CLIMATE CHANGE AND BIODIVERSITY IN MELANESIA

Series editors:
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Climate Change Impacts on Ecosystem Resilience and MPA Management in Melanesia

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CCBM Paper 7

Funding provided by:
John D. and Catherine T. MacArthur Foundation

Bishop Museum Technical Report 42(7)

This paper is produced as part of the Climate Change and Biodiversity in Melanesia Project, funded by the John D. and Catherine T. MacArthur Foundation. The aim of this project is to assess the vulnerability of Melanesian marine and terrestrial ecosystems to projected climate changes. The CCBM Paper Series, listed below, are published as part of the larger Bishop Museum Technical Report Series.

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Introduction

Climate change poses a major threat to marine ecosystems, species, and productivity from the tropics to the poles. The marine ecosystems of Melanesia are no exception, but many may be well positioned to survive expected climate impacts, including coral bleaching, sea-level rise, ocean acidification, and increased severity of tropical storms.

Coral reefs, mangroves and seagrass beds are naturally dynamic and adaptive ecosystems (Nystrom and Folke 2001). In Melanesia they are impacted by seasonal trade winds and rainfall as well as episodic storms, flooding, tsunamis, earthquakes, volcanic eruptions, and increasingly in recent decades by such climate impacts as coral bleaching. These systems undergo continuous disturbance and change at their margins in particular, which helps form their extent and structure. The ability of these systems to absorb, resist or recover from such disturbances or to adapt to change while continuing to maintain essential functions and processes is the essence of ecological resilience (Holling 1973).

For example, tropical storms and flooding may wreak havoc on riverine mangrove systems, changing waterways and drainage patterns, isolating some pockets and uprooting others. Yet the mangrove systems survive to adapt, colonize new alluvial banks, and maintain their role in trapping sediments, cycling nutrients, and supporting fisheries. Future tropical storms are projected to be more intense, with large peak wind speeds and more heavy precipitation associated with ongoing increases in tropical SSTs (IPCC 2007). Tropical storms and floods have resulted in mass mortality in mangroves systems (Jimenez *et al.* 1985, Armentano *et al.* 1995, Cahoon *et al.* 2003), thus compromising a mangrove systems ability to reorganize and recover.

Similarly, global warming is degrading reef environments through coral bleaching and related mortality. Well managed reefs with good water quality, connectivity to larval sources, healthy herbivore populations, and a minimum of anthropogenic stressors can and have recovered strongly from mass bleaching. However, despite effective management and the minimum influence of anthropogenic stressors, small reefs that lack larval sources may not recover from mass bleaching and may experience a phase shift to an alternate state, such as an algae dominated assemblage (Hughes *et al.* 2007, Ledlie *et al.* 2007). Where tropical storms and bleaching events follow each other closely and often, as is likely under future climate scenarios (IPCC 2007, Hoegh-Guldberg and Hoegh-Guldberg 2004), the reefs may suffer massive damage and lose their resilience and ability to recover.

Sea turtles are threatened species and an important conservation target in Melanesia, which has some of the most important hawksbill and leatherback nesting populations of the Western Pacific. Turtles have demonstrated remarkable resilience, surviving millions of years and numerous previous changes in global climate. Global warming will increase turtle egg incubation temperatures, likely skewing hatchlings to all females when these temperatures reach above about 29°C (Freedberg and Wade 2001, Hays *et al.* 2003). Historically, sea-level rise has inundated and eroded nesting beaches and will do so again, leaving nesting turtles no choice but to locate alternative suitable sites. A major problem facing turtles today is that coastal development will pre-empt many potentially suitable alternative sites for turtles that lose their nesting beaches to sea level rise.

Understanding ecosystem dynamics and the factors that help them to resist or recover from perturbations can help us to develop management responses that are designed specifically to address climate change and build resilience to its impacts into marine protected areas (MPAs)[1] in Melanesia and elsewhere. The natural resilience of marine ecosystems and species populations in Melanesia are being undermined by human activities such as deforestation, mining, erosion, habitat encroachment, over-harvesting, pollution, and a host of other destructive practices. On the positive side, many parts of Melanesia are relatively undeveloped and the natural systems and species populations will retain their resilience. On the negative side, development is happening, will continue apace, and has already caused degradation or even complete loss of marine ecosystems, such as the smothering of coral reefs with silt.

Potential impacts of climate change

Global climate change, specifically increases in temperature, sea level, and CO_2, tropical storms, and precipitation, combined with anthropogenic threats will threaten the resilience of marine ecosystems and species in Melanesia.

Effects of changes in temperature

Since 1880, the earth has warmed 0.6-0.8°C (Houghton *et al.* 2001) and it is projected to warm between 2-4°C by 2100 mostly due to human activity (IPCC 2007). Mangroves are not expected to be adversely impacted by the projected increases in sea temperature (Field 1995). Some species show a declining leaf formation rate at temperatures above 25°C (Saenger and Moverly 1985), impaired seedling establishment at temperatures above 35°C (UNESCO 1992), and almost no photosynthesis at leaf temperatures of 38-40°C (Clough 1982, Andrews *et al.* 1984).

Temperature stress on seagrasses will result in distribution shifts, changes in patterns of sexual reproduction, altered seagrass growth rates, metabolism, and maintenance of carbon balance (Short *et al.* 2001, Short and Neckles 1999). When temperatures reach the upper thermal limit for individual species, productivity is reduced and the seagrasses can burn and die (Coles *et al.* 2004). Elevated temperatures increase the growth of competitive algae which can overgrow seagrasses and reduce the available sunlight they need to survive.

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[1] MPAs are interpreted here in the internationally accepted context, which is broader than often applied in the USA: Any area of intertidal or subtidal terrain, together with its overlying water and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part or all of the enclosed environment (Kelleher, 1999).

Elevated sea surface temperature (SST) working synergistically with increased light levels is the principal cause of mass coral bleaching. SSTs of 1-2°C above the average annual maximum are sufficient to stress corals and induce bleaching. If the heat stress is too acute or maintained for too long, the corals will die. Stress resulting from elevated SSTs also increases the incidence of coral disease (Rosenberg and Ben-Haim 2002). The degradation of coral reefs caused by mass bleaching and impaired growth may adversely impact mangrove and seagrass systems that depend on the reefs to provide shelter from wave action.

Effects of changes in CO_2

Atmospheric CO_2 has increased from 280 parts per million by volume (ppmv) in 1880 to nearly 379 ppmv in 2005, and about 30% of all atmospheric CO_2 resulting from fossil fuels has been taken up by the ocean (IPCC 2007).

For seagrasses, the effect of increases in CO_2 will vary according to species and local environmental condition, but scientists predict that short-term CO_2 enrichment will lead to increases in photosynthesis, growth, total biomass, root/shoot ratio, and tissue carbon/nitrogen ration (Short and Neckles 1999, Duarte 2002). For mangroves, increased levels of CO_2 are expected to enhance photosynthesis and mangrove growth rates (UNEP 1994). For example, increased levels of CO_2 significantly increased photosynthesis and the average growth rates in two Australian mangrove species found in Melanesia, *Rhizophora stylosa* and *Rhizophora apiculata*, but only when grown at lower salinity levels (Ball *et al.* 1997). The differential response of different seagrass and mangrove species to increased CO_2 levels could alter the species composition of existing communities and favour certain algae that overgrow seagrasses (Beer and Koch 1996).

Increased CO_2 leads to acidification of ocean water and decreased calcification and growth rates of corals (Kleypas *et al.* 2001, Langdon, 2003, Buddemeier *et al.* 2004), weakening coral skeletons and making them more prone to breakage.

Effects of changes in precipitation

By 2050, a 25% increase in precipitation rates is predicted due to global warming. However, the precipitation will be unevenly distributed with either increases or decreases in different locations (Knutson and Tuleya 1999, Walsh and Ryan 2000, Houghton *et al.* 2001).

Decreased precipitation results in lowered mangrove productivity, growth, and seedling survival, and may change species composition favoring more salt tolerant species (Ellison 2000, 2004). It is also likely to result in decreased mangrove area and diversity and loss of the landward zone to barren hypersaline flats (Snedaker 1995). Increased precipitation may increase mangrove area, diversity of mangrove zones, and mangrove growth rates in some species (Field 1995) and may also allow mangroves to migrate into and replace salt marsh vegetation (Harty 2004).

Increased precipitation is likely to increase run-off, erosion, and silt deposition in the inshore environment. This will increase turbidity and reduce primary productivity in nearshore waters, and smother fringing reefs and seagrasses with silt.

Effects of changes in hurricanes and storms

Climate change will also cause tropical storms to increase in intensity (IPCC 2007) and possibly to increase their frequency (Trenberth 2005) further stressing mangroves and coral reefs in particular. Large storms can cause considerable damage to mangrove forests, coral reefs, and seagrasses. The species composition and structure of these ecosystems may change because of differences among species to tolerate storm waves and to regenerate (Roth 1997). Storm surges may flood mangroves, covering their aerial roots for prolonged periods, and cause them to drown (Ellison 2004). Storm waves and surges may also erode seagrass beds, break or move coral colonies, and redistribute sediments over seagrasses and coral colonies, smothering them.

Effects of changes in sea level

Sea-level rise projections for the end of the 21st century (relative to 1980-99) range from 0.18 - 0.59 m (IPCC 2007). However, these estimates are considered low by many scientists because they do not take into account melting of the Greenland and Antarctic ice sheets. The melting of the ice sheets can contribute meters of sea level rise, thus scientists now suggest that a 1 – 5 m rise in sea level by 2100 is more likely (Overpeck *et al.* 2006, Hansen 2007, Rahmstrof 2007). Sea-level changes will also be decreased or accelerated by tectonic and isostatic adjustments (i.e., ocean basin deformation and land subsidence or emergence) (Kennish 2002).

Sea-level rise is the greatest climate change challenge that mangrove ecosystems will face (Field 1995). Mangroves may adapt to changes in sea level by building peat and growing upward in place, or by expanding landward or seaward if adequate expansion space exists. However, their ability to migrate landward is determined by local conditions, such as infrastructure (e.g., roads, seawalls, and shipping channels) and topography (e.g., steep slopes and cliffs). If inland migration or peat accumulation cannot occur fast enough to keep pace with the rise in sea level, mangrove forests will become progressively narrower and may disappear from certain parts of their present range. Also, reduction or diversion of sediment supply into estuaries will compromise the mangroves' ability to colonize prograding alluvial deposits and expand seaward. Mangroves on small low-lying islands that have no external sources of sediment or higher ground for expansion will likely disappear.

Seagrasses isolated on submerged banks will eventually die off as depth increases and light becomes too attenuated to support their continued growth. Coral growth rates are adequate to keep pace with predicted sea-level rise. However, their ability to keep pace with sea-level rise may be compromised if growth rates are slowed by acidification.

Managing for climate change

We need to recognize a fundamental truth: the only long-term solution for addressing climate change is to roll back greenhouse gas emissions to tolerable levels. We need to lend whatever support we can to this mitigation effort until it yields positive results, while doing all we can to ensure the survival of ecosystems and species in the interim.

If we were to be able to address climate change simply by coming up with management strategies that promoted adaptation in natural systems and populations, we would be lucky indeed. The challenge is larger than that and confounded by an overlay of anthropogenic stressors that further weaken ecosystems, inhibit their ability to recover or adapt, and hasten phase shifts to irretrievably altered states or local extinction of populations. Designing and managing marine protected areas (MPAs) for resilience offers us a potentially effective means to address the present climate and anthropogenic challenges, as well as the uncertainties of the future.

Because of our limited understanding of the impacts of climate change on marine ecosystems in Melanesia and how to address them, it is difficult to propose with confidence specific management strategies for climate change adaptation. Consequently, it becomes increasingly critical to maximise the resilience or capacity of the ecosystem to cope with changes generally. Management for resilience is thus not only a general strategy for conservation, but an important part of responding to the impending threat and uncertainties of climate change (Salm *et al.* 2001, 2006, Salm and Coles 2001, Hughes *et al.* 2003).

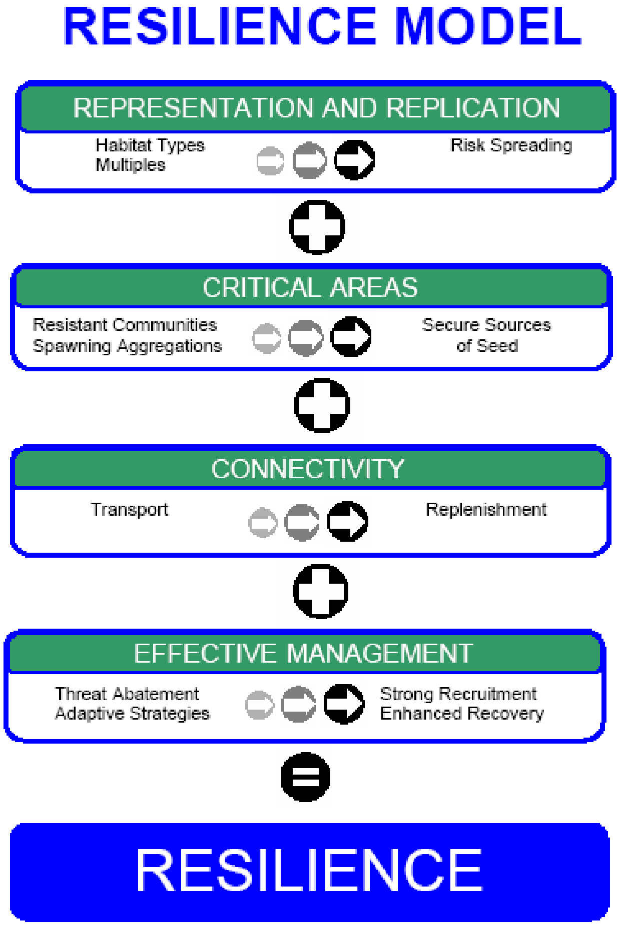
MPAs have been identified as one of the most effective tools for conserving reefs and related marine systems (Lubchenco *et al.* 2003, Palumbi 2003). However, MPA managers will need to incorporate climate change along with increasing human impacts into their conservation strategies, or MPAs may not be able to safeguard biodiversity and resource values effectively. Networks of MPAs, including no-take areas, provide a critical means to protect marine systems from human stresses and, if designed for resilience, from climate change stressors as well.

Key to addressing climate change impacts is being prepared – this requires acknowledging the threat it poses and being proactive in developing and applying adaptation strategies and building sufficient flexibility into management systems to enable adaptive responses.

What Can MPA Managers do?

While there is little that MPA managers can do to control climate change, the “Resilience Model” (Figure 1) developed by the Nature Conservancy, provides a simple tool that is being increasingly used to build resilience into MPA networks (TNC 2004, Salm *et al.* 2006). The four strategies of the model and their application to MPA network design are described below.

Figure 1. The Nature Conservancy's Resilience Model



Strategy 1: *Apply risk-spreading strategies to address the uncertainties of climate change:* Protect multiple examples of a full range of habitat types, seeking to represent the area's total biodiversity. Replication within each habitat type reduces the chance of any one type being completely compromised by an unmanageable impact such as a major bleaching event.

To fully represent regional biodiversity within MPAs, aim to protect 30% of the complete range of habitat types. For example, include samples of offshore reefs (barriers, atolls) in areas with greater and lesser wave energy and exposure to trade wind, mid-shelf reefs (patch and fringing reefs) where these exist, and inshore fringing and patch reefs in sheltered locations. For mangroves, include samples of fringing, overwash island, riverine, and basin forests in areas with varying salinity, tidal fluctuation, and sea level (McLeod & Salm 2006). For long, linear coastlines, samples of all these habitat types should be selected at regular intervals. Wherever possible, aim to include at least three samples of each habitat type in MPA networks or larger management frameworks, such as multiple-use MPAs or areas under rigorous integrated management regimes. Maintaining biodiversity can enhance resilience if sufficient functional redundancy exists to compensate for species/habitat loss (Bellwood *et al.* 2004). This approach also has the advantage of protecting essential habitat for a wide variety of commercially valuable fish and macroinvertebrates.

Managers will need to develop a classification scheme of habitat types and major zones, and categorize these by their biodiversity, condition, level of threat, resilience, and ecosystem services.

Strategy 2: *Protect critical areas that are resilient to climate change and that serve as refuges to reseed affected areas:* Identify and fully protect communities or habitats that have resisted or recovered rapidly from climate change impacts and that can serve as refuges and provide seed to repopulate and enhance recovery of areas damaged by catastrophic events.

For example, by analysing local environmental factors, managers can identify areas of cooling, shading, screening, stress tolerance, and strong currents that contribute to coral community resistance and resilience to mass bleaching (Salm *et al.* 2001, West and Salm 2003, Salm *et al.* 2006, Grimsditch and Salm 2006). For mangrove ecosystems, local conditions like the presence of sediment-rich, macrotidal environments, and the availability of freshwater to compensate for increased salinity, will aid mangrove survival and increase their resilience to sea-level rise (McLeod and Salm 2006). These refugia should be incorporated into MPA design or otherwise included into integrated coastal management programs.

Refugia must be large enough to support high species richness. Large areas of suitable habitat maintain high species richness as well as high genetic diversity because they may support larger populations that produce more offspring (Palumbi 1997, Bellwood and Hughes 2001). Aim for these areas to be 10-20 km across.

Areas that demonstrate persistence over time are important sites to protect. Indicators of mangrove persistence may include a range of small young and large old trees as well as mangrove roots with dense epibiont communities such as oysters, sponges, tunicates, and corals. Finally, mangrove forests with abundant mature trees producing a healthy supply of seeds and propagules should be protected as sources for colonizing new areas and repopulating areas damaged or destroyed by a disturbance (Nystrom and Folke 2001). Indicators of coral persistence include high coral cover, presence of large, old colonies, and a range of colony size classes demonstrating active recruitment

Viewed in a larger geographic and longer temporal context, the Raja Ampat Islands to the west of Indonesia’s Papua Province provide an example of a place that has survived climate change impacts. This group of islands, which has over 75% of the world’s known reef building corals, is located in a major convergence of marine currents that circulate nutrients, transport larvae through the islands, and cool its waters, protecting the reefs from bleaching effects. The high biodiversity and apparent lack of coral bleaching, suggest that Raja Ampat is a key refuge, both as a major reservoir of biodiversity and as a secure source of seed for Papua New Guinea reefs connected to it by currents. Historically, this region has been important in generating, maintaining and dispersing genetic diversity across large geographic areas of the Indo-West Pacific (Grigg 1988, Veron 1995) and is a strategically important area for anchoring coral reef conservation efforts in Melanesia.

Strategy 3: *Understand and preserve connectivity between habitats to enhance mutual replenishment and recovery and to maintain functional linkages among associated habitats:* Identify patterns of connectivity among source and sink areas and among associated habitats (such as coral reefs, mangroves and seagrass beds), so that these can be used to inform site selection in the design of MPA networks, ensuring strong recruitment and recovery of damaged or depleted areas. Maintain critical habitats for different life stages of key species, and provide stepping-stones for species dispersal over longer time frames.

Connectivity describes the natural linkages among habitats and ecosystems that result from the dispersal of organisms by ocean currents and active migration. The strength of connectivity depends on the abundance and fecundity of source populations, the longevity and pre-competency periods of their larvae, and the spawning sites and movement patterns of adults. Connectivity is thus a key driver of the level and reliability of biodiversity replenishment in habitats damaged by natural or human-related agents, including climate change.

Mangroves, reefs, and fisheries often have a synergistic relationship, based on their connectivity (Mumby *et al.* 2004). Coral reefs buffer ocean currents and waves to create a suitably sheltered environment for mangroves and seagrasses. Mangroves and seagrasses filter freshwater discharge from land, trap silt, heavy metals, and nutrient rich run-off, and stabilize sediments, thus maintaining the water quality necessary for coral reef growth and healthy fish communities. Mangroves and seagrasses also enhance the biomass of coral reef fish species through the provision of food and nutrients. Mangroves are important intermediate nursery habitats between seagrass beds and patch reefs that increase young fish survival. Consequently, MPA managers should secure pathways of connectivity among them to enhance resilience (Mumby *et al.* 2004) and fisheries. Areas where mangroves benefit adjacent ecosystems by filtering sediments and pollutants or providing nursery habitats should be protected.

Managers should also endeavour to maintain the connectivity between mangrove systems and upland water catchments to ensure adequate supplies of sediment and freshwater necessary for mangrove peat formation, growth, and reproduction. This will increase the chances of mangrove growth keeping pace with sea-level rise.

Strategy 4: *Manage ecosystems for both health and resilience, and monitor multiple indicators of the effectiveness of these actions as the basis for adaptive management:* Control human threats to MPAs and their conservation targets, monitor the response of species, communities, and ecosystems to climate change, and manage adaptively to compensate for changes in species ranges and environmental conditions and accommodate new science-based strategies as knowledge increases.

Because unstressed ecosystems will be better able to resist shocks and adapt to change, MPA managers will need to reduce anthropogenic threats to them and thereby strengthen their resilience to climate change. Such threats to mangroves and coral reefs are expected to increase with climate change. For example, seawalls and dykes may be built to protect low-lying areas from erosion and flooding caused by sea-level rise. These structures may prevent mangroves from retreating landward in response to sea-level rise or they may accelerate coastal erosion and cause redistribution of sand over coral reefs and seagrass beds. Sea-level rise and storm damage may intensify demand for mangrove timber and coral blocks for coastline protection and repair of houses damaged by flooding. MPA managers will need to look beyond marine ecosystems and collaborate with others to integrate marine conservation with land-use practices.

Establish buffer zones

It is important to establish buffer zones bordering the seaward and landward margins of MPAs to provide a transition of partial protection to the intensively used land and sea areas surrounding human settlements. Such buffer zones will become increasingly important as sea level rises, potentially expanding the extent of some shallow water and coastal habitats for expansion of coral reefs and mangroves. To plan proactively for landward migration in areas where mangroves have the potential to expand, the adjacent land gradients should be used to determine how wide a buffer is necessary to accommodate the mangrove migration for different sea-level rise projections.

Mangrove greenbelts are useful buffers that can provide significant coastal protection from erosion and should be set aside along erosion-prone coastlines and riverbanks and in areas which experience significant damage from storms and tidal surges, cyclones, and geomorphic erosion (Macintosh and Ashton 2004). Aim to set aside greenbelts of at least 100m width (preferably 500m where feasible) along open coasts, 30-50m wide along riverbanks, and >10 m around islands, creeks and channels (Macintosh and Ashton 2002, Macintosh and Ashton 2004).

Restore degraded critical areas that have high survival prospects

Areas that are currently degraded but that meet resilience criteria (See West and Salm 2003, McLeod and Salm 2006) should be restored. For the restoration of degraded coral reefs, it is critical to stabilize substrates, improve water quality, and control or remove macroalgae. The most successful and cost-effective approach for mangrove restoration is through restoring tidal hydrology through excavation or back-filling and/or reconnecting blocked areas to normal tidal influences (Lewis and Streever 2000).

The concept of Local Managed Marine Areas (LMMAs) is well tested and successfully applied in Melanesia, providing a potentially practical platform for involving local people in ecosystem restoration activities.

Manage Functional Groups

A functional group is a collection of species that perform a similar function, irrespective of their taxonomic affinities (Steneck and Dethier 1994). Some areas have more species in each functional group; thus they have functional redundancy. Communities with functional redundancy may have a better chance of recovery if one species is lost from a functional group. The concept of functional group management has been best considered for coral reefs.

For example, bioeroders, grazers, and scrapers are three functional groups of herbivores that play complementary roles in controlling algal cover, reducing algal competition with corals, and in preconditioning reefs to facilitate coral recovery, all of which are required to maintain reef resilience (Bellwood *et al.* 2004, McCook *et al.* 2007). A dense cover of algae over the reef substrate can pre-empt coral recruitment and will retard or even prevent coral recovery following a mass die-off. MPA managers will need to monitor herbivore populations and take measures to regulate fisheries before they show signs of depletion. When top-level fish predators are fished out, populations of such lower level grazers as sea urchins explode. In such circumstances, reef surfaces are eroded, coral recruits are destroyed, and grazing rates can become too high for corals to re-establish themselves (McClanahan 1997). Some balance in herbivore species, size classes and grazing levels is important for MPA managers to establish and maintain.

Manage water quality

Managers can manage water quality by addressing sources of pollution, especially enrichment of water, which creates conditions that favor algal growth and prevent coral larvae from settling. To manage water quality effectively, managers should link their MPAs into the governance systems of adjacent areas, as well as controlling the pollution sources within their own boundaries.

Implement Monitoring and Adaptive Management

Ecosystem management needs to be adaptive and informed by developing science, the findings of ongoing monitoring activities, and changes relative to established baselines. Monitoring programs measure change against indicators of ecosystem condition, uses, and levels of threat. Such programs provide useful time series data that can yield important information on ecosystem dynamics, long-term trends for key species, habitats, and resource uses, and their recovery response and potential following over-exploitation or severe damage from catastrophic events, including climate change impacts. As such, monitoring provides key information to inform adaptive management and can lead to changes in MPA design and zoning and in management strategies, intensity, and geographic focus.

There is no substitute for direct field observations in tracking the course, impact and recovery of an event, such as a mass bleaching, disease outbreak, or storm damage. This will help MPA managers to understand the vulnerabilities and diverse responses of key species and communities in different locations to climate change, to identify places of greater or lesser resilience, and review and revise MPA zoning and management plans.

Because of the anticipated increasing level of both anthropogenic and climate change threats on marine ecosystems in Melanesia, establishing baseline data for these systems is urgent and essential. Data should include a range of variables relating to areal extent, degree of development, biodiversity, resilience, resource use and values, threats, dependence by local communities, critical species habitats, etc. with details specific to each site. These data provide the baseline from which to measure long-term trends and the ability of species, habitats, and ecosystems to cope with climate change.

If conservation strategies are to be successful in protecting species and habitats, they will need to adapt to the changing climate conditions. The ability to predict the location of future habitat sites, and build these potential sites into MPA design and adaptation, will be a crucial element of long-term planning to ensure sustainable MPAs in the face of global change. Flexible strategies and boundaries should be established and tracked to allow for adaptive management.

Link to broader management frameworks

The most robust configuration for an MPA system would be a network of no-take areas nested within a broader management framework that controls the impacts of activities beyond the borders of the MPAs (Salm *et al.* 2006), such as a vast multiple use reserve managed for sustainable fisheries as well as the protection of biodiversity. MPA networks should be integrated with coastal zone management regimes to enable effective control of threats originating upstream and to maintain high water quality (Done and Reichelt 1998).

Develop sustainable livelihoods

Expanding the number and area of MPAs increases the restrictions on people’s activities, access, and resource uses. Effective management must therefore address the socioeconomic impacts of both the climate events themselves, and of the conservation measures introduced to counteract them. While local stewardship and sustainable harvest of marine resources still offers great promise in Melanesia where strong traditional rights and management structures persist, traditional practices – including locally managed marine areas – need to be nested within more robust and enduring governance frameworks to help ensure that they survive change. They also need to be buffered against increased demands for food and income by the development and introduction of alternative sustainable livelihoods as societies shift from subsistence based to cash economies.

Scientists and practitioners now recognize that governance and management frameworks should include diverse patterns of resource use to maintain social and ecological resilience (Adger *et al.* 2005). Alternative livelihood options and diverse income opportunities allow communities to be flexible to adapt to social, political, and economic changes.

Conclusion

Given that climate will continue to stress tropical marine ecosystems for decades to come, even were carbon emissions to be reduced from today onward, our only hope is to alleviate the impacts of climate change and implement actions that build resilience into these ecosystems. Strategically placed and well-managed MPA networks that are specifically designed for resilience to climate change offer the most viable means of protecting and conserving key marine species and ecosystems in perpetuity.

The development of MPA networks that are resilient to the impacts of global climate change in the seas of Melanesia requires an integrated multidisciplinary approach that includes:

- collaboration among government agencies, conservation organizations, the private sector, and local communities
- policy reform to build flexibility into formal MPA designations and require periodic review and revisions of their boundaries, zones and management strategies
- scientific research to increase understanding of resilience, including factors determining resistance and connectivity, and the principles guiding MPA network design
- adaptive management of MPAs to enable effective response to change in climate, demands, and pressures on the MPAs
- increased levels of scientific support for locally managed marine areas to ensure that they are located, designed, and managed to be resilient to climate change.

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