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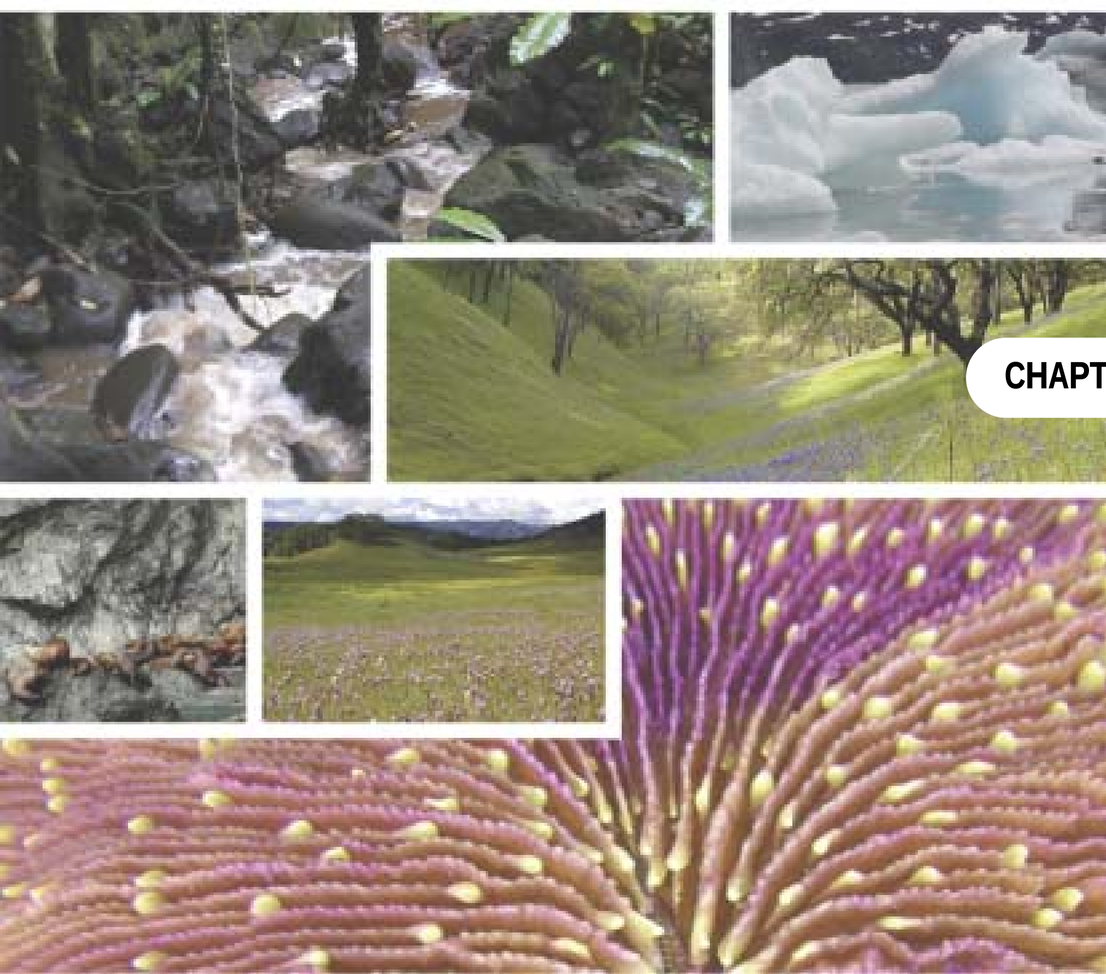
BUYING TIME:

A User's Manual for Building Resistance and Resilience to Climate Change in Natural Systems



CHAPTER 6: Tropical Marine

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Increasing the Resistance and Resilience of Tropical Marine Ecosystems to Climate Change

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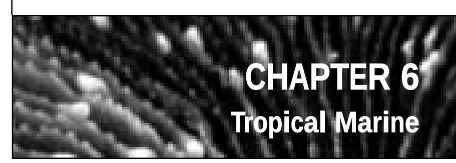


TROPICAL MARINE ECOSYSTEMS ARE rich in biodiversity and provide productivity to support almost one billion people every year in Asia alone (Kaufman and Dayton, 1997). They include coral reefs, mangrove forests, seagrass beds and vast pelagic systems, and support local subsistence fishing as well as international commercial fisheries. Not only do coral reefs support biodiversity and provide sustenance for communities, but they also support extensive tourism activities around the world. Coral reefs and mangroves offer protection from coastal erosion, while seagrasses and mangroves both trap sediment from terrestrial run-off. Mangroves act as a filtration system for estuarine and fresh water. These habitats also serve as nurseries for many invertebrates and fish. The complex ecology of these systems is well appreciated but not fully understood. Efforts toward greater understanding are being constantly challenged as theses systems are altered by local anthropogenic stresses (fishing, development, extraction) and global climate change.

The resistance (ability to withstand change) and resilience (ability to recover from change) of an ecosystem determine how well it can deal with this barrage of challenges (Noss, 2001). Conservation efforts can enhance resistance and resilience to climate change by alleviating the overall pressures on the system, giving it more flexibility to mobilize its natural defenses. For example, coral reefs that experienced greater disturbance prior to a bleaching event tend to have a poor ability to recover (Brown, 1997a). The following chapter offers an introduction to the effects of climate change on tropical marine systems, as well as an overview of the types of strategies that might be adopted to increase the resistance and resilience of tropical marine protected areas. This chapter focuses mostly on coastal systems, touching on pelagic where information exists.

What Stresses Threaten Tropical Marine Systems Other Than Climate Change?

DEVELOPMENT

Tropical marine ecosystems are currently threatened by an array of local stresses associated with human activities. Although coastal regions encompass only 20% of Earth's landmass, almost 60% of the world's population lives within 100 kilometers of the coast (Vitousek et al., 1997). Growing human populations and the desirability of coastal property increases coastal development, resulting in the loss or degradation of coral reefs, mangroves and sea grasses. Conversion of reef habitat to land for development has a "complete and irreversible" effect on reefs, effectively destroying them. Such development is extensive in Egypt, the Seychelles, the Maldives, Singapore and some south Pacific atolls (Spalding et al., 2001; Bryant et al., 1998). Historically, 75% of all tropical coasts where inhabited by mangroves, but this is no longer the case (Farnsworth and Ellison, 1997). Accurate estimates of global mangrove loss are not available, but a recent survey characterized 55% of sites as "threatened" due to clear-cutting and reclamation (Farnsworth and Ellison, 1997). Seagrass loss is also poorly quantified, but at least 90,000 hectares were lost in the decade prior to 1996, with 45,000 hectares of that in Australia and 25,220 ha in the United States (Short and Wyllie-Echeverria, 1996). Losses were primarily due to dredge and fill activities and related changes in water quality. These numbers almost certainly underestimate global seagrass losses, which some researchers put at nearly 90% (Burke et al., 2001).

POLLUTION

Pollution is ubiquitous in marine waters and the tropics are no exception. Run-off from industry, cities and agriculture contain pesticides, metals and nutrients; oil and chemical spills are other pollutant sources, along with deposition of atmospherically transported compounds such as persistent organic compounds and mercury. Even in remote pelagic systems, many high level predators such as tuna have high tissue concentrations of these compounds and there is evidence that levels have been increasing over the past 20 years (Nakagawa et al., 1997). All of these pollutants disturb the oligotrophic waters that characterize most tropical marine systems; since many tropical marine environments have limited populations of biodegrading microbial fauna, they may be more sensitive to pollution than other systems. For example, on Laysan Island in the northwest Hawaiian Islands, there was a carbamate pesticide spill, likely due to a container washed off a passing ship (David et al., 2001). While the container was not found, its existence was inferred from an area referred to as "The Dead Zone", which was identified in 1988. Surveys of the beach have found dead insects, ghost shrimp, Laysan albatross *(Diomedea immutabilis)* and, most significantly, Laysan finches *(Telespiza cantans)*, an endemic and endangered species (Woodward et al., 1998). Under normal terrestrial soil conditions, such pesticides are readily biodegraded. However tropical and subtropical sand beaches seem to have slower degredation of xenobiotics (Siegrist et al., 1994, Campbell et al., In Prep). As a result, mitigation of this site in 2002 required the removal of all of the contaminated sand for treatment. This raises substantial concern regarding the fate and effects of all contaminant spills in oligotrophic regions.

Corals in particular are affected by local nutrient run-off from land. Run-off changes the chemistry of the near-shore waters to favor algae over corals, and is often associated with greater siltation, decreasing coral growth rates (Koop et al., 2001; Ferrier-Pages et al., 2000; Pittock, 1999; Shimoda et al., 1998; Carpenter et al., 1998). Mangrove systems have not escaped the impacts of pollution either. Following oil spills, mangroves suffer defoliation, loss of associated species and death, with recovery times on the order of 15 to 20 years (Burns et al., 1993; Ellison and Farnsworth, 1996). There are fewer studies on the effects of pollution on seagrasses. Some seagrass communities have been adversely affected by oil spills (Zieman et al., 1984) and they are known to accumulate heavy metals, although no detrimental responses have been noted (Nienhuis, 1986). Herbicides, not surprisingly, have been found to adversely affect seagrasses. Photosynthetic activity was depressed in three species of seagrass *(Cymodocea serrulata, Halophila ovalis and Zostera capricorni)* when exposed to concentrations of diuron that were found in marine sediments off the coast of Australia (Haynes et al., 2000).

TOURISM

Tourism is a powerful tool for increasing public awareness of biodiversity and support for conservation efforts and funding, but it can create additional stress as well. Over-visitation and poorly managed visits cause severe degradation of tropical ecosystems. Poorly trained divers and snorkelers, as well as ill-placed boat anchorages damage coral reefs and seagrass beds. Tourism increases coastal development, pollution and extraction due to the increased number of people at a given location each year (Spalding et al., 2001). In some cases, seagrasses have even been removed from hotel beaches to create a more “aesthetically pleasant swimming zone” (Daby, 2003). Mangroves are also removed for development, and are trampled by other human activities.

OVERHARVEST OF FISHERIES

Fisheries are being depleted globally (Myers and Worm, 2003) and there is exceptional pressure on the tropics (Jackson et al., 2001). This includes large commercial fishing operations, such as tuna and other pelagic species, as well as small-scale efforts such as dynamite and cyanide fishing that damage not only fish populations but the entire community and reef-structure as well. In Tanzania, for example, dynamite fishing has been practiced for at least 30 years, resulting in substantial degradation of coral reef communities with loss of fish, invertebrates and coral (Guard and Masaiganah, 1997). Cyanide fishing was developed for the live fish trade and is now common on coral reefs in much of Southeast Asia. Sodium cyanide is “squirted” onto target fish, stunning them and allowing for easy collection. Although application of the poison is somewhat local, it spreads to cause lethal or sub-lethal impact on other organisms in the surrounding environment. In the Philippines, it has been in practice since the early 1960s (Halim, 2002).

OTHER EXTRACTIVE USES

While some coral rock is collected for the aquarium trade, coral reefs are also “mined” for building materials, especially in regions where there is little terrestrial rock. In the Maldives, for example, over a 13-year period, 93,450 m^3 of coral was extracted from a single atoll (Brown and Dunne, 1988). Such a large coral removal has reduced local fish and invertebrate populations, and compromised the physical protection that the reef offered to the island. Coral remnants left after mining seem to have very limited and slow recovery (Brown and Dunne, 1988).

Mangroves are extensively harvested for wood and wood-products. In the past their bark was collected for tannin production, but the dominant use of mangroves now is fuel and building materials (Ellison and Farnsworth, 1996).

INVASIVE SPECIES

Tropical marine systems are also affected by the spread of non-native species. The majority of these species are introduced accidentally (Carlton and Geller, 1993), although there are some cases of intentional introduction, especially for aquaculture (Randall, 1987). In Hawaii, for example, a recent survey of the archipelago determined that of the 23,150 species identified, 5,047 were nonindigenous (Eldredge, 2000); of these 343 are marine or estuarine and most were introduced through hull fouling or ballast release (Eldredge and Carlton, 2002).

Mangrove ecosystems are relatively protected from invasive species because of the unique environment in which they live. There are very few plants that are halophytes (salt tolerant), making the pool of potential invaders quite limited (Lugo, 1997). However, there are examples following hurricanes where disturbance opens up an opportunity for an introduced species (Loope et al., 1994). Additionally, mangroves themselves can be invasive. Red mangroves were introduced to Hawaii in 1902 from Florida in an effort to support coastlines. There are now on-going efforts to remove this species from the islands. While seagrass communities are almost certainly affected by invasive species, there is little literature on the effects.

What is the Effect of Climate Change on Tropical Marine Systems, Now and In the Future?

While it is clear from the previous section that there are already myriad threats to tropical marine ecosystems, it should be noted that at least some of these threats are beginning to be addressed through conservation efforts, especially in the case of coral reefs. However, Wilkinson (2002) noted that, “These improvements could be largely negated if the predicted threat posed by Global Climate Change of increasing sea surface temperatures and concentrations of CO_2 in seawater cause catastrophic bleaching and result in major reductions in the capacity of corals to calcify and grow.” This sort of dire assessment indicates how crucial it is that the impacts of climate change be considered and planned for in any contemporary conservation efforts. A variety of emergent stressors associated with climate variability and change, reviewed below, are of increasing concern to scientists and mangers.

INCREASING SEA TEMPERATURES

While water has a high heat capacity, it is not immune to changes in atmospheric temperature; as air temperatures rise, so will water temperatures. Ocean temperature changes actually lag behind air temperature changes to such a degree that even if atmospheric CO_2 concentration were stabilized today, the oceans would continue to warm for another century (Albritton et al., 2001). This may be a particular challenge to marine species that have relied on the thermal buffering capacity of the world’s oceans to maintain a relatively consistent environment. The response of these species to rising sea temperatures will depend on their thermal tolerances and the thermal tolerances of their competitors. Most species have an optimal physiological temperature range for respiration and growth (and photosynthesis in the case of primary producers). Outside that range, individuals are energetically challenged. In the case of some seagrasses, such as the eelgrass *Zostera marina*, increasing temperature favors respiration over photosynthesis, decreasing the seasonal growth optimum (Marsh et al., 1986; Short and Neckles, 1999). Other seagrasses in other parts of the world, however, increase photosynthesis with increasing temperature (Perez and Romero, 1992). For regions where seagrasses are living near their thermal maximum, such as shallow lagoons and near warm effluent from power plants, a 2 ºC increase in sea temperature will be detrimental as these populations are already living closer to their thermal limit, and a 4-5 ºC increase would result in extensive mortality (Edwards, 1995). Increasing water temperatures can also result in seagrasses being outcompeted by algal species, including epiphytic algae (Neckles et al., 1993).

The most dramatic effect of increasing temperature in tropical marine ecosystems is coral bleaching. Coral bleaching is defined by the loss of symbiotic dinoflagellates (zooxanthellae) or their pigments by the host coral animal (Glynn, 1993; Brown, 1997a). Normally, the symbiotic dinoflagellates provide the coral host with additional energy through photosynthetic activity. Long-term loss of the dinoflagellates can result in death of the affected coral (Harriott, 1985). Bleaching is considered to be a stress response caused primarily by increased water temperature (Glynn, 1993) and synergistically enhanced by increased solar irradiance levels (Jokiel and Coles, 1990; Lesser et al., 1990; Fitt and Warner, 1995). The water temperature need only increase by 1 to 2 ºC over the average annual thermal maxima for days to weeks to result in a bleaching event (Hoegh-Guldberg, 1999). These conditions have led some to rank climate change as potentially “the single greatest threat to reefs worldwide” (West and Salm, 2003).

SEA LEVEL RISE

Sea level is predicted to rise between 20 and 80 cm over the next century (IPCC, 2001a). This is due to both the thermal expansion of water and the melting of terrestrial ice masses (glaciers and ice sheets). Sea level rise will affect intertidal and coastal ecosystems by inundating them with water and affecting the availability of light, as well as altering patterns of water movement both intertidally and subtidally. For seagrasses, distribution and abundance are determined by salinity, light, depth and currents (Short and Neckles, 1999); rising sea levels could therefore dramatically alter seagrass communities and their composition.

Stable mangrove forests require stable sea level; prior to sea-level stabilization 6,000 years before present, large mangrove communities did not exist (Ellison and Stoddart, 1991). Thus, rapid sea level rise will likely be the greatest climate change challenge to mangrove ecosystems (Field, 1995). During past changes in sea level (8-9 mm/year) mangroves have migrated landward or seaward as necessary (Parkinson et al., 1994); with coastal development the ability of mangroves to migrate may be severely limited

(Ellison and Farnsworth, 1996). Reduced rates of sediment input due to coastal armoring and the damming of rivers will further limit the ability of mangrove forests to keep up with sea level rise (Field, 1995). The Intergovernmental Panel of Climate Change (IPCC) has recognized the severity of the threat of sea level rise to mangroves, and past floods in east Africa's coastal regions demonstrate the high vulnerability of this region (IPCC, 2001b). In Bangladesh and India, the mangroves of the Sunderbans are at great risk due to rising seas; a one meter rise in sea level will likely cause the Sunderbans and the tigers living there to disappear (IPCC, 2001b).

Under ideal conditions coral reef growth would likely be able to keep up with sea level rise predicted over the next century, but coral condition is not ideal and will become less so as the climate continues to change (Buddemeier and Smith, 1988). Bioerosion can erode reefs at rates up to 6 mm/year (Eakins, 1992), and changes in ocean chemistry will slow coral growth and may decrease the strength of coral skeletons (see further discussion of this under section on effects of Increasing Atmospheric CO_2). If bioerosion rates exceed calcification rates, then corals will not be able to keep up with sea level rise and may "drown".

EXTREME WEATHER EVENTS (HURRICANES, CYCLONES, ENSO PATTERNS)

The role of climate change in increasing the frequency and intensity of extreme weather is not well established (IPCC, 2001a). However if such effects do occur, this increases the importance of mangroves and coral reefs, which buffer coastlines against storm surge and high winds (Edwards, 1995). Increased frequency and intensity of storms would also threaten these critical ecosystems. Storm damage to corals, especially from hurricanes, is well documented throughout the tropics (Woodley, 1992; Harmelin-Vivien and Laboute, 1986; Done, 1992). Between December 1982 and April 1983, six hurricanes hit French Polynesia, and reef surveys following these events showed 50 to 100% damage depending on depth (Harmelin-Vivien and Laboute, 1986). Done (1992) points out that in some high-energy regions, like the Great Barrier Reef, damage from cyclone-generated waves is already dramatic with reef commonly lost to such events. Hurricane Gilbert "disturbed" the Cayman Islands in 1988 to the extent that reef surveys eight years later required no quantitative transects for reefs of less than 8 m depth (Riegl, 2001). Additionally, historic *Acropora palmata* zones were no longer present.

Seagrasses also suffer significant damage from current levels of tropical storms (Short and Wyllie-Echeverria, 1996) and are often slow to recover (Williams, 1990). Non-climatic pressures further exacerbate this slow recovery. Should storm frequency increase, some seagrass beds may not be able to recover sufficiently between storms. In Hervey Bay, on the coast of Queensland, Australia, a 100,000-hectare community was lost after two flood events and a cyclone in 1992, coupled with pressures from terrestrial nutrient and sediment run-off and shrimp trawling (Preen et al., 1995).

The damage of hurricanes to mangroves, through high winds and flooding, is less well studied. Of the reports that do is exist is one from Belize where large hurricanes have a frequency of about one every 30 years (Murray et al., 2003). Hurricane Hattie in 1961 had such force that it altered the coastline, elevating former mangrove habitat above saline influence and allowing it to become a pine forest (Murray et al., 2003).

The predicted increase in major climatic events, such as El Niño/Southern Oscillations (ENSO) (Timmermann et al., 1999; IPCC, 2001b), may have drastic effects on fish stocks, especially when combined with stressors such as overfishing. Reduced survival and growth rate, and altered migratory routes can all be caused by ENSO events, exacerbating the effects of intensive harvesting (Miller and Fluharty, 1992). Both 1972-73 and 1997-98 ENSO events significantly reduced Peruvian anchovy populations (Caviedes and Fik, 1992; Pfaff et al., 1999). ENSO events cause temporary range shifts, as well as introducing changes in reproductive physiology, egg and larvae survival, recruit and adult biomass, and fish schooling behavior (Jordán, 1991).

The ENSO event of 1982-83 marked the first contemporary broad scale coral bleaching and mortality event (Glynn, 1984). Since then, there have been subsequent bleaching events including the 1997-98 ENSO event. The rate of occurrence (annually in some cases) and almost global scale since the early 1980's is in stark contrast to the trend of the first half of the century in which bleaching events were localized and linked to local events (D'Elia, 1991; Glynn, 1993). From 1876-1979, only three bleaching events were recorded, whereas 60 are on record from 1980-1993 (Glynn, 1993). The increase in bleaching suggests that anthropogenic alterations of the environment are responsible, such as increases in annual sea surface temperature and occurrence of ENSO events (Hoegh-Guldberg, 1999; Pittock, 1999). The future for corals in regard to bleaching is grim. It has been suggested that by 2020 bleaching events like that caused by the 1997-98 ENSO will become "commonplace" (Hoegh-Guldberg, 1999). There has also been some correlation between ENSO events and disease outbreaks in coral and oysters (Harvell et al., 2002). Opportunistic pathogens can exacerbate the impact of bleaching events. For example, the gorgonian coral *Briareum asbestinum* suffered extensive mortality when affected simultaneously by bleaching and a suspected cyanobacterial pathogen (Harvell et al., 2001).

Clearly hurricanes, tropical cyclones and ENSO events have substantial effects on tropical marine systems even now. For the most part species in this region have evolved with these pressures and have clear cycles of recovery. However, this recovery is markedly slow even at historic frequencies of disturbance. If climate change does indeed increase the frequency and severity of these weather types, it could alter the tropical marine seascape, with more rapidly growing and less disturbable species becoming dominant.

INCREASING ATMOSPHERIC CO_2

Besides acting as a greenhouse gas, increasing atmospheric CO_2 will result in increased dissolved CO_2 in the water column, which in turn will cause a reduction in the pH of the oceans. As a result, less carbon will be biologically available to calcium-carbonate-forming organisms. To date pH-related changes in aragonite saturation levels have resulted in a 6-11% decrease in biogenic aragonite and calcite precipitation rates; a doubling of CO_2 is expected to result in another 8 to 17% reduction (Kleypas et al., 1999).

This would weaken shells and other calcium carbonate structures, as well as slow growth rates of marine invertebrates with calcium carbonate skeletons; these effects would be particularly pronounced in coral communities (Kleypas et al., 1999). Hoegh-Guldberg (1999) estimates that by 2050 calcification rates could be reduced by 14-30%.

Changes in available carbon may also affect seagrasses, as there is variability among species in how well they compete for available carbon (Short and Neckles, 1999). Also, as epiphytic algal growth is enhanced due to increased temperature and CO_2, in addition to local eutrophication, seagrasses will have to grow faster to keep pace with their epiphytes (Short and Neckles, 1999). Mangroves have been shown over the course of a single year to increase growth and reach reproductive maturity faster under enhanced CO_2 conditions (Farnsworth et al., 1996), however ecological ramifications are not clear. Field (1995) suggests that the real effect of enhanced CO_2 cannot be ascertained without a "long-term" experiment in which CO_2, water stress and nutrient stress are all monitored. For example, studies on marshes under elevated CO_2 conditions have shown changes in response over time, such as increased release of methane and other greenhouse gases, following initial increases in primary productivity (Dacey et al., 1994).

ULTRAVIOLET RADIATION

Ultraviolet (UV) radiation increases are generally equated with stratospheric ozone depletion. While there is some ozone thinning in the tropics (Madronich et al., 1995) and ultraviolet radiation is already naturally highest in the tropics, climate change induced tropical warming may also result in increased UV-penetrance into the water column. Warming results in doldrum conditions, causing increased stratification of the water column and decreased dissolved organic matter [including chromophoric dissolved organic matter (CDOM)], leading to higher levels of UV deeper in the water column (Vodacek et al., 1997; Siegel and Michaels, 1996). This means that as thermal stress increases, so does the stress of UV radiation. The negative synergistic effects of temperature and UV radiation on coral are well established (Lesser et al., 1990; Dunne and Brown, 2001). UV is also expected to affect seagrass photosynthetic ability (Larkum and Wood, 1993), although they may have some ability to protect themselves from slow changes through increased production of UV-blocking pigments (Dawson and Dennison, 1996).

Mangroves and seagrasses are both sources of CDOM and other UV-blocking compounds that can be transferred to the marine water column when plants die or leaves are lost (Lovelock et al., 1992; Stabenau et al., In Prep). Therefore, as mangroves and seagrass systems suffer degradation and losses due to various stresses, a result may be continued exacerbation of UV stress to all systems.

EFFECTS ON SPECIES OF CONCERN

Seagrasses provide a primary food source for dugongs, manatees and green turtles (Lanyon et al., 1989), all species of conservation concern, and loss of seagrass beds or shifts in species composition could have significant impacts on these species. In addition to the potential loss of food source and habitat (seagrasses, coral reefs), turtles face an additional threat from climate change: skewed sex ratios. Sex determination in turtles is temperature dependent (Davenport, 1997). Higher temperatures lead to more female turtles with only 1.5 ºC separating the sexes (Morreale et al., 1982). A two-ºC increase in temperature is expected to dramatically skew the sex ratio and a four-ºC increase would virtually eliminate male offspring (Janzen, 1994).

What are Possible Options for Increasing the Resilience and Resistance of Tropical Marine Systems to Climate Change?

The basic premise of increasing resistance and resilience of ecosystems in responses to a changing climate is very similar to that used in designing conservation strategies to protect biodiversity from any threat. Given the scope and multi-faceted effects of climate change, the challenge is to broaden our thinking on both spatial and temporal scales, employ greater rigor in setting limits and enforcement, and make sure that a few new facets are considered. Here the strategies are divided up into three categories: 1) create sufficient space for change, 2) reduce all non-climate stresses and 3) identify resistant and resilient populations for special protection. While most of the effort to date on these approaches has focused on coral reefs, and the examples following reflect that, it should be noted that they are also applicable to other coastal, tropical marine systems.

CREATING SUFFICIENT AND APPROPRIATE SPACE

1. CREATE RESERVES THAT CONTAIN REPRESENTATIVE SYSTEM TYPES (CORAL REEF, MANGROVE, SEAGRASS) ACROSS ENVIRONMENTAL GRADIENTS

Human development is unlikely to cease anytime soon. It is thereby crucial that areas be protected from human encroachment as a first step in biodiversity protection. There are a few things to keep in mind when designing reserves in response to climate change. While many of these overlap with standard conservation requirements, climate change may require additional diligence in meeting these requirements.

a) It is not enough simply to have space: it must be ecologically significant space. Done (2001) describes “the perfect regional configuration” of a marine protected area (MPA) as one which contains a “full suite” of regional biodiversity. He also suggests the need for MPAs to encompass large areas, depth gradients and a high diversity of species. Maximazing the heterogeneity of the reserve is crucial (see #4 below)

b) Reserves also require effective management and enforcement. The absence of these activities leads to “paper parks” with no real functionality (Westmacott et al., 2000).

c) Although the effects of climate change will not stop at the borders of reserves, they can provide an area in which non-climate stresses can be more effectively limited. If this does in fact confer resilience, decrease adverse effects, or increase recovery potential, then reserves may act as the seed populations for numerous sites beyond reserves that were not experiencing the same benefits.

d) One reserve of each habitat type is also insufficient. “Replication” of habitats in multiple protected areas is necessary so that loss of a single reserve would not mean loss of the only remaining examples of habitats protected by the reserve.

Designing protected areas in response to climate change will require additional care for some tropical marine systems. For example, communities dependent on biological rather than physical matrices, such as seagrass beds or mangroves, are often the least resistant or resilient to environmental perturbations (Roberts et al., 2003).

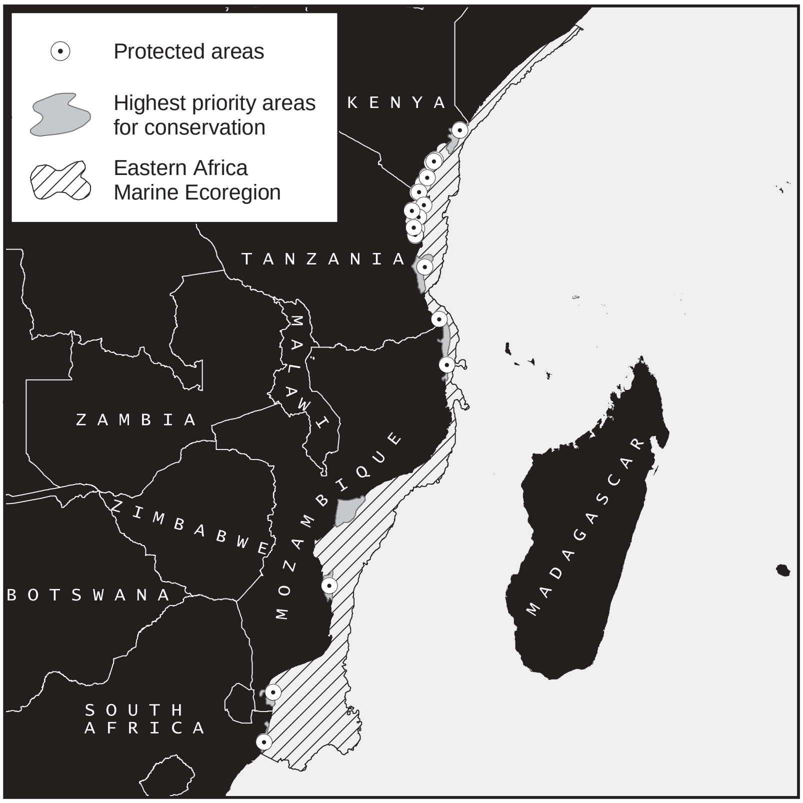
2. CREATE NETWORKS OF RESERVES

The “single large or several small” debate regarding reserve size has a long history in both terrestrial and marine conservation circles, but reserve networks are increasingly recognized as a powerful tool for the protection of marine ecosystems. Such networks confer a number of advantages. First, they allow coverage across a gradient of biogeographic and oceanographic conditions without the social, political and economic complexity of establishing a single large reserve. This is especially important where such gradients and the communities dependent on them cross political boundaries. The Eastern Africa Marine Ecoregion (Olson and Dinerstein, 1998), for example, is a network of marine protected areas that includes 4600 km of shoreline covering an extensive latitudinal and thermal gradient along the coasts of five countries (Somalia, Kenya, Tanzania, Mozambique and South Africa) (Figure 1). Networks are also more effective than single reserves at supporting organisms with a diversity of dispersal distances, which in marine flora and fauna may range from centimeters to thousands of kilometers (Shanks et al., 2003). By protecting large total areas while keeping individual protected areas somewhat smaller, networks are better able to provide source populations for recolonization of damage areas in other reserves in the network, as well as areas outside the network (Done, 2001; Westmacott, 2000). Finally, they have the added advantage of creating replicate reserves, spreading the risk while increasing the probability that representative biodiversity will avoid complete loss with a single damaging event.

3. PROTECT CLIMATIC REFUGIA

Identifying locations that are more stable during periods of global climate change can be very useful for conservation. These sites may have strong currents, upwelling or other oceanographic features that make them less prone to thermal fluxes. For example, at the south end of the island of Sulawesi, and along the Makassar Strait (between Borneo and Sulawesi), there is a region for which a 17-year analysis (1985-2001) showed no thermal anomalies greater than 1°C in many parts of the region. It is hypothesized that this is due to high current flow in this region, or other oceanographic features. (Kassem et al., 2002). Such areas may offer at least temporary refuge from warming waters resulting from climate change, and should be considered as sites or extensions of sites for conservation efforts (Done, 2001; West and Salm, 2003). Other local physical features that may create thermal refugia include proximity to deep water, shade, high wave energy and turbidity (West and Salm, 2003). Some of these have the added benefit of reducing exposure to light, including UV radiation.

Figure 1 Creating networks of reserves such as the String of MPAs along the East coast of Africa, is one approach to increasing resilience.



4. PROTECT PHYSICAL AND BIOLOGICAL HETEROGENEITY

It will not always be clear what aspects of a system confer resistance or resilience. This requires adoption of a bet-hedging strategy in which heterogeneous areas are selected for protection, providing as many options as possible. There has been limited research on this approach; however, a nice example exists involving two populations of checkerspot butterfly *(Euphydryas editha bayensis)*, with strong climatic influences on population extinction rates (McLaughlin, 2002). The population living in the more homogeneous habitat went extinct first, and prior to its extinction had more dramatic fluctuations in response to climatic changes than the population from the more heterogeneous site. This indicates that in addition to reserve size, it is important the protected area also encompass a variety of habitat types, including small-scale variability. Even for species for which we believe we know the ideal habitat type, it is possible that as the climate changes their habitat requirements will also change.

5. RESTORATION OF DEGRADED HABITATS

Some ecosystems have been dramatically degraded, but retain sufficient importance from an ecological or global biodiversity standpoint that it is worth trying to resurrect them. Mangrove forests, for example, have been substantially degraded globally yet serve an important ecosystem function when intact. In Vietnam (see details below under Case Studies) and east Africa, efforts are being made to restore mangrove forests to improve coastal protection and estuarine condition. They may also convey some advantage for nearshore coral reef systems, releasing protective CDOM (Lovelock et al., 1992; Stabenau et al., In Prep). Thus restoration of mangroves is advantageous not only for the mangrove trees themselves, but the adjacent biodiversity as well.

Restoration of seagrass beds is also recognized as environmentally and economically important, and a number of techniques for conservation and restoration have been developed (Fonseca et al., 1998). Some restoration techniques harness the natural behavior of wild animals: workers in the southern United States have installed bird roosts to provide natural fertilization for troubled seagrass beds (NOAA, 2003).

REDUCE OR ELIMINATE NON-CLIMATE STRESSES

6. ELIMINATE DESTRUCTIVE FISHING PRACTICES AND OVERFISHING

Reducing the damaging effects of destructive fishing will require creating regulations to limit these practices, as well as creation of no fishing zones to ease recovery and enforcement (Westmacott et al., 2000). To alleviate the root cause of the pressure it will be necessary to develop alternative livelihoods (Westmacott et al., 2000) or alternative techniques for fishing communities (Bryant et al., 1998). For example, in the Philippines where cyanide fishing has been a problem for decades, a government and NGO (International MarineLife Alliance) partnership has created the Cyanide Fishing Reform Program. This program trains fishermen in alternative fishing practices while the government is increasing enforcement of anti-cyanide fishing regulations. Efforts are being made to export the program to Indonesia where cyanide fishing is also a widespread concern.

7. REDUCE POLLUTION, INCLUDING TERRESTRIAL OF NUTRIENTS AND PESTICIDES

Limited research on interactions between climate and non-climate-related stresses, indicates synergistic responses (McLusky et al., 1986). For example, when rainbow trout (*Salmo gairdneri*) are exposed to the pesticide permethrin over a range of temperatures the toxicity increases as temperature increase (Kumaraguru and Beamish, 1981). Additionally, adverse effects of nutrient run-off on coastal ecosystems are well established (Koop et al., 2001) and less disturbed reefs generally have a greater likelihood of recovering from bleaching events (Brown, 1997a). Efforts to reduce pollution will generally focus on activities outside of reserves. This may require improving terrestrial land use practices to decrease nutrient and sediment run-off, eliminating local use of persistent pesticides or improving the quality of effluent from municipal and industrial sources. In the case of atmospheric deposition of contaminants the efforts will need to be similar to those needed to reduce greenhouse gas emissions. However, some atmospherically transported compounds, such as mercury, also have local sources. Mercury is used extensively in gold mining which in many cases occurs in watersheds adjacent to tropical marine systems.

8. REDUCE DAMAGING EXTRACTION

Tropical marine ecosystems have long been a source of materials to sustain life, be it food, clothing or even building materials. As human populations have grown, the extent of these extractive activities has become unsustainable. In addition to quantifying the problem of coral mining in the Maldives, Brown (1997b) has attempted to delineate alternatives for local construction. She estimates that, through increasing use of concrete blocks created from coral sand and dead coral material, local demand could be satisfied until 2050. Reducing extraction pressure on these slow recovery systems (corals, mangroves and seagrasses) will make them better able to respond to the stress of climate change. Additionally, decreasing removal of organisms and populations, increases the potential for greater genetic diversity in these systems, again increasing the likelihood that they will be better able to respond to the stress of climate change (e.g. Dodd and Rafii, 2001).

PROTECT RESISTANT AND RESILIENT POPULATIONS OR COMMUNITIES

9. IDENTIFY THOSE POPULATIONS OR COMMUNITIES THAT HAVE ENDOGENOUS FACTORS WHICH MAKE THEM LESS SUSCEPTIBLE TO THE EFFECTS OF CLIMATE CHANGE

Some populations or communities may possess endogenous factors that enhance their ability to deal with the added stress of climate change. For example, some coral bleaching events are caused by high temperatures exacerbated by UV (Lesser et al., 1990; Dunne and Brown, 2001). Zooxanthellae produce compounds called mycosporine-like amino acids (MAAs), which can effectively act as sunscreens. Concentrations of MAAs vary between species and populations (Gleason, 1993; Shick et al., 1996) and they can be induced to varying degrees by exposure to UV. It may be that some populations with naturally higher MAA concentrations, or an enhanced ability to induce these compounds during times of stress, are less prone to bleaching under combined UV/heat stress conditions. Such endogenous factors may be present in a population as a result of surviving a previous bleaching event, effectively a preadaptation (West and Salm, 2003; Done, 2001).

10. MAINTAIN DIVERSE GENE POOLS, AND NATURAL DIVERSITY OF ECOSYSTEMS

This is also a bet-hedging strategy. Since it is currently not possible to predict exactly how any location will change, it is best to retain a range of response options in ecosystems. Evolutionarily this protection from the unknown has come from genetic diversity. It is uncertain what gene or trait might confer a future advantage, but the more options you have the greater the likelihood that you have a combination that will survive (see review in Dodd and Rafii, 2001). It is similarly beneficial to maintain diversity at the species level; you never know which species will be the key to helping the system through a stressful period.

This list is by no means complete. It should be seen as a starting point for developing ideas and more importantly, for developing field testing strategies to begin assessing how these will work in your own system.

Adequate monitoring of individual sites is essential to best assess how each ecosystem is being affected and what strategies can be implemented. For example, you can only protect climate refugia if you know where they are. This monitoring must be coupled with field testing to see which strategies are most successful. In the case of climate change, it is necessary to start implementing some strategies—which can be seen as "do no harm"—before they are fully tested. Otherwise, as the effects of climate change become more apparent and pressing, it will be too late to implement many of the strategies and expect to have an enhancement in resilience or resistance.

What is Necessary to Implement These Strategies?

The first step is to gain the interest of informed resource managers and local communities. They will need to have sufficient levels of concern for their systems in relation to climate change. The next step requires involvement of stakeholders in the resilience-building process. Much of the stress of protected areas is caused by those who live outside the reserve through their competition for or damaging use of resources. More rigorous no-take and protective status enforcement, more and larger protected areas and limiting of development and extraction even outside of protected areas will not happen unless stakeholders can understand the benefit to them and are made part of the process in delineating this new level of protection. Finally, there must be vested long-term resources and vision for maintaining the protections that are created. Climate change is not a threat that can be solved in the short term. Systems will need to be resilient for decades to come and the stress will become more intense as atmospheric concentrations of CO_2 increase and temperatures rise.

Case Studies

It is crucial that we learn more about which strategies are effective and what additional factors may play a role in increasing the resistance and resilience of natural systems to climate change. Unfortunately, while there are many ideas about possible strategies, there is limited empirical evidence to aid those trying to make decisions. Waiting for full experimental conclusions before taking action is not an option. Climate change is already affecting ecosystems, and waiting could allow windows of conservation opportunity to close. There are a few studies that have begun to assess the success of various strategies and may serve as models for developing other studies.

MANGROVES

Vietnam has an extensive coastline (3000 km) with the majority of its populations living in the lowland alluvial plains. Since 1945, there has been a 45% loss in mangrove cover in Vietnam (Jameson et al., 1995), mostly due to conversion of mangrove forests to agriculture, including shrimp aquaculture (Tri et al., 1998). As previously mentioned, mangroves play an important role in coastal protection, and the plains previously protected by mangroves are threatened by rising sea level (potentially a third of the Red River's delta will be inundated) and a possible increase in the frequency of storms, such as tropical cyclones. As a result, Red Cross/Red Crescent societies are supporting efforts to restore mangroves to enhance protection for these regions. Since the project began in 1997, 18,000 ha of mangroves have been planted along 100 km of coast. The increased mangrove forest cover is improving conditions for associated species, including 109 species of bird. Harvestable marine resources also seem to be increasing in number:

areas with restored mangroves are no longer having to purchase "sea products" such as crabs from other provinces. (D. V. Tao, Pers. Comm.)

CORAL REEFS

Protecting coral reefs from the effects of bleaching might seem an impossible task. While nothing can be done to lower the temperature of the warming oceans, actions can be taken that limit other stresses that make reefs more susceptible to bleaching. In 2000, then-Governor Tauese Pita Fiti Sunia declared his intention to achieve a goal of protecting 20% of American Samoa's coral reefs in "no take" MPAs. To improve the likelihood that these MPAs would meet their long-term goals of protecting biodiversity, WWF developed a project to help identify not only the sites that are less likely to bleach and more likely to recover, but also to determine what factors account for these differences. To this end, the project is comparing seven sites with varying levels of formal protection, impact from high nutrient terrestrial run-off and concentrations of endogenous protective factors in their corals. Researchers survey the coral reefs quarterly for bleaching and recovery, monitor nutrient concentrations and water temperatures and assess the concentration of the sunscreening mycosporine-like amino acids in corals at each site. The project includes sites in protected areas such as the National Park of American Samoa and the Fagatele National Marine Sanctuary. Additionally, researchers are working with local stakeholders (managers, villages) to not only conduct the research but to begin discussions on possible response to study findings. In March of 2003, there was a bleaching event in the waters of American Samoa associated with elevated water temperatures. Bleaching ranged from 5 to 30% at the study sites. The recovery of the reefs from this bleaching event is now being tracked. WWF hopes to be able to use results over the next two years to assist in making management decisions for coral reefs in response to climate change. To this end a Coral Bleaching Monitoring Protocol is also being developed and efforts are underway to expand the approach of the American Samoa project to other coral reefs around the world.

Conclusion

Protection of natural resources from climate change will require a two-pronged approach. In addition to taking the types of measures outlined in this chapter, it will also be necessary to limit the rate and extent of anthropogenic climate change. This does not require that resource managers become advocates, but it may be useful to start documenting the impacts of climate change, the cost of preparing for the changes and the prognosis for success in responding at a local level. This information could be shared at management and scientific fora to indicate the need for broader-scale action.

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WWF Climate Change Program

Climate change poses a serious threat to the survival of many species and to the well-being of people around the world.

WWF's program has three main aims:

- to ensure that industrialized nations make substantial reductions in their domestic emissions of carbon dioxide—the main global warming gas—by 2010
- to promote the use of clean renewable energy in the developing world
- to reduce the vulnerability of nature and economies to the impacts of climate change

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WWF's mission is to stop the degradation of the planet's natural environment and to build a future in which humans can live in harmony with nature, by:

- conserving the world's biological diversity
- ensuring that the use of renewable resources is sustainable
- promoting the reduction of pollution and wasteful consumption

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