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Designing marine protected area networks to address the impacts of climate change

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Principles for designing marine protected area (MPA) networks that address social, economic, and biological criteria are well established in the scientific literature. Climate change represents a new and serious threat to marine ecosystems, but, to date, few studies have specifically considered how to design MPA networks to be resilient to this emerging threat. Here, we compile the best available information on MPA network design and supplement it with specific recommendations for building resilience into these networks. We provide guidance on size, spacing, shape, risk spreading (representation and replication), critical areas, connectivity, and maintaining ecosystem function to help MPA planners and managers design MPA networks that are more robust in the face of climate change impacts.

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Scientists have predicted a dire future for the world's coral reefs, including a 70% loss of reefs by 2050 (Wilkinson 2000) and their descent down the "slippery slope to slime" (Pandolfi *et al.* 2005), which refers to a shift from a coral to an algal-dominated environment. To protect marine biodiversity and associated ecosystem services, marine protected area (MPA) networks are being established worldwide. In this paper, MPAs are defined as "any area of the 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). An MPA network is a "collection of individual MPAs operating cooperatively and synergistically, at various spatial scales, and with a range of protection levels, in order to fulfill ecological aims more effectively and comprehensively than individual sites could alone" (WCPA/IUCN 2007).

Marine protected area managers in the 21st century continue to be faced with the threats of overfishing, destructive forms of fishing, pollution, and coastal development; now, they must also address climate-change impacts that can adversely affect marine environments, such as increasing temperature, sea-level rise, and ocean acidification.

In a nutshell:

- Climate change impacts threaten the survival of marine ecosystems
- Recommendations are needed to ensure that MPA networks are effective in conserving biodiversity and fisheries
- Recommendations that specifically address climate-change impacts will help MPA planners and managers to protect marine biodiversity and associated ecosystem services

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Designing MPA networks without taking these climate impacts into account could result in major investments being made in areas that will not survive the next several decades. Although numerous papers outline MPA design criteria, including recommendations on MPA size, shape, and spacing (eg Ballantine 1997; Airame *et al.* 2003; Botsford *et al.* 2003; Friedlander *et al.* 2003; Halpern 2003; Roberts *et al.* 2003a, b; Shanks *et al.* 2003; Fernandes *et al.* 2005; Mora *et al.* 2006), they do not specifically address the threats represented by climate change.

To address this gap, we propose a list of general recommendations for best practices in MPA network design (size and shape recommendations) and specific ones that will help managers to build resilience to climate change into these networks (Table 1). The specific recommendations include identification and inclusion of key refuges (eg sites resistant to bleaching) that will survive and provide the larvae needed to reseed areas that succumb to coral bleaching, pathways of connectivity that link these refuges with damaged areas, and measures to build redundancy into networks, thereby ameliorating the risk that climate-change impacts will result in irrevocable biodiversity loss. To address the uncertainty associated with increases in sea temperatures, we recommend selecting MPAs in a variety of temperature regimes, to increase the likelihood that some reefs will survive future bleaching events. These recommendations, combined with existing biophysical principles, allow managers to design MPA networks that are more likely to survive, despite climate-change impacts. While both biophysical and social factors must be taken into account in MPA network design, this paper focuses on the former only.

Resilience

Ecosystem resilience refers to the ability of an ecosystem to maintain key functions and processes in the face of stresses or pressures, either by resisting or adapting to

Figure 1. *Indicators of coral reef resilience include high recruitment, high diversity, broad size/age range, healthy and disease-free corals, healthy populations of herbivorous fishes, and a history of surviving stress.*

change (Holling 1973; Nyström and Folke 2001). For coral reefs, resilience relates to a reef ecosystem's ability to recover from a disturbance, to maintain the dominance of hard corals, and/or to maintain morphological diversity as opposed to shifting to an algal-dominated state or a single coral morphology (Marshall and Schuttenberg 2006). Indicators of resilience in coral reefs include high periodic recruitment, healthy and disease-free corals, a range of coral colony sizes and ages (suggesting persistence and recruitment over time), and robust populations of herbivorous fishes (Figure 1).

Resilience indicators can also be applied to other systems, such as mangroves (McLeod and Salm 2006). For example, mangroves that demonstrate high recruitment, indicated by the presence, variety, and abundance of established mangrove propagules, and a range of sizes of mangroves (from new recruits to maximum size classes) suggests effective survival and recruitment over time. Mangroves backed by low-lying natural areas (allowing for landward migration) and mangroves on actively accreting coasts or deltas (allowing for peat build up) are more likely to survive rises in sea level.

MPA size

There is no ideal size applicable to all MPAs; size should be determined by the specific management objectives for each MPA and the species and habitats targeted for protection. In broad terms, MPAs must be large enough to protect the suite of marine habitat types and the ecological processes that take place within their boundaries, including movement patterns of mobile species. Although there is no biological upper limit to MPA size, such practical considerations as cost or user conflict (Roberts *et al*. 2003a) will generally impose limits. A small MPA (< 1 km^2) may be sufficient to protect a discrete critical habitat, such as a fish spawning aggregation or turtle nesting beach, but will be insufficient to protect the full compliment of biodiversity for any reef system. The advantage of smaller MPAs is that they are often easier to enforce and monitor compared to larger areas. Also, small areas can attract a higher degree of local support and cost less to manage, especially where there is a history of locally managed reefs (eg Melanesia and the Pacific Islands). Larger MPAs are more likely to support high genetic diversity, because they tend to support larger populations, which produce more offspring (Palumbi 1997), and to accommodate the movements of mobile species. Larger MPAs can also reduce the impacts of disasters, because they provide more individuals to re-establish damaged populations following disturbance (Airame 2003); on the other hand, large MPAs are more likely to infringe on local fishing grounds and are therefore at greater risk of losing the support of concerned communities. However, a few large MPAs may be preferable to many smaller ones, because edge effects are reduced, and multiple smaller MPAs may be more difficult to monitor than a single area of equal total size (Roberts *et al*. 2001). Both large and small MPAs have value, and the selection of size should be based on local management objectives and enforceability. The most effective configuration would be a network of highly protected areas, meeting minimum size requirements (Table 1), and nested within a broader management framework. Such a framework could include a vast, multiple-use reserve, managed for sustainable fisheries as well as the protection of biodiversity. The ideal MPA network would be integrated with coastal management regimes, to enable effective control of threats originating upstream and to maintain high water quality (eg Done and Reichelt 1998).

Recommendations for a minimum MPA size range from 4–20 km in diameter to effectively conserve biodiversity (Salm 1984; Friedlander *et al*. 2003; Shanks *et al*. 2003; Fernandes *et al*. 2005; Mora *et al*. 2006). Based on these examples from temperate and tropical systems, we recommend that the minimum diameter of an MPA should be 10–20 km, to ensure exchange of propagules among protected benthic populations (Friedlander *et al*. 2003; Shanks *et al*. 2003; Fernandes *et al*. 2005; Mora *et al*. 2006). While MPAs that are 10–20 km in diameter may protect the majority of benthic species, they offer little protection for highly migratory or mobile species (eg turtles,

Table 1. General recommendations for resilient MPA network design

Category	*Recommendations*
Size	"Bigger is better" – MPAs should be a minimum of 10–20 km in diameter to be large enough to protect the full range of marine habitat types and the ecological processes on which they depend (Palumbi 1997; Friedlander *et al*. 2003; Palumbi 2004; Fernandes *et al*. 2005; Mora *et al*. 2006; Green *et al*. 2007), and to accommodate self-seeding by short distance dispersers.
Shape	Simple shapes should be used, such as squares or rectangles, rather than elongated or convoluted ones, to minimize edge effects while maximizing interior protected area (Carr *et al*. 2003; Friedlander *et al*. 2003; California Department of Fish and Game 2007).
Risk spreading (representation, replication, and spread)	Representation: protect at least 20–30% of each habitat type (Bohnsack *et al*. 2000; Airame *et al*. 2003; Fernandes *et al*. 2005; Green *et al*. 2007). Replication: protect at least three examples of each marine habitat type (Fernandes *et al*. 2005; Salm *et al*. 2006; Green *et al*. 2007). Spread: ensure that replicates are spread out to reduce the chances they will all be affected by the same disturbance event (Salm *et al*. 2006; Green *et al*. 2007). Select MPAs in a variety of temperature regimes using historical sea-surface temperatures and climate projections to ameliorate the risk of reefs in certain areas succumbing to thermal stress caused by climate change.
Critical areas	Protect critical areas that are biologically or ecologically important, such as nursery grounds, spawning aggregations, and areas of high species diversity (Green *et al*. 2007). Protect critical areas that are most likely to survive the threat of climate change (eg areas that are naturally more resilient to coral bleaching; Roberts *et al*. 2003b; Salm *et al*. 2006; Green *et al*. 2007). These may include areas cooled by local upwelling, areas shaded by high, steep-sided islands or suspended sediments and organic material in the water column, reef flats where corals are adapted to stress, and areas with large herbivore populations that graze back algae and maintain suitable substrates for coral larvae to settle on.
Connectivity	Take biological patterns of connectivity into account to ensure MPA networks are mutually replenishing, to facilitate recovery after disturbance (Roberts *et al*. 2003b; Green *et al*. 2007). MPAs should be spaced a maximum distance of 15–20 km apart to allow for replenishment via larval dispersal (Shanks *et al*. 2003; Mora *et al*. 2006). Accommodate adult movement of mobile species by including whole ecological units (eg offshore reef systems), including a buffer around the core area of interest. Where this is not possible (eg coastal fringing reefs), protect larger versus smaller areas (Fernandes *et al*. 2005; Green *et al*. 2007). Take connectivity among habitat types into account by protecting adjacent areas of coral reefs, seagrass beds, and mangroves (Roberts *et al*. 2003b; Mumby 2006; Green *et al*. 2007). Model future connectivity patterns to identify potential new coral reef substrates, so that measures can be taken to protect these areas now, and accommodate expansion of coral distribution to higher latitudes.
Maintain ecosystem function	Maintain healthy populations of key functional groups, particularly herbivorous fishes that feed on algae, facilitating coral recruitment and preventing coral–algal phase shifts following disturbances (Bellwood *et al*. 2004; Hughes *et al*. 2005).
Ecosystem-based management	Embed MPAs in broader management frameworks that address other threats external to their boundaries (eg integrated coastal zone management or an ecosystem approach to fishing; Salm *et al*. 2006; Green *et al*. 2007). Address sources of pollution (especially enrichment of water), which create conditions that favor algal growth and prevent coral larvae from settling. Monitor changes in precipitation caused by climate change that may increase runoff and smother reefs and seagrass beds with sediment.

sharks, and large bony fishes) that may spend large portions of their lives outside MPAs. Recommendations to safeguard these species include protecting critical areas (eg predictable breeding and foraging habitats and migratory corridors, where practical) within MPAs and ensuring that these areas have extensive buffers, in addition to establishing fisheries regulations to avoid overfishing.

MPA shape

Few recommendations have been made regarding the ideal shape of an MPA, although a few notable exceptions include Friedlander *et al.* (2003) and the California Department of Fish and Game (2007). For example, shapes that allow for clear marking and enforcement of boundaries (eg straight-line borders) and that also incorporate biological considerations are recommended (Friedlander *et al.* 2003), and simple shapes (ie shapes with low perimeter-to-surface area ratio) are preferred over highly convoluted boundaries. Ultimately, the shape of the MPA will be site specific, based on biophysical characteristics, including local bathymetry, nutrient upwellings, habitat complexity, species distribution and abundance (California Department of Fish and Game 2007), and enforcement feasibility.

Edge effects are an important consideration for MPA shape. These occur when MPA boundaries are extensively fished and adjacent habitats do not offer the same refuge to harvested species as those that are toward the center of the MPA. Greater amounts of edge habitat can also lead to negative effects on "interior" target species (Carr *et al.* 2003). The ideal shape of an MPA is therefore one that minimizes edge effects while maximizing interior protected area.

Risk spreading (representation, replication, and spread)

Recognizing that the science underlying resilience to climate change is still developing and that climate change will not impact marine species equally everywhere, strategies for spreading the risk must be built into MPA network design. To spread the risk of losing one habitat type in a bleaching event or other natural disaster, managers should protect multiple examples of the full range of marine habitat types (Ballantine 1997; Salm *et al.* 2006), spread them out to minimize the chance that they will all be wiped out by the same disturbance (Green *et al.* 2007), and include these examples in MPA networks (Salm *et al.* 2006). Protecting multiple replicates of each habitat type and spreading them out ameliorates the risk of climate change, because if one example of a habitat is destroyed, others may remain to provide the larvae required to replenish these areas (Green *et al.* 2007). While the exact number of replicates will be determined by a balance of the desired number and such practical concerns as funding and enforcement capacity (Airame *et al.* 2003), at least three replicates are recommended to effectively protect a particular habitat or community type (Fernandes *et al.* 2005).

These marine habitat types include the critical habitats of target species, coral reef types (taking geomorphology into account), distance to shore and varying degrees of exposure to wave energy (eg offshore, mid-shelf, and inshore reefs), seagrass beds, and a range of mangrove communities (eg riverine, basin, and fringe forests in areas of varying salinity, tidal fluctuation, and sea level). For long, linear coastlines, samples of all these reef types should be selected at regular intervals along the coast and reef tract.

The best available information suggests that 20%–30% of each habitat type should be included in MPA networks, based on guidelines developed in temperate and tropical systems from Australia's Great Barrier Reef to the US (Bohnsack *et al.* 2000; Day *et al.* 2002; Airame *et al.* 2003; Fernandes *et al.* 2005). By protecting a representative range of habitat types and communities, MPA networks have greater potential to protect a region's biodiversity, biological connections between habitats, and ecological functions (Day *et al.* 2002).

Selecting MPAs in a variety of temperature regimes spreads the risk of reefs in certain areas succumbing to thermal stress caused by climate change. Analyses of historical sea-surface temperatures (SSTs), and projections of SSTs using satellite data and climate models, yield sea-temperature patterns that may indicate reefs with higher or lower vulnerability to coral bleaching. The SST patterns alone may not accurately predict bleaching and coral survival; therefore, these patterns must be compared with bleaching history. For example, corals that experience chronic spikes in temperature may seem more vulnerable to bleaching, but these corals may be adapted to thermal stress, and thus more likely to survive increases in water temperature.

In addition to historical analyses of SSTs, a variety of tools are available that monitor SST anomalies and accumulated heat stress and function as early warning systems for coral bleaching (eg "hotspots" and "degree heating weeks", a measure of thermal stress on coral reefs; Strong *et al.* 2006). However, these products are not always accurate in predicting the severity of bleaching at regional or local scales (McClanahan *et al.* 2007). Therefore, combining satellite data with in situ reef monitoring data is essential for determining the extent and intensity of bleaching during anomalous warm-water events. General circulation models at a higher grid resolution, and hydrodynamic models that can describe surface heating and local upwellings, are being developed; these products are crucial for refining projections of reef response to climate impacts (Donner *et al.* 2005). The ability to predict bleaching events allows managers to respond rapidly when such an event occurs. Rapid response is critical for collecting accurate coral bleaching and recovery data, which can be used to verify MPA network design. Areas where recovery is consistently high are good choices for inclusion in networks, and areas that consistently avoid bleaching or mortality are essential to include in such networks.

Critical areas

Consistent with current practice, areas that are biologically or ecologically important should be identified and included in MPA network design (Figure 2). These critical areas include nursery grounds, fish spawning aggregation sites, regions that feature high species diversity or high rates of endemism, and areas that contain a variety of habitat types in close proximity to one another (Sadovy 2006). It may be important to include areas that exhibit high productivity, predictable upwelling, and efficient larval retention as well (Palumbi 2001).

In addition, it is essential to protect areas that may be naturally more resistant or resilient to the threat of climate change. For example, some coral communities may resist bleaching due to environmental and/or genetic factors, or may recover rapidly after disturbance. These refuges provide secure and essential sources of larvae to enhance the replenishment and recovery of reefs damaged by bleaching, hurricanes, or other events (Salm and Coles 2001; West and Salm 2003). A variety of biological and environmental factors appear to influence the differences in responses to bleaching among various coral communities, making some communities more resistant or resilient to these events. Some corals are genetically able to withstand larger increases in temperature due to greater thermal tolerance of their symbiotic algae (Baker *et al.* 2004). Environmental factors that support coral resistance and resilience include those that: (1) reduce temperature stress (eg local upwelling areas); (2) decrease light stress (eg shading from high, steep-sided islands or suspended sediments and organic material in the water column); (3) harden corals to adverse conditions and help in the development of stress tolerance (eg regularly stressful environments inhabited by stress-adapted corals, such as reef flats, where corals are regularly exposed during low tides); and (4) favor conditions that enhance recovery potential (eg high herbivore populations to graze back algae and maintain suitable substrates for coral larvae to settle on, low incidence of disease; Salm *et al.* 2001; Salm and Coles 2001; West and Salm 2003). Reefs influenced by these factors, such as those occurring in naturally turbid waters or that are exposed at low tides, are often overlooked by MPA managers, who focus their attention on the clear-water reefs favored by recreationalists and tourists. These areas proved to be key refuges in the 1998 mass bleaching event (Hoeksema 1991; Goreau *et al.* 2000; Salm *et al.* 2001; West and Salm 2003; Berkelmans *et al.* 2004; Wooldridge and Done 2004; Golbuu *et al.* 2007). These reefs merit greater representation in MPA networks as they demonstrate greater resilience to bleaching events relative to reefs in clearer or deeper waters. Sites where these factors reliably occur are critical components of MPA networks.


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Figure 2. *Critical areas, such as fish spawning aggregation sites, are essential for maintaining ecosystem function and need to be protected in MPAs.*

Connectivity

Connectivity is the natural linkage between marine habitats (Roberts *et al.* 2003a), which occurs via larval dispersal and the movements of adults and juveniles. Connectivity is an important part of ensuring larval exchange and the replenishment of biodiversity in areas damaged by natural or human-related agents. Consequently, it is important that biological patterns of connectivity among reefs be identified and incorporated into MPA network design (Salm *et al.* 2006). This principle also applies to other marine ecosystems; for example, healthy mangroves on accreting coastlines that are up-current from areas vulnerable to sea-level rise should be identified and selected for priority conservation and management programs. Such mangroves would provide secure sources of propagules to replenish down-current mangroves following a disturbance event (Mcleod and Salm 2006).

Genetic data from a variety of tropical and temperate marine species indicate that larval movements of 50–100 km appear common for marine invertebrates, and from 100–200 km for fishes (Kinlan and Gaines 2003; Shanks *et al.* 2003). One approach in MPA network design has been to establish the size of reserves based on the adult neighborhood sizes of highly fished species, and space the reserves based on larval neighborhood scales (Palumbi 2004). Recommendations on minimum spacing to ensure larval connectivity among MPAs in networks range between 10–20 km (Shanks *et al.* 2003; Mora *et al.* 2006). However, recent studies confirm that larval dispersal in some species is more localized than previously thought; short-lived species may require more regular recruitment from nearby connected sites, and larvae of certain reef species may settle back onto the reef of origin (Cowen *et al.* 2006; Steneck 2006; Almany *et al.* 2007). Current patterns and retention features (eg fronts, eddies, bays, and the lees of headlands) may also create recruitment sinks and sources. In areas where larval retention is substantial, such as lees of headlands, dispersal distances may be shorter, and MPAs may need to be more closely spaced (California Department of Fish and Game 2007) or larger to enable self-seeding.

Where possible, entire ecological units (eg coral reef systems comprising the reefs and associated soft bottom substrates, seagrass beds, and mangroves) should be included in MPA network design (Salm *et al.* 2001), to accommodate self-seeding through larval dispersal and movement of adults and juveniles of mobile species. If entire ecological units cannot be included, then larger areas (10–20 km in diameter; Table 1) should be chosen over smaller areas (Green *et al.* 2007). A system-wide approach should be adopted that addresses patterns of connectivity between ecosystems like mangroves, reefs, and seagrass beds to enhance resilience (Mumby *et al.* 2006). For example, mangroves in the Caribbean increase the biomass of coral reef fish communities by providing essential nursery habitat. Coral reefs also protect mangroves by buffering the impacts of wave erosion, while mangroves can protect reefs and seagrass beds from siltation. Thus, connectivity between functionally linked habitats is essential for maintaining ecosystem function and resilience.

As climate change causes warm tropical waters to extend polewards, it is timely to model future connectivity patterns and to identify potential new coral reef substrates, possibly indicated by the extremes of coral distribution at higher latitudes. This will help guide planning of MPA networks in anticipation of possible latitudinal expansion of coral distributions. For example, as seas warm and cold water barriers to coral reef distribution expand away from the tropics, potential new reef areas will need to be considered for inclusion in MPA networks. These range shifts should be monitored to ensure species survival, because range shifts in response to changing temperature may be limited by other factors, such as light penetration and changes in seawater pH levels (Hoegh-Guldberg 1999).

Ecosystem function

Maintaining species diversity is important for ecosystem function, since it may increase ecosystem resilience by ensuring that enough redundancy exists to maintain ecological processes and to protect against environmental disturbance (McClanahan *et al.* 2002; but see also Bellwood *et al.* 2003; Hughes *et al.* 2005). Species diversity generally increases with habitat diversity and complexity, so the greater the variety of habitats protected, the greater the biodiversity conserved (Carr *et al.* 2003; Friedlander *et al.* 2003). Thus, MPAs should include large areas, a broad range of habitats, and a high diversity of species (Roberts *et al.* 2003b).

Protecting functional groups is an important strategy for supporting ecosystem function. Steneck and Dethier (1994) defined a functional group as a collection of species that perform a similar function, irrespective of their taxonomic affinities. For example, corals form an important functional group that provides three-dimensional habitats for fishes and other organisms and contributes to reef growth. Herbivores constitute another functional group that plays a key role in controlling algal growth, thereby helping to enhance coral recruitment, reef recovery, and resilience (Steneck and Dethier 1994; Bellwood *et al.* 2004; Hughes *et al.* 2005). Some areas have more species in each functional group and may have greater functional redundancy, that is, more species that can assume the role of the others, so the loss of one species is potentially compensated for by the actions of another (but see Bellwood *et al.* 2004; Hughes *et al.* 2005). Reef communities with functional redundancy may have a better chance of recovery if a species is lost from a functional group. Therefore, managing functional groups, such as herbivorous fishes, can play a critical role in facilitating reef recovery following a large-scale disturbance.

Where protected areas are surrounded by intensively used land and water, water quality must be monitored and maintained to ensure that conservation objectives are achieved. Managers can manage water quality by addressing pollution sources, especially enrichment of water, which creates conditions that favor algal growth and prevent coral larvae from settling. To manage water quality effectively, managers must link their MPA networks to the governance systems of adjacent areas – through integrated coastal management programs, for instance – as well as controlling the pollution sources within their own boundaries.

Climate-change impacts pose additional challenges to maintaining water quality. For example, changes in precipitation may increase runoff and smother reefs and seagrass beds with sediment, making it especially important to link MPA networks to regional coastal management strategies (Richmond *et al.* 2007). Thus, water quality must be maintained over source and sink reefs and along the corridors that connect them. Buffer zones should be established to provide a transition area of partial protection; such buffer zones will become increasingly important for coral reefs as sea level rises, potentially expanding the extent of some shallow water habitats for reefs and mangroves.

Ecosystem values

The concept of ecosystem resilience should include the maintenance of ecosystem function, to secure the valuable services provided to people. Coral reef ecosystem values include the provision of essential fish habitat, coastal protection, food, income and employment through tourism and recreation, and medicinal applications. Humans have domesticated ecosystems and landscapes to enhance food supplies, promote commerce, and reduce exposure to natural dangers (Kareiva *et al.* 2007). Scientists and managers need to recognize the importance of maximizing the outputs of the services that ecosystem functions generate, quantifying and managing trade-offs among ecosystem services to benefit both humans and nature. Economic evaluations can assist managers in determining the full suite of ecosystem values for a particular MPA network and using these values to help inform site selection and priorities for protection (Roberts *et al.* 2003a).

Designing resilient MPA networks around the globe

A recent scientific assessment indicates that the rate and extent of coral loss in the Indo-Pacific is greater than expected; average Indo-Pacific coral cover has declined by about 20% since the early 1980s (Bruno and Selig 2007). This finding underscores the need to design MPA networks to be resilient to climate change, and to manage these areas effectively to address other stresses such as overfishing, pollution, and coastal development. To address these threats, managers should include the elements indicated in Figure 3 at the local, regional, and global scale.

The need to manage coral reef systems across jurisdictional boundaries, maintain connectivity, and address regional trade pressures has been recognized at the highest levels of government in the central and western Pacific. Instigated by the Presidents of Palau and Indonesia, the Micronesia Challenge and the Coral Triangle Initiative, respectively, have brought together the heads of state in these regions to commit to increased marine conservation efforts and collaboration across national boundaries. Such commitments provide the necessary political and financial support and the mechanism to implement MPA recommendations that address the impacts of climate change.

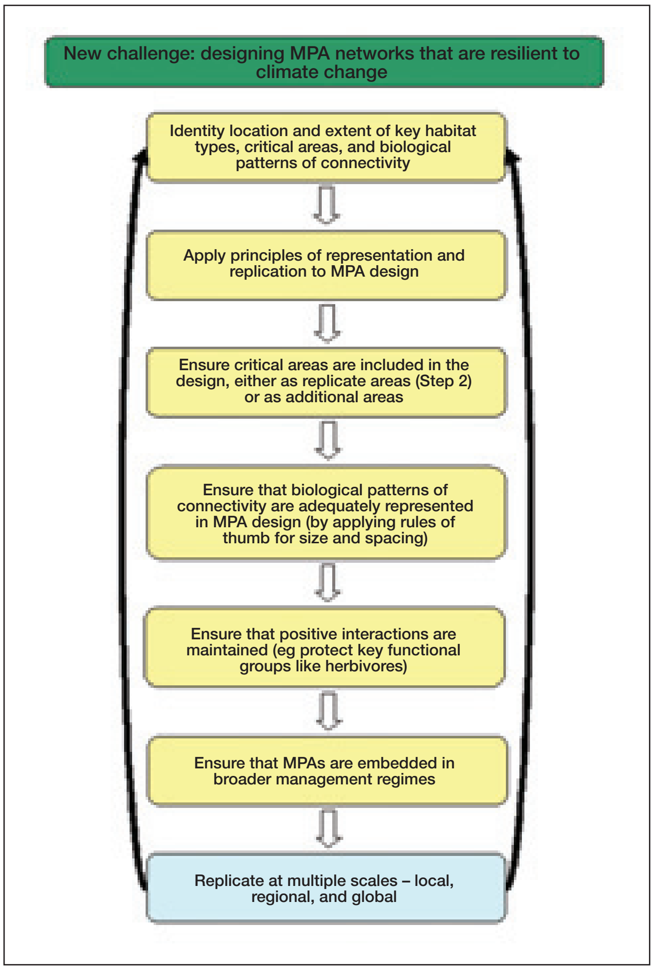

Figure 3. *Flow diagram for design considerations across local, regional, and global scales.*

Although coral reefs are in dire straits, there is good news; management steps can and are being taken around the world to address the impacts of climate change using the recommendations outlined in this paper (see The Nature Conservancy projects in the Coral Triangle, Palau, Florida, MesoAmerican Reef, and Bahamas at www.nature.org/initiatives/marine/strategies/resilient.html; Green *et al.* 2007). Fifteen years ago, MPA managers were not considering the threat of climate change, whereas today MPA networks are designed to be resilient to these impacts by a network of practitioners around the world (Figure 4). While scientists are developing the principles underlying resilience, practitioners are refining and testing adaptation approaches. The simple steps outlined here provide actions MPA managers can take to mitigate these threats to shallow-water marine ecosystems. Only by specifically addressing the threat of climate change can we hope to improve the survival prospects for coral reefs in our changing world.

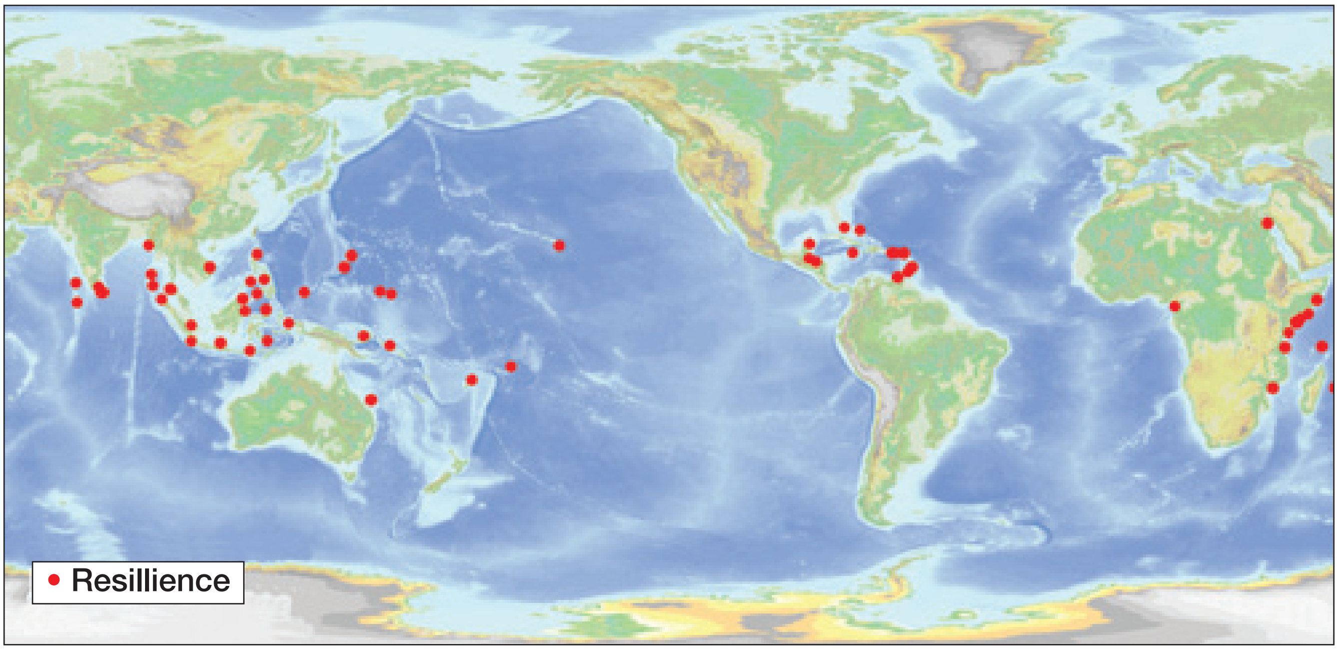

Figure 4. *Sites where resilience is being applied in MPA design (including The Nature Conservancy and partner sites).*

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