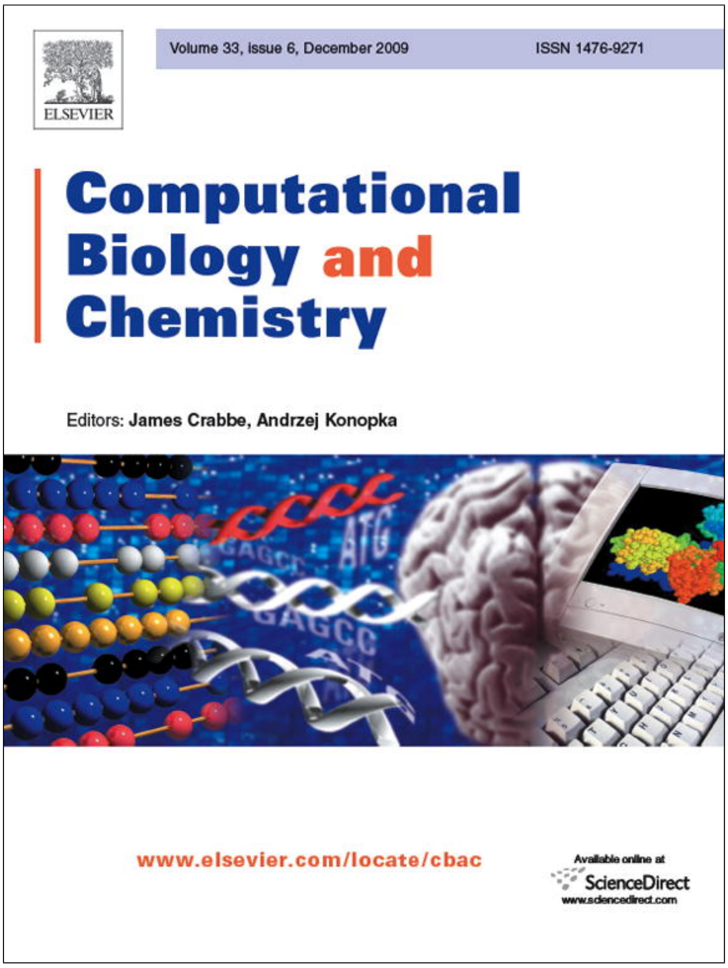

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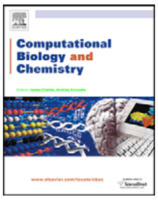

Review article

Modelling effects of geoengineering options in response to climate change and global warming: Implications for coral reefs

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ABSTRACT

Climate change will have serious effects on the planet and on its ecosystems. Currently, mitigation efforts are proving ineffectual in reducing anthropogenic CO_2 emissions. Coral reefs are the most sensitive ecosystems on the planet to climate change, and here we review modelling a number of geoengineering options, and their potential influence on coral reefs. There are two categories of geoengineering, shortwave solar radiation management and longwave carbon dioxide removal. The first set of techniques only reduce some, but not all, effects of climate change, while possibly creating other problems. They also do not affect CO_2 levels and therefore fail to address the wider effects of rising CO_2, including ocean acidification, important for coral reefs. Solar radiation is important to coral growth and survival, and solar radiation management is not in general appropriate for this ecosystem. Longwave carbon dioxide removal techniques address the root cause of climate change, rising CO_2 concentrations, they have relatively low uncertainties and risks. They are worthy of further research and potential implementation, particularly carbon capture and storage, biochar, and afforestation methods, alongside increased mitigation of atmospheric CO_2 concentrations.

Contents

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1. Introduction

Climate change will have serious effects on the planet and on its ecosystems. The impacts of climate change and global warming may be modified by mitigation, and where that is not enough by geoengineering. Mitigation is the reduction of anthropogenic emissions of greenhouse gasses, particularly of CO_2. Geoengineering may be defined as engineering of the planetary environment to mediate the effects of elevated greenhouse gases, particularly of CO_2. Currently, mitigation efforts are proving ineffectual in reducing anthropogenic CO_2 emissions post-2000 (Canadell et al., 2007), and it is timely to consider the possibility of geoengineering options (Crutzen, 2006; Boyd, 2008). Fundamental criteria for evaluating geoengineering options are their cooling effectiveness, and their impact on planet ecosystems. Here we discuss the potential influence of current geoengineering options on one of the most critical and sensitive ecosystems on the planet, coral reefs.

1.1. Coral reefs and climate change

Correlations between rising carbon dioxide levels, rising ocean temperature and the biological responses of reefs are well known, and provide a well-grounded basis for future prediction (Parry et al., 2007). The more recently recognised effects of atmospheric CO_2 on ocean acidification will have even more profoundly detrimental long-term effects on reefs, as well as on other organisms producing calcified skeletons, including calcite-secreting molluscs, crustose coralline algae and deep-water corals (Anthony et al., 2008).

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 (Reaka-Kudla, 1997) 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. 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 species (Mumby and Steneck, 2008; Crabbe, 2009a).

Carbon dioxide concentrations in the atmosphere are now increasing at a rate unprecedented for at least 44.9 million years (Zachos et al., 2005) and are at c. 387 ppm, a level not experienced on Earth for more than 20 million years (Richardson et al., 2009; Veron et al., 2009). However, other gases and aerosols contribute to global warming or counteract it (see e.g. Fig. 1), meaning that the overall warming we are now experiencing exceeds the forcing from current CO_2 levels (Richardson et al., 2009; Veron et al., 2009). Along with greenhouse gas emissions, many aspects of climate change, in particular relevant for corals, are at the upper bounds or are exceeding previous IPCC projections (Richardson et al., 2009). For example, ocean warming is up to 50% greater than that has been previously reported by IPCC (Richardson et al., 2009). The thermal limits for reef-forming corals have already been exceeded at which coral reefs are a stable feature of the Earth's tropical marine ecosystems. This means that coral reefs have entered a phase of degradation in which their future survival is in serious jeopardy. As the concentration of greenhouse gases continues to increase in the atmosphere additional climate change phenomena will continue to impact on coral reefs. In 2005–2006, corals at sites dominated by high-frequency variability in SSTs showed reduced bleaching, despite experiencing high thermal stress (Thompson and van Woesik, 2009). Such bleaching resistance was probably a consequence of rapid directional selection following the extreme thermal event of 1998, and may come at considerable cost of large changes in coral species composition on reefs worldwide (Loya et al., 2001).

1.1.1. Modelling simulations and predictions for coral reefs

Modelling is based on WGI (Working Group I) of the Inter-Governmental Panel on Climate Change (IPCC) simulations and multi-model mean responses to (i) the A2 radiative forcing scenario (lowest per capita growth, population continuously increasing, slow and fragmented development of technology) and (ii) an extended B1 scenario (fast per capita growth, population peaking in 2050, then declining, clean and resource-efficient technology), where radiative forcing beyond 2100 was kept constant at the 2100 value. Climate models can be found at: http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Print_Ch08.pdf.

The latest IPCC report (Parry et al., 2007) identified coral reefs as the most vulnerable ecosystems (along with sea-ice biomes), with mangroves very vulnerable. Seagrass beds, intimately linked with coral reefs and mangroves, are also under serious threst (Waycott et al., 2009). A rise of 1–2 °C will cause most corals to be bleached; a rise of 2 °C or over will cause widespread coral mortality. Annual bleaching of corals is predicted from 2030 to 2050,

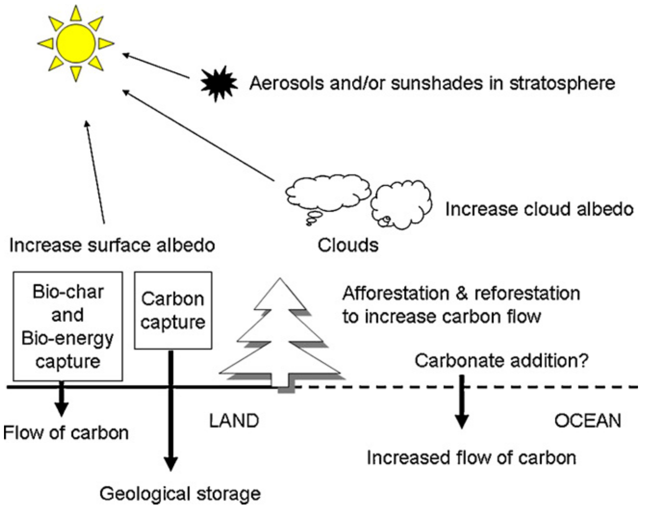

Fig. 1. Schematic overview of the climate geoengineering proposals considered. Modified from Lenton and Vaughan (2009).

from the Great Barrier Reef (GBR) to the Caribbean. Surface ocean pH will decrease by 0.5 pH unit by 2100. Salt marshes and mangroves will be negatively impacted by sea level rises—global losses of 33% given a 36 cm rise in sea level from 2000 to 2080. Corals could become rare on tropical and sub-tropical reefs by 2050 due to the combined effects of increasing dissolved carbon dioxide (CO_2) and increasing frequency of bleaching events. Since the impacts of increased CO_2 are greater at higher latitudes, cold-water corals are likely to show large reductions in geographical range this century.

About half of the extra CO_2 from the atmosphere will dissolve in the oceans making the water more acidic. The effects of making the ocean more acid are inevitable, and are easy to predict, as they rely on simple chemistry, not on complex computer models of climate. The ocean already holds 400 billion tons of fossil fuel CO_2. Consequently, the ocean is already 0.1 pH units more acidic than before industrial CO_2 emissions (Caldeira and Wickett, 2003).

1.2. Geoengineering as a complement to mitigation of carbon dioxide emissions

At today's level of c. 387 ppm CO_2 (Richardson et al., 2009), reefs are seriously declining and time-lagged effects will result in their continued demise with parallel impacts on other marine and coastal ecosystems. International proposals to limit CO_2 levels to 450 ppm (Richardson et al., 2009; Veron et al., 2009) will not prevent the catastrophic loss of coral reefs from the combined effects of climate change and ocean acidification (Parry et al., 2007; Veron et al., 2009). To ensure the long-term viability of coral reefs the atmospheric CO_2 level must be reduced significantly below 350 ppm. In addition to the major reductions in CO_2 emissions, achieving this safe level will require the active removal of CO_2 from the atmosphere.

National targets give virtually no chance of constraining warming to 2 °C and no chance on their own of protecting coral reefs (Silverman et al., 2009; Rogelj et al., 2009). Active removal is one of the geoengineering options to restore the planet's current – and indeed future – radiative imbalance.

1.3. Shortwave and longwave radiation

In simple terms, the temperature of the Earth at its surface results from the net balance of incoming solar shortwave radiation and outgoing terrestrial longwave radiation (Kiehl and Trenberth, 1997). Shortwave radiation from the sun penetrates through space to the outer edge of the atmosphere unimpeded by the vacuum of outer space. About 30% of the available solar radiation at the top of the atmosphere is reflected or scattered back to space by particulates and clouds before it reaches the ground. The gases of the atmosphere are relatively poor absorbers of solar radiation, absorbing only about 20% of what is available at the outer edge of the atmosphere.

A portion of the incoming solar radiation is absorbed by the surface and a portion is also reflected away. The proportion of light reflected from a surface is the albedo. Albedo values range from 0 for no reflection to 1 for complete reflection of light striking the surface (grass has an albedo of c. 0.23; snow has an albedo upwards of 0.87).

The energy absorbed at the surface is radiated by the Earth as terrestrial longwave radiation. The amount of energy emitted is primarily dependent on the temperature of the surface; the hotter the surface the more radiant energy it will emit. The gases of the atmosphere are relatively good absorbers of longwave radiation and thus absorb the energy emitted by the Earth's surface.

2. Shortwave solar radiation techniques

2.1. Shading the sun

To offset the doubled pre-industrial atmospheric concentration of CO_2, a decrease of incoming solar radiation of c. 1.8% is assumed (Govindasamy and Caldeira, 2000). In order to achieve this, a sunshade at an appropriate point in the atmosphere would need to be 4.7 million km^2 (Angel, 2006). However, to keep pace with increasing emissions, that surface area would need to increase year on year (Lenton and Vaughan, 2009).

Within the limits for coral reef growth, photosynthesis tends to increase with irradiance. However, some studies suggest that photosynthesis is also more efficient under diffuse light conditions (Mercado et al., 2009). Changes in cloud cover or atmospheric aerosol loadings alter both the total Photosynthetic Active Radiation (PAR) reaching the surface and the fraction of this radiation that is diffuse. This impacts both plants (Luo et al., 2009) and corals (Crabbe and Smith, 2005). While from 1960 to 1999 (the 'global dimming period') variations in the diffuse fraction enhanced the land carbon sink by c. 25%, climate mitigation, where sulphate aerosols decline before atmospheric CO_2 is stabilised, the 'diffuse radiation' fertilisation effect has been modelled to decrease to zero by the end of the 21st century (Mercado et al., 2009).

However, sunshading schemes might lead to a slow-down in the global hydrological cycle (Bala et al., 2008; Bala, 2009), and cause variable effects in different parts of the planet (Govindasamy et al., 2003), while not addressing ocean acidification or the terrestrial carbon cycle.

2.2. Aerosols

Simulations of the aftermath of Mt. Pinatubo eruptions have been used to model aerosols in the stratosphere limiting radiative forcing (Hansen et al., 2005). The residence time and spread of aerosol particles vary with the site of injection, and global coverage is maximised when injections are into the lower stratosphere over the tropics (Crutzen, 2006; Robock et al., 2008).

Because of the millennial persistence of the fossil fuel CO_2 in the atmosphere, high levels of stratospheric aerosol loading would have to continue for thousands of years until CO_2 was removed from the atmosphere (Brovkin et al., 2009).

2.3. Increasing cloud albedo

There are two ways to increase cloud albedo, mechanically by the generation of sea salt spray as a source of cloud condensation nuclei (CCN) (Latham, 1990), and biologically by increasing CCN from dimethyl sulphide emissions from iron fertilisation in the ocean (Wingenter et al., 2007). Both methods are by their nature regional and patchy in their effectiveness, although they have the potential for significant shortwave reflections (Lenton and Vaughan, 2009).

2.4. Increasing terrestrial albedo

Methods have been suggested for increasing desert (Gaskill, 2004), grassland (Hamway, 2007), cropland (Woodward et al., 2009; Ridgwell et al., 2009) and urban (Akbari et al., 2009) albedo.

While all these processes would be biased towards their terrestrial location, arid area geoengineering is probably the most feasible (Lenton and Vaughan, 2009). Heat Reflecting Sheets are effective on arid areas, and combine anti-desertification measures with comparatively minimal costs involved, as well as relatively quick realisation and positive results (Toyama and Stainer, 2009). A feasibility study based on this notion would provide a warning and a back-up move against radical actions that might be detrimental for the future of planet Earth and its sustainability.

A 1000-acre plant in the Mojave desert, CA, USA, has 55,000 mirrors to increase albedo and generate power for 112,500 homes in Southern California (2009: http://www.bloomberg.com/apps/news?pid=20601109&refer=home&sid=a_TUtlIwV7Fw).

3. Longwave CO_2 removal techniques

3.1. Afforestation and reforestation

Afforestation is establishing a forest on land that is not a forest, or has not been a forest for a long time by planting trees or their seeds. Reforestation refers to the re-establishment of the forest after its removal, or planting more trees for example from a timber harvest. Since the industrial revolution many countries have experienced centuries of deforestation, and some governments and non-governmental organisations directly engage in programs of *afforestation* to restore forests and assist in the preservation of biodiversity. In some places, forests need help to re-establish themselves because of environmental factors. For example, once forest cover is destroyed in arid zones, the land quickly dries out and becomes inhospitable to new tree growth. Other critical factors include overgrazing by livestock, especially animals such as goats, and over-harvesting of forest resources. Together these may lead to desertification and the loss of topsoil; without soil, forests cannot grow until the very long process of soil creation has been completed—if erosion allows this. In some tropical areas, forest cover removal may result in a duricrust or duripan that effectively seal off the soil to water penetration and root growth. In many areas, reforestation is impossible because people are using the land. In other areas, mechanical breaking up of duripans or duricrusts is necessary, careful and continued watering may be essential, and special protection, such as fencing, may be needed.

Forests currently absorb billions of tons of CO_2 globally every year, an economic subsidy worth hundreds of billions of dollars if an equivalent sink had to be created in other ways. Concerns about the permanency of forest carbon stocks, difficulties in quantifying stock changes, and the threat of environmental and socioeconomic impacts of large-scale reforestation programs have limited the uptake of forestry activities in climate policies. With political will and the involvement of tropical regions, forests can contribute to climate change protection through carbon sequestration as well as offering economic, environmental, and sociocultural benefits. A key opportunity in tropical regions is the reduction of carbon emissions from deforestation and degradation (Canadell and Raupach, 2008).

3.2. Biochar production

Biochar is charcoal created by pyrolysis of biomass. The resulting charcoal-like material is a form of carbon capture and storage. Charcoal is a stable solid and rich in carbon content, and thus, can be used to lock carbon in the soil (Lehmann et al., 2006; Winsley, 2007). Since biochar can sequester carbon in the soil for hundreds to thousands of years, it has received considerable interest as a potential tool to slow global warming. The burning and natural decomposition of trees and agricultural matter contribute a large amount of CO_2 released to the atmosphere. Biochar can store this carbon in the ground, potentially making a significant reduction in atmospheric greenhouse gas levels; at the same time its presence in the Earth can improve water quality, increase soil fertility, raise agricultural productivity and reduce pressure on old growth forests.

Application of charcoal to soils is hypothesized to increase bioavailable water, build soil organic matter, enhance nutrient cycling, lower bulk density, act as a liming agent, and reduce leaching of pesticides and nutrients to surface and ground water. The half-life of carbon in soil charcoal is in excess of 1000 years. Hence, soil-applied charcoal will make both a lasting contribution to soil quality and carbon in the charcoal will be removed from the atmosphere and sequestered for millennia (Laird, 2008).

3.3. Air capture and storage

Carbon capture and storage technology has three individual steps:

(1) Capture or removal of CO_2 from fossil fuel combustion or biofuel combustion at industrial processes, especially electrical power stations.
(2) Transportation of the carbon dioxide from the point of capture to a storage site.
(3) Injection of the CO_2 underground into deep geological formations for long-term (>10,000 years) storage.

Carbon capture and storage is the only direct CO_2 reduction method. The capture step is the most expensive, and least developed technologically (Bushby et al., 2008).

Injecting CO_2 into deep geological strata has been proposed as a safe and economically favourable means of storing CO_2 captured from industrial point sources (Gilfillan et al., 2009). Geological mineral fixation appears to be a minor trapping mechanism in natural gas fields, so that long-term anthropogenic CO_2 storage models in similar systems should focus on the potential mobility of CO_2 dissolved in water (Gilfillan et al., 2009). A large CO_2 well in the North Sea would be the Utsira formation linked to the Sleipner gas field (Kongsjorden et al., 1998; see also: http://www.bellona.org/filearchive/fil_Factsheet_Security_of_CO2_storage_in_Norway_-_english_-_rev_16aug07.pdf). However a key unknown in aquifer storage worldwide is storage volume (Van der Meer and Egberts, 2008).

3.4. Additions to oceans

The oceans are now a net sink of atmospheric CO_2 whereas in the pre-industrial era they were a source, and the trophic state of the coastal oceans is progressively moving towards increased heterotrophy from an earlier autotrophic state (Mackenzie et al., 2002; Lerman et al., 2007).

Iron fertilisation of macronutrient-rich but biologically unproductive ocean waters has been proposed for sequestering anthropogenic CO_2 (Buesseler et al., 2004; Zeebe and Archer, 2005). The first carbon export measurements in the Southern Ocean—Iron Experiment (SOFeX) yielded c. 900 tons carbon exported per 1.26 tons Fe added. Carbon cycle modelling suggested that if 20% of the world's surface ocean were fertilised 15 times per year until 2100, that would reduce atmospheric CO_2 by $\leq$15 ppmv at an expected level of c. 700 ppmv for business-as-usual scenarios. Thus based on these results, large-scale oceanic iron fertilisation appears not to be a feasible strategy to sequester anthropogenic CO_2 (Zeebe and Archer, 2005). In addition, side effects might include a long-term reduction in ocean productivity worldwide, alteration in marine food webs, a more rapid increase in ocean acidity, and potentially increased production of the third most important long-lived greenhouse gas N_2O, from the increased downward export of organic carbon particles (Saito et al., 2006; Denman, 2008; Lampitt et al., 2008).

It might be possible to enhance the absorption of CO_2 from the atmosphere by adding calcium carbonate ($CaCO_3$) powder to the ocean and of partially reversing the acidification of the ocean and the decrease in calcite supersaturation resulting from the absorption of anthropogenic CO_2.

Table 1
Relative effectiveness of different geoengineering options. Effects are calculated relative to a mitigation scenario where atmospheric CO_2 reaches 450 ppm. ΔCO_2 represents radiative forcing potential (from Lenton and Vaughan, 2009). Relative safety values are modified from (Royal Society, 2009) where 1 = high safety, 2 = medium safety and 3 = low safety.

Option	ΔCO_2	Relative safety
Afforestation	−41	1
Biochar	−10	2
Air capture and storage	−58	1
Iron fertilisation	−9.0	3
Carbonate addition	−0.4	3
Phosphorus addition	−5.9	3
Nitrogen fertilisation	−4.5	3
Enhance upwelling	−0.1	2
Enhance downwelling	−0.08	2

$CaCO_3$ could be added to the surface layer in regions where the depth of the boundary between supersaturated and unsaturated water is relatively shallow (250–500 m) and where the upwelling velocity is large (30–300 m a^{-1}) (Kheshgi, 1995). The $CaCO_3$ would dissolve within a few 100 m depth below the saturation horizon, and the dissolution products would enter the mixed layer within a few years to decades, facilitating further absorption of CO_2 from the atmosphere. This absorption of CO_2 would largely offset the increase in mixed layer pH and carbonate supersaturation resulting from the upwelling of dissolved limestone powder. However, if done on a large scale, the reduction in atmospheric CO_2 due to absorption of CO_2 by the ocean would reduce the amount of CO_2 that needs to be absorbed by the mixed layer, thereby allowing a larger net increase in pH and in supersaturation in the regions receiving $CaCO_3$. The reduction in atmospheric pCO_2 would cause outgassing of CO_2 from ocean regions not subject to addition of $CaCO_3$, thereby increasing the pH and supersaturation in these regions as well. Geographically optimal application of 4 billion tons of $CaCO_3$ a^{-1} (0.48 Gt C a^{-1}) could induce absorption of atmospheric CO_2 at a rate of 600 Mt CO_2 a^{-1} after 50 years, 900 Mt CO_2 a^{-1} after 100 years, and 1050 Mt CO_2 a^{-1} after 200 years (Harvey, 2008).

3.5. *Ocean downwelling*

Downwelling ocean currents carry carbon into the deep ocean and play a role in controlling the level of atmospheric carbon. The formation of North Atlantic Deep Water also releases heat into the atmosphere, and contributes to the mild climate in Europe. Increasing carbon concentration in downwelling currents is not practicable owing to the high degree of saturation of high latitude surface water. Formation of thicker sea ice by pumping ocean water onto the surface of ice sheets is the least expensive of the methods to enhance downwelling currents and carbon (Zhou and Flynn, 2005), but it is unlikely to be a competitive method of carbon sequestration.

Rapid biological consumption and remineralisation of carbon in the zone between the euphotic zone and 1000 m reduce the efficiency of sequestration to a large and variable extent (Buesseler et al., 2007).

4. Summary

Shortwave solar radiation techniques act quickly, and so may represent the only way to lower global temperatures quickly in the event of a climate crisis. However, they only reduce some, but not all, effects of climate change, while possibly creating other problems (Royal Society, 2009). They also do not affect CO_2 levels and therefore fail to address the wider effects of rising CO_2, including ocean acidification, important for coral reefs. Solar radiation is important to coral growth and survival, and solar radiation management is not in general appropriate for this ecosystem. In addition, the effects of these techniques would cross international boundaries, and so present serious legal, ethical and governance problems.

The relative effectiveness of different longwave CO_2 removal geoengineering options is shown in Table 1. Effects are calculated relative to a mitigation scenario where atmospheric CO_2 reaches 450 ppm. As they address the root cause of climate change, rising CO_2 concentrations, they have relatively low uncertainties and risks. However, these techniques work slowly to reduce global temperatures. Nonetheless, they are worthy of further research and potential implementation, alongside increased mitigation of atmospheric CO_2 concentrations. In addition, ecosystem-based management (Bouma et al., 2008; Crabbe, 2009b, 2009c) 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.

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