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Coral Reefs

Jean-Pierre Gattuso (France), Ove Hoegh-Guldberg (Australia), Hans-Otto Pörtner (Germany)

Coral reefs are shallow-water ecosystems that consist of reefs made of calcium carbonate which is mostly secreted by reef-building corals and encrusting macroalgae. They occupy less than 0.1% of the ocean floor yet play multiple important roles throughout the tropics, housing high levels of biological diversity as well as providing key ecosystem goods and services such as habitat for fisheries, coastal protection, and appealing environments for tourism (Wild et al., 2011). About 275 million people live within 30 km of a coral reef (Burke et al., 2011) and derive some benefits from the ecosystem services that coral reefs provide (Hoegh-Guldberg, 2011), including provisioning (food, livelihoods, construction material, medicine), regulating (shoreline protection, water quality), supporting (primary production, nutrient cycling), and cultural (religion, tourism) services. This is especially true for the many coastal and small island nations in the world's tropical regions (Section 29.3.3.1).

Coral reefs are one of the most vulnerable marine ecosystems (*high confidence*; Sections 5.4.2.4, 6.3.1, 6.3.2, 6.3.5, 25.6.2, and 30.5), and more than half of the world's reefs are under medium or high risk of degradation (Burke et al., 2011). Most human-induced disturbances to coral reefs were local until the early 1980s (e.g., unsustainable coastal development, pollution, nutrient enrichment, and overfishing) when disturbances from ocean warming (principally mass coral bleaching and mortality) began to become widespread (Glynn, 1984). Concern about the impact of ocean acidification on coral reefs developed over the same period, primarily over the implications of ocean acidification for the building and maintenance of the calcium carbonate reef framework (Box CC-OA).

A wide range of climatic and non-climatic drivers affect corals and coral reefs and negative impacts have already been observed (Sections 5.4.2.4, 6.3.1, 6.3.2, 25.6.2.1, 30.5.3, 30.5.6). Bleaching involves the breakdown and loss of endosymbiotic algae, which live in the coral tissues and play a key role in supplying the coral host with energy (see Section 6.3.1. for physiological details and Section 30.5 for a regional analysis). Mass coral bleaching and mortality, triggered by positive temperature anomalies (*high confidence*), is the most widespread and conspicuous impact of climate change (Figure CR-1A and B, Figure 5-3; Sections 5.4.2.4, 6.3.1, 6.3.5, 25.6.2.1, 30.5, and 30.8.2). For example, the level of thermal stress at most of the 47 reef sites where bleaching occurred during 1997–1998 was unmatched in the period 1903–1999 (Lough, 2000). Ocean acidification reduces biodiversity (Figure CR-1C and D) and the calcification rate of corals (*high confidence*; Sections 5.4.2.4, 6.3.2, 6.3.5) while at the same time increasing the rate of dissolution of the reef framework (*medium confidence*; Section 5.2.2.4) through stimulation of biological erosion and chemical dissolution. Taken together, these changes will tip the calcium carbonate balance of coral reefs toward net dissolution (*medium confidence*; Section 5.4.2.4).

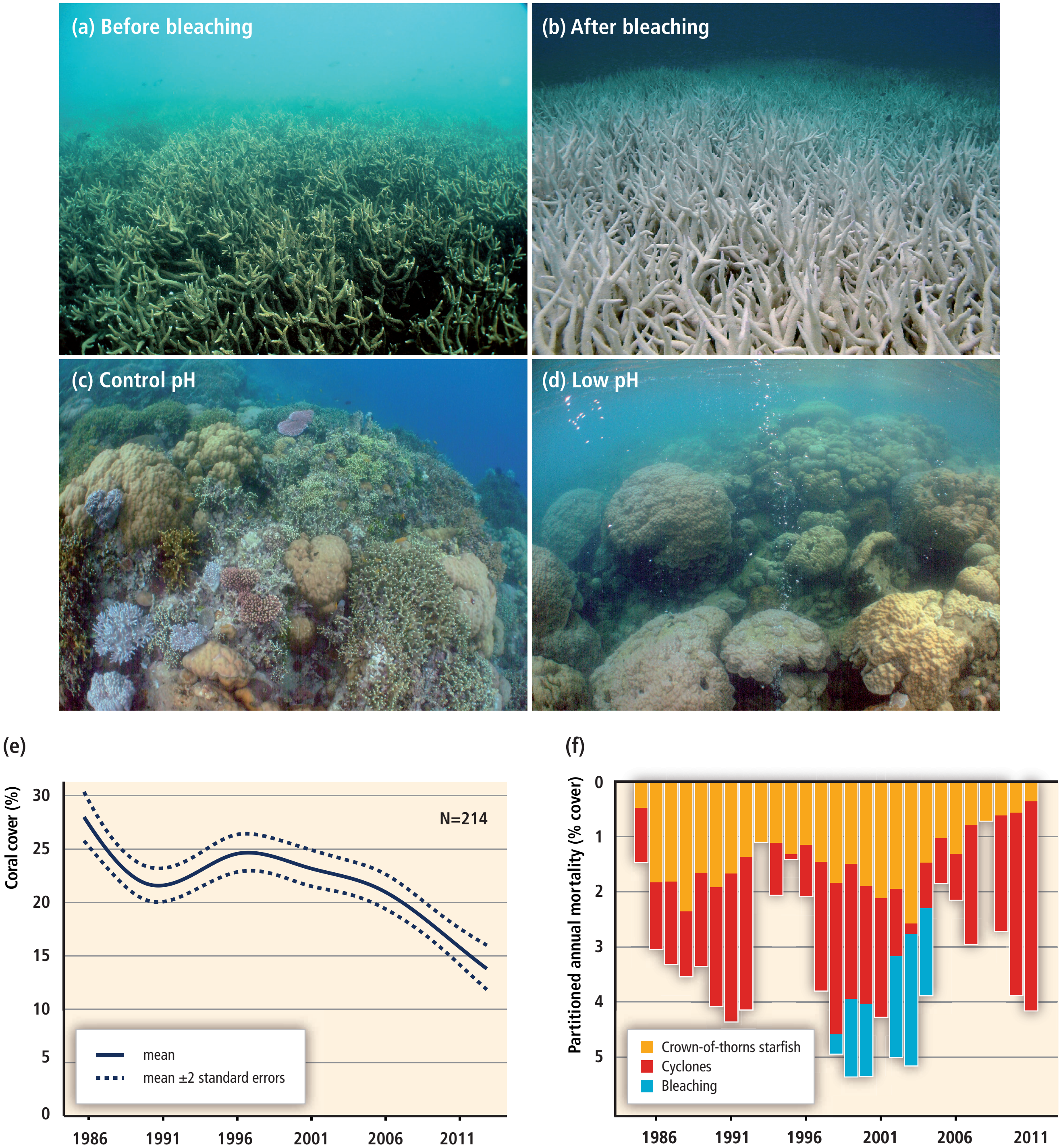

Figure CR-1 | (a, b) The same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Approximately 95% of the coral community was severely bleached in 2002 (Elvidge et al., 2004). Corals experience increasing mortality as the intensity of a heating event increases. A few coral species show the ability to shuffle symbiotic communities of dinoflagellates and appear to be more tolerant of warmer conditions (Berkelmans and van Oppen, 2006; Jones et al., 2008). (c, d) Three CO_2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO_2 is related to fundamental changes in the ecology of coral reefs (Fabricius et al., 2011), including reduced coral diversity (–39%), severely reduced structural complexity (–67%), lower density of young corals (–66%), and fewer crustose coralline algae (–85%). At high CO_2 sites (d; median pH_T ~7.8, where pH_T is pH on the total scale), reefs are dominated by massive corals while corals with high morphological complexity are underrepresented compared with control sites (c; median pH_T ~8.0). Reef development ceases at pH_T values below 7.7. (e) Temporal trend in coral cover for the whole Great Barrier Reef over the period 1985–2012 (N=number of reefs, De'ath et al., 2012). (f) Composite bars indicate the estimated mean coral mortality for each year, and the sub-bars indicate the relative mortality due to crown-of-thorns starfish, cyclones, and bleaching for the whole Great Barrier Reef (De'ath et al., 2012). (Photo credit: R. Berkelmans (a and b) and K. Fabricius (c and d).)

Ocean warming and acidification have synergistic effects in several reef-builders (Section 5.2.4.2, 6.3.5). Taken together, these changes will erode habitats for reef-based fisheries, increase the exposure of coastlines to waves and storms, as well as degrading environmental features important to industries such as tourism (*high confidence*; Section 6.4.1.3, 25.6.2, 30.5).

A growing number of studies have reported regional scale changes in coral calcification and mortality that are consistent with the scale and impact of ocean warming and acidification when compared to local factors such as declining water quality and overfishing (Hoegh-Guldberg et al., 2007). The abundance of reef building corals is in rapid decline in many Pacific and Southeast Asian regions (*very high confidence*, 1 to 2% per year for 1968–2004; Bruno and Selig, 2007). Similarly, the abundance of reef-building corals has decreased by more than 80% on many Caribbean reefs (1977–2001; Gardner et al., 2003), with a dramatic phase shift from corals to seaweeds occurring on Jamaican reefs (Hughes, 1994). Tropical cyclones, coral predators, and thermal stress-related coral bleaching and mortality have led to a decline in coral cover on the Great Barrier Reef by about 51% between 1985 and 2012 (Figure CR-1E and F). Although less well documented, benthic invertebrates other than corals are also at risk (Przeslawski et al., 2008). Fish biodiversity is threatened by the permanent degradation of coral reefs, including in a marine reserve (Jones et al., 2004).

Future impacts of climate-related drivers (ocean warming, acidification, sea level rise as well as more intense tropical cyclones and rainfall events) will exacerbate the impacts of non-climate–related drivers (*high confidence*). Even under optimistic assumptions regarding corals being able to rapidly adapt to thermal stress, one-third (9 to 60%, 68% uncertainty range) of the world's coral reefs are projected to be subject to long-term degradation (next few decades) under the Representative Concentration Pathway (RCP)3-PD scenario (Frieler et al., 2013). Under the RCP4.5 scenario, this fraction increases to two-thirds (30 to 88%, 68% uncertainty range). If present-day corals have residual capacity to acclimate and/or adapt, half of the coral reefs may avoid high-frequency bleaching through 2100 (*limited evidence*, *limited agreement*; Logan et al., 2014). Evidence of corals adapting rapidly, however, to climate change is missing or equivocal (Hoegh-Guldberg, 2012).

Damage to coral reefs has implications for several key regional services:

- *Resources*: Coral reefs account for 10 to 12% of the fish caught in tropical countries, and 20 to 25% of the fish caught by developing nations (Garcia and de Leiva Moreno, 2003). More than half (55%) of the 49 island countries considered by Newton et al. (2007) are already exploiting their coral reef fisheries in an unsustainable way and the production of coral reef fish in the Pacific is projected to decrease 20% by 2050 under the Special Report on Emission Scenarios (SRES) A2 emissions scenario (Bell et al., 2013).
- *Coastal protection*: Coral reefs contribute to protecting the shoreline from the destructive action of storm surges and cyclones (Sheppard et al., 2005), sheltering the only habitable land for several island nations, habitats suitable for the establishment and maintenance of mangroves and wetlands, as well as areas for recreational activities. This role is threatened by future sea level rise, the decrease in coral cover, reduced rates of calcification, and higher rates of dissolution and bioerosion due to ocean warming and acidification (Sections 5.4.2.4, 6.4.1, 30.5).
- *Tourism*: More than 100 countries benefit from the recreational value provided by their coral reefs (Burke et al., 2011). For example, the Great Barrier Reef Marine Park attracts about 1.9 million visits each year and generates A$5.4 billion to the Australian economy and 54,000 jobs (90% in the tourism sector; Biggs, 2011).

Coral reefs make a modest contribution to the global gross domestic product (GDP) but their economic importance can be high at the country and regional scales (Pratchett et al., 2008). For example, tourism and fisheries represent 5% of the GDP of South Pacific islands (average for 2001–2011; Laurans et al., 2013). At the local scale, these two services provided in 2009–2011 at least 25% of the annual income of villages in Vanuatu and Fiji (Pascal, 2011; Laurans et al., 2013).

Isolated reefs can recover from major disturbance, and the benefits of their isolation from chronic anthropogenic pressures can outweigh the costs of limited connectivity (Gilmour et al., 2013). Marine protected areas (MPAs) and fisheries management have the potential to increase ecosystem resilience and increase the recovery of coral reefs after climate change impacts such as mass coral bleaching (McLeod et al., 2009). Although they are key conservation and management tools, they are unable to protect corals directly from thermal stress (Selig et al., 2012), suggesting that they need to be complemented with additional and alternative strategies (Rau et al., 2012; Billé et al., 2013). While MPA networks are a critical management tool, they should be established considering other forms of resource management (e.g., fishery catch limits and gear restrictions) and integrated ocean and coastal management to control land-based threats such as pollution and sedimentation. There is *medium confidence* that networks of highly protected areas nested within a broader management framework can contribute to preserving coral reefs under increasing human pressure at local and global scales (Salm et al., 2006). Locally, controlling the input of nutrients and sediment from land is an important complementary management strategy (Mcleod et al., 2009) because nutrient enrichment can increase the susceptibility of corals to bleaching (Wiedenmann et al., 2013) and coastal pollutants enriched with fertilizers can increase acidification (Kelly et al., 2011). In the long term, limiting the amount of ocean warming and acidification is central to ensuring the viability of coral reefs and dependent communities (*high confidence*; Section 5.2.4.4, 30.5).

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