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Impacts of Climate Change on Coral in the Coastal and Marine Environments of Caribbean Small Island Developing States (SIDS)

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EXECUTIVE SUMMARY

Coral reefs are integral to life in the Caribbean - providing protection from storms, sustaining national economies and livelihoods through tourism and fishing, and supporting culture, recreation and biodiversity conservation. Over a decade ago, their value was estimated at US$3.1 - 4.6 billion each year.

Climate change is already impacting coral reefs in the Caribbean, through coral bleaching, disease outbreaks, ocean acidification and physical damage from stronger hurricanes. Coral beaching is the most visible, wide-spread and iconic manifestation of climate change on reefs, with major events in the Caribbean in 1998, 2010 and 2015/16. The extent of bleaching and associated mortality varies by location and event, but has resulted in some mortality. Coral disease has already significantly altered the community composition of reefs in the Caribbean, and is projected to result in increasing frequency of outbreaks as seas warm. The lack of a centralized database to coordinate reef monitoring information, hampers efforts to measure these effects.

Ocean acidification is a direct chemical result of increased carbon dioxide, but it has a variety of different responses in different reef organisms. Corals are the brick foundations of the reef, with crustose coralline algae as their mortar. Both these critical functional groups are already being affected by the reduced pH of surface water, making it more difficult to calcify and grow.

Future impacts are expected to follow and accelerate on these trends.

By 2040–2043 projections are for the onset of annual severe bleaching, which would likely result in significant coral mortality. Disease outbreaks are predicted to become annual events several years earlier. Projections for future ocean acidification result in ocean carbonate saturation levels potentially dropping below those required to sustain coral reef accretion by 2050.

Cutting emissions in CO_2 (within RCP6.0) would buy many coral reefs a couple of decades more time before the worst impacts occur, but it delays rather than mitigates the threats posed to coral reefs by acidification and bleaching (Maynard et al, 2016). National leaders of the Caribbean need to adamantly fight for CO_2 emissions reductions, and ensure their reef management agencies take all precautionary measures needed to reduce local stress on their reefs to buy them additional time and resiliency potential for withstanding the stress of climate change.

Introduction

Coral reefs provide shoreline protection from storms and hurricanes, medicines, food, and recreational activities, with a recent estimated global value of 172 billion U.S. dollars per year (EurekAlert-AAAS, 2009). They also harbour the greatest biodiversity within all marine ecosystems, yet are regarded as one of the planet's must vulnerable ecosystems, due in part to local and regional impacts of overfishing, pollution, and climate change.

The 2004 Reefs at Risk Caribbean Report (http://www.wri.org/publication/reefs-risk-caribbean) estimated that the coral reefs of the Caribbean provide an estimated US$3.1-4.6 billion each year in goods and services, based on tourism, fisheries, and shoreline protection. This report also estimated that annual economic losses due to reef degradation (including climate change and local impacts) amount to $US 350-870 million per year, which at current dollar values would be higher.

On the national scale, World Resources Institute (WRI) has estimated that Belize's coral reef and coastal mangroves provided around US $395-559 million per year in direct benefits and ecosystem services (Cooper et al, 2008).

Global climate change, caused by rapidly increasing concentrations of anthropogenic greenhouse gases, has a number of resulting impacts on coral reefs worldwide, as illustrated in Fig. 1 (Hoegh-Guldberg et al., 2007). The specific drivers of reef degradation include elevated sea-surface temperature, sea-level rise, ocean acidification, and solar radiation (Spillman et al., 2011). They result in various physiological and ecological responses of reef organisms, including corals, and are generally exasperated by local stressors, including overfishing, pollution, etc.

Coral beaching is the most visible, wide-spread and iconic manifestation of climate change on reefs, but it is far from the only one. Bleaching is a generalized term for the loss of symbiotic dinoflagellates, or their pigments, in stony corals and is typically associated with sustained, unusually warm water temperatures (Hoegh-Guldberg, 1999), particularly when it occurs over a large geographic scale. Bleaching events can change colorful vibrant coral reefs into pale rocky graveyards, ominous shadows of possible future scenarios.

What is Already Happening?

Climate change is already impacting coral reefs through coral bleaching, disease outbreaks, ocean acidification and physical damage from stronger hurricanes.

Changes already observed over the last century (from the 2012 Reef Scientists Consensus Statement on Climate Change, signed by almost 2500 reef scientists):

- Approximately 25-30% of the world's coral reefs are already severely degraded by local impacts from land and by over-harvesting.
- The surface of the world's oceans has warmed by 0.7°C, resulting in unprecedented coral bleaching and mortality events.
- The acidity of the ocean's surface has increased due to increased atmospheric CO_2.
- Sea-level has risen on average by 18cm.

Elevated sea temperature has triggered dramatic declines in coral reef ecosystem health globally, most recently including the devastating third Global Bleaching Event 2015/16 with three global-scale mass bleaching events on record (1998, and currently 2015/16). The current (third) global event has received substantial media attention, because the Great Barrier Reef in Australia, experienced unprecedented levels of coral reef death on a large-scale. The Caribbean has not yet experienced that degree of bleaching-induced mass coral mortality, although there have been a number of bleaching events damaging various areas of the Caribbean in different years.

The most severe bleaching event recorded in the Caribbean is widely considered to be 2005, with 80% of coral reefs being affected by bleaching and 40% dying at many locations across 22 countries (Eakin et al., 2010). However, for the Northwestern Caribbean, including Belize, the 1998 event remains the most devastating on record. Impacts were compounded by physical damage from a catastrophic hurricane, which can also be considered linked to climate change, due to warmer temperatures fuelling stronger storms.

The extent of these bleaching events often varies on a 50-100km scale, with even finer scale differences on a site by site basis. Belize has the longest barrier reef in the Western Hemisphere and a relatively good amount of reef data available, including a field study describing the first coral bleaching event in 1995 (McField, 1999).

The role of disease has been generally under-appreciated as a significant driver of climate change-driven decline in coral reef health. Maynard et al. (2016) strongly suggest that disease is as likely to cause coral mortality as bleaching in the coming decades and needs to be given greater consideration in management planning. As evidence of this, at 96% of reef

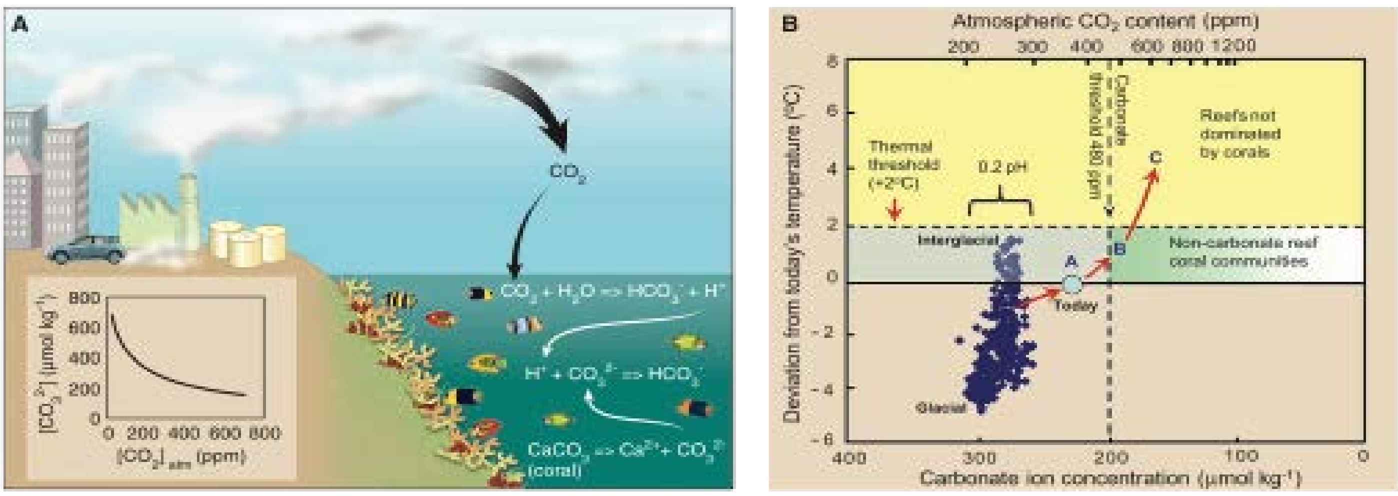


Figure 1: A) Link between the build up of atmospheric Co2 and coral calcification due to ocean acidification. B) Temperature and carbonate-ion concentrations for the past 420,000 years. Reproduced with permission from Hoegh-Guldberg et al. (2007).

Box 1: National-scale variability

As an example of national-scale variability, the main coral bleaching events in Belize are listed, and include:

- 1995 – first documented coral bleaching event, caused widespread bleaching (~50% corals bleached), with coral mortality (~10% mortality in Belize)
- 1998 -the most significant known coral bleaching event causing significant coral mortality in the MAR combined with a catastrophic hurricane
- 2005 - low level bleaching with minimal mortality
- 2008 - moderate coral bleaching event with little coral mortality
- 2010 - moderate coral bleaching event with little coral mortality
- 2015 - moderate bleaching with little coral mortality
- 2016 (underway) moderate bleaching with isolated partial mortality

locations, at least 2 of the 3 temperature-related disease conditions examined occur years before annual severe coral bleaching events are projected to occur. There have already been substantial shifts in the abundance and composition of coral communities affected by bleaching and disease outbreak events (Aronson et al, 2000).

In addition to the more visible coral bleaching and disease outbreaks, increases in sea temperature have already had other more hidden impacts including declines in coral reproductive success (Baird et al., 2009), metabolic rates (Munday et al., 2009), and shifts in geographic ranges (Hughes et al., 2012). In combination with more localized stresses, such as overfishing and degraded water quality, unprecedented thermal stress impacts could undermine significant investments in protection of coral reefs over recent decades (Game et al., 2005). The rapid pace of climate warming is likely to increase damage to coral reefs; consequently, improved understanding of proactive conservation strategies is pivotal to sustainably managing marine populations.

Reef-building corals are particularly vulnerable to rising sea temperatures and are among the most sensitive organisms to climate change (Hoegh-Guldberg et al., 2007). Corals under temperature stress lose the ability to synthesize protective sunscreens, making them more sensitive to sunlight (Hallock, 2005). In addition, reef-building corals have relatively long generation times and low genetic diversity, a combination that slows adaptation to environmental changes (Hoegh-Guldberg et al., 2007). Although adaptive responses to thermal stress could increase with climate warming (Logan et al., 2014), adaptive capacity might include a shift to symbiont species with higher thermal tolerances, which can still be considered a kind of reef degradation (Frieler et al., 2012). Because corals are currently living in conditions at or near their thermal limits, increased temperatures that exceed normal summer maxima by only 1°C are enough to cause coral bleaching, and prolonged high temperatures over large areas can lead to extensive mortality (Glynn and D'croz, 1990). Disruption of coral growth and composition can also be protracted because rates of recovery vary considerably across species and environmental conditions; such disruption is linked to the recurrence of mortality events, and other concurrent stressors (Hughes et al., 2003; Baker et al., 2008).

Ocean Acidification

Even healthy Caribbean reefs have minimal net growth, due to the relatively slow growth rates of most corals and the constant forces of chemical and biophysical erosion. Maintaining a positive balance of carbonate material being deposited from the calcification of corals, calcareous and coralline algae is critical to maintain the vertical relief and overall structure that defines a coral reef. This topographic complexity is needed to support to high biodiversity, including commercial fish species which are generally more abundant in areas of greater reef complexity. Coral reefs are naturally subjected to both bio-erosion by a wide variety of organisms and chemical erosion, which has already increased due to increased CO_2 and the resulting decreased saturation state of aragonite (need for coral growth).

This process of increasing atmospheric and oceanic carbon dioxide, resulting in decreased carbonate and aragonite saturation, is called ocean acidification. Some reefs are thought to already be eroding, at least for part of the year, as a result of the current level of ocean acidification (Yates & Halley, 2006; Albright et al., 2013). The percentage decline in calcification required to shift reefs from net accreting to net eroding varies from place to place but is minimal, meaning very small changes can have major negative consequences for reef structure. A recent study found that 37% of reefs in the Caribbean are already net eroding, with only 26% accreting, but with low net calcification rates (Perry et al., 2013). This reduced overall growth of reefs makes them less able to keep up with rising sea levels, and less able to protect shorelines from wave damage, including hurricanes. Eroding reefs reduces the availability of sand on Caribbean beaches, lowering the tourism values and requiring expensive mitigation efforts. The eventual flattening of reefs also reduces their ability to support commercial fisheries, further reducing the goods and services produced by the reefs for the economy and food security.

Physical damage

Given that warmer sea temperatures generally fuel stronger hurricanes, we can consider hurricane induced physical damage to reefs as related to climate change, although not exactly a result of climate change. Hurricanes are a natural disturbance in reef systems, but if either their frequency in a given area, or their average strength increases, it can have devastating effects.

What Could Happen?

Climate change has the potential to severely damage or destroy coral reefs, particularly if stronger local management actions are not taken.

Hoegh-Guldberg et al. (2007) provides a comprehensive overview of projected climate impacts on coral reefs including the following: Increases in $[CO_2]_{atm}$ > 500 ppm (11) will push carbonate-ion concentrations well below 200 mmol kg^{-1}

(aragonite saturation < 3.3) and sea temperatures above +2°C relative to today's values (Scenario CRS-C, Fig. 1).

Under these conditions, reefs will become rapidly eroding rubble banks such as those seen in some inshore regions of the Great Barrier Reef, where dense populations of corals have vanished over the past 50 to 100 years (Hoegh-Guldberg et al. 2007). Rapid changes in sea level (+23 to 51 cm by 2100, scenario A2) (8), coupled with slow or nonexistent reef growth, may also lead to "drowned" reefs (36) in which corals and the reefs they build fail to keep up with rising sea levels.

Projections for future ocean acidification result in ocean carbonate saturation levels potentially dropping below those required to sustain coral reef accretion by 2050 (Kleypas & Langdon 2006). van Hooidonk et al. (2014) modelled both bleaching and ocean acidification effects under different climate scenarios finding that 90% of the world reefs are projected to experience severe bleaching annually by 2055. Furthermore, 5% declines in calcification are projected for all reef locations by 2034 under RCP8.5, assuming a 15% decline in calcification per unit of Ωarag. Drastic emissions cuts, such as those represented by RCP6.0, would delay this annual bleaching threshold by ~20 years (2062 vs. 2044). However, based on past experience, global emissions will likely exceed the current worst-case scenario, as has happened in previous emission scenarios.

More recently, van Hooidonk et al (2015) developed a downscaled model for the Caribbean projections of the onset of annual coral bleaching conditions in the Caribbean under Representative Concentration Pathway (RCP) 8.5. Spatial patterns in all three projections are broadly similar; the average year for the onset of annual severe bleaching is 2040–2043 for all projections. However, downscaled projections show many locations where the onset of annual severe bleaching (ASB) varies by 10 or more years within a single GCM grid cell. Managers in locations where this applies can identify specific reefs that represent relative, albeit temporary, refugia.

Reduced or loss of reef accretion will result in additional 'flattening' of reef rugosity, with negative consequences for fish and invertebrate recruitment and populations (Alvarez-Filip et al., 2009).

For future conditions of >500ppm CO_2 and 3 °C above current conditions there is a probability of 50% or more, that coral-associated fauna would become rare or extinct given their dependence on living corals and reef rugosity (Hoegh-Guldberg et al 2007).

van Hooidonk et al. (2014) used the 8 Degree Heating Week threshold to mark the onset of severe annual bleaching, thereby establishing a timeline until the year in which any reef would be bleaching annually, and so unlikely to survive. For 85% of global reef locations that timeframe is less than 40 years from now.

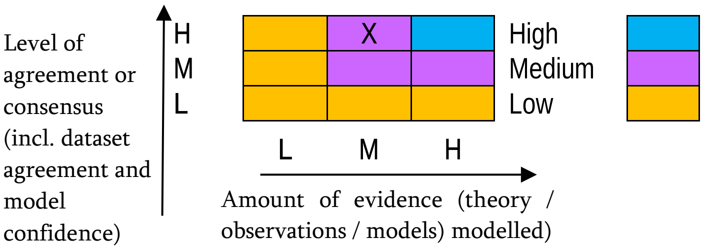
Maynard et al. (2016) compare climate model projections of temperature conditions that will increase coral susceptibility to disease, pathogen abundance and pathogen virulence under both moderate (RCP 4.5) and fossil fuel aggressive (RCP 8.5) emissions scenarios. They also compare projections for the onset of disease-conducive conditions and severe annual coral bleaching, and produce a disease risk summary that combines climate stress with stress caused by local human activities. The emissions scenarios RCP8.5 and 4.5 take time to diverge and there is little difference between the scenarios for the timing of the various disease-promoting conditions being met. This is further evidence that reducing stress caused by local human activities will be critically important to reducing disease impacts in the coming decades. (Maynard et al. 2016).

The increasing intensity of Tropical hurricanes (Webster et al., 2005) suggest that losses of beach sand from coastal zones are likely to increase (Sadd, 1984), likely exacerbated by reduced reef accretion, carbonate production, and rising sea levels. This loss of beach sand will likely have negative impacts on sea turtle and crocodile nesting, foraging and nesting of shore birds and have enormous losses to tourism value. A study in Bonaire found up to 32% of the beach area could be lost with a 0.5-m rise in sea level (Fish, et al., 2005).

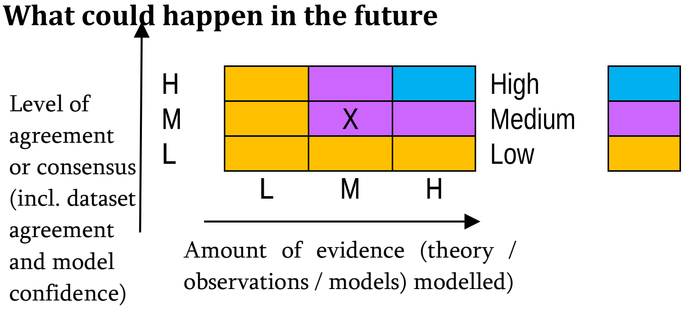
Cutting emissions in CO_2 within RCP6.0 compared to RCP8.5 buys many coral reefs a couple of decades, but delays rather than mitigates the threats posed to coral reefs by acidification and bleaching. (Maynard et al., 2016). Even buying a two-decade delay, which applies to nearly all reefs, has enormous value to society. This captures the potential benefit for coral reefs and dependent communities of global action to reduce emissions outputs.

Confidence Assessment

What is already happening



What could happen in the future



There is reasonably high confidence in what is already happening, e.g. measuring the extent of acidification at any location, although scientists don't fully understand the ecological implications of these changes, because they have different effects on different species. Species-interactions and dependencies are often not known until a disturbance alters the balance, sometimes resulting in an ecological collapse. Even with coral bleaching, one of the more well-studied climate change impacts on reefs (the physiological effects like reduced reproductive output and increased disease outbreaks) lack empirical data and often cannot be predicted with good precision, thus the score of medium precision of data. The fundamental physiological and ecological processes are generally understood, but the precise response to any disturbance depends on many internal and external factors, and needs further research, offering the medium score for amount of evidence.

For future impacts there is more uncertainty. A minority of scientists have more expectation for coral adaptation to temperature (through symbiont shuffling or their temperature adaptation). With ocean acidification, the results are highly variable by species so predicting ecological outcomes is extremely difficult. However, a few key functional groups, like coralline algae (which provide the mortar for the reef framework construction) seem clearly impacted across species, hence a score of medium. The Maynard et al. models showed a high level of concordance using different approaches. OA studies do empirically test different levels and so are sound evidence of impact and future CO_2 levels, resulting in a medium/low score.

Knowledge Gaps

Additional laboratory and field based studies of OA are needed to understand the longer-term impacts on a variety of key taxa. They should also include synergistic effects with elevated temperature and nutrient conditions, and altered rates of water flow.

The link between OA and temperature elevation on disease outbreaks is needed. We need a better understanding of the causal agents of diseases in general and the environmental factors (temperature, etc.) that accelerate the growth of these pathogens. Subsequently more models and validation with real time data/monitoring efforts are needed.

Better understanding of biophysical feedbacks is necessary, particularly with regards to ocean circulation and potential changes in circulation patterns including non-surface flows. Monitoring data from bleaching events recently has found cases of apparently deep warm water affecting reefs and not being captured by satellite based temperature monitoring of Sea Surface Temperature and Degree Heating Week. More physical oceanographic research of actual circulation in the Caribbean could inform this field.

Socio-economic Impacts

Caribbean culture is largely centered around the sea, with high social dependency on coastal natural resources. Artisanal fishers in most countries provide an important contribution to daily protein intake and food security, as well as participating the long time cultural tradition of fishing.

In the Caribbean, tourism is a major source of foreign exchange, accounting for half of the gross domestic product in some countries (Bryant et al., 1998). Marine focused tourism such as scuba diving, snorkeling, sports fishing, and even beach going is dependent on maintaining functional reef ecosystems to maintain provision of the services. Scuba and snorkeling activities are particularly sensitive to reef degradation, as the attractiveness of coral reefs is lost along with its biodiversity and shift from coral to algal dominated states. Thus, reefs that are dominated by dead coral, potentially from a coral bleaching event, are less attractive to scuba divers. In addition, degraded reefs harbour fewer commercial fish, affecting commercial fisheries, recreational activities, and subsistence fishing for local populations. Lowered availability of protein for local human populations can reduce their health.

Coral reefs and associated mangrove ecosystems provide vitally important goods and services. Coral reef and mangrove-lined coastlines provide critical protection against erosion and wave-induced damages from tropical storms and hurricanes, protecting property and lives. In total, the value of reef- and mangrove-related fisheries, tourism, and shoreline protection services in Belize was estimated to be US$395-559 million per year in 2007 - compared to its total GDP of US$1.3 billion. Thus, loss of these ecosystem services would result in losses equivalent to over a third of Belize's GDP, with similar situations expected in the other small island states of the Caribbean also largely dependent on marine-based tourism.

Reef degradation from climate change can be rapid and obvious (bleaching and disease outbreaks) or slow and insidious (reduced growth from acidification), but the ultimate result is degraded reefs, reduced economies, and marginalized communities which rely upon these valuable natural assets. Further degradation of Caribbean reefs could cost US$95-140 million per year in losses to coral reef-associated fisheries, US$100-300 million per year through declines in dive tourism, and US$140-420 million per year as a result of reduced shoreline protection services (Burke et. al, 2004).

Management interventions

Local and national (Caribbean) management responses to the impacts of climate change need to focus on reducing local stressors, including solutions to reduce degradation of water quality (inadequate sewage treatment, excessive runoff nutrients and sediments from agro-industrial contamination). The Australia Caribbean Coral Reef Collaboration describes a Regional Plan of Action for Improving the outlook for Caribbean coral reefs, in the face of climate change (ACCRC) (2014).

Parallel to the intervention efforts to increase herbivory on reefs by protecting parrotfish is learning more about how to facilitate natural recruitment of *Diadema*, the long-spined sea urchin. This species was once the foremost grazer on Caribbean reefs before suffering a disease-induced mass mortality in the early 1980s.

Direct replenishment or restoration of corals through fragmentation and out-planting can also assist their recovery and include analysis of bleaching-related responses of different genotypes of coral (and their symbionts) potentially helping corals adapt to rising temperatures. Coral replenishment of genotypes that are more resistant to bleaching pose one potential mechanism to directly offset coral losses from climate change (Bowden-Kirby and Carne, 2012).

NOAA's predictive modeling and alert system (https://coralreefwatch.noaa.gov/satellite/index.php) suggest where and when stressful elevated sea surface temperatures accumulate to warning levels, thus providing alerts to managers. However, only detailed real-time monitoring of the extent of bleaching can determine the spatial extent and severity of coral bleaching and subsequent mortality and validate this and other models.

There is an urgent need to develop more integrated bleaching monitoring systems and databases, that can help validate and improve the models. In order to ensure standardization of data collection methods and timing, reef managers should adopt an emergency response plan such as developed in Belize in 2008 (Searle et al., 2008) and implemented during several mild bleaching events (2003, 2005, 2009, 2010), and more widely throughout the Mesoamerican Reef region for monitoring of the 2015 and 2016 events.

Data should be entered into a regional standardized database that can validate the models of predicted responses and be early warning tools for disease as an add-on to NOAA Coral Reef Watch (https://coralreefwatch.noaa.gov/satellite/index.php).

One major driver of reef resilience is herbivory by parrotfish and recent action to protect parrotfish in Belize was found to have increased resilience 6-fold. (Mumby et al., 2013). This study found that under a 'business-as-usual' greenhouse gas emissions scenario, the average reef took just 8.0 years to drop below a 10% coral cover 'viability' threshold, mainly due to coral bleaching impacts. However, if parrotfish were fully protected and allowed to graze the reefs, this doubled the length of time taken for the average reef to reach the 10% threshold to 17.6 years (Mumby et al., 2013). So, the presence of grazing parrotfish on the reef helped double the time it takes for reefs to drop into a non-viable state. Mumby et al. (2013) also found that combined global and local action reduced the rate of reef degradation threefold. However, global action to reduce greenhouse gas emissions had little impact on average coral state unless it was accompanied by local controls of fishing.

MPA network design can also be improved by prioritizing areas and considering long-term vulnerabilities to climate warming based on spatially and temporally quantitative analysis of accounts historical and projected sea surface temperatures (Margris, 2015); (Chollet and Mumby, 2013).

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