Annex B: Confidence Estimates for SAP 4.4 Adaptation Approaches

Authors

Susan Herrod Julius, U.S. Environmental Protection Agency
Jordan M. West, U.S. Environmental Protection Agency
Jill S. Baron, U.S. Geological Survey and Colorado State University
Brad Griffith, U.S. Geological Survey
Linda A. Joyce, U.S.D.A. Forest Service
Brian D. Keller, National Oceanic and Atmospheric Administration
Margaret Palmer, University of Maryland
Charles Peterson, University of North Carolina
J. Michael Scott, U.S. Geological Survey and University of Idaho

Annex Contents

B1 Introduction

For each adaptation approach, authors were asked to consider two separate but related elements of confidence. The first element is the amount of evidence that is available to assess the effectiveness of a given adaptation approach (indicating that the topic is well-studied and understood). The second is the level of agreement or consensus across the different lines of evidence regarding the effectiveness of the adaptation approach. Authors were asked to rate their confidence according to the following criteria:

High/low amount of evidence
Is this adaptation approach well-studied and understood, or instead is it mostly experimental or theoretical and not well-studied? Does your experience in the field, your analyses of data, and your understanding of the literature and performance of specific adaptation options under this type of adaptation approach indicate that there is a high/low amount of information on the effectiveness of this approach?

High/low amount of agreement
Do the studies, reports, and your experience in the field, analyzing data, or implementing the types of adaptation strategies that comprise this approach reflect a high degree of agreement on the effectiveness of this approach, or does it lead to competing interpretations?

The authors' responses are provided in the following sections, organized by adaptation approach.

B2 Adaptation Approach: Protecting Key Ecosystem Features

Description: Focusing management protections on structural characteristics, organisms, or areas that represent important "underpinnings" or "keystones" of the overall system. ***Confidence:*** Is strategic protection of key ecosystem features an effective way to preserve or enhance resilience to climate change?

National Forests
Amount of evidence: High

1) There is ample theoretical and empirical evidence to support the positive relationship between biodiversity and ecosystem resilience. Based on a study in Australian rangeland, Walker, Kinzig, and Langridge (1999) concluded that functional group diversity maintains the resilience of ecosystem structure and function. Resilience is increased when ecosystems have multiple species that fulfill similar "functions" but that respond differently to human actions (Walker, 1995; Fischer, Lindenmayer, and Manning, 2006). Elmqvist *et al*. (2003) concluded that the diversity of responses to management and disturbance enabled by diverse ecosystems "insures the system against the failure of management actions and policies based on incomplete understanding." Brussaard, de Ruiter, and Brown (2007) concluded that soil biodiversity confers resilience against stress and disturbance and protecting it is necessary to sustain agricultural and forestry

production. Keystone species and structural elements of ecosystems are particularly important because many species and ecological processes rely on them (Fischer, Lindenmayer, and Manning, 2006). Because keystone species largely “control the future” (*i.e.*, guide the successional trajectories and characteristics) of ecosystems (Walker, 1995; Gunderson, 2000), protecting them (and biodiversity in general) is a fundamental feature of conservation and restoration schemes.

2) Restoration research currently discussing climate change concludes that key processes may be the only way to address restoration under climate change.
3) The United States Forest Service (USFS) emphasizes biodiversity conservation and protection of critical habitat and other key ecosystem features in its management of national forests. Some national forest managers currently seek to enhance landscape and species diversity as the most sensible way to adapt to climate change in the absence of contradictory information (see Olympic National Forest case study). Major USFS programs and plans—such as the early detection program for invasive species, the forest health program (which tries to prevent or reduce the impact of insect and disease outbreaks) and the National Fire Plan—also aim to protect key ecosystem features and values. Similarly, efforts to reduce the impacts of fragmentation and create larger, connected landscapes with continuous habitat help conserve keystone species. Maintenance of old-growth habitat and particular characteristics of old-growth is also emphasized in many national forests.

Amount of agreement: Low

1) Ecologists have engaged in heated debates for the past century about the extent to which diversity begets stability (*i.e.*, resilience). The current state of the debate appears to be somewhat nuanced. Although it appears that “a large number of species is required to sustain the assembly and functioning ecosystems in landscapes subject to increasingly intensive land use,” there is still uncertainty about the specific mechanism and details of this dependence on diversity (Loreau *et al.*, 2001). Recent reviews (Loreau *et al.*, 2001; Hooper *et al.*, 2005) note that the debate has become more nuanced because of theoretical and experimental advances (e.g., Tilman, Reich, and Knops, 2006).
2) Functional groups have been used to explore ecosystem function and the role of suites of species. However, the makeup and composition of these functional groups and their roles in the ecosystem is not always agreed upon by the research community
3) The inability to accurately define either species or functional groups that ensure the viability of the ecosystem result in an uncertainty and likelihood that as many species as possible must be maintained, a distinct challenge for resource management.

National Parks

Amount of evidence: High

While the large body of literature related to protection of key ecosystem features does not address resiliency in light of climate change, it provides evidence that in the absence of protection of natural flow regimes, natural fire regimes, and physical structures natural processes are compromised.

Protection of soils from erosion using natural materials reduced soil loss, promoted vegetation regrowth, and reduced siltation of streams in northern New Mexico and Colorado (Allen *et al.*, 2002).[1]

Use of wildland fire, mechanical thinning, or prescribed burns where it is documented to reduce risk of anomalously severe fires has been shown to work, but only to work where forest stands are unnaturally dense due to fire suppression such that removal of fuels reduces the risk of anomalous fires.

River systems with minimal disturbance maintain higher levels of native biodiversity than disturbed systems, suggesting the converse is also true, that disturbance of natural flow regimes reduces native biodiversity (Poff *et al.*, 2007).

Studies of certain species, such as whitebark pine in the western United States, show that they are important food sources for many species, including bears and Clark's nutcrackers. In their absence animals find alternative food sources or become locally extirpated (Tomback and Kendall, 2002).

Studies of the effects of reintroducing wolves to Yellowstone ecosystem show a strong cascading positive effect on ecosystem performance, ranging from improved riparian habitat (less trampling by elk), increased beaver activity, and restored habitat leading to increased numbers of migratory birds.

Studies of habitat requirements for bighorn sheep survival and reproduction demonstrated the need for specific vegetation mosaics and densities. In the absence of such vegetation structure (vegetation too dense or too sparse), sheep are exposed to predators and populations decline (Singer, Bleich, and Gudorf, 2000).

Several papers describe the benefits of maintaining corridors for species migrations (Novacek and Cleland, 2001; Levey *et al.*, 2005).

Amount of agreement: High

There seems to be high agreement, as well as a fair bit of common sense, that maintaining ecosystem structure, including physical structure and natural processes will be at least somewhat protective of ecosystems and their species under climate change, and allow some ability to respond to climate change.

Many papers in the literature that recommend ways to ameliorate the effects of climate change strongly promote protecting features and processes that structure ecosystems as one of their first recommendations (Welch, 2005).

---

[1] See also **Sydoriak**, C.A., C.D. Allen, and B.F. Jacobs, 2000: Would ecological landscape restoration make the Bandelier Wilderness more or less of a wilderness? *Proceedings: Wilderness Science in a Time of Change Conference-Volume 5: Wilderness Ecosystems, Threats, and Management*, Proceedings RMRS-P-15-VOL-5, 209-215.

National Wildlife Refuges

Amount of evidence: High

The refuge system has a long history of habitat enhancement to maintain high quality habitat and sustain ecological processes for waterfowl and other aquatic species. There are large number of studies documenting response of species to prescribed burns and altered water regimes. Magnitude of the response varies among species and seasons. Prescribed fire is frequently used for managing grasslands and fire and prescribed cuts for forest lands. The changes projected from climate change are an additional variable. There are many references in the literature to the consequences of altered ecological processes on the integrity, diversity, and health of natural communities. Protection of nesting islands for colonial nesting birds from predators has been shown to positively affect reproductive success of many species. Reintroduction of keystone species such as beavers on refuges significantly alters habitat conditions and population size of other species.

Amount of agreement: High

There is wide agreement that protecting key ecosystem features will preserve or enhance resilience to climate change. Logically, protection will allow more of the resilience capacity to be "dedicated" to climate change because protection will minimize the challenges of non-climate stressors.

Wild and Scenic Rivers

Amount of evidence: Low

It is generally believed that there are no "keystone species" in running water ecosystems. Beaver can affect streams, but they convert them to wetlands and certainly there have been no attempts to protect them.

Headwater streams are the closest thing for WSRs that are "critical" because the rest of the river system is influenced by them and there is growing research evidence showing they have a disproportionate impact on the health of rivers. They should be the focus of protection, but have not been to date.

Amount of agreement: High

This is a difficult question because there is high agreement that headwater streams are disproportionately important, based on studies measuring rates of processes and the impacts of excluding some headwater inputs/processes to downstream reaches. But this research has not been done it a management/protection context. It is all basic research experiments.

National Estuaries

Amount of evidence: Low

(1) There has been much oyster reef restoration, but none testing success in protecting shoreline from erosion.

(2) Managed realignment is good in concept, but no tests exist of its success.
(3) Many tests have been done of how biodiversity affects resilience and observational studies exist relating structural complexity to biodiversity.
(4) No real test exists to assess success of protecting estuarine zones of high biogeochemical functioning.
(5) There is little empirical testing of bulkheads impacts on long enough time scales.
(6) No development or tests of effectiveness of rolling easement concept exist.

Amount of agreement: Low

(1) There are many more failed than successful oyster reef restorations.
(2) Some disagreement exists over need for realignment, due to uncertainty over rate of natural soil accretion in marshes.
(3) Mixed, conflicting results exist in tests of how biodiversity influences resilience.
(4) No data test the success of protecting biogeochemical zones of importance.
(5) There is high conceptual agreement that bulkheads inhibit transgression.
(6) There is high conceptual agreement that many species need corridors but this is of debatable applicability to estuaries, where larval or seed dispersal is almost universal.
(7) The debate over need for rolling easements is only just beginning.

Marine Protected Areas

Amount of evidence: Low

This approach is fundamental to place-based management and MPAs that are designed to protect ecosystems. Palumbi (2002) summarized the situation at the time of his review: "…there are very few data that examine the relative resilience of marine habitats inside and outside reserves, nor are there comprehensive studies available that address whether ecosystems inside reserves can better weather climate shifts." There are some studies that have documented changes in ecosystem features in MPAs (Babcock *et al.* in New Zealand; McClanahan, Mwaguni, and Muthiga in Kenya; Mumby *et al.* in the Bahamas), and Hughes *et al*. (2007) concluded that managing herbivorous fishes is a key component of managing reef resilience. Mumby *et al*. (2007) documented higher coral recruitment rates in a 20-year-old marine reserve, which likely would enhance rates of coral population recovery after disturbances and thus increase resilience compared with areas outside the reserve. One might argue that the evidence is moderate, but "low" was selected to reflect the limited amount of research on this topic directly relevant to resilience to climate change.

Amount of agreement: High

The existing studies, though limited in number, appear consistent. Studies that have not found changes in ecosystem features in MPAs, such as unpublished research in the Florida Keys National Marine Sanctuary, probably reflect the relatively short duration (10 years) of no-take regulations.

B3 Adaptation Approach: Reducing Anthropogenic Stresses

Description: Minimizing localized human stressors (*e.g.*, pollution) that hinder the ability of species or ecosystems to withstand climatic events
Confidence: Is reduction of anthropogenic stresses effective at increasing resilience to climate change?

National Forests
Amount of evidence: High

1) There is considerable literature that current stressors (air quality, invasives, altered fire regimes) increase the stress on plants and animals within ecosystems, and that management to reduce these stressors has a positive impact on ecosystem health.
2) With respect to air quality impacts, there is extensive literature on the impacts associated with ozone, nitrogen oxides, and mercury; the interactions of these pollutants; and the value of protecting ecosystems from air quality impacts (*e.g.*, National Research Council, 2004). Current levels of ozone exposure are estimated to reduce eastern and southern forest productivity by 5–10% (Joyce *et al.*, 2001; Felzer *et al.*, 2004). In the western United States, increased nitrogen deposition has altered plant communities and reduced lichen and soil mychorriza (Baron *et al.*, 2000; Fenn *et al.*, 2003). Interaction of ozone and nitrogen deposition has been shown to cause major physiological disruption in ponderosa pine trees (Fenn *et al.*, 2003). Mercury deposition negatively affects aquatic food webs, as well as terrestrial wildlife, as a result of bioaccumulation (Chen *et al.*, 2005; Ottawa National Forest, 2006; Driscoll *et al.*, 2007; Peterson *et al.*, 2007). Given that climate change is likely to increase drought, exposure to ozone may further exacerbate the effects of drought on both forest growth and stream health (McLaughlin *et al.*, 2007a; 2007b).
3) There is considerable literature on the impact of invasives on ecosystems, biodiversity (Stein *et al.*, 1996; Mooney and Hobbs, 2000; Pimentel *et al.*, 2000; Rahel, 2000; Von Holle and Simberloff, 2005). Disturbances such as fire, insects, hurricanes, ice storms, and floods (all of which are likely to increase under climate change), create opportunities for invasive species to become established on areas ranging from multiple stands to landscapes. In turn, invasive plants alter the nature of fire regimes (Williams and Baruch, 2000; Lippincott, 2000; Pimentel *et al.*, 2000; Ziska, Reeves, and Blank, 2005)[2] as well as hydrological patterns (Pimentel *et al.*, 2000), in some cases increasing runoff, erosion, and sediment loads (*e.g.*, Lacey, Marlow, and Lane, 1989). Potential increase in these disturbances under climate change will heighten the challenges of managing invasive species. Climate change is expected to compound the invasive species problem because of its direct influence on native species distributions and because of the effects of its interactions with other stressors (Chornesky *et al.*, 2005). The need to protect, sustain, and restore ecosystems that are either threatened or

[2] See also **Tausch**, R.J., 1999: Transitions and thresholds: influences and implications for management in pinyon and juniper woodlands. In: *Proceedings: Ecology and Management of Pinyon-Juniper Communities Within the Interior West* US Department of Agriculture, Forest Service, Rocky Mountain Research Station, pp. 361-365.

impacted by invasives has been recognized by management agencies (USDA Forest Service, 2004).

4) Adaptation literature describes the value of minimizing these current stressors to reduce ecosystem vulnerability to climate change and to enhance ecosystem resilience to climate change (*e.g.*, Spittlehouse and Stewart, 2003; Schneider *et al.*, 2007; Adger *et al.*, 2007).

Amount of agreement: High

1) The literature is in agreement that reducing these stressors is an important management strategy.
2) The literature also agrees that the effectiveness of these restoration approaches is influenced by the current environmental conditions, current condition of the ecosystem, and current status and degree of other human alterations of the ecosystem (*i.e.*, presence of invasives, departure from historical fire regimes, condition of watersheds).

National Parks

Amount of evidence: High

There is a vast amount of literature, plus a lot of common sense, demonstrating that ecosystems and their biota are more resilient to both natural and human-caused disturbances (although not necessarily climate change) when they are not stressed by pollution, habitat alteration, erosion of physical features such as beaches or soil, or prevention of natural disturbance cycles. Some methods may be more effective than others.

The IPCC Working Group II report on coasts offers literature about restoration of natural coastal processes as a way to promote shore, wetland and marsh protection from climate change (IPCC, 2007).

Restoration can protect salmon fisheries from some effects of climate change (Battin *et al.*, 2007).

While there is ample evidence that man-made barriers prevent natural migration of aquatic species, there is also growing evidence that it may not increase ecosystem resilience. Upstream migration of non-native species or diseases may compromise gains made by removal of barriers. Other management activities or land use may similarly compromise gains (U.S. Geological Survey, 2005).

Literature demonstrating that managing visitor use patterns in national parks works to minimize the effects of climate change is not readily available, although there are many examples of where restrictions of use has either been effective in restoring vegetation or enabled birds to nest successfully.

Amount of agreement: High

Reduction of human-caused stressors is the root of restoration ecology, a respected field of applied ecology. Many papers demonstrate recovery of at least some ecosystem attributes when pollutants are removed, including examples of recovery of zooplankton in Ontario lakes recovering from acid rain, increase in lake and stream acid-neutralizing capacity in the Adirondacks and Europe after reductions of SO_2 emissions, and restoration of native fishes after recovery from acid mine drainage or phosphorus reduction.

Removal of non-native fishes in Alberta lakes allowed for natural (and assisted) recovery of natural food webs (Parker and Schindler, 2006).

National Wildlife Refuges

Amount of evidence: High

Management of anthropogenic stresses such as introduced predators, ungulates, etc. has been shown to increase numbers and reproductive success of waterfowl and ground nesting game birds. Reduction in pollutants (*e.g.*, DDT, selenium) has also been shown to increase survival and reproductive success of many species. Control of nest parasites, such as cowbirds, has been widely and successfully used as a management tool for endangered songbirds. The magnitude of the demographic response varies among species and ecological conditions. Provision of contaminant-free food has been used to reduce exposure of carrion feeding birds to lead with mixed success.

Amount of agreement: High

There is wide agreement that reducing anthropogenic stresses will increase resilience to climate change. Reducing anthropogenic stressors will increase the survival, reproductive success, and population size of most organisms (particularly those not dependent on disturbed anthropogenic habitats), and these increases will enhance the resilience capacity of trust species.

Wild and Scenic Rivers

Amount of evidence: High

There have been extensive studies demonstrating that the amount of degradation of a watershed increases directly in relation to human stresses such as deforestation, dam-building, urbanization, and agriculture.

There is very strong scientific data to show that when human stresses are reduced, the systems recover. There is also strong scientific evidence that a “healthy” river corridor that has minimal human stress imposed on it is very resilient to new stresses of the magnitude expected in the near term for climate change.

Amount of agreement: High

There are an incredible number of studies showing that reducing impervious cover and agriculture (and other human stressors) impart a healthy, more resilient river. This is probably one of the few areas where there is almost total agreement.

There are many existing and newly forming management actions for rivers that are directly related to the amount of human stress. The management is doing this by capping the total amount of development and land clearing that can occur in a watershed, followed up by data collection.

National Estuaries
Amount of evidence: High

(1) A prodigious amount of research has been conducted to show the role of nutrient loading and organic loading in eutrophication, and to assess BMPs for successful control. It is also clear from many models that climate change will enhance eutrophication in many estuaries.
(2) There is limited but some research on salt water intrusion and groundwater recharge rates with rising sea level.

Amount of agreement: High

(1) There is excellent agreement that reducing one driver of eutrophication will benefit the system and reduce the level of overall eutrophication.
(2) The disagreement applies to models of precipitation change, which provide results that are generally too coarse in scale to project which estuaries will experience increased precipitation and which will receive less.

Marine Protected Areas
Amount of evidence: Low

This theme crops up in reviews dating back to at least Boesch, Field, and Scavia (2000) and Scavia *et al*. (2002), as well as recent works such as Marshall and Schuttenberg (2006) and Marshall and Johnson (2007). The principle is well established, though not well tested. Our understanding of synergistic stressors at a physiological level has substantial evidence for individual species, but the extension to ecosystems is largely through conceptual modeling. This is a logical, common-sense approach, but the hard evidence is limited.

Amount of agreement: High

Although the evidence is low, there appears to be agreement among a number of authors over a long period. On the other hand, the analysis of decline of Indo-Pacific reefs by Bruno and Selig (2007) concluded that high vs. low levels of management did not appear to influence the trajectory of decline.

B4 Adaptation Approach: Representation

Description: Protecting a portfolio of variant forms of a species or ecosystem so that, regardless of what climatic changes occur, there will be areas that survive and provide a source for recovery.

Confidence: Is representation effective in supporting resilience through preservation of overall biodiversity?

National Forests

Amount of evidence: Low

1) Reserves and national networks are often established on the premise that additional sites will ensure the persistence of a particular vegetation type. Under a constant climate, this premise for duplication within networks is well accepted.
2) However, while it is common to duplicate vegetation types, the recent literature on paleoecology demonstrates that plant and animal species respond individualistically and uniquely in time and space, incorporating competition and ecological disturbance as well as climatic factors in their response. Thus, vegetation types are not likely to retain the same composition and structure under change.
3) If this adaptation were focused on species, the literature would suggest that the evidence is high with respect to this adaptation strategy and its effectiveness.
4) On the species level, the distributions of species display distinct "leading" edges that are well incised and indistinct "trailing" edges showing the microsites where species can survive locally, but not under the regional climate. This pattern merely displays that there are a myriad of microhabitats outside of the primary range of a species' distribution that will support that species. There is a scale issue regarding the importance of the survival of that species with respect to the overall ecosystem in the region. Survival of the individual species does not necessarily guarantee the survival of the entire ecosystem.

Amount of agreement: Low

1) While the literature would support agreement on the effectiveness of this approach for species, there is little agreement that this approach is effective for vegetation types or ecosystems. Therefore agreement is low that this approach would increase resilience in the system.

National Parks

Amount of evidence: Low

Multiple representatives of valued populations or systems is a form of bet-hedging and has been shown to protect species of populations when one or more patches or communities are destroyed.

Individual species respond to climate according to specific climate needs. There is at least one paper suggesting multiple representatives of a species within their specific climate niche will have little value in a changing climate (Williams, Jackson, and Kutzbach, 2007). If the different populations all have narrow tolerances to climate, having more of them when all will change beyond their range if viability will not be beneficial.

Amount of agreement: Low

There is insufficient evidence that representation will be effective in promoting resilience of species of ecosystems, although there is ample evidence that having only few populations or representatives of species increases their vulnerability to extinction.

National Wildlife Refuges

Amount of evidence: High

There is a large body of evidence in the literature showing that species that are found on National Wildlife Refuges are more abundant on refuges than on adjacent habitats. Several studies have shown that capturing the full geographical, ecological ,and genetic variation of a species in the wild or in captivity is a hedge against extinction and other losses. Thus, greater numbers of refuges that support higher densities of trust species will reduce the chances that climate change will completely eliminate any trust habitats, populations, or species. Evidence is lacking for most species regarding what degree of representation is sufficient. Each population of a species or ecosystem example on a refuge will experience different effects of climate change. As a result each one is a different entry in the evolutionary sweepstakes under climate change.

Amount of agreement: High

There is wide agreement that increasing representation will be effective in supporting resilience through preservation of overall biodiversity. Logically, and statistically, the broader the range of trust species and/or trust habitats that are included in the refuge system, the lower the likelihood that biodiversity will be lost due to climate change. However, individual refuges or refuge complexes need to be large enough to maintain viable populations to maximize the advantages of increased representation.

Wild and Scenic Rivers

Amount of evidence: High

This is a difficult question because most of the evidence available is from fisheries. If they are becoming threatened, then some areas have been set aside as special conservation areas to ensure some populations remain alive. Then if they do recover, they are released in rivers elsewhere. In the event of climate change, we may need to release fish and other species in to new regions where the climate is now appropriate for them (assuming their old regions are now too warm or otherwise inappropriate). This is a major management strategy that has been around a long time, and in fact Habitat Conservation Plans are required once a riverine species becomes endangered.

Protecting representative running-water ecosystems themselves (*i.e.*, distinguished from species) has not been a management or scientific focus to date in the United States, but it is being tried in Australia. Because of their dire drought situation, many riparian zones along rivers in Australia are losing all of their vegetation. So managers are setting aside some areas where they ensure minimum water needs (through regulating withdrawals and dam releases) to keep the vegetation alive. The idea is then that these plants can be used for “seed” at other sites once the drought is over.

Amount of agreement: High

There are many things coupled together in this management strategy. There is good agreement that maintaining local fish populations when other populations around them (*i.e.*, in different rivers) are dying makes a great deal of sense, and we have the science to support that.

There is not as much agreement on the ecosystem "set-aside" idea, only because it has not been extensively tried. However, most scientists would agree it is a low risk venture—*i.e.*, likely to work.

National Estuaries

Amount of evidence: Low

(1) There is limited study of effects of genetic diversity on resilience of estuarine species (but see Hughes and Stachowicz, 2004).
(2) There has been growing scientific attention to landscape effects of multiple habitats in salt marshes (Minello; Able; Zedler; Grabowski) and some for seagrass beds, but the scope of these studies is limited.

Amount of agreement: High

(1) There is no ambiguity in the theory of natural selection that genetic diversity is the substrate on which adaptation through evolution acts.
(2) The effects of landscape proximity among marsh and other shoreline habitats are reasonably well established, and the importance of habitat edge effects is also becoming clearer.

Marine Protected Areas

Amount of evidence: Low

This is a cornerstone of the zoning approach for the Great Barrier Reef Marine Park (Fernandes *et al.*, 2005)[3]. It is very logical (Salm, Done, and McLeod, 2006) and has been effectively applied to the marine park. Similar approaches for other marine systems are not readily available, although the representative areas approach has broad applicability.

Amount of agreement: High

Although the evidence is low there appears to be agreement among a number of authors (Palumbi, 2002; Sobel and Dahlgren, 2004; Fernandes *et al.*, 2005; Salm, Done, and McLeod, 2006; Roberts *et al.*, 2006; McCook *et al.*, 2007).[3] A contrary line of evidence is not known.

[3] See also **Day**, J., L. Fernandes, A. Lewis, G. De'ath, S. Slegers, B. Barnett, B. Kerrigan, D. Breen, J. Innes, J. Oliver, T. Ward, and D. Lowe, 2002: The representative areas program for protecting biodiversity in the Great Barrier Reef World Heritage Area. In: *Proceedings of the Ninth International Coral Reef Symposium* 23, October 2000, pp. 687-696.

B5 Adaptation Approach: Replication

Description: Maintaining more than one example of each ecosystem or population within a reserve system such that if one area is affected by a disturbance, replicates in another area provide insurance against extinction and a source for recovery of affected areas.
Confidence: Is replication effective in supporting resilience by spreading the risks posed by climate change?

National Forests
Amount of evidence: Low

1) The literature is extensive in terms of the value of maintaining numerous animal and plant populations of species to maintain species viability. The concept is certainly well-supported in both theoretical and experimental (lab) approaches and for some situations in the field. The rationale for maintaining more than one population or ecosystem is often associated with the probability of extreme events, such as drought or fire, that may be associated with future climate change.
2) A strategy that combines practices to restore vigor and redundancy (Markham, 1996; Noss, 2001) and ecological processes (Rice and Emery, 2003), so that after a disturbance these ecosystems have the necessary keystone species and functional processes to recover to a healthy state even if species composition changes, would be the goal of managing for ecosystem change.
3) Agreement for this approach is rated as low, however, because few examples have been documented in the field at the ecosystem level.

Amount of agreement: Low

1) For populations of plants and animals, the literature is in agreement with the effectiveness of this concept.
2) For ecosystems, less information is available.
3) Therefore, agreement is low that this approach would increase resilience in the system.

National Parks
Amount of evidence: Low

Multiple representatives of valued populations or systems is a form of bet-hedging and has been shown to protect species of populations when one or more patches or communities are destroyed. This has been a foundation of endangered species protection.

While one paper was found that promotes replication of desired species (Bengtsson *et al.*, 2003), the National Parks chapter does not promote this as a means of building resilience. Human intervention to move species adds a decidedly anthropomorphic slant to natural resources. Only species of interest are considered, while the majority of insects, plants, soil microbes and biota will be ignored.

Species move independently according to their biophysical needs (Williams, Jackson, and Kutzbach, 2007), so that replication of populations with narrow climatic niches may not provide protection against novel climates, or similar climates too far away for effective natural establishment of new colonies.

Amount of agreement: Low

This approach is sanctioned by conservationists, but papers like those of Kutzbach *et al*. (2007) suggest it is insufficient for promoting resilience of ecosystems in novel climates.

National Wildlife Refuges

Amount of evidence: High

A basic principle of conservation by design is redundancy, and this concept is repeatedly addressed in the scientific literature. Having multiple refuges for a trust species or trust habitat in each of the ecological and climate domains in which it occurs provides logical and statistical insurance against loss of a species or habitat from the refuge system due to a catastrophic event at a single refuge. There are several examples of species becoming extinct after storms affected the last known population.

Amount of agreement: High

There is wide agreement in the science community that redundancy in refuges and species populations increases the logical and statistical likelihood that biodiversity will be preserved. There is some discussion regarding how much redundancy is required.

Wild and Scenic Rivers

Amount of evidence: High

The same evidence is available for the last question (fisheries): maintaining multiple populations spreads the risk of total extinction. There is good evidence available for this risk reduction in fisheries. Less evidence is available for river insects and even less for ecosystem processes.

The critical piece of data needed (for fauna other than fish) is how far they disperse and what their dispersal requirements are. This is an important current research area because of the obvious conservation implications—if we know this then we can design the spatial arrangement of the protected “representative ecosystems/populations” in a way that allows organisms to disperse naturally (*i.e.*, no transplants necessary).

Amount of agreement: High

The emerging interest and efforts by nongovernmental organizations to establish freshwater protected areas is a sign of the confidence that this approach is worthwhile.

There has been extensive research in river networks to determine if there are particular configurations of river reaches that minimize extinction risk.

National Estuaries

Amount of evidence: Low

(1) Oyster reef restoration done in replication along a depth gradient was shown to allow fish and crustaceans to survive when environmental degradation occurred that was depth-dependent: the fishes moved to reefs that were not affected and found enough prey to survive (Lenihan *et al.*, 2001).
(2) Migrating shorebirds require replicated estuaries along the flyway so that they can move to more rewarding feeding sites to fuel up for the migration and breeding.
(3) Otherwise, there is little research on replication at the spatial and temporal scales appropriate to project its value in a climate change context.

Amount of agreement: High

(1) There is a high level of agreement, although in part perhaps because so few studies of relevance have been done.
(2) There is agreement in concept that populations of mobile vertebrates such as fishes, birds, and mammals benefit from replication. However, many such species, such as salmon, exhibit high faithfulness to natal sites; replication would not provide much if any benefit for them.

Marine Protected Areas
Amount of evidence: Low

There are numerous modeling studies of reserve networks (*e.g.*, Allison, Lubchenco, and Carr, 1998), but empirical data are lacking. Areas such as the Great Barrier Reef Marine Park and the Channel Islands National Marine Sanctuary should produce relevant results over time. This approach also might be ranked as moderate (per question 1).

Amount of agreement: High

Replication and representation in the marine literature generally go hand-in-hand; please refer to question 3 for literature citations. Again, a contrary line of evidence is not known.

B6 Adaptation Approach: Restoration

Description: Rebuilding ecosystems that have been lost or compromised.
Confidence: Is restoration of desired ecological states or ecological processes effective in supporting resilience to climate change?

National Forests
Amount of evidence: High

1) There is a large body of literature describing and documenting restoration theory and practices across a wide variety of ecosystems and ecological processes.

Amount of agreement: Low

1) While there is high agreement that the current theories and practices can be used to restore a number of different ecosystems, climate change has the potential to

significantly influence the practice and outcomes of ecological restoration under a changing climate (Harris *et al.*, 2006), where the focus is on tying assemblages to one place. The restoration literature is now in discussion about the impact that a changing climate may have on the theories and practices that have been developed. For example, natural resource management, planning, conservation, restoration, and policy are deeply founded on strategies based on the historic range of variability ecological concept (Landres, Morgan, and Swanson, 1999). However, use of such strategies will become increasingly problematic as the potential for a "no analog" futures are realized (Millar, Westfall, and Delany, in press; Williams, Jackson, and Kutzbach, 2007).

2) The climate sensitivity of best management practices, genetic diversity guidelines, restoration treatments, and regeneration guidelines may need to be revisited. Space for evolutionary development under climate change may be important to incorporate into conservation and restoration programs under a changing climate (Rice and Emery, 2003).

National Parks

Amount of evidence: High

Restoration of some species, such as wolves, into habitats where they have been extirpated has been highly successful by nearly all ecological standards.

There are some examples showing that restoration of natural flow regimes in rivers by dam removal has been successful in restoring reproducing fish populations

There are at least several instances in the literature that decry the lack of restoration standards that allow managers to evaluate the effectiveness of restoration efforts (Bernhardt *et al.*, 2005).

Restoration of wetlands or riparian areas has been shown to bring back some ecosystem services, such as nutrient or pollutant retention, but there is uncertainty among wetland scientists whether restoration activities truly reproduce natural conditions.

Restoration of damaged systems will allow climate change to occur with fewer ecological disruptions than if soils have eroded, invasive species dominate, river banks are trampled, or pollutants contaminate native populations (discussed above in reducing anthropogenic stresses).

Amount of agreement: High

There is an entire professional society devoted to ecological restoration, the Society for Ecological Restoration, with journals that describe the theory behind restoration and practical applications of restoration science.[4]

National Wildlife Refuges

Amount of evidence: Low

[4] Society for Ecological Restoration, http://www.ser.org/about.asp

Habitat restoration is a widely used tool in relatively small-scale conservation biology activities. There is a large body of literature on the topic, with several journals devoted solely to habitat restoration (*e.g.*, Ecological Management and Restoration, Restoration Ecology) as well as a professional society dedicated to restoration ecology. In Hawaii, restoration of pasture lands to *ohia koa* forests resulted in recolonization by endangered birds. Re-creation of wetlands has been used widely and successfully to restore/attract migratory water birds. However, the magnitude of the site response to restoration can vary due to (1) temporal shifts in habitat use by species, (2) scale of restoration in relation to the desired population goals, (3) introduced species, (4) long-term and large-scale ecological processes, or (5) barriers to recolonization. Further, few restoration studies have been conducted in a controlled experimental design, and reoccupancy of restored habitats by native plants and invertebrates is not well documented. Although there is small-scale evidence for effectiveness of restoration, there is little evaluation or evidence regarding the effectiveness at the larger scales of ecological processes that would be necessary to provide resilience to climate change.

Amount of agreement: Low

There is little general agreement that restoring a desired ecological state or process will be effective in supporting resilience to climate change. There is little logical support for the idea that restoring a state or a process to a historical condition will provide resilience to climate change, because it is expected that the historical restored condition will no longer be appropriate in a changed climate.

Wild and Scenic Rivers
Amount of evidence: Low

Very little rigorous monitoring has been done on stream restoration. This is a very current area of research and data are just starting to come in. The evidence suggests that if the restoration not only repairs the degraded portion of the stream but removes the stress, then the restoration is usually successful. But if the restoration is a local fix, such as regrading streambanks and stabilizing them without taking care of the underlying problem (*e.g.*, inadequate stormwater infrastructure above the reach), then the restoration project will most likely fail or else huge resources will be needed to maintain it.

Amount of agreement: Low

The effectiveness of restoration is a contentious issue. Many scientists are skeptical that most projects work, because many are done poorly or the underlying problem is not addressed. Other scientists point toward data from projects that were adequately monitored and were well-done projects—success has clearly been shown. So to a certain extent the low agreement is that some scientists believe we must focus on what is done *in reality* while others focus on what is possible.

National Estuaries
Amount of evidence: High

(1) There are many studies of salt marsh restoration (beginning 40 years ago with *Spartina* methods developed by Seneca, Woodhouse, and Broome).
(2) Similarly, a lot of effort has gone into oyster reef restoration and SAV restoration.
(3) There is not much research on exterminating invasive estuarine species: *Meloluca* is everywhere along Florida waterways; *Phragmites* dominates many areas of East Coast marshes; San Francisco Bay suffers from persistent *Spartina* invasion, etc.
(4) The value of positioning salt marsh restorations where transgressive retreat is possible is strongly supported in concept, although no empirical tests of the effectiveness with sea level rise exist, except for paleontological evidence (*e.g.*, Bertness work) of substantial transgressions of marsh historically.

Amount of agreement: High

(1) There is uniform agreement that salt marsh can be successfully restored.
(2) Some challenges exist in assuring the durability of SAV and oyster reef restorations.
(3) Nevertheless, there is also good agreement that exterminating invasives is generally infeasible for estuaries (although easier for large plants than for mobile animals or microbes).
(4) There is high agreement in concept that building the capacity for transgression will provide a viable means for marshes and other shoreline habitats to become resilient to sea level rise.

Marine Protected Areas
Amount of evidence: Low

Reef restoration following vessel groundings has a long history of application in the Florida Keys (and elsewhere) and more general discussions of restoration are in Marshall and Schuttenberg (2006), Salm, Done, and McLeod (2006), and Precht and Aronson (2006). The discussion has been extended to include restoring herbivory, coral recruitment, and other topics with regard to ecological processes. There is an appreciation by managers that it may be necessary to employ more restoration because of the widespread degradation of marine ecosystems. Nevertheless, it appears that evidence about effectiveness in supporting resilience to climate change is low.

Amount of agreement: Low

There appears to be agreement among several authors (Halpin, 1997; Burke and Maidens, 2004; Salm, Done, and McLeod, 2006; references in Precht and Miller, 2006; Jaap *et al.*, 2006; Gunderson, 2007) but some question the value or potential for success of restoration efforts (Jameson, Tupper, and Ridley, 2002; Hughes *et al.*, 2007). Jameson, Tupper, and Ridley (2002) note that expensive restoration efforts are questionable unless environmental conditions are healthy enough to warrant them.

B7 Adaptation Approach: Refugia

Description: Using areas relatively less affected by climate change as sources of "seed" for recovery or as destinations for climate-sensitive migrants.
Confidence: Are refugia an effective way to preserve or enhance resilience to climate change at the scale of species, communities or regional networks?

National Forests
Amount of evidence: High

1) The paleo literature has documented the presence of refugia under past climate changes. Local climate trajectories, local topography, and microclimatology interact in ways that may yield very different climate conditions than those given by broad-scale models. In mountainous terrain especially, the climate landscape is patchy and highly variable, with local inversions, wind patterns, aspect differences, soil relations, storm tracks, and hydrology influencing the weather that a site experiences. Sometimes lower elevations may be refugial during warming conditions, as in inversion-prone basins, deep and narrow canyons, riparian zones, and north slopes. Such patterns, and occupation of them by plants during transitional climate periods, are corroborated in the paleoecological record (Millar and Woolfenden, 1999; Millar *et al.*, 2006). Further, unusual and nutritionally extreme soil types (*e.g.*, acid podsols, limestones etc.) have been noted for their long persistence of species and genetic diversity, resistance to invasive species, and long-lasting community physiognomy compared with adjacent fertile soils (Millar, 1989). During historic periods of rapid climate change and widespread population extirpation, refugial populations persisted on sites that avoided the regional climate impacts and the effects of large disturbance. For example, Camp *et al.* (1995) reported that topographic and site characteristics of old-growth refugia in the Swauk Pass area of the Wenatchee National Forest were uniquely identifiable. These populations provided both adapted germplasm and local seed sources for advance colonization as climates naturally changed toward favoring the species.

Amount of agreement: Low

1) While the literature has documented these refugia either in the paleo record or on current landscapes, the use of this technique as an adaptation option has been little tested.

National Parks
Amount of evidence: Low

A refugium implies a place where climate conditions will remain similar to present conditions so that species can persist. According to Williams, Jackson, and Kutzbach (2007) many parts of the world will acquire novel climates unseen before on Earth. Selecting, and then protecting, specific habitats for species may in the long run be a matter of chance.

Some very high elevation habitats may provide refugia for cold-loving species such as tundra and pika. High elevation streams where non-native fish can be excluded with natural barriers might provide refugia for cold-water fishes.

Phenological changes that accompany climate change may disrupt mutualistic species associations, regardless of the availability of refugia.

Amount of agreement: Low

Species are currently migrating north and to high elevations as climate changes. Preselecting areas to serve as refuges for individual species or assemblages might or might not work to protect them, with the exception of the high elevations or latitudes where cold-loving species may persist. Therefore, there is low agreement.

National Wildlife Refuges
Amount of evidence: High

Climate refugia, areas where effects of past climate change were minimized, are documented in the paleontological record, and refugia are projected to occur in a changed climate of the future. Historically these refugia were the only areas in which some species survived, and they provided colonization sources when conditions became suitable elsewhere as environmental conditions changed. An analogous situation can be expected to occur with the current episode of climate change. However, large areas of projected climate refugia have no wildlife refuges. There is some evidence that refugia will often be found at the ecological or geographical extremes of species ranges.

Amount of agreement: Low

There is generally low agreement that refugia will be effective at preserving resilience to climate change at all scales, from species to regions. Creating refugia from climate change is not possible; refugia will emerge in response to heterogeneity in landscape characteristics and realized climate change. Further, it is difficult to project the explicit location of future climate change refugia at scales that are ecologically relevant or useful for identifying new sites for strategic growth of the refuge system, particularly at the scale of individual refuges. There may be opportunities to take advantage of emerging refugia, particularly for threatened/endangered species or small scale habitats, but refugia will be difficult to impossible to manage in the adaptive management framework. Predicting species specific responses to potential refugia will be a challenge.

Wild and Scenic Rivers
Amount of evidence: High

1) There is good evidence that small-scale, local refugia (within-channel such as diverse habitat types) are important to the survival of stream plants and animals, if those areas are protected from significant disturbance events such as unusual floods or droughts. This is directly tied to resilience, because these local refugia act as a protective place from which surviving organisms can disperse. These dispersing individuals then reproduce and re-populate areas denuded of biota.

2) There is some evidence for plants and fish, but little evidence to date for smaller organisms, that some habitat types, even if widely dispersed, can act as refugia for moderate to large scale (landscape scale) disturbances. Examples include distant floodplains, tributaries that remain intact or undisturbed, or any region that for some reason is protected from the full brunt of a disturbance. Thus, resilience at broad scales (*e.g.*, entire watersheds or perhaps even ecoregions) may depend on setting aside such refuge areas. Since most climate-induced disturbances are expected to be exacerbated by development in a watershed (this makes entire rivers downstream of the development more vulnerable), one form of protection that could be part of a management strategy to provide refugia could include limits to development or protection of floodplains or surrounding forests.

Amount of agreement: High

The only reason there might be some disagreement is if we are considering an organism for which we know nothing or little about its dispersal abilities. If we protect or establish in-stream or regional refugia, but organisms can not move to areas formerly affected by disturbances such as those related to climate change, then the value of the refugia is somewhat reduced. However, because we should be able in most or all cases to transport the biota ourselves (seed, larvae, nymphs, juveniles, etc) using some management programs, this concern is minor. Thus, most river ecologists would strongly agree that provision of refugia is a great way to enhance long term resilience in the face of climate change. In fact, use of such approaches (setting aside "preserves," which are a form of refugia) is already in place in some cases, on the advice of scientific boards in advance of any research or data showing that there is high agreement.

National Estuaries

Amount of evidence: Low

(1) There has been little work done on this topic in estuaries. However, if features such as oyster reefs are restored in replication along a depth gradient or along some other environmental gradient, then when perturbations occur that are depth-dependent or vary in intensity along the gradient, one end of the gradient is more likely to serve as a refugium into which mobile species can escape the threat or impact of the perturbation. This is illustrated by the Lenihan *et al.* (2001) example, in which fish and crabs escape hypoxia/anoxia (which can be climate change-induced) that develops in deep water by retreating to shallow water refugia.

(2) Relative sea level rise does vary geographically, so some salt marsh systems may be able to build soils at rates fast enough to keep up with sea level rise for a relatively long time. However, patterns of geographic distribution in relative rates of sea level rise are too coarse geographically to enable "surviving" estuaries to be successful refugia and sources of migrants. Most estuarine fishes and most marine invertebrates possess highly dispersive planktonic larvae, so there may be some value to refugia at these large distances, but little information is available.

Amount of agreement: Low

(1) There is simply insufficient scientific evidence to determine which marshes may be able to keep up in soil elevation with sea level rise, so a debate will go on.
(2) As regards both oyster reefs and networks of estuaries, virtually no research has been done to assess the effectiveness of refugia, except for the value of alternative estuaries as stop-over sites for migrating shorebirds. Thus, the literature of relevance that exists is relatively speculative and reflects several disagreements.

Marine Protected Areas
Amount of evidence: Low

A number of authors note the potential value of refugia (e.g., McClanahan, Polunin, and Done, 2002; West and Salm, 2003; Coles and Brown, 2003; Salm, Done, and McLeod, 2006; Marshall and Schuttenberg, 2006).[5] Nevertheless, experimental or empirical evidence is limited (*e.g.,* Riegl and Piller, 2003).

Amount of agreement: High

Both the more-speculative as well as at least one empirical study are consistent, so agreement is considered to be high.

B8 Adaptation Approach: Relocation

Description: Human-facilitated transplanting of organisms from one location to another in order to bypass a barrier (*e.g.*, urban area).
Confidence: Is relocation an effective way to promote system-wide (regional) resilience by moving species that would not otherwise be able to emigrate in response to climate change?

National Forests
Amount of evidence: High

1) For plants, relocation has been a common technique for commercial plant species. Provenance studies demonstrate the appropriateness of different germplasm, and management is based on the likelihood of planting different provenances across widely scattered landscapes and within landscapes.
2) For other plant species and for animals, a nascent literature is developing on the advantages and disadvantages of "assisted migration," that is, intentional movement of propagules or juvenile and adult individuals into areas assumed to become their future habitats (Halpin, 1997; Collingham and Huntley, 2000; McLachlan, Hellmann, and Schwartz, 2007). At this point, insufficient data exists to judge the success of such techniques.

Amount of agreement: Low

---

[5] See also **Salm**, R.V. and S.L. Coles, 2001: Coral bleaching and marine protected areas. In: *Proceedings of the Workshop on Mitigating Coral Bleaching Impact Through MPA Design* [Salm, R.V. and S.L. Coles (eds.)]. Proceedings of the Coral Bleaching and Marine Protected Areas, pp. 1-118.
See chapters in **Johnson**, J. and P. Marshall, 2007: *Climate Change and the Great Barrier Reef: a Vulnerability Assessment*. Great Barrier Reef Marine Park Authority.

1) Protocols for "assisted migration" of species need to be tested and established before approaches are implemented more broadly.

National Parks

Amount of evidence: Low

Some studies have shown successful colonization of native after removal of invasive species; aggressive control of invasives followed by restoration of native species might be successful in preventing, or slowing, the establishment of unwanted species.

This approach is not well understood, particularly with respect to system-wide resilience.

Amount of agreement: Low

Relocation of desired species may allow that species to persist, but ecosystems are made up of complex webs of living organisms, including insects, soil flora and fauna, and many other types of organisms that would not be relocated.

There is little agreement about whether relocation would increases system resilience.

National Wildlife Refuges

Amount of evidence: Low

Translocation of species is a very common species-specific management tool. However few of these efforts are conducted with appropriate experimental design. Translocation has been successfully used to introduce game species around the globe. Efforts to use translocation for establishing or re-establishing populations of threatened or endangered species have been highly variable in their success. Synthesis studies indicate that success is very dependent on quality of available habitat and the mitigation of stressors at translocation site prior to relocation. Movement of a species across a dispersal barrier (*e.g.*, fish over dams) assumes that suitable habitat is available beyond the barrier and the uncertainty of climate change challenges that assumption. Climate change projections engender a fear that changes in habitat will result in the loss of species on refuges as conditions become unsuitable and the ability of refuges to mitigate changes is exceeded. The extreme risks would be extinction or extirpation from refuge lands. This presents a very different situation than movement across a barrier (*e.g.*, salamanders, toads and frogs across a highway during dispersal from wintering habitat). Because most evidence has been focused on individual species, the success of species relocation has been variable and there is little to no evidence of the effect of relocated species on recipient communities, there is little evidence that relocation is an effective way to promote system-wide (regional) resilience.

Amount of agreement: Low

There is generally low agreement that relocation will be an effective way to promote system-wide (regional) resilience to climate change. Ethical concerns regarding the unpredictable effects on other species and communities that result from introducing a species into a previously unoccupied habitat are notable; it is not clear that the net effect of translocation will be positive at the system-wide scale. Relocation may be effective at smaller scales; for example, in the case of a threatened or endangered non-disperser that was unlikely to negatively affect a suitable target area.

Wild and Scenic Rivers
Amount of evidence: Low

While fish have been translocated and are able to survive if put into an appropriate reach, there is no evidence that this will end up promoting system-wide recovery. Most scientists would say the more critical thing for system wide recovery is removing the "insult" to the system. With climate change, that will be pretty hard to do. If you can move the species to a totally new watershed where the climate is appropriate then it is hard to say.

Amount of agreement: Low

Some scientists speculate that we may be able to, for example, shift fish species from lower latitude/altitude places that have become too warm to higher latitude/altitude places that are appropriate under future climates. However, others will argue that even if the temperature is comparable, getting the flow conditions and ecosystem processes that are needed to support the species in the long-run is unlikely.

National Estuaries
Amount of evidence: N/A

(1) Little, if any, work has been done transplanting estuarine species to overcome dispersal barriers to latitudinal shifts, largely because so many estuarine species are actually highly dispersive at some life stage. Therefore, it is not applicable to rate confidence levels for relocation with regard to estuaries.

Amount of agreement: N/A

(1) There is very little agreement that this approach is suitable for most estuarine species. It may, however, play a future role for some reptiles and mammals of salt marshes or mangroves that have limited dispersal capacity, but this requires investigation.

Marine Protected Areas
Amount of evidence: N/A

An assessment of "relocation" as a management approach is not made for MPAs because advanced web searches on all the major literature databases result in very little information on the concept of relocation as defined in this report.

Amount of agreement: N/A

Since there is virtually no scientific evidence and little discussion of relocation as it would apply to MPAs, it is not applicable to discuss level of agreement in this approach at this time. However, such an approach should not necessarily be written off as a future option; despite the cost, relocation may become an attractive option to managers of small, secluded, higher-impacted reef environments.

B9 References

Adger, W.N., S. Agrawala, M. M. Q. Mirza, C. Conde, K. O'Brien, J. Pulhin, R. Pulwarty, B. Smit, and K. Takahashi, 2007: Assessment of adaptation practices, options, constraints and capacity, In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK, pp. 717-743.

Allen, C.D., M. Savage, D.A. Falk, K.F. Suckling, T. Schulke, T.W. Swetnam, P.B. Stacey, P. Morgan, M. Hoffman, and J.T. Klingel, 2002: Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. *Ecological Applications*, **12(5)**, 1418-1433.

Allison, G.W., J. Lubchenco, and M.H. Carr, 1998: Marine reserves are necessary but not sufficient for marine conservation. *Ecological Applications*, **8 Supplement-Ecosystem Management for Sustainable Marine Fisheries(1)**, S79-S92.

Babcock, R.C., S. Kelly, N.T. Shears, J.W. Walker, and T.J. Willis, 1999: Changes in community structure in temperate marine reserves. *Marine Ecology Progress Series*, **189**, 125-134.

Baron, J.S., H.M. Rueth, A.M. Wolfe, K.R. Nydick, E.J. Allstott, J.T. Minear, and B. Moraska, 2000: Ecosystem responses to nitrogen deposition in the Colorado Front Range. *Ecosystems*, **3(4)**, 352-368.

Battin, J., M.W. Wiley, M.H. Ruckelshaus, R.N. Palmer, E. Korb, K.K. Bartz, and H. Imaki, 2007: Projected impacts of climate change on salmon habitat restoration. *Proceedings of the National Academy of Sciences of the United States of America*, **104(16)**, 6720.

Bengtsson, J., P. Angelstam, T. Elmqvist, U. Emanuelsson, C. Folke, M. Ihse, F. Moberg, and M. Nystroem, 2003: Reserves, resilience and dynamic landscapes. *Ambio*, **32(6)**, 389-396.

Bernhardt, E.S., M.A. Palmer, J.D. Allan, G. Alexander, K. Barnas, S. Brooks, J. Carr, S. Clayton, C. Dahm, J. Follstad-Shah, D. Galat, S. Gloss, P. Goodwin, D. Hart, B. Hassett, R. Jenkinson, S. Katz, G.M. Kondolf, P.S. Lake, R. Lave, J.L. Meyer, T.K. O'Donnell, L. Pagano, B. Powell, and E. Sudduth, 2005: Synthesizing U.S. river restoration efforts. *Science*, **308**, 636-637.

Boesch, D.F., J. C. Field, and D. Scavia, 2000: The potential consequences of climate variability and change on coastal areas and marine resources, In: *U.S. National*

Assessment of the Potential Consequences of Climate Variability and Change, Report of the Coastal Areas and Marine Resources Sector Team, for the U.S. Global Change Research Program, Silver Spring, MD.

Bruno, J.F. and E.R. Selig, 2007: Regional decline of coral cover in the Indo-Pacific: timing, extent, and subregional comparisons. *PLoS ONE*, **2(8)**, 1-8.

Brussaard, L., P.C. de Ruiter, and G.G. Brown, 2007: Soil biodiversity for agricultural sustainability. *Agriculture, Ecosystems and Environment*, **121(3)**, 233-244.

Burke, L.M. and J. Maidens, 2004: *Reefs at Risk in the Caribbean*. World Resources Institute, Washington, DC.

Camp, A.E., P.F. Hessburg, R.L. Everett, and C.D. Oliver, 1995: *Spatial Changes in Forest Landscape Patterns Resulting From Altered Disturbance Regimes on the Eastern Slope of the Washington Cascades*. General Technical Report INT-GTR-320, US Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, Utah, pp.1-283.

Chen, C.Y., R.S. Stemberger, N.C. Kamman, B.M. Mayes, and C.L. Folt, 2005: Patterns of Hg bioaccumulation and transfer in aquatic food webs across multi-lake studies in the Northeast US. *Ecotoxicology*, **14(1)**, 135-147.

Chornesky, E.A., A.M. Bartuska, G.H. Aplet, K.O. Britton, J. Cummings-carlson, F.W. Davis, J. Eskow, D.R. Gordon, K.W. Gottschalk, and R.A. Haack, 2005: Science priorities for reducing the threat of invasive species to sustainable forestry. *BioScience*, **55(4)**, 335-348.

Coles, S.L. and B.E. Brown, 2003: Coral bleaching-capacity for acclimatization and adaptation. *Advances in Marine Biology*, **46**, 183-223.

Collingham, Y.C. and B. Huntley, 2000: Impacts of habitat fragmentation and patch size upon migration rates. *Ecological Applications*, **10(1)**, 131-144.

Driscoll, C.T., Y.J.I. Han, C.Y. Chen, D.C. Evers, K.F. Lambert, T.M. Holsen, N.C. Kamman, and R.K. Munson, 2007: Mercury contamination in forest and freshwater ecosystems in the Northeastern United States. *BioScience*, **57**, 17-28.

Elmqvist, T., C. Folke, M. Nyström, G. Peterson, J. Bengtsson, B. Walker, and J. Norberg, 2003: Response diversity, ecosystem change, and resilience. *Frontiers in Ecology and the Environment*, **1(9)**, 488-494.

Felzer, B., D. Kicklighter, J. Melillo, C. Wang, Q. Zhuang, and R. Prinn, 2004: Effects of ozone on net primary production and carbon sequestration in the conterminous

United States using a biogeochemistry model. *Tellus Series B-Chemical and Physical Meteorology*, **56(3)**, 230-248.

Fenn, M.E., J.S. Baron, E.B. Allen, H.M. Rueth, K.R. Nydick, L. Geiser, W.D. Bowman, J.O. Sickman, T. Meixner, and D.W. Johnson, 2003: Ecological effects of nitrogen deposition in the western United States. *BioScience*, **53(4)**, 404-420.

Fernandes, L., J. Day, A. Lewis, S. Slegers, B. Kerrigan, D. Breen, D. Cameron, B. Jago, J. Hall, D. Lowe, J. Tanzer, V. Chadwick, L. Thompson, K. Gorman, M. Simmons, B. Barnett, K. Sampson, G. De'ath, B. Mapstone, H. Marsh, H. Possingham, I. Ball, T. Ward, K. Dobbs, J. Aumend, D. Slater, and K. Stapleton, 2005: Establishing representative no-take areas in the Great Barrier Reef: large-scale implementation of theory on Marine Protected Areas. *Conservation Biology*, **19(6)**, 1733-1744.

Fischer, J., D.B. Lindenmayer, and A.D. Manning, 2006: Biodiversity, ecosystem function, and resilience: ten guiding principles for commodity production landscapes. *Frontiers in Ecology and the Environment*, **4(2)**, 80-86.

Gunderson, L., 2007: Ecology: a different route to recovery for coral reefs. *Current Biology*, **17(1)**, 27-28.

Gunderson, L.H., 2000: Ecological resilience-in theory and practice. *Annual Review of Ecology and Systematics*, **31**, 425-439.

Halpin, P.N., 1997: Global climate change and natural-area protection: management responses and research directions. *Ecological Applications*, **7(3)**, 828-843.

Harris, J.A., R.J. Hobbs, E. Higgs, and J. Aronson, 2006: Ecological restoration and global climate change. *Restoration Ecology*, **14(2)**, 170-176.

Hooper, D.U., F.S. Chapin, III, J.J. Ewel, A. Hector, P. Inchausti, S. Lavorel, J.H. Lawton, D.M. Lodge, M. Loreau, S. Naeem, B. Schmid, H. Setälä, A.J. Symstad, J. Vandermeer, and D.A. Wardle, 2005: Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. *Ecological Monographs*, **75(1)**, 3-35.

Hughes, A.R. and J.J. Stachowicz, 2004: Genetic diversity enhances the resistance of a seagrass ecosystem to disturbance. In: *Proceedings of the National Academy of Sciences of the United States of America* 2004.

Hughes, T.P., M.J. Rodrigues, D.R. Bellwood, D. Ceccarelli, O. Hoegh-Guldberg, L. McCook, N. Moltschaniwskyj, M.S. Pratchett, R.S. Steneck, and B. Willis, 2007: Phase shifts, herbivory, and the resilience of coral reefs to climate change. *Current Biology*, **17(4)**, 360-365.

IPCC, 2007: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK, pp. 1-976.

Jaap, W.C., J. H. Hudson, R. E. Dodge, D. Gilliam, and R. Shaul, 2006: Coral reef restoration with case studies from Florida, In: *Coral Reef Conservation*, [Côté, I.M. and J.D. Reynolds (eds.)]. Cambridge University Press, Cambridge, UK, pp. 478-514.

Jameson, S.C., M.H. Tupper, and J.M. Ridley, 2002: The three screen doors: can marine" protected" areas be effective? *Marine Pollution Bulletin*, **44(11)**, 1177-1183.

Joyce, L.A., J. Aber, S. McNulty, D. H. Vale, A. Hansen, L. C. Irland, R. P. Neilson, and K. Skog, 2001: Potential consequences of climate variability and change for the forests of the United States, In: *Climate Change Impacts on the United States: the Potential Consequences of Climate Variability and Change, National Assessment Synthesis Team Report for the US Global Change Research Program*, Cambridge University Press, Cambridge, UK, pp. 489-522.

Lacey, J.R., C.B. Marlow, and J.R. Lane, 1989: Influence of spotted knapweed (*Centaurea-maculosa*) on surface runoff and sediment yield. *Weed Technology*, **3(4)**, 627-631.

Landres, P.B., P. Morgan, and F.J. Swanson, 1999: Overview of the use of natural variability concepts in managing ecological systems. *Ecological Applications*, **9(4)**, 1179-1188.

Lenihan, H.S., C.H. Peterson, J.E. Byers, J.H. Grabowski, G.W. Thayer, and D.R. Colby, 2001: Cascading of habitat degradation: oyster reefs invaded by refugee fishes escaping stress. *Ecological Applications*, **11(3)**, 764-782.

Levey, D.J., B.M. Bolker, J.J. Tewksbury, S. Sargent, and N.M. Haddad, 2005: Effects of landscape corridors on seed dispersal by birds. *Science*, **309**, 146-148.

Lippincott, C.L., 2000: Effects of *Imperata cylindrica* (L.) Beauv. (Cogongrass) invasion on fire regime in Florida sandhill (USA). *Natural Areas Journal*, **20(2)**, 140-149.

Loreau, M., S. Naeem, P. Inchausti, J. Bengtsson, J.P. Grime, A. Hector, D.U. Hooper, M.A. Huston, D. Raffaelli, B. Schmid, D. Tilman, and D.A. Wardle, 2001: Biodiversity and ecosystem functioning: current knowledge and future challenges. *Science*, **294(5543)**, 804-808.

Markham, A., 1996: Potential impacts of climate change on ecosystems: a review of implications for policymakers and conservation biologists. *Climate Research*, **6**, 171-191.

Marshall, P. and J. Johnson, 2007: The Great Barrier Reef and climate change: vulnerability and management implications, Chapter 24, In: *Climate Change and the Great Barrier Reef: a Vulnerability Assessment*, Great Barrier Reef Marine Park Authority.

Marshall, P. and H. Schuttenberg, 2006: Adapting coral reef management in the face of climate change, In: *Coral Reefs and Climate Change: Science and Management*, [Phinney, J.T., O. Hoegh-Guldberg, J. Kleypas, W.J. Skirving, and A. Strong (eds.)]. American Geophysical Union, Washington, DC, pp. 223-241.

McClanahan, T.R., S. Mwaguni, and N.A. Muthiga, 2005: Management of the Kenyan coast. *Ocean and Coastal Management*, **48**, 901-931.

McClanahan, T.R., N. V. C. Polunin, and T. J. Done, 2002: Ecological states and the resilience of coral reefs, In: *Resilience and Behaviour of Large-Scale Ecosystems*, [Gunderson, L.H. and L. Pritchard, Jr. (eds.)]. Island Press, Washington, DC, pp. 111-163.

McCook, L.J., C. Folke, T. Hughes, M. Nyström, D. Obura, and R. Salm, 2007: Ecological resilience, climate change and the Great Barrier Reef, Chapter 4, In: *Climate Change and the Great Barrier Reef: a Vulnerability Assessment*, Great Barrier Reef Marine Park Authority.

McLachlan, J.S., J.J. Hellmann, and M.W. Schwartz, 2007: A framework for debate of assisted migration in an era of climate change. *Conservation Biology*, **21(2)**, 297-302.

McLaughlin, S.B., M. Nosal, S.D. Wullschleger, and G. Sun, 2007a: Interactive effects of ozone and climate on tree growth and water use in a southern Appalachian forest in the USA. *New Phytologist*, **174(1)**, 109-124.

McLaughlin, S.B., S.D. Wullschleger, G. Sun, and M. Nosal, 2007b: Interactive effects of ozone and climate on water use, soil moisture content and streamflow in a southern Appalachian forest in the USA. *New Phytologist*, **174(1)**, 125-136.

Millar, C.I., 1989: Allozyme variation of bishop pine associated with pygmy-forest soils in northern California. *Canadian Journal of Forest Research*, **19(7)**, 870-879.

Millar, C.I., J.C. King, R.D. Westfall, H.A. Alden, and D.L. Delany, 2006: Late Holocene forest dynamics, volcanism, and climate change at Whitewing

Mountain and San Joaquin Ridge, Mono County, Sierra Nevada, CA, USA. *Quaternary research*, **66**, 273-287.

Millar, C.I., R.D. Westfall, and D.L. Delany, in press: Mortality and growth suppression in high elevation limber pine (*Pinus flexilis*) forests in response to multi-year droughts and 20th century warming. *Canadian Journal of Forest Research*.

Millar, C.I. and W.B. Woolfenden, 1999: The role of climate change in interpreting historical variability. *Ecological Applications*, **9(4)**, 1207-1216.

Mooney, H.A. and R.J. Hobbs, 2000: *Invasive Species in a Changing World*. Island Press, Washington, DC.

Mumby, P.J., A.R. Harborne, J. Williams, C.V. Kappel, D.R. Brumbaugh, F. Micheli, K.E. Holmes, C.P. Dahlgren, C.B. Paris, and P.G. Blackwell, 2007: Trophic cascade facilitates coral recruitment in a marine reserve. *Proceedings of the National Academy of Sciences of the United States of America*, **104(20)**, 8362-8367.

National Research Council, 2004: *Air Quality Management in the United States*. National Academies Press, National Academies of Science.

Noss, R.F., 2001: Beyond Kyoto: Forest management in a time of rapid climate change. *Conservation Biology*, **15(3)**, 578-590.

Novacek, M.J. and E.E. Cleland, 2001: The current biodiversity extinction event: scenarios for mitigation and recovery. *Proceedings of the National Academy of Sciences of the United States of America*, **98(10)**, 5466-5470.

Ottawa National Forest, 2006: Affected environment and environmental consequences, Chapter 3, In: *Draft Environmental Impact Assessment*, USDA Forest Service, available at http://www.fs.fed.us/r9/ottawa/forest_management/forest_plan/revision/fp_final/volume_1_final_eis/final_eis_chapter_3.pdf.

Palumbi, S.R., 2002: *Marine Reserves: a Tool for Ecosystem Management and Conservation*. Pew Oceans Commission, Arlington, VA, pp.1-45.

Parker, B.R. and D.W. Schindler, 2006: Cascading trophic interactions in an oligotrophic species-poor alpine lake. *Ecosystems*, **9(2)**, 157-166.

Peterson, S.A., J. Van Sickle, A.T. Herlihy, and R.M. Hughes, 2007: Mercury concentration in fish from streams and rivers throughout the western united states. *Environmental Science & Technology*, **41(1)**, 58-65.

Pimentel, D., L. Lach, R. Zuniga, and D. Morrison, 2000: Environmental and economic costs of nonindigenous species in the United States. *BioScience*, **50(1)**, 53-64.

Poff, N.L.R., J.D. Olden, D.M. Merritt, and D.M. Pepin, 2007: Homogenization of regional river dynamics by dams and global biodiversity implications. *Proceedings of the National Academy of Sciences of the United States of America*, **104(14)**, 5732-5737.

Precht, W.F. and R. B. Aronson, 2006: Death and the resurrection of Caribbean reefs: a palaeoocological perspective, In: *Coral Reef Conservation*, [Cote, I.M. and J. Reynolds (eds.)]. Cambridge University Press, Cambridge, pp. 40-77.

Precht, W.F. and S. L. Miller, 2006: Ecological shifts along the Florida reef tract: the past as a key to the future, In: *Geological Approaches to Coral Reef Ecology*, [Aronson, R.B. (ed.)]. Springer, New York, NY, pp. 237-312.

Rahel, F.J., 2000: Homogenization of fish faunas across the United States. *Science*, **288(5467)**, 854-856.

Rice, K.J. and N.C. Emery, 2003: Managing microevolution: restoration in the face of global change. *Frontiers in Ecology and the Environment*, **(1)**, 469-478.

Riegl, B. and W.E. Piller, 2003: Possible refugia for reefs in times of environmental stress. *International Journal of Earth Sciences*, **92(4)**, 520-531.

Roberts, C.M., J. D. Reynolds, I. M. Côté, and J. P. Hawkins, 2006: Redesigning coral reef conservation, In: *Coral Reef Conservation*, Cambridge University Press, Cambridge, UK, pp. 515-537.

Salm, R.V., T. Done, and E. McLeod, 2006: Marine protected area planning in a changing climate, In: *Coral Reefs and Climate Change: Science and Management*, [Phinney, J.T., O. Hoegh-Guldberg, J. Kleypas, W. Skirving, and A. Strong (eds.)]. American Geophysical Union, Washington, DC, pp. 207-221.

Scavia, D., J.C. Field, D.F. Boesch, R.W. Buddemeier, V. Burkett, D.R. Cayan, M. Fogarty, M.A. Harwell, R.W. Howarth, C. Mason, D.J. Reed, T.C. Royer, A.H. Sallenger, and J.G. Titus, 2002: Climate change impacts on U.S. coastal and marine ecosystems. *Estuaries*, **25(2)**, 149-164.

Schneider, S.H., S. Semenov, A. Patwardhan, I. Burton, C. H. D. Magadza, M. Oppenheimer, A. B. Pittock, A. Rahman, J. B. Smith, A. Suarez, and F. Yamin, 2007: Assessing key vulnerabilities and the risk from climate change, In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK, pp. 779-810.

Singer, J.F., C.V. Bleich, and A.M. Gudorf, 2000: Restoration of bighorn sheep metapopulations in and near western National Parks. *Restoration Ecology*, **8(4)**, 14-24.

Sobel, J.A. and C. Dahlgren, 2004: *Marine Reserves: a Guide to Science, Design, and Use*. Island Press, Washington, DC, pp. 1-383.

Spittlehouse, D.L. and R.B. Stewart, 2003: Adaptation to climate change in forest management. *BC Journal of Ecosystems and Management*, **4(1)**.

Stein, B.A., S.R. Flack, N.B. Benton, and N. Conservancy, 1996: *America's Least Wanted: Alien Species Invasions of US Ecosystems*. The Nature Conservancy, Arlington, VA.

Tilman, D., P.B. Reich, and J.M.H. Knops, 2006: Biodiversity and ecosystem stability in a decade-long grassland experiment. *Nature*, **441(7093)**, 629-632.

Tomback, D.F. and K. C. Kendall, 2002: Rocky road in the Rockies: challenges to biodiversity, In: *Rocky Mountain Futures, an Ecological Perspective*, [Baron, J. (ed.)]. Island Press, Washington, DC, pp. 153-180.

U.S. Geological Survey, 2005: *The State of the Colorado River Ecosystem in Grand Canyon*. USGS Circular 1282, U.S. Department of the Interior, U.S. Geological Survey, pp.1-220.

USDA Forest Service, 2004: *National Strategy and Implementation Plan for Invasive Species Management*. FS-805.

Von Holle, B. and D. Simberloff, 2005: Ecological resistance to biological invasion overwhelmed by propagule pressure. *Ecology*, **86(12)**, 3212-3218.

Walker, B., 1995: Conserving biological diversity through ecosystem resilience. *Conservation Biology*, **9(4)**, 747-752.

Walker, B., A. Kinzig, and J. Langridge, 1999: Plant attribute diversity, resilience, and ecosystem function: the nature and significance of dominant and minor species. *Ecosystems*, **2(2)**, 95-113.

Welch, D., 2005: What should protected areas managers do in the face of climate change? *The George Wright Forum*, **22(1)**, 75-93.

West, J.M. and R.V. Salm, 2003: Resistance and resilience to coral bleaching: implications for coral reef conservation and management. *Conservation Biology*, **17(4)**, 956-967.

Williams, D.G. and Z. Baruch, 2000: African grass invasion in the Americas: ecosystem consequences and the role of ecophysiology. *Biological Invasions*, **2(2)**, 123-140.

Williams, J.W., S.T. Jackson, and J.E. Kutzbach, 2007: Projected distributions of novel and disappearing climates by 2100 AD. *Proceedings of the National Academy of Sciences of the United States of America*, **104(14)**, 5738-5742.

Ziska, L.H., J.B. Reeves, and B. Blank, 2005: The impact of recent increases in atmospheric CO_2 on biomass production and vegetative retention of Cheatgrass (*Bromus tectorum*): implications for fire disturbance. *Global Change Biology*, **11(8)**, 1325-1332.