1-1-2010

2010 Tropical Coral Reefs (Appendix 10)

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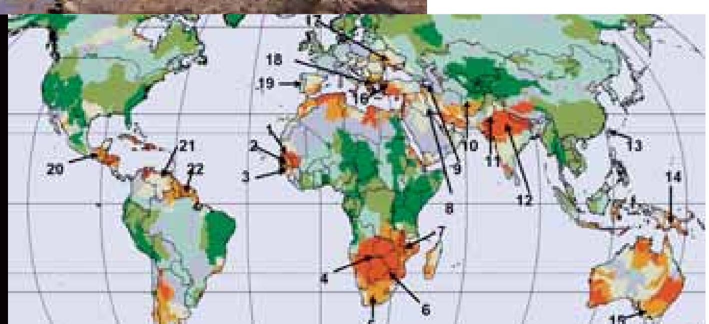
Secretariat of the Convention on Biological Diversity

CBD Technical Series No. 50

BIODIVERSITY SCENARIOS: PROJECTIONS OF 21st CENTURY CHANGE IN BIODIVERSITY AND ASSOCIATED ECOSYSTEM SERVICES

A Technical Report for the Global Biodiversity Outlook 3



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Published by the Secretariat of the
Convention on Biological Diversity.
ISBN 92-9225-219-4

Citation

Leadley, P., Pereira, H.M., Alkemade, R., Fernandez-Manjarrés, J.F., Proença, V., Scharlemann, J.P.W., Walpole, M.J. (2010) Biodiversity Scenarios: Projections of 21st century change in biodiversity and associated ecosystem services. Secretariat of the Convention on Biological Diversity, Montreal. Technical Series no. 50, 132 pages.

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DIVERSITAS (an international program of biodiversity science) and UNEP-WCMC coordinated this synthesis for the Secretariat of the Convention on Biological Diversity as a contribution to the third Global Biodiversity Outlook (GBO-3). Paul Leadley is the co-chair and Rob Alkemade and Miguel Araujo are members of the scientific steering committee of DIVERSITAS' bioDISCOVERY core project. Georgina Mace and Bob Scholes are vice-chairs and David Cooper a member of the scientific committee of DIVERSITAS.

The lead authors would like to thank Lucy Simpson for organising the workshop, Anna Chenery and Francine Kershaw for their assistance with getting permission to reproduce the figures, Simon Blyth and Gillian Warltier for assistance with proof reading, and Kieran Mooney for photo searches.

This study was funded by the Department of the Environment, Food and Rural Affairs of the United Kingdom with additional financial assistance from the European Commission and UNEP. The views expressed herein can in no way be taken to reflect the official opinion of the these bodies, or of the Convention on Biological Diversity.

CONTENTS

Appendix 10. TROPICAL CORAL REEFS

Joana Figueiredo (University of Lisbon, jcfigueiredo@fc.ul.pt)

SUMMARY

- Coral reef ecosystems are global biodiversity hotspots that depend on the massive calcium carbonate structures mainly deposited by scleractinian (i.e., "hard") corals. Scleractinian coral distribution is primarily limited by sea-surface temperature, light, depth, ocean pH, sea water salinity, nutrients and sediment loads. These ecosystems are currently threatened by localized stresses such as overfishing and destructive fishing practices, pollution, terrestrial nutrient and sediment run-off, but are increasing impacted by direct and indirect impacts of rising CO_2 concentrations and climate change.
- Coral reefs provide a broad range of ecosystems services with high socio-economic value: tourism, fisheries (food and employment), nutrient cycling, climate regulation, protection of the shoreline and other ecosystems (e.g. mangroves), and constitute the habitat for a wide range of species.
- Rising atmospheric CO_2 concentrations have already led to a slight acidification of ocean surface waters and are projected to lead to levels of acidification that will severely impede calcium carbonate accretion. Global warming associated with greenhouse gas emissions has resulted in increased sea-surface temperatures, leading to frequent coral bleaching. Acidification and the increased frequency of local and global disturbances are projected to seriously degrade coral reefs world-wide.
- If current trends continue coral reef ecosystems may undergo regime shifts from coral to sponge or algae dominated habitats. The tipping point for this phase shift is estimated to be a sea-surface temperature increase of 2°C and/or atmospheric CO_2 concentrations above 480 ppm (estimated to occur by 2050).
- Shifts in dominance from corals to sponges or algae would have dramatic consequences for coral reef communities. The reduction of habitat complexity through erosion would reduce the niches for numerous species that rely on corals for shelter, food, substrate, settlement and nursery.
- In order to avoid this phase shift, urgent local and global action is necessary. Reducing local stresses, such as the reduction of terrestrial inputs of sediment, nutrients and pollutants, is paramount to promote a higher resistance to disturbance and ensure ecosystem resilience. Fisheries require the sustainable management of marine species and should aim to conserve key functional groups such as herbivores that control algae growth. Marine protected areas networks should be designed and implemented to provide refuges and serve as larval sources to replenish harvested areas outside reserves. Globally, urgent and ambitious action to reduce CO_2 emissions is necessary to limit sea surface temperature increase and water acidification.

DESCRIPTION

Status and Trends

Coral reef ecosystems are found throughout the world's tropical seas and are some of the most productive marine ecosystems. Coral reefs are largely constructed of calcium carbonate deposited over centuries by the activity of scleractinian (i.e., "hard") corals. The largest number of scleractinian coral species occurs in the Indo-Pacific region with around 80 genera and 700 species and constitutes a global biodiversity hotspot. Although scleractinian corals constitute the basic reef structure, reefs are inhabited by a myriad of species that depend on it for substrate, shelter, feeding, reproduction and settlement. The taxonomic groups inhabiting the reefs vary from calcareous algae to gorgonians, soft corals, mollusks, echinoderms, polychaete worms, sponges, and fishes.

Scleractinian coral development is constrained by several physical factors, with temperature the most limiting. Scleractinian corals only develop in locations where the mean annual sea temperature is above 18°C, optimally between 23-25°C, with some corals temporarily tolerating 36-40°C. This thermal tolerance means that hard corals do not develop on tropical coasts where upwelling (cooler water that

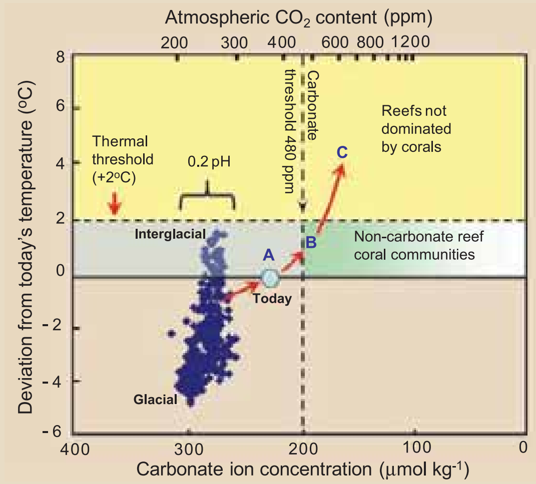

FIGURE 1

Temperature, $[CO_2]_{atm}$, and carbonate-ion concentrations reconstructed for the past 420,000 years. Carbonate concentrations were calculated from CO_2 atm and temperature deviations from today's conditions with the Vostok Ice Core data set, assuming constant salinity (34 parts per thousand), mean sea temperature (25°C), and total alkalinity (2300 mmol kg^{-1}). Temperature, atmospheric CO_2 concentrations and sea-water carbonate-ion concentrations were reconstructed for the past 420,000 years using data from the Vostok Ice Core data set (see Hoegh-Guldberg et al. 2007 for methods). The thresholds for major changes to coral communities are indicated for thermal stress (+2°C) and atmospheric CO_2 concentrations 480 ppm). Points and red arrows indicate projected pathways of temperature and CO_2 concentrations (A = state in ca. 2005, B = projected state in mid-century and C = projected for end of the 21st century in "business as usual scenarios". Source: Hoegh-Guldberg et al. 2007.

surfaces from greater depths) occurs, such as the west coast of South America. Scleractinian corals have a symbiotic relationship with zooxanthellae, endosymbiotic algae that, through photosynthesis provide energy to the coral (almost 90% of coral energy requirements) in the form of glucose, glycerol and amino acids; in return, the coral provides the zooxanthellae with protection, shelter, nutrients (especially nitrogen and phosphorus) and a constant supply of CO_2 required for the photosynthesis. Corals may briefly survive without the algae (for example, during bleaching events when the algae are expelled and the coral appear white after the loss of the pigmented zooxanthellae) but their health will be greatly reduced, particularly for energy-costly processes like lesion repair, growth and reproduction (Fine and Loya 2002). For the zooxanthellae to perform photosynthesis, corals usually inhabit depths above 25 m (maximum 50-70 m depth). A high sediment load, besides clogging the coral feeding structures and smothering them, also increases turbidity and reduces access to light (Anthony and Connolly 2004). This is the main reason why corals are absent in areas where rivers of tropical regions discharge to the oceans, such as the Amazon River. Corals occur in waters with salinity 32-35 ppt and do not support air exposure.

The unsustainable fishing practices on coral reefs can reduce fish populations to unviable levels, and ultimately disturbs all trophic levels. Robbins et al. (2006) found the overharvesting of top predators (i.e. sharks) can impact the entire community since their ecosystem function was diminished. Similarly, on coral reefs, the removal of herbivores is known to upset the competitive balance between coral and algae. In the 80's, a loss of herbivores due to overfishing combined with an acute disease outbreak resulted in considerable coral mortality which resulted in a phase shift from coral-dominated Caribbean reefs to algal-dominated communities (Hughes 1994).

The marine ornamental aquarium trade continues to rely on wild caught organisms (e.g. corals, fish, crustaceans and clams, etc.), particularly from Southeast Asia. Furthermore, many collected organisms die during transportation before arriving at their final destination (mainly U.S.A., Europe and Japan). The removal of reproductive individuals combined with destructive collecting techniques (e.g. cyanide) and damage/death of non-target species damages wild populations and jeopardizes its sustainability (FAO 2009).

Land use activities, namely agriculture, sewage treatment, increased runoff, and coastal zone modification (house and harbour construction in coastal areas, dredging, etc.) contribute with the addition of contaminants, nutrients and sediments to the water (Buddemeier et al. 2004). Toxic or bioactive contaminants (including heavy metals, pesticides/herbicides and fuel) are discharged in the ocean and absorbed in the sediments. The increased nutrient load promotes phytoplankton blooms (which reduces water clarity and light availability) and algal growth that compete with corals. As previously mentioned, increased sediment flux reduces light access (and the ability of zooxanthellae to photosynthesize) and can interfere with coral feeding ability. Coral reef ecosystems can undergo a phase shift from predominantly coral cover to fleshy algae cover, each state having its own inherent resilience and resistance. Nevertheless, there are other possible phase shifts (Bellwood et al. 2004) (Figure 2).

Coral reef ecosystems are declining in productivity and experiencing a dramatic phase shift in dominant species due to intensified human disturbance such as over-harvesting, pollution, increased nutrient and sediment loads and the direct and indirect impacts of climate change, particularly sea-surface temperature increase and ocean acidification (Hughes et al. 2005, Anthony et al. 2007).

Tipping point mechanisms
One of the greatest future threats to the coral reef ecosystems is climate change. Over the 20th century, atmospheric CO_2 concentrations increased from ca. 280 ppm to 367 ppm (IPCC 2007) (Figure 1). Present levels exceed 380 ppm, which is more than 80 ppm above the maximum values of the past 740000 years, if not 20 million years (Hoegh-Gulberg et al. 2007).

Based on IPCC (2007) emissions scenarios, atmospheric CO_2 levels may increase to ca. 460-620 ppm by 2050 and 480-1100 ppm by 2100. The world's oceans are absorbing 25-33% of the CO_2 released by anthropogenic actions, and consequently becoming increasingly acid. When CO_2 dissolves in the water, it forms carbonic acid.

$H_2O + CO_2 \leftrightarrow H_2CO_3$

Carbonic acid is unstable and will easily release one or two hydrogen ions to form bicarbonate or carbonate, respectively.

$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$ (bicarbonate)

$HCO_3- \leftrightarrow H^+ + CO_3^{2-}$ (carbonate)

Increased absorption of CO_2 in the oceans alters the relative proportions of the several forms of carbon: dissolved CO_2, carbonic acid, HCO_3^- (bicarbonate) and CO_3^{2-} (carbonate). Increasing the dissolved CO_2 promotes bicarbonate ion formation and decreases carbonate ion formation. This is problematic since calcifying organisms such as scleractinian corals, calcareous algae and many others, combine Ca^{2+} with CO_3^{2-} to accrete their skeletons ($CaCO_3$). A reduction of available CO_3^{2-} ions may slow the calcification rate of calcifying organisms, promote the formation of less dense skeletons that are more susceptible to physical fragmentation during severe weather events and/or accelerate erosion. In the last century, the ocean pH has already dropped 0.1 and seawater carbonate concentrations have been depleted by ~30 $\mu mol\ kg^{-1}$ seawater (IPCC 2007). Recent studies project pH to decline another 0.4 units by the end of the century, with ocean carbonate saturation levels potentially dropping below those required to sustain coral reef accretion by 2050 (Kleypas and Langdon 2006).

In the 20th century, sea surface temperature has increased 0.4-0.8°C, and it is expected to increase an additional 1-3°C (IPCC 2007) in this century, which may severely affect corals symbiotic relationship with the zooxanthellae. Studies have observed the expulsion of zooxanthellae by the coral host when temporarily subjected to higher temperatures, inducing the coral to bleach. As previously mentioned, zooxanthellae are essential to provide energy for the coral to perform more energetically costly processes such as growth, reproduction and lesion repair.

Projected global temperature increases of 1.4-5.8°C by the end of the 21st century are expected to lead to sea level rise of 0.1 to 0.9 m (Buddemeier et al. 2004). Despite the the fact that rate of sea level rise might exceed coral growth rates, most corals are believed to be able to adapt to rising sea level, with the exception of some corals in the lower depth limit. However, the predicted rise of sea level might also cause increased shoreline erosion and in some cases the submersion of islands could increase sediment load in the water.

Some researchers also predict an increase in the frequency and intensity of catastrophic weather events, such as hurricanes/typhoons (Webster et al. 2005), and major alterations to ocean circulation (Harley et al. 2006) due to rising sea surface temperatures. The later phenomenon could alter larval supply and jeopardize population connectivity, gene flow, genetic diversity, risk of extinction and biodiversity.

The macro algae-dominance state can again alternate with a sea urchin barren state. In the later state, if echinoid predators are overfished, the system can degrade completely and become lifeless (Bellwood et al. 2004). The stressors expected to have a greater influence in pushing the system towards a phase shift from coral to algal dominance are those that are gradual and chronic, namely increased sea surface temperatures

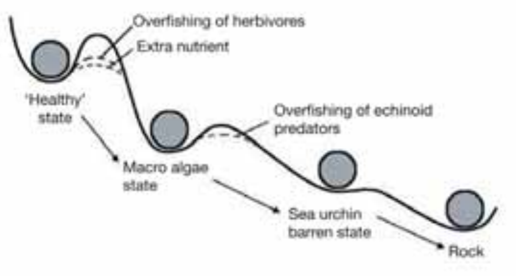

FIGURE 2
A graphic model depicting transitions between ecosystem states. 'Healthy' resilient coral dominated reefs become progressively more vulnerable owing to fishing pressure, pollution, disease and coral bleaching. The dotted lines illustrate the loss of resilience that becomes evident when reefs fail to recover from disturbance and slide into less desirable states. Reprinted by permission from Macmillian Publishers Ltd: [Science] (Bellwood, D.R., T.P. Hughes, C. Folke, and M. Nyström. 2004. Confronting the coral reef crisis. Nature 429:827-833), copyright (2004).

and ocean acidification. Nevertheless, the frequency and intensity of temporary and localized acute stressors (e.g. severe weather, disease) combined with manageable anthropogenic local impacts (e.g., overfishing, pollution, terrestrial runoff) can exacerbate the process and contribute to the loss of resistance and resilience. For instance, increased nutrient input is believed to promote the outbreak of coral predators like crown-of-thorns sea stars (*Acanthaster planci*) (Brodie et al., 2005). If these outbreaks occur more frequently on chronically disturbed reefs, the ability of corals to recover would be seriously compromised.

The tipping point of the coral-algal phase shift appears to occur when sea temperatures exceed the upper thermal tolerance of the coral (~2-3°C above species optimal level), which results in the expulsion of the zooxanthellae, i.e., coral bleaching. Thermal tolerance is species-specific, therefore species will not be affected equally. The optimal temperature for most coral species is 23-25°C (annual average), but some species can tolerate 36-40°C. However, with the expected rise in sea surface temperatures, coral cover and species-richness will likely decrease and undergo a dramatic change from coral to algal dominance (Buddemeier et al. 2004, Hoegh-Guldberg et al. 2007).

If atmospheric CO_2 levels exceed 480 ppm and carbonate ion levels drop below 200 $\mu mol.kg^{-1}$, the ability for reef organisms to accrete calcium will be compromised. Simulations have predicted that doubling the pre-industrial CO_2 level to 560 ppm would result in a calcification reduction of 11-37% in corals and 16-44% in calcareous algae (Langdon et al. 2000, Marubini et al. 2003) by 2050. The loss of coral cover and the ability to accrete calcium would hasten erosion and permit algae to outcompete coral recruits for suitable settlement substrate.

IMPACTS ON BIODIVERSITY

Since coral reefs are biodiversity hotspots and centres of endemism (Hughes et al. 2002), the regime shift from coral to algae dominance could potentially result in numerous extinctions (Roberts et al. 2002) and substantial changes in the abundance and distribution of species and communities at local to global scales.

Climate change is predicted to impact adult corals' survival, growth and reproductive output. Increased sea-surface temperatures and high solar irradiance have been reported to cause coral bleaching (release of the symbiotic zooxanthellae), which may lead to death (Anthony et al. 2007) as coral will have less energy available for growth, reproduction, lesion repair, disease resistance and recovery (Fine and Loya 2002). Water acidification is expected to compromise coral growth and/or weaken its calcified structure (Kleypas et al. 1999, Hoegh-Guldberg et al. 2007, Madin et al. 2008). All these threats will increase the risk of extinction of several coral species. Furthermore, as sea surface temperature increases, bleaching events are predicted to become more frequent and severe. Coral bleaching frequently causes immediate loss of live coral and may lead to long-term reduction in topographic complexity due to erosion. However, according to Hughes et al. (2003), reefs will change rather than disappear entirely, with certain species already exhibiting greater tolerance to climate change and coral bleaching than others. We expect a loss of less thermally tolerant coral species (the majority), and a replacement by algae species. This change in dominance and subsequent reduction in habitat topography/complexity will be dramatic for the entire coral reef community (e.g. sponges, crustaceans, molluscs and fishes) as available shelter, settlement substrate, nursery, and/or feeding grounds are projected to gradually disappear due to reduction in calcium accretion that offsets erosion (Almany 2004, Pratchett et al. 2008).

Climate change might also impact coral reef fishes' individual performance, trophic linkages, recruitment dynamics and population connectivity (Munday et al. 2008). Ocean acidification has been reported to impair olfactory discrimination and homing ability of settlement stage marine fish (Munday et al. 2009a). Furthermore, according to Nilsson et al. (2009), elevated sea surface temperatures may cause a decline in fish aerobic capacity (resting and maximum rates of oxygen consumption); however, the degree of thermal tolerance is species-specific. Certain species are likely to persist at higher temperatures, while thermally sensitive species may decline at low latitudes and/or move to higher, cooler latitudes. This differential impact and possible alteration to species relative abundance might have serious consequences for the coral reef community and disturb the trophic chain (Munday et al. 2008).

The expected increased frequency and intensity of catastrophic weather events (such as hurricanes/typhoons) (Webster et al. 2005) and weaker carbonate materials associated with more acidic oceans will increase the vulnerability of coral reefs to mechanical damage. Short term, the reduction of coral size is expected to reduce fecundity. On a longer temporal scale, we expect dramatic shifts in assemblage structure following hydrodynamic disturbances, including switches in species' dominance on coral reefs (Madin et al. 2008). The increased frequency and intensity of severe weather events might rule future reefs to have lower colony abundances and be dominated by small and morphologically simple, yet mechanically robust species, which will in turn support lower levels of whole-reef biodiversity than do present-day reefs (Madin et al. 2008).

Coral reef ecosystems typically develop as patches of shallow habitat that can be separated by long distances. Corals and other sedentary reef organisms' long distance dispersal is achieved through larval dispersal. The predicted alterations to large-scale ocean circulation (Harley et al. 2006) are likely to alter the dynamics of larval supply. Increased sea-surface temperatures and reduced pH are expected to affect larval development, settlement, and cause physiological stress (Bassim and Sammarco 2003). These factors could potentially increase larval mortality, reduce competency time, and consequently, reduce dispersal distances, reef connectivity, gene flow, and biodiversity (Jones et al. 2009, Munday et al. 2009b).

Since corals act as barriers altering wave energy and circulation near-shore, other types of tropical and sub-tropical ecosystems, like mangroves (highly protected nurseries), are predicted to experience some negative impacts as well.

ECOSYSTEM SERVICES

Coral reefs provide an extensive and valuable list of services to humans. Cesar et al. (2003) estimated the global net economic benefit from coral reefs to be US$30 billion year^{-1}. Its aesthetic is the prime reason for attracting millions of tourists annually. The revenue generated from tourism/diving is an important income for many coastal countries, states and islands (e.g., Caribbean islands, Southeast Asia, Australia, Hawaii and the Maldives). In addition, coral reefs support the seafood, recreation and aquarium trade industries. The highly productive coral reefs from Asia provide almost one quarter of the annual total catch and food for nearly one billion people. Reefs also supply building materials, fibres, and pharmaceuticals (Balmford et al. 2002).

The geologic and biologic structure of coral reefs creates a complex habitat that provides food, shelter, and nursery habitat for hundreds of marine species. The high biodiversity is not limited to marine animals; many terrestrial plant and animal species (e.g. birds, humans, etc.) have colonized the coastal environments and islands formed by coral reef communities (Buddemeier et al. 2004).

Corals reefs also provide less visible services such as nutrient cycling, climate regulation and protection for the shoreline and other ecosystems (e.g. mangroves). Reefs reduce wave energy during storm events, preventing beach erosion and protecting human settlements from waves, floods and beach erosion (Buddemeier et al. 2004, Hoegh-Guldberg et al. 2007).

UNCERTAINTIES

The projected increase in carbon dioxide production and temperature over the next 50 years exceeds the conditions under which coral reefs have flourished over the past half-million years (Hughes et al. 2003).

Climate and localized non-climate stresses interact, often synergistically, to affect the health and sustainability of coral reef ecosystems (Buddemeier et al. 2004). Scientists have invested a great deal of resources predicting the impact of several disturbances, but the projections are usually based on studies examining one or a few disturbances at a time. Therefore, it is still difficult to predict the outcome of their possible interactions. For instance, one of the expected scenarios for increased sea-surface temperature is the alteration of ocean currents. This phenomenon alone could produce changes in coral larval supply and potentially alter the connectivity between populations of sedentary species by disrupting the gene flow, genetic diversity, speciation rate, and susceptibility to extinction (Jones et al. 2009). Additionally, rising sea-surface temperatures may negatively impact the reproduction of adult corals and/or the larval viability, survival and competence time (i.e., the period during which larvae are competent to settle and form new colonies is expected to decrease as their metabolic rate accelerates with increasing temperatures). However, the effects of increased sea-surface temperature acting simultaneously on ocean currents and coral reproductive characters remain unclear.

However, some interactions (e.g. increased temperature and calcification rates) might not be negative. Small increases in temperatures, which keep corals below their upper thermal limit, accelerate growth through increased metabolism and the increased photosynthetic rates of zooxanthellae. Under this condition, calcification is increased and corals do not respond as significantly to the decrease in carbonate ion concentration (Carricart-Ganivet 2004). Also, Anthony et al. (2007) conducted laboratory experiments that suggest high sediment concentrations reduced the mortality of certain coral species under high temperature and/or high light (irradiance) potentially by alleviating light pressure and by providing an alternative food source for bleached corals.

One of the greatest uncertainties involves the ability of corals to adapt to rising temperatures and acidification. Relatively modest degrees of adaptation would substantially reduce damage to coral reefs, especially in scenarios with strong climate mitigation (Donner 2009, Weiss 2010). For coral reef fishes, small temperature increases might favour larval development but could be counteracted by negative effects on adult reproduction. Several fish species have a large geographical distribution where they are exposed to various temperatures. When this characteristic is allied to a short life cycle, there might be some potential for adaptation to climate change (Munday et al. 2008).

LOCAL TO GLOBAL ACTIONS AND OPPORTUNITIES

In order to sustain the ecosystem's resistance and, in case of significant change in the ecosystem, allow a faster recovery, local and global action must be taken. International integration of management strategies that support reef resilience need to be vigorously implemented, and complemented by strong policy decisions to reduce the rate of global warming (Hughes et al. 2003).

Globally, the reduction of CO_2 emissions is necessary to minimize increasing sea-surface temperatures and water acidification. The levels of atmospheric CO_2 need to be kept below 480 ppm to avoid an almost irreversible phase shift (Hoegh-Guldberg et al. 2007).

As an international consensus of how to reduce CO_2 emissions remains unclear, Bellwood et al. (2004) advocates that we should accept that climate change will eventually occur, and concentrate our efforts in studying how can we help corals reef ecosystems to counter these disturbances.

If we minimize local human impacts (such as terrestrial run-off, coastal pollution and over exploitation of key functional groups), the stresses associated with climate change are likely to be less severe (Hughes et al. 2003, Buddemeier et al. 2004). Fisheries must be managed to keep populations at sustainable levels and particularly protect the populations of key functional groups such as herbivores (fish and invertebrate grazers such as parrotfish and sea urchin species, respectively; Mumby 2006) that control the algae growth and enable corals to recover from disturbances (Bellwood et al. 2004). The reduction of fishing effort cannot be done without considering the local socio-economic impacts. Fishermen must be provided education/training for new trades (e.g. eco-tourism related activities) and more sustainable fishing practices while considering traditional and/or cultural values. The collection of wild caught organisms for the marine aquarium trade must be reduced and replaced by aquacultured individuals. Aquaculture facilities should be placed in regions that supply the aquarium trade and employ former ornamentals collectors.

Marine reserves appear to be an effective means of reducing local stresses on coral reefs and allowing for rapid recovery from bleaching events (Mumby & Harborne 2010). In addition, the implementation of marine protected areas (MPAs) can provide refuges for living organisms and serve as larval sources for replenishment of harvested areas outside the reserve (Botsford et al. 2009). MPAs should be located where the stresses associated with climate change are likely to be less severe (West and Salm 2003). A successful implementation and management of MPAs will require international conservation efforts across larger spatial and temporal scales that match the biogeographic scales of species distributions and life-histories (Hughes et al. 2003).

In order to generate and maintain the biodiversity of coral reef ecosystems we must assure reef connectivity (Hughes et al. 2005). Coral population connectivity patterns are likely to change due to alterations to oceanic currents, reduced reproductive output, lower larval survival and shorter competence time. Therefore, to retain their efficacy, the design (size and spacing) and management of marine reserves may have to be adjusted to contribute to an effective minimization of climate change and anthropogenic pressures (Almany et al. 2009, Bostsford et al. 2009, Munday et al. 2009b).

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