

The Coral Reef Crisis: scientific justification for critical CO₂ threshold levels of < 350ppm

**Output of the technical working group meeting. The Royal Society,
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On the 6th July, 2009, the Royal Society, the Zoological Society of London and the International Programme on the State of the Ocean facilitated a Coral Reef Crisis meeting to identify key thresholds of atmospheric carbon dioxide needed for coral reefs to remain viable. The following statement summarises the conclusions of the meeting's technical working group:

1. Coral reefs are the most biologically diverse habitats of the oceans and provide essential ecosystem goods and services to hundreds of millions of people.
2. Temperature-induced mass coral bleaching causing widespread mortality on the Great Barrier Reef and many other reefs of the world started when atmospheric CO₂ exceeded 320ppm.
3. At today's level of 387ppm CO₂, reefs are seriously declining and time-lagged effects will result in their continued demise with parallel impacts on other marine and coastal ecosystems.
4. Proposals to limit CO₂ levels to 450ppm will not prevent the catastrophic loss of coral reefs from the combined effects of climate change and ocean acidification.
5. To ensure the long-term viability of coral reefs the atmospheric CO₂ level must be reduced significantly below 350ppm.
6. In addition to major reductions in CO₂ emissions, achieving this safe level will require the active removal of CO₂ from the atmosphere.
7. Given the above, ecosystem-based management of other direct human-induced stresses on coral reefs, such as over-fishing, destructive fishing, coastal pollution and sedimentation, will be essential for the survival of coral reefs on which we are all dependent.

Scientific justification

The statements above are founded on the extensive study of coral reefs over the past thirty years, synthesised with a wealth of recent data from many disciplines. This document provides a condensed overview of the pertinent scientific background.

Introduction

Temperature-related effects of climate change on coral reefs are highly visible, well-defined and extensively documented. Correlations between rising carbon dioxide levels, rising ocean temperature and the biological responses of reefs are therefore known in detail, providing a particularly well-grounded basis for future prediction. The more recently recognised effects of atmospheric CO₂ on ocean acidification will have even more profoundly detrimental long term effects on reefs but the full range of biological responses is, as yet, incompletely understood.

The importance of coral reefs

Although they make up only 0.2% in area of the marine environment, coral reefs are the most biodiverse ecosystems of the ocean, estimated to harbour around one third of all described marine species^{1,2}, most of which are found nowhere else. Their intricate three dimensional landscapes promote elaborate adaptation, richly complex species interdependencies, and a fertile source of medically active compounds^{3,4}. The extensive ramparts formed by reefs shield thousands of kilometres of coastline from wave erosion, protecting essential lagoon and mangrove habitat for vulnerable life stages of a wide range of commercial and non-commercial species⁵.

More than 100 countries have coastlines with coral reefs⁶ and almost 500 million people (8% of the world's population) live within 100 km of a reef⁷. Consequently, tens of millions of people depend on reef ecosystems for protein and other services⁸. Resulting exploitation, combined with lack of regulation, has resulted in severe depletion of many reef resources and has caused widespread reef degradation particularly in highly populated regions⁹. Despite these impacts, human dependence on reefs continues to increase. The values of goods and services provided by reefs have not been accurately determined, but estimates range from \$172 billion to \$375 billion per year^{10,11,12,13}. This is probably underestimated given that many of the benefits of coral reefs pass through non-market economies¹⁴ or involve intangible ecosystem services such as sand production and gas exchange.

A world without coral reefs is hard to contemplate, but would not be limited to the loss of the value of these goods and services, for the demise of reefs would also mean the extinction of a large part of the Earth's total biodiversity – something never experienced before in human history.

Impacts of climate change

The fossil record of reefs provides an unparalleled window into the effects of climate change through geological time. In the broadest context, today's reef-forming corals have existed for 240 million years during which time they have been repeatedly decimated by climate changes from many different causes, most of which are linked to upheavals of the carbon cycle¹⁵. To some, this may provide reassurance that, on vast geological timescales, the great ecosystems of the world can be persistent. Unfortunately the geological record also offers a number of crucial warnings: that on human timescales reefs can indeed be lost; that a large proportion of coral and other calcifying species can go extinct; and that once lost reefs can take thousands to millions of years to re-establish. Perhaps most importantly, there is no evidence to suppose that reefs have *ever* experienced true parallels to today's anthropogenically-driven combination of stressors. At the rate at which these stressors are currently compounding we are going into uncharted waters¹⁶.

Already 19% of the world's coral reefs have been lost and a further 35% are seriously threatened¹⁷. As a result, one-third of all reef building corals are considered to be at risk of extinction¹⁸. To date, there have been a range of principal causes: predation by the coral-eating crown-of-thorns starfish, sedimentation from urban development and deforestation, over-fishing, destructive fishing practices, eutrophication from agriculture and sewage, pollution from herbicides and pesticides, diseases and climate change. However, climate change has now overtaken all other impacts in importance because it is the singular cause of increasingly destructive and extremely widespread mass bleaching events^{19,20,21}.

The multiple nature of stressors on reefs associated with climate change is unprecedented in human history and comprehensive studies of its synergisms are still in their infancy^{22,23}. It is therefore virtually certain that the likely consequences of synergistic impacts will be far more severe than indicated from studies of individual stressors to date.

Mass bleaching and mortality: the current crisis

Regionally significant mass bleaching of corals (bleaching of multiple species on an ecologically significant scale) was first observed in the late 1970s and was soon correlated with abnormally high sea temperatures, especially pulses induced by natural weather cycles (El Niño events²⁴, which currently recur every 4-7 years)^{25,26,27} superimposed on generally elevated sea temperatures due to global warming²⁸. Detailed surveys of mass bleaching were first conducted in 1979/1980 in the Caribbean and surrounding seas²⁹ (notably in Jamaica and the Bahamas), the far eastern Pacific (Panama and the Galápagos Islands), in isolated instances in the Pacific (notably French Polynesia and Thailand)^{30,31}, and on the Great Barrier Reef^{32,33}.

Although there are many other causes of more restricted bleaching in corals, the worldwide phenomenon colloquially known as 'mass bleaching' has been shown to require a combination of both sunlight and abnormally high water temperature³⁴. Small increases (1-2°C) in sea temperature above the long-term summer maxima destabilises the relationship between host corals and their symbiotic dinoflagellate algae

(zooxanthellae), on which they rely for energy and growth^{35,36}. In high light conditions, there is a breakdown of the photosymbiotic system which causes a toxic buildup of reactive oxygen derivatives and results in a loss of the brown algae from the tissues leaving them white or 'bleached'³⁷. Corals may recover if some algae remain, otherwise they die. This dependence on both light and temperature as been confirmed in corals kept in shaded aquaria³⁸ as well as those growing naturally on reefs³⁹.

Unlike most ecosystems where the effects of climate change are matters of future prediction, mass bleaching of corals has been studied for thirty years and is understood in considerable detail^{40,41,42,43}.

Carbon dioxide levels

When the mass bleaching of coral was first noted (1978/79), the CO₂ level in the atmosphere was 336ppm⁴⁴. On the basis of an optimistic lag-time of 10 years^A, this event may be considered the outcome of a CO₂ level of ~320ppm. Since that time there have been seven major world-wide bleaching events. It was the 1982/83 mass bleaching that really drew attention to the association between bleaching, CO₂ level, and ocean temperature^{45,46,47,48,49}. That summer, about two-thirds of all inshore reefs and about 14% of offshore reefs of the Great Barrier Reef, had moderate to high levels of bleaching. CO₂ then was at a level of 340ppm, with water temperatures reflecting a 10-year time-lagged response to <~326ppm⁵⁰.

The 1997/1998 mass bleaching event killed approximately 16% of coral communities globally^{51,52}. It was also the start of a decline from which there has been no significant long-term recovery. By then, the CO₂ level was ~365ppm, with water temperatures reflecting a 10-year time-lagged response to a level of <~350ppm⁵³.

The 2002 mass bleaching event was particularly serious for Asia and the Great Barrier Reef⁵⁴ and the 2005 event commenced a new phase of decline characterised by a diminishing habitat complexity in reefs of the Caribbean and a deterioration of species diversity⁵⁵.

It is now clear that the vulnerability of coral reefs to bleaching varies geographically^{56,57,58} according to resilience⁵⁹ (see below) which, in turn is dependent on the frequency and severity of bleaching^{60,61}, the thermal history of the location^{62,63}, and levels of other stressors, notably sedimentation, over-fishing and water quality^{64,65}. Significantly, although there are some taxonomic differences in susceptibility of both corals and algae to bleaching, it is virtually certain that all zooxanthellate corals will

^A Lag time, the time it takes for the Earth's temperature to equilibrate with any particular CO₂ level, is generally estimated to be in the order of several decades. There can be no precise measurement of lag times when CO₂ levels are changing; however it cannot be less than a single decade, the time interval factored-in here. Note that if the lag time is assumed to be longer than the 10 years used here, the equivalent forcing CO₂ level would be lower (ie. worse).

ultimately succumb to bleaching if sea temperatures remain 1-3°C above the long-term summer maxima for any length of time.

The time-line Apart from isolated occurrences of bleaching in severely stressed environments⁶⁶, there are no substantiated records of mass bleaching before the late 1970s. Further evidence that mass bleaching is a recent phenomenon is seen in long-lived corals, especially large colonies of *Porites* which can be over 600 years old and which have died en masse since 1970 across much of the Indo-Pacific.

Further back in time the possible existence of mass bleaching can only be inferred from CO₂ levels. It is possible that clades of zooxanthellae not seen today may have occurred in past intervals of high temperature, the most recent being the temperature peaks of the Pliocene (5-2.6 million years ago), especially if temperature increase occurred sufficiently slowly for evolutionary adaptation to occur. Since the Pliocene peaks, global temperatures, though variable, have been only marginally higher than at present⁶⁷ and there is no evidence that rates of global temperature increase relevant to the thermal thresholds of corals were anywhere near as rapid as they are today^{68,69}. There is thus no reason to believe that mass bleaching would have been a major stress on reefs at any time since the temperature peaks of the Pliocene.

In contrast, the future path of mass bleaching events is only too clear. Rising sea surface temperatures will lead to increased severity of El Niño-associated thermal anomalies and consequently mass bleaching^{70,71,72,73}. However, incidence of mass bleaching is now likely to decouple from El Niño cycles in many parts of the world as indicated by the observation that damaging temperatures are already starting to occur during non-El Niño years. This will put affected reefs at increasing annual risk, greatly shortening event return times and decreasing resilience⁷⁴.

Some reefs, notably those of the southern Red Sea (which has naturally high temperature) and parts of the 'Coral Triangle'^{75,76,77} (which has natural refugia) are likely to be relatively less vulnerable to mass bleaching. Nevertheless, this can only be a short-term reprieve: at the current rate of increase in global CO₂ emissions (now exceeding 3% per year) a level of 450ppm, which far exceeds the most optimistic outlook for the viability of almost all reefs, will be reached by ~2030^{78,79}. The result will be widespread destruction of coral communities exposed to strong sunlight; only coral communities shaded by turbidity or depth (>20 m) will escape bleaching. However, as it is these shallow communities that provide most of the habitat that give reefs their biodiversity and productivity, as well as their role in coastal protection, the consequences for human populations reliant on reefs will be severe.

In the very long term (centuries to millennia) mass bleaching alone is unlikely to cause widespread extinctions of corals because the complexities of reef topographies provide refuges from which re-seeding could occur. Such refuges, however, may not provide protection for other taxa restricted to shallow-water reef habitats and will not provide protection for corals from ocean acidification which looms as a distant but even more serious threat.

Ocean acidification: the ultimate threat

Prior to the industrial revolution, absorption and release of CO₂ by the oceans was in approximate equilibrium⁸⁰. Since then, atmospheric CO₂ has risen from 280ppm to today's level of 387ppm⁸¹ and is estimated to be increasing at a rate approximately 100 times faster than has occurred for at least the past 650,000 years⁸². About half of all CO₂ from anthropogenic sources still remains in the atmosphere⁸³. A further 20% has been taken up by terrestrial life and the remaining 30% has been taken up by the oceans, a process that has now used up about one-third of the total storage capacity of the ocean surface⁸⁴. This uptake by the oceans is causing acidification of surface waters because dissolved CO₂ forms carbonic acid which alters the ratio of the pH-maintaining carbonate/bicarbonate buffers^{85,86}. These changes are now clearly observable in cold high latitude oceans where CO₂ is relatively soluble⁸⁷. On current trajectories of atmospheric CO₂ levels, the acidification process, likely to be already underway, will severely impact the tropics by 2030-2050 and all reefs of the world will be under increasing acidification stress^{88,89}.

Although correlations between CO₂ levels, depth changes in ocean chemistry and geographic patterns of acidification that result are imperfectly known, the process itself is not in doubt^{90,91}. Historically, studies of carbonate compensation depths have been based on calcite, the dominant form of calcium carbonate, but coral skeletons are made of aragonite which is more soluble.

Aragonite saturation

Shallow tropical seawater is supersaturated with respect to aragonite ($\Omega_{\text{aragonite}} > 4$), but saturation levels have fallen significantly over the past century (from 4.6 to 4.0) and will continue to fall as atmospheric CO₂ rises⁹². Although field confirmation is in its early stages there is growing evidence of sub-lethal changes on tropical reefs that are consistent with predicted responses to acidification (see below). It is therefore probable that most sub-tropical reefs are already in sub-optimal conditions, although more research is needed to verify this. When atmospheric CO₂ reaches 560ppm, most ocean surface waters will be adversely undersaturated with respect to aragonite and the pH will have reduced by about 0.24 units – from almost 8.2 today to just over 7.9. At this point (sometime in the third quarter of this century at current rates of increase) only a few parts of the Pacific will have levels of aragonite saturation adequate for uninhibited coral growth⁹³ and all will be stressed by climate-related synergies (see below). If CO₂ levels are allowed to reach 800ppm, the pH decrease will be 0.4 units^{94,95,96} and total dissolved carbonate ion concentration will have decreased by at least 60%. At this point it is almost certain that all reefs of the world will be in erosional states⁹⁷. Impacts will be further exacerbated in coastal areas from atmospheric pollutants forming nitric and sulphuric acids⁹⁸.

The levels of CO₂ and pH predicted around the end of this century may not have occurred since the Middle Eocene⁹⁹ (45 million years ago). However, the all-important rate of change we are currently experiencing may have no precedent over any time scale¹⁰⁰.

Impacts on reef biota

Although much is known about the chemistry of ocean acidification described above, its effects on biota are likely to be complex¹⁰¹. The vulnerability of different taxa to acidification depends on the form of carbonate that they secrete. Coralline algae, which are essential for cementing coral rubble into solid reef and form a critical habitat for the early life history stages of many organisms including corals, secrete high magnesium calcite and are therefore particularly vulnerable to acidification^{102,103}. Coral skeletons are formed of aragonite and most molluscs have shells of calcite.

There is a roughly direct relationship between aragonite saturation and the capacity of corals to calcify when temperatures are near optimum levels^{104,105,106}. This can be studied experimentally¹⁰⁷ although most effects on reefs will be ecological responses to decreased growth rates and skeletal strength. A decrease in coral growth rate of 14% has already been observed on corals of the Great Barrier Reef, as a likely response to acidification, in combination with elevated temperature stress^{108,109}.

When CO₂ levels reach approximately 450ppm, calcification of coralline algae will probably be completely inhibited^{110,111} while calcification of reef-building corals will be reduced by up to 50%^{112,113} even without consideration of further harmful synergies. Branching corals, especially shallow-water *Acropora* which are primary habitat builders, will become brittle and more easily damaged leading to extensive habitat deterioration. Overall reef building processes will be severely diminished or will cease altogether^{114,115,116,117} because as much as 90% of carbonates involved in reef building are removed by erosion, even under ideal building conditions¹¹⁸. Average decreases in calcification of more than about 10 to 20% are expected to put most if not all coral reefs into a net negative carbonate budget (i.e. reef structures and frameworks are no longer maintained)¹¹⁹. At 800ppm, all calcification including that of calcite-secreting molluscs, will cease or be greatly reduced.

Changes in ocean acidification are also likely to have impacts on a range of biological processes in addition to calcification, including impacts on photosynthesis, oxygen exchange and reproduction (see below). Understanding of these changes and their consequences is in its infancy, but most research indicates that relatively subtle changes in dissolved carbon dioxide and pH can potentially have large-scale impacts¹²⁰.

Critical issues

Three issues of particular importance to the future of coral reefs are highlighted in this document: (1) the role of synergies, (2) the nature of resilience and (3) the importance of domino effects.

1. Synergies

Reef deterioration may occur as a direct response to an individual stressor such as mass bleaching, but it more commonly occurs in response to synergies of different stressors acting simultaneously and in different combinations^{121,122}. Rising sea-levels, increasing numbers of high intensity storms, deterioration in water quality and various biotic influences are the principal stressors that will exacerbate the effects of mass bleaching

and ocean acidification. It has been shown, for example, that corals bleach at lower temperatures in acidified water¹²³. Although studies of these complex synergies are at a very early stage it is clear that synergies substantially hasten the deterioration of reefs.

Sea-level changes The great sea-level variations that have taken place in geological time have been due to slow changes (millions of years) in the shape of ocean basins, not to the much more rapid (millennia-long) changes of ice volume that have caused sea-level variations during the Pleistocene. However, in both cases, coral communities have successfully re-located; something which they are clearly able to do. Anticipated rates of sea-level change this century ($\geq 1\text{mm/yr}$)^{124,125,126} are greater than rates of reef growth ($\sim 0.6\text{mm/yr}$)^{127,128} but are probably no greater than the rate of sea-level rise at the end of the last glaciation^{129,130}. In the short term and acting in isolation from other stressors, sea-level change will alter the composition and zonation of shallow coral communities, but is unlikely to have serious ecological impacts. However, in today's context it will probably have a material impact in synergy with other stressors, especially ocean acidification and high-impact weather events, driving shallow reef communities towards an erosional state. This effect of sea-level rise is not likely to be significant for reefs until mid-century but will be preceded by deterioration of living conditions on human-occupied atolls.

Storm impacts Predicted increases in high-energy storms created by increases in ocean surface temperature^{131,132} may already be affecting reefs in some geographic regions including the Great Barrier Reef¹³³. The damage from such storms will be exacerbated by weakening of the reef structure resulting from increasing acidification. Increases in rainfall from changed weather events can also be damaging to reefs as demonstrated by very destructive rainfall on the Great Barrier Reef in 2009¹³⁴. In some geographic regions, changes in the seasonal pattern of rainfall poses a risk to annual reproductive cycles of corals as surface-born coral larvae are intolerant of low salinity.

Fisheries impacts Over-fishing affects almost all reefs, to varying degrees while destructive fishing practises, notably blast fishing, is more geographically confined, but its effects can be intense. The close connection between healthy fish communities and wider reef health has long been known^{135,136}, although more recent studies have greatly enhanced our understanding of this relationship. The removal of top predators, especially sharks, reduces overall species diversity and alters the trophic structure, leading to loss of biomass and the demise of other critical tropic groups including many larger herbivores^{137,138,139}. This, and the widespread direct removal of herbivorous fish, allows macro-algae to overgrow corals and to prevent resettlement of new corals in damaged reefs^{140,141}. Destructive fishing destroys the very structure of the reef as well as living communities and often leaves loose rubble which can take many years to recover^{142,143}. Overall, where fishing impacts can be minimised the diverse and productive ecosystems which result appear to be more resilient and recover more rapidly from bleaching or other perturbations¹⁴⁴.

Water quality Water quality that is good for particular coral reefs or coral communities is assumed to have tolerable levels of sediments, nutrients and environmental contaminants. The term is therefore used in the context of the health of reefs and possible degradations of that health by human activities. Terrestrial runoff from urban development, agriculture and deforestation is the principal cause of diminished water

quality¹⁴⁵. Runoff impacts have become such a worldwide phenomenon, that only reefs well removed from highly populated land masses have escaped degradation of some sort. This is now the subject of considerable research and mitigation expenditure on the Great Barrier Reef^{146,147} as it offers one of the few management options that will enhance reef resilience prior to critical threshold levels being reached due to climate change.

Biotic responses Mass bleaching has enormous, wide ranging repercussions for reef biodiversity because corals create the three-dimensional habitat that provides refuge for most reef fauna. Coral communities destroyed by bleaching can be quickly reduced to beds of debris which have little of the biodiversity of healthy reefs. These can recover if the frequency of bleaching events and resilience allow. However, they will go into a state of ecological collapse if conditions for recovery are inadequate. When this happens, the substrate usually becomes covered with blue-green cyanobacterial slime, a covering which is ecologically stable. In such cases, only some macro-algae, notably *Halimeda*, can form any sort of three dimensional re-growth¹⁴⁸ supporting only a tiny fraction of the former reef diversity. There are now many examples of these degraded reefs; banks of coral debris remaining as the solitary reminders of once flourishing coral communities.

There are many other biotic stressors that are impacting coral communities now, or are likely to do so in the near future. These include disease, and reductions in the growth and fecundity of corals, both of which act in synergy with the main drivers of climate change.

2. Resilience

Resilience – the capacity of a reef to recover from major damage – is primarily determined by the frequency, intensity and nature of stressors, the extent and nature of the damage, and the ‘health’ of the reef and its environment.

Since their first occurrences in the late 1970s, most mass bleaching events in the Indo-Pacific have been linked to El Niño cycles which occur at intervals of 4-7 years. The intensity of events has varied, but at these frequencies most reefs have made at least partial recovery^{149,150}. In future, mass bleaching events will become more frequent as they de-couple from El Niño cycles, and more severe as ocean temperatures rise. They are currently on track to becoming annual events, with lethal temperature thresholds being reached most summers¹⁵¹. As the frequency and intensity of bleaching events rise, the extent and number of reefs involved will also rise, involving ever-increasing numbers of species over increasing depth-ranges. As this damage becomes more extensive, the capacity of corals to regrow from fragments or from immigration of larvae will inevitably decline.

A degraded environment, whether natural or human-induced, has a strong influence on reef resilience. Thus, over-fishing and water quality degradation (through sedimentation and nutrient pollution, as commonly occurs throughout the Caribbean, south-east Asia and the Indian Ocean perimeter) reduce the resilience of reefs to bleaching¹⁵². These chronically stressed reefs are now at high risk of reverting to semi-permanent algal or cyanobacterial communities¹⁵³. In contrast, reefs remote from

additional human stresses can make rapid recoveries^{154,155,156}, returning to their former diversity in as little as a decade¹⁵⁷.

There is substantial geographic variation in temperature thresholds for bleaching. During the time of early mass bleaching events, the occurrence of unbleached corals in areas of naturally high temperatures (notably the southern Red Sea and Persian/Arabian Gulf) suggested a substantial degree of natural tolerance. However, most of these areas have more recently been damaged to some extent¹⁵⁸. In short, the temperature at which bleaching occurs varies geographically, but the incidence of bleaching is almost universal.

Genetic diversity among corals and zooxanthellae can potentially enable adaptation, and thereby enhance resilience. Where there has been sufficient time and suitable conditions, many reefs that have been impacted by bleaching have recovered or are in the process of recovery^{159,160,161,162}. This can involve an increase in the temperature tolerance of individual colonies by a shift to relatively heat-tolerant clades of zooxanthellae in surviving colonies^{163,164,165}. Such modification of symbioses is important^{166,167}, but it is exceptionally unlikely to offer any long-term solution to mass bleaching because of a mismatch in time scales. The time scale of current impacts is in years to decades whereas that of evolutionary adaptation is in millennia at least.

3. Domino effects

Coral reefs occupy a truly unique position on Earth, for they are geological structures made by combinations of living organisms that have evolved the capacity to harness the abundant resources of air, seawater and sunlight. Reefs grow on solid substrates, but only at the interface of sea and atmosphere and only where light and temperature permit. To do this, reef-building organisms have evolved complex ecologies with tight interdependencies between key species, all dominated by many types of symbiotic relationships between plants and animals.

Reefs are particularly vulnerable to environmental changes, especially disruptions to the pathways of the carbon cycle on which they are totally dependent. Unlike any other major ecosystem, such disruptions can be of both marine and terrestrial origin. It is therefore hardly surprising that reefs have been especially impacted by all the great mass extinction events^{168,169}.

The outlook for reefs in the face of today's rapid climate change is exceptionally serious. The mounting evidence warning of the imminent demise of reefs is perhaps the strongest signal yet that the planet is on the brink of an environmentally-led mass extinction, for this appears to have been what happened in the remote past¹⁷⁰. Whether or not this is so, reefs are likely to be the first major planetary-scale ecosystem to collapse in the face of climate changes now in progress. This raises the question: will this collapse be restricted to reefs or does it have wider implications? It is already clear that, although mass bleaching is a reef phenomenon, the effects of ocean acidification^{171,172} will directly impact all carbonate-dependent taxa: not only corals, but calcareous algae, most molluscs, many crustaceans, echinoderms and planktonic taxa, and other groups that rely on carbonates for skeletal growth^{173,174}. This includes fish¹⁷⁵ which are particularly vulnerable during early stages in their life-cycle^{176,177} and also the

pelagic ecosystem of the Southern Ocean¹⁷⁸ which is dependent on krill. Research on these issues is still in its infancy, but the enormity of the threat is nevertheless real.

As far as the immediate future is concerned, the failure of reefs will have flow-on effects to other reef-associated ecosystems¹⁷⁹. These impacts have been reviewed for the Great Barrier Reef^{180,181,182,183} and associated island biota¹⁸⁴, seagrass beds^{185, 186}, mangroves¹⁸⁷, marine reptiles¹⁸⁸, marine mammals¹⁸⁹, seabirds¹⁹⁰, pelagic ecosystems¹⁹¹ and estuarine habitats¹⁹².

Remedial options

The speed at which climate change is impacting reef ecosystems leaves little or no opportunity for evolutionary processes to come to the aid of corals and other reef inhabitants as they would have done over geological intervals of time. Survival will be highly dependent upon any natural resistance already existing in the gene pools today. While we can hope that this is greater than existing studies would suggest, there is little or no evidential basis for this. Some management interventions will, for a time, increase reef resilience, the most important of which are (a) reducing the harvest of herbivorous fish to sustainable levels (coral reefs with healthy grazing communities recover three times as fast from bleaching events compared with those with depleted communities¹⁹³), (b) maintaining an effective trophic pyramid by protecting sharks and other top predators, (c) managing all aspects of water quality and (d) minimising any other impacts and stressors. Such actions can be supported through the use of large networks of marine protected areas and other direct management interventions such as improved control of watershed-based activities whose effects on water quality are often severe. Most of these management activities are already in place for the Great Barrier Reef Marine Park¹⁹⁴ and must be a priority for all reef regions. A wide array of other actions has also been recommended by a reef management workshop¹⁹⁵.

Nevertheless, these actions cannot offer long-term protection from the consequences of increasing atmospheric CO₂ levels as they pass critical thresholds.

Efforts at emissions reductions have thus far been limited in magnitude and weak in implementation, and it is critical that this situation is reversed to enable rapid and dramatic cuts¹⁹⁶. However, cumulative carbon emissions to date have already committed atmospheric CO₂ to remaining above 330 ppm for at least the next millennium^B. Thus, it appears inevitable that maintaining, enhancing and possibly creating carbon sinks and other mitigation options will be required as a complement to necessary emissions cuts. If so, it will be critical to consider all possible benefits and limitations and employ great

^B Over 350 PgC have been emitted from fossil fuel burning and 165 PgC from land use change to date, equivalent to nearly 250ppm. The airborne fraction of added CO₂ remains around 20% on the millennial timescale, i.e. 50ppm of the already added CO₂ will be with us for over a thousand years. Adding this to the preindustrial level of 280ppm gives 330ppm.

caution, before allowing planetary scale mitigations schemes of this nature to proceed. Some climate engineering options, such as reducing the amount of solar radiation absorbed by the earth, will have no effect on ocean acidification¹⁹⁷, and some large scale mitigation options such as ocean fertilization still have to be proven effective^{198,199}.

As custodians of geological history, reefs offer both immense geological evidence and stark recent testimony to the potentially catastrophic effects of destabilising global climates. Although, being carbonate platforms, they are particularly sensitive to disruptions of the carbon cycle, their demise is symptomatic of damage to the entire biosphere as this cycle plays a dominant part in all ecosystems. When taken together, the abruptly accelerating deterioration of terrestrial and marine ecosystems and the increasingly disturbing global extinction rates may eventually become indistinguishable from the records of mass extinctions captured in the remains of long-fossilised coral reefs. The difference is that this time humanity will have been the cause and also one of species to suffer.

The extreme gravity of the current predicament is now widely acknowledged by reef and climate scientists. It is also acknowledged that only drastic action starting now will prevent wholesale destruction of reefs and other similarly affected ecosystems. Should humanity not be successful in preventing these threats from becoming reality, no amount of management or expenditure will save future generations from the consequences of our failed guardianship.

Summary of CO₂ impact levels

Links between CO₂ levels and the response of reefs after a decade of lag-time are as follows. Contributions of non-CO₂ greenhouse gases are assumed to be constant. However, the precise *rate* of CO₂ increase has little relevance because most biota (in any ecosystem) adapts to environmental changes over time intervals of centuries to millennia, not decades.

At 320ppm Occasional mass bleaching occurs. Return-times of successive bleaching events would allow most coral communities to exist indefinitely.

At 345ppm Sporadic but highly destructive mass bleaching occurs in most reefs world-wide. Recovery is dependent both on the geographic vulnerability of individual reef areas, and on the reef's previous history and resilience.

At today's level of 387ppm Factoring in the lag-time of 10 years from today, most reefs world-wide will be in obvious and irreversible decline. Mass bleaching events will probably no longer be dependent on the 4-7 year return-time of El Niño cycles, exposing reefs to more frequent and eventually annual mass bleaching. Synergistic impacts include degraded water-quality, the effects of increased severe weather events, reduction of coral growth and retardation of the growth of high magnesium calcite-secreting coralline algae.

At 450ppm (by 2030-2040 assuming emissions continue to rise at current rates) Reefs will be in rapid and terminal decline world-wide from both temperature-induced bleaching²⁰⁰ and ocean acidification. Additional synergistic effects may occur from sea-

level increase and total loss of reef-building capacity. Damage to shallow reef communities will become extensive with consequent reduction of biodiversity followed by extinctions. Reefs will cease to be large-scale nursery grounds for fish and will cease to have most of their current value to humanity. There will be flow-on effects to ecosystems associated with reefs and impacts on other pelagic and benthic ecosystems.

At 600ppm (by the 2050s in the worst case scenarios) Reefs will have little in common with their counterparts today. Additional synergistic effects will include declining aragonite saturation with consequent effects on corals and reef habitats. Extinctions will be widespread due to both ocean acidification and habitat loss. Reefs will be eroding geological structures with populations of surviving biota restricted to refuges.

Conclusion

Coral reefs speak unambiguously about climate change. Abrupt carbonising of the environment will destroy carbonate-based ecosystems. Changes to water chemistry will flow on to all marine ecosystems as the oceans turn hostile to a high proportion of marine life. This is the path of mass extinctions, the most destructive events in all Earth history.

The Earth's atmospheric CO₂ level *must* be returned to <350ppm to reverse this escalating ecological crisis and to 320ppm to ensure permanent planetary health. Actions to achieve this *must* be taken *urgently*. The commonly mooted best-case target of 450ppm and a time-frame reaching to 2050 will plunge the Earth into an environmental state that has not occurred in millions of years and from which there will be no recovery for coral reefs and for many other natural systems on which humanity depends.

Working group signatories Prof. John Veron* (Coral Reef Research), Dr Mary Stafford-Smith (Coral Reef Research), Prof. Ove Hoegh-Guldberg (University of Queensland), Dr David Obura (IUCN SSC Coral Specialist Group and CORDIO), Paul Pearce-Kelly (Zoological Society of London and IUCN Invertebrate Conservation Committee), Dr Mark Spalding (The Nature Conservancy), Prof. Charles Sheppard (University of Warwick), Prof. Tim Lenton (University of East Anglia), Sir David Attenborough FRS (working group co-chair), Prof. Ken Caldeira (Carnegie Institution for Science), Dr Ann Clarke (Frozen Ark Project), Prof. James Crabbe (University of Bedfordshire), Prof. Andreas Fischlin (Swiss Federal Institute of Technology, in his own capacity), Dr Simon Harding (Zoological Society of London), Rachel Jones (Zoological Society of London), Dr Dirk Peterson (SECOR), Dr Peter Read (Pacific Marine Environmental Laboratory), Prof Philip C. Reid (Sir Alister Hardy Foundation for Ocean Science/Marine Institute, University of Plymouth), Prof. Callum Roberts (University of York), Dr Kristian Teleki (International Coral Reef Action Network), John Taylor (World Wildlife Fund), Dr John Turner (Bangor University), Dr Dr Alex Rogers* (International Programme on the State of the Ocean).

* Corresponding authors.

Website link to Prof. Veron's presentation "Is the Great Barrier Reef on Death Row?" with introduction by the Royal Society and Sir David Attenborough:
<http://royalsociety.org/page.asp?id=3093>

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