving vulnerable species, including those on coral reefs, has been through the Convention on International Trade of Endangered Species and Wild Fauna and Flora (CITES), listing them in Appendices II and III (http://www.cites.org/).

5. Integrated assessment of the status of the habitat.

Reefs in Southeast Asia, the Caribbean and along the East coast of Africa are the most threatened, and this is correlated with high levels of human exploitation of, and dependence on, coral reef resources. In the wider Caribbean, live coral cover has declined by 80 per cent between 1976 and 2001 (Gardner et al., 2003). Further declines following mass coral bleaching linked to climate change occurred in 2005 (Wilkinson and Souter, 2008; Eakin et al., 2010). According to Burke et al. (2011a), coral reefs around Australia were less degraded, although a year later De'ath et al. (2012) reported a loss of 50 per cent of initial coral cover occurred over the 1985-2012 period on the GBR, especially for the central and southern sections where more anthropogenic disturbances occur. In the Central Pacific, far from continents and with low human pressure, reefs are much less threatened and are in better condition and more resilient to natural destructive effects (Salvat et al., 2008; Burke et al., 2011a; Chin et al., 2011). On a regional basis, and based mainly on material from Wilkinson (2008), the condition of reefs is summarized as follows:

Marine Protected Area, the United Kingdom failed to give due regard to these rights and had breached its obligations under the United Nations Convention on the Law of the Sea.

5.1 Indian Ocean

During the first half of 1998, the most severe El Niño event ever recorded resulted in the loss of more than 90 per cent of live coral cover throughout large parts of the Indian Ocean. Damage was particularly severe in the Maldives, Chagos Archipelago, Seychelles and Kenya. Prior to 1998, reefs adjacent to large human populations along the coast of East Africa, India and Sri Lanka had already suffered serious damage from excessive and destructive fishing, nutrient pollution, increased sediment input from land and direct development over the reefs, including coral mining.

Reefs on remote islands and in the Red Sea were generally in good health prior to 1998. Since 1998, coral recovery has been minimal in the Persian Gulf and Gulf of Oman, with recovery often reversed by more bleaching. Throughout the Arabian Peninsula region, massive coastal development and dredging to create oil industrial sites and residential and tourist complexes has occurred. Many reefs in the Red Sea continue to be healthy, although COTS (crown-of-thorns starfish) have caused damage, and expanding tourism in the Northern Red Sea is accelerating some coral losses.

Along the coastline of Eastern Africa, a mix of reef recovery and reef degradation is observed as management efforts are directed at controlling the effects of rapidly growing populations and at involving local communities in coastal management. All States are increasing their networks of marine protected areas and States are improving management capacity and legislation.

Reefs of the southwestern islands in the Indian Ocean continue to recover after devastation in 1998. Some reefs of the Seychelles and Comoros have regained about half or more of their lost coral cover but recovery has been poor on reefs damaged by human activities. Recovery rates in the Seychelles varied, in part, due to factors that have now been shown to increase reef resilience – depth and structural complexity (Graham et al., 2015).

The reef decline in South Asia continues, as large human populations further impact coral reefs, adding to the damage that occurred in 1998. Recovery has been observed in the reefs of the western Maldives, Chagos Archipelago, the Lakshadweep Islands (India) and off northwest Sri Lanka, with seemingly locally extinct corals making major recoveries, e.g., some reefs have gone from less than five per cent coral cover to 70 per cent in 10 years. The 2004 Indian Ocean earthquake and tsunami caused significant reef damage at some sites, but many are recovering. In Sri Lanka, bleaching was reported in 2010, fisheries continue to be the biggest chronic impact, and pollution has increased tremendously in the coastal waters of Colombo. Although fisheries management areas have been declared, lack of enforcement is still hindering effectiveness.

5.2 Southeast and Northeast Asia

The reef areas of Southeast Asia contain the highest concentration of biodiversity and also the largest concentrations of human populations. Overfishing, increasing sedimentation and urban and industrial pollution from rapid economic development are accelerating reef degradation and more than 50 per cent of the region's mangroves have been lost.

Coral reefs in Northeast Asia have shown an overall decline since 2004; most reefs are coming under significant levels of human pressures, as well as bleaching and COTS stress. In China, coastal development and overfishing has destroyed 80 per cent of coral cover over the past 30 years (Hughes et al., 2013). A few reefs with high coral cover remain, such as Dongsha Atoll between Taiwan Province of China and the mainland of China. Increased coral reef monitoring and research, including the establishment of a regional database, is occurring in Japan; Hong Kong, China; Taiwan Province of China; and Hainan Island (China), and the region is stimulating more awareness and cooperation by having held the Asia Pacific Coral Reef Symposium in 2006, 2010 and 2014. Awareness of the need for coral reef conservation is rising rapidly in most countries.

5.3 Australia and Papua New Guinea

Australian reefs continue to be relatively stable due to several management measures. Since 2004, no major bleaching events have occurred, although two significant cyclones have resulted in major damage to some reefs. Particular features are the effective partnerships between coral reef science and management. The future outlook for the GBR is regarded as poor, especially in the southern half of the area, where anthropogenic stresses are strongest. Climate-change impacts are considered to be the greatest long-term threat to the whole GBR system (GBRMPA 2014).

In Papua New Guinea, capacity-building for reef management is being conducted via large NGOs working with local communities. Papua New Guinea still has vast areas of healthy and biologically diverse coral reefs, but human pressures are increasing.

5.4 Wider Pacific

The coral reefs of the Pacific remain the most healthy and intact, compared to reefs elsewhere. Many of these reefs grow on seamounts in deep oceans far removed from land-sourced pollution. Moreover, the human populations are not concentrated as they are in Asia and the Caribbean. In the broader Micronesian region, reefs are recovering well after major coral bleaching in 1998, when, coral mortality was as high as 90 per cent on many reefs around Palau. The Federated States of Micronesia, Marshall Islands, Palau, Guam (United States) and Northern Mariana Islands (United States) seek to conserve 30 per cent of their marine resources by 2020 through the designation of more protected areas (www.themicronesiachallenge.org/).

Climate-related coral bleaching continues to be the greatest threat to the reefs of the southwestern Pacific; human impacts, although growing, are not (yet) resulting in major reef loss on large scales. The University of the South Pacific and the CRISP (Coral Reef

Initiatives for the South Pacific) programme (www.crisponline.net) focused on building more capacity for monitoring and conservation, with the Locally Managed Marine Area network developed in Fiji leading the way in the establishment of community-managed MPAs. It is noted that periodically harvested reserves (modelled on the traditional Qoliqoli or rahui system of management) have significantly higher target fish biomass than other fished areas. Outbreaks of COTS have re-appeared in Fiji, starting in the Mamanucas (2006-10), then moving to the Coral Coast and Beqa (2009-12). Currently active outbreaks exist in Taveuni and the lower Lomai Viti Islands. Large reef areas of New Caledonia (France) have gained World Heritage listing in recognition of the large extent and high biodiversity content of the reefs and adjacent ecosystems.

Climate change impacts, tropical cyclones and COTS have also caused major reef damage in the Southeast Pacific (Polynesia). The reefs have remained relatively stable since the 1998 bleaching event, although COTS are still present in some sites, especially in French Polynesia (France). Reef awareness and conservation activities have gradually increased. Many coral reefs surround uninhabited islands; climate-change bleaching and ocean acidification are at present the only major future threats. Thus, many Pacific reefs are considered to be ideal targets for the creation of "reservoir" protected areas to conserve species threatened with over-exploitation or other human stresses. Kiribati has recognized this with the declaration of the Phoenix Islands Protected Area (PIPA), which is also a World Heritage site.

The United States Pacific islands are regarded as globally important reservoirs of virtually pristine coral reefs. Thus the Northwestern Hawaiian Islands were declared to be the Papahānaumokuākea Marine National Monument and in 2014 more islands were included in the enormous Pacific Remote Islands Marine National Monument. Management is increasing around the main Hawaiian Islands, but overfishing and sediment pollution continue as major threats. The depletion of aquarium species is being addressed through the establishment of industry-recognised MPAs.

Warm water corals are limited to the northern region of New Zealand with the situation in Kermadec Ridge being unique with warm- and cold-water corals present. The warm-water (hermatypic) zooxanthellate stony corals are at or near their southernmost limit at shallow depths around the various Kermadec Islands, with *Pocillopora* and *Tubinaria* genera prevalent. Of the 17 hermatypic species, 16 are found on the Australian Great Barrier Reef; but these corals do not form coral reefs (Brook 1999). Ahermatypic corals without zooxanthellae occur in deeper waters along the ridge, including black, gorgonian, scleractinian, and stylasterid corals.

5.5 The Wider Caribbean

These reefs suffered massive losses from coral diseases since the mid-1980s and more recently during the major climate-related events of 2005, when all regions of the Wider Caribbean were affected by record coral bleaching and tropical cyclone (hurricane) damage.

Reefs of the United States Caribbean are the focus of increased scientific and conservation efforts and results are variable: some improvements but also major coral reef losses are observed. The reefs immediately adjacent to the Florida protected areas (Florida Keys National Marine Sanctuary) are showing minimal recovery, if any, as pollution and excessive tourism threats impede many years of management efforts. More remote reefs, like the Tortugas and Flower Garden Banks, are healthier, but Puerto Rico and the United States Virgin Islands are threatened by overfishing, pollution from the land, and these threats are all compounded by coral bleaching and disease.

Reefs in the Northern Caribbean and Western Atlantic were also severely damaged in 2005 including those under strong conservation efforts. A wide disparity exists in the economic status of the States and territories in the region. Some wealthier territories, such as Bermuda (United Kingdom) and the Cayman Islands (United Kingdom), are applying considerable reef management programmes. Some encouraging signs of coral recovery after major losses in the 1980s and 1990s are found, especially around Jamaica, but unusually frequent and intense tropical cyclones are affecting reef recovery. A ban on using fish traps has been followed by significant increases in fish populations, accompanied by coral cover increases, especially in Bermuda (United Kingdom).

The 2005 coral bleaching event caused major damage in the Lesser Antilles, where coral cover was reduced by about 50 per cent on many reefs. Recovery has been slow or non-existent in reefs under high human pressures. Algal cover has increased and coral diseases have been particularly prevalent since 2005. Most of these small islands depend heavily on their coral reefs for tourism income and fisheries, and this awareness is increasing calls for reef conservation, such as the Caribbean Challenge (http://www.caribbeanchallengeinitiative.org/), as well as local initiatives. Reefs of the Netherlands Antilles harbour some of the highest coral cover seen throughout the wider Caribbean.

Reef status along the Mesoamerican Barrier Reef and Central America has similarly declined, after a long series of losses that started in the 1980s. Bleaching and especially tropical cyclones in 2005 caused considerable destruction around Cozumel (Mexico). The trend is for decreasing coral cover, averaging around 11 per cent since 2004, and some reefs have lost more than 50 per cent coral cover. Major programmes have considerably raised capacity and improved management of MPAs, but sedimentation and overfishing continue to impede reef recovery. While fisheries regulations like the 2009 ban on the take of parrotfish have helped, MPAs in Belize have not been adequately managed, such that the Belize Barrier Reef Reserve System was listed as World Heritage in Danger in 2014.

The main drivers of coral decline in the Southern Tropical Americas are pollution, sedimentation and overfishing. Coastal reefs have been historically affected by sedimentation due to deforestation of the Atlantic forests (Macedo and Maida, 2011). Coral bleaching associated with the El Niño phenomenon is affecting both coastal and oceanic systems, in varying degrees of intensity (Ferreira et al., 2013; Kelmo and Attrill, 2013). Coastal reefs in the region are particularly affected by pollution and sedimentation (Bruce et al., 2012; Silva et al., 2013). Overfishing of key large-bodied herbivorous fish is a worrying trend (Francini-Filho and Moura, 2008; Ferreira et al., 2012). An important threat to coral reefs in Brazil is the invasion and rapid spread of the sun coral *Tubastraea coccinea* and *Tubastraea tagusensis* (Silva et al., 2014). Diseases were first recorded in 2005, and now represent an increasing threat (Francini-Filho et al., 2008). Comparison with reports from earlier surveys indicate dramatic declines in costal reefs during the last 50 years (Ferreira and Maida, 2006), with signs of stability in coral cover (Francini-Filho et al., 2013) or disturbance followed by recovery (Kelmo and Attrill, 2013) in the last two decades. Recent trends include the Brazilian Coral Reef National Action Plan and regulation of fisheries over reef fish species considered as threatened (MMA, 2014).

6. Gaps in scientific knowledge

One long-lasting difficulty with monitoring the state of marine ecosystems is the lack of long-standing databases. Although coral reefs have been monitored for decades within countries in many parts of the world, in other regions monitoring is more recent, or interrupted, or collected with a wide range of methods that preclude standardization. Coral reefs are iconic ecosystems and around the world national governments and voluntary organizations have been engaged in coral reef monitoring. The International Coral Reef Initiative (ICRI)[2] has specifically assisted many countries with assessment and monitoring of their coral reefs by supporting the Global Coral Reef Monitoring Network. Other networks for monitoring, awareness and protection are also organized by NGOs; the largest is Reef Check, operating in 90 countries since 1998 (www.reefcheck.org).

A study published by Wilson et al. (2010) canvassed the opinions of 33 experts to identify crucial knowledge gaps in current understanding of climate-change impacts on coral reef fishes. Out of 153 gaps reported by the experts, 42 per cent related to habitat associations and community dynamics of fish, reflecting the established effects and immediate concerns pertinent to climate change-induced coral loss and habitat degradation (i.e., how does coral mortality influence the capacity of a wide range of fish populations to persist?).

Existing maps of the spatial distribution of coral reefs largely are based on satellite images and aerial photographs. Submerged coral reefs (also known as mesophotic coral reefs) that occur below a water depth of around 30 m cannot easily be detected using satellites or aerial photography, even in clear waters. Consequently, their spatial

[2] The Global Coral Reef Monitoring Network (http://www.icriforum.org/gcrmn) is assisted by the International Coral Reef Initiative (ICRI), an informal partnership between 34 States and a range of organizations, governmental and non-governmental, that also establishes committees to deal with several coral reef conservation- and management-related issues.

distribution and even their existence are unknown in most reef provinces. For this reason, deeper reefs have been underestimated in analyses of the available area of coral habitat and are not included in assessments for conservation measures, despite recent evidence that these areas may be significant (Locker et al., 2010; Bridge et al., 2013). A recent study suggests that the area of submerged reefs in the GBR may be equal to that of near-surface reefs (Harris et al., 2013). Understanding the extent of submerged reefs is therefore important, because they can support large and diverse coral communities (Bridge et al., 2012) and hence may provide vital refugia for corals and associated species from a range of environmental disturbances (Riegl and Piller, 2003; Bongaerts et al., 2010).

The scientific consensus is that threats associated with climate change (bleaching, ocean acidification, stronger storms etc.) pose the greatest threat to the medium- to long-term existence of coral reefs around the world. What is unknown is whether reefs can and will respond to these threats with greater resilience. Reefs contain very high biodiversity and have progressed through major climate change events in the geological past; how will they be able to respond in the next decades to rapid climate changes? There are early indications that some corals can adapt to warmer temperatures and grow in more acidic water, but it is predicted that many corals and other reef organisms do not have that capacity. The adaptation potentials of coral reef organisms are areas for more targeted research which will significantly increase our ability to reliably predict how reefs will fare into the future.

7. Final remarks

There are strong economic, cultural, biodiversity and natural-heritage reasons to conserve tropical and sub-tropical coral reefs and to ensure that their goods and ecosystem services continue to be provided to user communities and the world at large. There are three levels at which these pressures come together and emphasise the knowledge and capacity-building gaps in this field:

7.1 At the level of the local community

Coral reefs will not be able to continue to provide the goods and ecosystem services on which local communities have relied for generations, unless:

(i) The fishing techniques that are adopted are focused on maintaining a sustainable fishery, and destructive fishing practices (such as dynamiting) cease;

(ii) Populations of breeding fish and invertebrates, including spawning aggregations, are conserved;

(iii) The pollution of coastal waters by harmful substances (heavy metals and persistent organic pollutants) is prevented, and amounts of inputs of sediment and nutrients are kept at levels that do not damage the reefs (see chapter 20);

(iv) Any development in coastal areas is kept to levels and forms that are consistent with the continued health of the reefs.

Without the active involvement of the coastal communities that have the necessary knowledge and skills, there are likely to be serious difficulties in achieving these goals.

7.2 At the national level

In many of the countries that are the guardians of tropical and sub-tropical coral reefs, there are significant gaps in the knowledge and skills needed for the relevant authorities to play their part in sustaining the reefs. In particular, where marine protected areas are an appropriate method of delivering some of the goals, there are gaps at both national and local levels in capacities for the scientific identification of such areas, for the development of management plans for them, and in enforcing the regulations that may be required.

7.3 At regional and supra-regional levels

The conservation of specific local areas can frequently only be achieved as part of a network of such areas, since the ocean is a dynamic ecosystem and biota are commonly mobile in their early life-stages. Given the interactions among many forms of human activity in the ocean and between them and local ecosystems, management methods that do not take account of those interactions will be ineffective in delivering a sustainable future for tropical and sub-tropical reefs. Integrated management methods on a large scale can only be achieved where there is a widespread social understanding and knowledge of the pressures (such as climate change, acidification, fisheries, seabed mining (see Van Dover et al., 2012; Boschen et al., 2013), pollution and coastal development), the scales on which they operate and their interactions. All this implies that, without efforts to promote understanding of the ocean and without cooperation at the appropriate national, regional and (in some cases) global level between the relevant regulatory authorities, the pressures described in this chapter will persistently undermine the continued delivery by tropical and sub-tropical coral reefs of the goods and ecosystem services on which local communities, countries and the world have been relying.

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