Annex A: Case Studies

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A1 National Forests Case Studies

A1.1 Tahoe National Forest

A1.1.1 Setting and Context of Tahoe National Forest

Tahoe National Forest (TNF) is located in eastern California, where it straddles the northern Sierra Nevada (Fig. A1.1). The administrative boundary encompasses 475,722 ha (1,175,535 ac), of which one-third are privately owned forest industry lands arranged in alternate sections ("checkerboard") with TNF land. Elevations range from 365 m (1,200 ft) at the edge on the western slope to 2,788 m (9,148 ft) at the crest of the Sierra. The eastern slopes of TNF abut high-elevation (~1,525 m; 5,000 ft) arid steppes of the Great Basin. TNF experiences a Mediterranean-type climate with warm, dry summers alternating with cool, wet winters. The orientation of the Sierra Nevada paralleling the Pacific coast creates a steep west-east climatic gradient that contributes to strong orographic effects in temperature and a precipitation rainshadow. Near TNF's western boundary, average precipitation is low (125 cm; 50 in), highest at west-side mid-elevations (200 cm; 80 in), and lowest near the eastern boundary (50 cm; 20 in). Snow dominates winter precipitation in the upper elevations, providing critical water reserves for the long annual summer drought.

Figure A1.1. Map and location of the Tahoe National Forest, within California (a) and the Forest boundaries (b).[1]

Floral and faunal diversity of TNF parallels the topographic and climatic gradients of the Sierra Nevada, with strong zonation along elevational bands. The long Mediterranean drought is a primary influence on the species that can grow and the natural disturbance regimes. Pine forests occupy low elevations on the western side. These grade upslope to a broad zone of economically and ecologically important mixed-conifer forests. Higher, at the elevation of the rain-snow zone, true-fir forests dominate; diverse subalpine forests are the highest-elevation tree communities. East of the crest, sparse eastside pine communities grade downslope to woodlands and shrublands of the Great Basin. Terrestrial and aquatic environments of TNF support critical habitat for a large number of plant and animal species, many of which have long been subjects of intense conservation concern. The TNF environments are used by 387 vertebrate species and more than 400 plant species (Tahoe National Forest, 1990; Shevock, 1996). Several keystone species at the Sierra rangewide scale depend on now-limited old-growth forest conditions or other rare habitats.

[1] **USDA Forest Service**, 2007: Tahoe National Forest map. USDA Forest Service Website, http://www.fs.fed.us/r5/tahoe/maps_brochures/images/05_nov_01_tnf_map.jpg, accessed on 7-30-2007. And **USDA Forest Service**, 2007: National Forests in California. USDA Forest Service Website, http://www.fs.fed.us/r5/forests.html, accessed on 7-30-2007.

Cultural legacies have played significant roles in shaping present forest conditions and vulnerabilities in TNF. Timber, water, mining, and grazing, which started in the mid-1800s, remained intensive uses until the late 20th century. Low- to mid-elevation forests were denuded in the mid-1800s through early 1900s to provide wood for settlement (Beesley, 1996). Subsequently the forests regrew, but although they continued to be extensively harvested until recently, decades of fire suppression contributed to extremely dense stands, even-age classes, and low structural diversity. These conditions led to extreme fire susceptibilities; large fire events have occurred in recent years, and fire vulnerability is the highest concern for management. Modern human use of TNF and adjacent lands has changed the way in which natural resources are managed. Population and development in the communities adjacent to the low elevations have exploded in the past decades, creating extensive wildland-urban interface issues (Duane, 1996). Changing demographies and consequent resource values of new residents have forced re-evaluation of TNF goals and practices, many of which limit the capacity of TNF to implement adaptive but manipulative practices in the face of changing climates. Recreation is now a primary use of TNF lands; timber management is minor. Fuels reduction is a key issue both for protection of TNF resources and of adjacent rural communities.

A1.1.2 Recent and Anticipated Regional Climate Changes and Impacts

The trend of temperature increase over the 20th century for California has paralleled the global pattern (IPCC, 2007a), although at greater magnitude (1.5–2°C; Millar *et al.*, 2004).[2] Precipitation has not shown strong directional changes, but has been variable at annual and interannual scales (Cayan *et al.*, 1998). Forest insect and disease, mortality, and fire events have become more severe in TNF, as throughout the West (Logan and Powell, 2001; Westerling *et al.*, 2006). Decreases in average snowpack up to 80% are documented throughout much of the West; snowpacks peak as much as 45 days earlier (Hamlet *et al.*, 2005; Mote *et al.*, 2005) and peak streamflow peaks up to three weeks earlier in spring (Stewart, Cayan, and Dettinger, 2005) than during the 1950s, based on an analysis of the last 50 years.

Many of the climate and ecological trends documented for the 20th century are projected to continue and exacerbate in the 21st century. Future climate scenarios and effects on water, forests, fires, insects, and disease for California are summarized in Hayhoe *et al*. (2004) and the California Climate Action Team reports (California Climate Action Team, 2005). All models project increased annual temperatures over California ranging from 2.3–5.8°C (4.1–10.4°F) (range of models to show model uncertainties). Model projections also indicate slight drying, especially in winter; interannual and interdecadal variability is projected to remain high in the next century. Snowpacks, however, are consistently projected to decline by as much as 97% at 1,000 m (3,280 ft.) elevation and 89% for all elevations. The combined effects of continued warming, declining snowpacks, and earlier stream runoff portend longer summer droughts for TNF, and increasing soil moisture deficits during the growing season. This would increase stress that an already long, dry Mediterranean summer imposes on vegetation and wildlife.

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[2] See also, **Western Regional Climate Center**, 2005: Instrumental weather databases for western climate stations. Western Regional Climate Center Database, http://www.wrcc.dri.edu/, accessed on 4-27-2007.

Coupling climate models with vegetation models yields major contractions and expansions in cover of dominant montane vegetation types by the late 21st century (Hayhoe *et al.*, 2004; Lenihan *et al.*, 2006). By 2070–2099, alpine and subalpine forest types are modeled to decline by up to 90%, shrublands by 75%, and mixed evergreen woodland by 50%. In contrast, mixed evergreen forest and grasslands are each projected to expand by 100%. The following conditions are expected to be exacerbated in TNF as a result of anticipated changes (Dettinger *et al.*, 2004; Hayhoe *et al.*, 2004; Cayan *et al.*, 2006b):

- Increased fuel build-up and risk of uncharacteristically severe and widespread forest fire.
- Longer fire seasons; year-round fires in some areas (winter fires have already occurred).
- Higher-elevation insect and disease and wildfire events (large fires already moving into true fir and subalpine forests, which is unprecedented).
- Increased interannual variability in precipitation, leading to fuels build up and causing additional forest stress. This situation promotes fire vulnerabilities and sensitivities.
- Increased water temperatures in rivers and lakes and lower water levels in late summer.
- Increased stress to forests during periodic multi-year droughts; heightened forest mortality.
- Decreased water quality as a result of increased watershed erosion and sediment flow.
- Increased likelihood of severe flood events.
- Loss of seed and other germplasm sources as a result of population extirpation events.

A1.1.3 Current TNF Natural-Resource Policy and Planning Context

In addition to national laws and regional management directives, management goals and direction for the lands and resources of TNF are specified by several overarching planning documents. These relate to different landscape scales and locations. The 1990 Tahoe National Forest Land and Resource Management Plan (LMP) (Tahoe National Forest, 1990) remains the comprehensive document for all resource management in TNF. The primary mission of TNF is to "serve as the public's steward of the land, and to manage the forest's resources for the benefit of all American people…[and]…to provide for the needs of both current and future generations" (Tahoe National Forest, 1990). Within this broad mission, specific goals, objectives, desired future conditions, and standards and guidelines are detailed for the following resource areas: recreation; interpretive services; visual management; cultural resources; wilderness; wildlife and fish; forage and wood resources; soil, water, and riparian areas; air quality; lands; minerals management; facilities; economic and environmental efficiency; security; human and community resources; and research.

Specific direction in the LMP has been amended by the Sierra Nevada Forest Plan Amendment (FPA; USDA Forest Service, 2004) and the Herger-Feinstein Quincy Library Group Forest Recovery Act.[3] The FPA is a multi-forest plan that specifies goals and direction for protecting old forests, wildlife habitats, watersheds, and communities on the 11 NFs of the Sierra Nevada and Modoc Plateau. Goals for old-growth forests focus on protection, enhancement, and maintenance of old forest ecosystems and their associated species through increasing density of large trees, increasing structural diversity of vegetation, and improving continuity of old forests at the landscape scale. A 2003 decision by the U.S. Fish and Wildlife Service to not list the California Spotted Owl as endangered was conditioned on the assumption that NFs (including TNF) would implement the direction of the FPA.

In regard to aquatic, riparian, and meadow habitat, the FPA goals and management direction are intended to improve the quantity, quality, and extent of highly degraded wetlands throughout the Sierra Nevada, and to improve habitat for aquatic and wetland-dependent wildlife species such as the willow flycatcher and the Yosemite toad.

Fire and fuels goals are among the most important in the FPA. In general, direction is given to provide a coordinated strategy for addressing the risk of catastrophic wildfire by reducing hazardous fuels while maintaining ecosystem functions and providing local economic benefits. The specific approaches to these goals are conditioned by the National Fire Plan of 2000 (USDA Forest Service, 2000a) and the Healthy Forests Restoration Act of 2003,[4] which emphasize strategic placement of fuel treatments across the landscape, removing only enough fuels to cause fires to burn at lower intensities and slower rates than in untreated areas, and are cost-efficient fuel treatments.

The FPA contained a Sierra-wide adaptive management and monitoring strategy. This strategy is being implemented as a pilot project on two NFs in the Sierra Nevada, one of which includes TNF. This seven-year pilot project, undertaken via a Memorandum of Understanding between the U.S. Forest Service, the U.S. Fish and Wildlife Service, and the University of California, applies scientifically rigorous design, treatment, and analysis approaches to fire and forest health, watershed health, and wildlife. Several watersheds of TNF are involved in each of the three issue areas of the FPA adaptive management project.

The Herger-Feinstein Quincy Library Group Forest Recovery Act of 1998 provides specific management goals and direction for a portion of TNF (the Sierraville Ranger District, 164,049 ac) and adjacent NFs. The Act derived from an agreement by a coalition of representatives of fisheries, timber, environmental, county government, citizen groups, and local communities that formed to develop a resource management program to promote ecologic and economic health for certain federal lands and communities in the northern Sierra Nevada. The Act launched a pilot project to test alternative strategies for managing sensitive species, a new fire and fuels strategy, and a new adaptive management strategy. The Herger-Feinstein Quincy Library Group Pilot is the resulting

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[3] Title 4, Section 401(j), P.L. 103-354
[4] H. R. 1904

project with goals to test, assess, and demonstrate the effectiveness of fuelbreaks, group selection, individual tree selection, avoidance or protection of specified areas; and to implement a program for riparian restoration.

A1.1.4 TNF Management and Planning Approaches to Climate Change

Management practices identified by TNF staff as being relevant to climate issues are listed below, relative to the three categories of responses described in the National Forests chapter of this report: unplanned, reactive adaptation, or no adaptation measures planned or taken; management responses reacting to crisis conditions or targeting disturbance, extreme events; and proactive management anticipating climate changes.

A1.1.4.1 No Active Adaptation

Few if any of TNF's management policies or plans specifically mention or address climate or climate adaptation. Thus, while it would appear that "no adaptation" is the dominant paradigm at TNF, many practices are de-facto "climate-smart," where climatic trends or potential changes in climate are qualitatively or quantitatively incorporated into management consideration, as indicated in following sections.

A1.1.4.2 Management Responses Reacting to Changing Disturbance and Extreme Events

Most post-disturbance treatments planned by TNF were developed to meet goals of maintaining ecosystem health (*e.g.*, watershed protection, succession to forest after wildfire, fuel reduction after insect mortality) rather than catalyzing climate-adaptive conditions. Nonetheless, many of these best-forest-management practices are consistent with adaptive conditioning for climate contexts as well, as the example here suggests:

Salvage and Planting Post-Fire

While in most cases the capacity cannot meet the need, TNF is able to respond adaptively on a small number of acres post-disturbance if the effort to develop NEPA documentation is adequate to defend against appeal and litigation.[5] In these circumstances, watershed protection measures are implemented and species-site needs are considered in decisions about what and where to plant, or what seed to use.

A1.1.4.3 Management Anticipating Climate Change

While TNF has not addressed climate directly through intentional proactive management, staff have been discussing climate change and climate implications for many years. This proactive thinking in itself has pre-conditioned TNF to taking climate into account in early management actions, and has started the discussion among staff regarding potential changes in strategic planning areas. Further, advances have been made in integrated planning processes that may be useful vehicles for incorporating climate-related treatments, thus pre-adapting TNF institutionally to move forward with proactive climate management. The following examples of actions and opportunities demonstrate how the TNF is moving forward with dynamic management.

Staff Support by Line Officers

[5] **Levings**, W., 2003: *Economics of Delay*. Unpublished report on file at the Tahoe National Forest, pp.1-6.

The leadership team at TNF promotes broad science-based thinking and rewards adaptive and proactive behaviors. This practice clearly sets a stage where management responses to climate can be undertaken where possible, providing an incentive and the intellectual environment to do so.

Fireshed Assessment

The new Fireshed Assessment process is a major step toward integrated management of TNF lands. Effective implementation of this process already provides a vehicle for other dynamic and whole-landscape planning processes such as are needed for climate adaptation.

Fuel Reduction Projects

Strategies implemented by TNF as a result of FPA and Herger-Feinstein Quincy Library Group Pilot directions to reduce fuels and minimize chances of catastrophic fires are increasing the adaptability and resilience of TNF forests (Fig. A1.2). Strategically placed area treatments, a form of adaptive and dynamic approach to fuel management, are being tested on the adaptive management pilot of TNF.

Figure A1.2. Thinned stands for fuel reduction and resilience management, part of the Herger-Feinstein Quincy Library Pilot Project. Photo courtesy of Tahoe National Forest.

Riparian Management Policies

New policies in the FPA for riparian and watershed management restrict road construction for timber management (*e.g.*, near or across perennial streams). Helicopters are used for logging in all situations where roads cannot be built. This allows more flexibility, adaptability, and reduces fragmentation and watershed erosion.

Post-Event Recovery

While certain kinds of standardized post-fire restoration practices (*e.g.*, Burned Area Emergency Rehabilitation procedures) are not climate-proactive, a post-event recovery team at the Pacific Southwest regional level is investigating dynamic approaches to recovery post-major disturbance. These approaches might include planning for long-term changes on disturbed sites and taking advantage of new planting mixes, broadening gene pool mixes, planting in new spacing and designs, etc.

Revegetation and Silvicultural Choices

In stand improvement projects and revegetation efforts, choices are being considered to favor and/or plant different species and species mixes. For instance, where appropriate based on anticipated changes, white fir could be favored over red fir, pines would be preferentially harvested at high elevations over fir, and species would be shifted upslope within seed transfer guides.

Forest Plan Revision

The TNF LMP is due for revision. Climate considerations are being evaluated as the plan revision unfolds, including such options as flexible spotted owl (*Strix occidentalis occidentalis*) "Protected Activity Center" boundaries, species shifts in planting and thinning, and priority-setting for sensitive-species management.

Resisting Planned Projects That May Not Succeed Under Future Climate Conditions

Restoring salmon to TNF rivers is a goal in the current LMP (Fig. A1.3). With waters warming, however, future conditions of TNF rivers are not likely to provide suitable habitat for salmon. Thus, TNF is considering the option to not restore salmon. Meadow restoration is another example: Rather than proceeding with plans for extensive and intensive meadow restoration, some areas are being considered for non-treatment due to possible succession of non-meadow conditions in these locations.

Figure A1.3. Former salmon habitat (rivers marked in bold black) of the Sierra Nevada. Tahoe National Forest (TNF) rivers are scheduled to have salmon restored to them in current national forest planning. Adaptive approaches suggest that future waters may be too warm on the TNF for salmon to survive, and thus restoration may be inappropriate to begin. Map adapted from (Sierra Nevada Ecosystem Project Science Team, 1996).

Resilience Management

All forms of proactive management that improve the resilience of natural resources are improving the adaptiveness of TNF by decreasing the number of situations where TNF must take crisis-reaction responses.

Dynamic Management

TNF staff is using opportunities available at present (*i.e.*, under current policy) to manage dynamically and experimentally. An example is cases in which plans treat critical species' range margins differently, favoring active management at advancing edges or optimal habitat rather than static or stressed margins.

Managing for Process

TNF staff is also using opportunities available at present to manage for process rather than structure or composition in proposed projects; for example, those involving succession after fires, where novel mixes of species and spacing may reflect likely natural dynamic processes of adaptation.

A1.1.5 Proactive Management Actions Anticipating Climate Change

A1.1.5.1 Examples of Potential Future Proactive Management Actions

The ideas listed below were identified by TNF staff as being examples of how management actions could be leveraged in the future to increase the TNF adaptive responses to climate change.

- Rapid assessments of current planning and policy. A science-based (*e.g.*, U.S. Forest Service research team) rapid assessment or "audit" of existing TNF planning documents (*e.g.*, the LMP and project plans) could focus on the level of climate adaptedness, pitfalls, and areas for improvement in current TNF plans and operations. Such an audit could focus on current management direction (written policy); current management practices (implementation); and priorities of species (*e.g.*, specific targeted species) and processes (fire, insects/disease). The audit would highlight concrete areas of the plans and projects that are ill-adapted as well as those that are proactive and already climate-proactive, and would recommend a set of specific areas where changes are needed and improvements could be made.

- Assessment/audit of the Sierra Nevada FPA. This would be a similar assessment to that above, but would be undertaken at the FPA scale. The FPA did not originally include climate, and the science consistency review highlighted this problem. A more comprehensive assessment of the FPA's strengths and weaknesses is needed, with a call for revision as appropriate.

- TNF as a pilot for the U.S. Forest Service Ecosystem Services program. Tapping into the ecosystems services market opportunities and acting as a pilot national forest within the ecosystems services goals and objectives may provide management flexibility needed for climate adaptation.

- Management unit size. Increase sizes of management units on the forest, so whole landscapes (watersheds, forest types) could be managed in a single resource plan; decrease administrative fragmentation. Whole ecosystem management, rather than piecemeal by small management unit or by single species or single issue, would favor adaptability to climate-related challenges.

- Watershed management; water storage. To increase groundwater storage capacities, treatments to improve infiltration could be implemented. For instance, in TNF, consider decreasing road densities and other activities (evaluate grazing) in order to change surfaces from impervious to permeable.

- Watershed management; salvage harvest. To decrease erosion and sediment loss following disturbance, there is widespread need in TNF to salvage-harvest affected trees and reforest soon after disturbance. This is the plan at present, but mostly cannot be implemented in adequate time due to time required for NEPA processing and general public opposition.

- Event recovery. Post-disturbance mortality and shrub invasion must be dealt with swiftly to keep options open for forest regeneration on the site. The means are known; the capacity (money, legal defense) is needed.

A1.1.6 Barriers and Opportunities to Proactive Management for Climate Change at TNF

A1.1.6.1 Barriers

The situations listed below were identified by TNF staff as barriers that limit TNF's capacity to respond adaptively to climate change.

- Public opposition. Appeals and litigation of proposed active management projects directly restrict ability of TNF to implement adaptive practices.[5] There is a large public constituency that opposes active management of any kind. Thus, no matter the purpose, if adaptive management proposals involve on-the-ground disturbance, these publics attempt to prohibit their implementation. The likelihood of appeals and litigation means that a large proportion of staff time must necessarily be used to develop "appeal-proof" NEPA documents, rather than undertaking active management projects on the ground. This often results in a situation in which no-management action can be taken, regardless of the knowledge and intent to implement active and adaptive practices.

- Funding. Overall lack of funds means that adaptive projects, while identified and prioritized, cannot be implemented. General funding limitations are barriers throughout TNF operations. The annual federal budget process limits capacity to plan or implement long-term projects.

- Staff capacity. Loss of key staff areas (*e.g.*, silviculture) and general decline in resource staff and planning capacity translate to lower capacity to respond adaptively to needed changes.

- Scope of on-the-ground needs. As a result of legacy issues (fire-suppression, land-use history, etc.), as well as responses to changing climates (increasing densification of forests, increasing forest mortality), the area of land needing active management is rapidly escalating, and far exceeds staff capacity or available funds to treat it.

- Crisis reaction as routine planning approach. Inadequate TNF funding and staff capacity, combined with persistent legal opposition by external publics, force a continuous reactive approach to priority-setting. This results in crisis-management being the only approach to decision-making that is possible, as opposed to conducting or implementing long-term, skillful, or phased management plans.

- Checkerboard ownership pattern. The alternating sections of TNF and private land create barriers to planning or implementing landscape-scale management, which is needed for adaptive responses to climate challenges. Achieving mutually agreeable management goals regarding prescribed fire, road building, fire suppression, post-fire recovery, and many other landscape treatments is extremely difficult; thus, often no management can be done. This is especially challenging in the central part of TNF, where important corridors, riparian forests, and continuous wildlife habitat would be actively enhanced by management, but cannot be due to mixed ownership barriers.

- Existing environmental laws. Many current important environmental laws that regulate national forest actions such as the Endangered Species Act, the National Forest Management Act, and the National Environmental Policy Act are highly static, inhibit dynamic planning, and impede adaptive responses.[5] Further, these laws do not allow the option of not managing any specific situation—such choices may be necessary as triage-based adaptation in the future. Finally, while coarse-filter approaches are more adaptive, many existing laws force a fine-filter approach to management.

- Current agency management concepts and policies. Current agency-wide management paradigms limit capacity to plan in a proactive, forward-looking manner. For instance, the policies requiring use of historic-range-of-variability or other historic-reference approaches for goal-setting restrict dynamic, adaptive approaches to management. This problem was identified in vegetation management, dam construction ("100-year" flood references), and sensitive-species management (owls, salmon). Certain current regional policies and procedures limit adaptive responses. An example is the Burned Area Emergency Rehabilitation approach to post-fire rehabilitation. Burned Area Emergency Rehabilitation is a static and short-term set of practices that does not incorporate the capacity to respond flexibly and adaptively post-fire, such as taking actions to actively move the site in new ecological trajectories with different germplasm sources and different species mixes.

- Static management. Other current management paradigms that limit dynamic planning and managing include the focus on "maintaining," "retaining," and "restoring" conditions. The consequence of these imperatives in planning documents is to enforce static rather than dynamic management.

- Air quality standards. Regional regulatory standards for smoke and particulates are set low in order to optimize air quality. These levels, however, limit the capacity of TNF to conduct prescribed fires for adaptive fuel reduction or silvicultural stand treatment purposes.

- Community demographics and air quality/urban fuels. Changing demographics of foothill Sierran communities adjacent to TNF are moving toward less acceptance of smoke. Older and urban residents moving into the area in the past few years have little experience with fire and its effects, and have little understanding of or tolerance for smoke from prescribed fire treatments. Similarly, these residents are not apt to subscribe to Fire-Safe Council home ownership/maintenance recommendations, thus putting their homes and landscaping at high risk from wildfire.

- Agency target and reward system. The current system at the national agency level for successful accomplishments (*i.e.*, the reward system) focuses on achieving narrowly prescribed targets ("building widgets"). Funds are allocated to achieving targets; thus simplistic, in-the-box thinking, and routine, easily accomplished activities are encouraged. There are few incentives for creative project development or implementation.

- Small landscape management units. Fragmentation and inflexibility result from partitioning TNF into small management units; small unit sizes also restrict the capacity for full understanding of ongoing dynamics and process. For instance, even the adaptive management pilot projects under the FPA are too small to be meaningful under the conditions anticipated in the future—at least 20,000 acres (8,093 ha) are needed.

A1.1.6.2 Opportunities

The activities listed below were identified by TNF staff as current or potential future opportunities to enhance managers' ability to proactively manage for climate change, some of which are currently employed at TNF.

- Year-round management opportunities. TNF is experiencing later winters (snow arriving later in the year), lower snowpacks, and earlier runoff. The TNF staff has taken advantage of these changes by continuing fuel treatments far beyond the season where historically these treatments could be done. At present, winter-prescribed fires are being undertaken, and conditions are ideal to do so. This enables treating more acres in adaptive practices than could be done if only summer were available for these management activities.

- Responses to public concerns through active dialog. TNF has effectively maintained a capacity to implement adaptive projects when in-depth, comprehensive analysis has been done on NEPA process. In addition, intensive education of the interested publics through workshops, scoping meetings, face-to-face dialog, and informal disposition processes have helped to develop support for plans (avoiding appeal), and thus these activities are enabling TNF's adaptive projects to be conducted.

- Responses to public concerns by demonstration. Specifically, TNF was able to gain public approval to cut larger-diameter classes (needed for active management to achieve dynamic goals) than had been previously acceptable, through the use of 3-D computer simulations (visualizations), on-the-ground demonstration projects, "show-me" field trips, and other field-based educational efforts.

- Emerging carbon markets are likely to promote the (re-)development of regional biomass and biofuels industries. These industries will provide economic incentives for active adaptive management, in particular funds to support thinning and fuel-reduction projects.

- Planning flexibility in policy. The existence of the Herger-Feinstein Quincy Library Group Pilot and the FPA Adaptive Management project on TNF mean that there is more opportunity than in most other Sierra Nevada NFs to implement active management, especially at broader landscape scales.

- New staff areas defined. When capacity to add staff arises, new positions (climate-smart) may be added. Through incremental changes in staff, TNF may "reinvent and redefine" its institutional ability to better respond adaptively to novel challenges.

- Public education. There is an opportunity to further educate the local public about the scientific bases for climate change, the implications for the northern Sierra Nevada and TNF, and the need for active resource management.

A1.1.7 Increasing Adaptive Capacity to Respond to Climate Change

The ideas listed below were identified by TNF staff as being scientific, administrative, legal, or societal needs that would improve the capacity to respond adaptively to climate change challenges.

- New management strategies. Operationally appropriate and practical management strategies to address the many challenges and contexts implied by changing climates are needed.

- Scientifically supported practices for integrated management. Integration of resource management goals (*e.g.*, fuels, sensitive species, water, fire) rather than partitioning tasks into individual plans is already a barrier to effective ecosystem management. Changing climates are anticipated to increase the need for integration and integrated plans. Input from the science community on integrated knowledge, synthesis assessments, and toolboxes for integrated modeling, etc. will improve the capacity to respond adaptively.

- Projections and models. Modeled simulations of future climate, vegetation, species movements; rates of changes of all of these; and probabilities/uncertainties associated with the projections are needed.

- Case studies. Case studies of management planning and practices implemented as adaptive responses to climate are needed. Demonstration and template examples would allow ideas to disseminate quickly and be iteratively improved.

- Prioritization tools for managing a range of species and diverse ecosystems on TNF. Given the large number of species in the forest, it is impossible to manage all of them. Thus, new tools for adaptive decision-making are needed, as well as development of strategic processes to assist effective prioritizing of actions.

- Dynamic landscape and project planning. Scientific assistance is needed to help define targets and management goals that are appropriate in a changing climate context. Additional work on probabilistic management units, ranges of conditions likely, continuingly variable habitat probabilities, and habitat suitability contour mapping would be useful. Management planning guidelines that allow rules to change adaptively as conditions change need to be developed.

- Scientific clearinghouse on climate information. In high demand is a reference/resource center, such as a website, with current and practical climate-related material. To be useful at the scale of individual forests such as TNF, the information needs to be locally relevant, simply written, and presented in one clear, consistent voice.

- Scientific support and assistance to individual and specific TNF proposed actions. A consistent, clear voice from science is needed to help build the most appropriate and adaptive plans and actions. There is also a need for clear scientific evidence that demonstrates both the appropriateness of proposed TNF actions and the problems that would result from no action. A website could include such information as brief and extended fact sheets, regional assessments, archives of relevant long-term data or links to other websites with climate-relevant data, model output and primers (climate-relevant ecological, economic, and planning models), training packages on climate change that can be delivered through workshops and online tutorials, and access to climate-based decision-support tools.

- Seed banks. Seed banks need to be stocked to capacity as buffer for fire, insects and disease, and other population extirpation events.

A1.2 Olympic National Forest

A1.2.1 Setting and Context of the Olympic National Forest

A1.2.1.1 Biogeographic Description

The Olympic Peninsula, in western Washington State (Fig. A1.4), consists of a mountain range and foothills surrounded by the Pacific Ocean (west); the Strait of Juan de Fuca (north); Puget Sound (east); and low elevation, forested land (south). Its elevation profile extends from sea level to nearly 2,500 m (8,200 ft.) at Mount Olympus in the Olympic Mountains. The range creates a strong precipitation gradient, with historic precipitation averages of about 500 cm (197 in.) in the lowlands of the southwestern peninsula, 750 cm (295 in.) in the high mountains, and only 40 cm (16 in.) in the drier northeastern lowlands. The climate is mild temperate rainy, with a Mediterranean (dry) summer. Most of the precipitation falls in winter and at higher elevations; nearly all of it is snow that persists well into summer. The resulting biophysical landscape is a diverse array of seasonal climates and ecological conditions, including coastal estuaries and forests, mountain streams and lakes, temperate rainforests, alpine tundra, mixed conifer forests, and prairies.

Figure A1.4. Olympic Peninsula land ownership and Northwest Forest Plan allocation map. Olympic National Forest contains lands (dark boundary) with different land use mandates and regulations. These include adaptive management areas, late-successional reserves, and Wilderness areas. Map courtesy of Robert Norheim, Climate Impacts Group, University of Washington.

The ecosystems on the peninsula are contained within a mosaic of federal, state, tribal, and private ownership. Olympic National Forest (ONF), comprising ~257,000 ha (~635,000 acres) (including five wilderness areas), surrounds Olympic National Park (ONP, ~364,000 ha (~899,000 acres)), the core of the peninsula. ONP is both a World Heritage Site and an International Biosphere Reserve. There are 12 Native American tribes on the peninsula. Approximately 3.5 million people live within four hours' travel of the ONF, and thus it is considered an urban forest because of its proximity to the cities of the greater Seattle area. Ecosystem services from ONF are notably diverse and include water supply to several municipal watersheds, nearly pristine air quality, abundant fish and wildlife (including several unique/endemic species of plants and animals, such as the Olympic marmot (*Marmota Olympus*) and the Roosevelt elk (*Cervus elaphus roosevelti*), as well as critical habitat for four threatened species of birds and anadromous fish), recreation, and timber following implementation of the Northwest Forest Plan amendment (NWFP) to the Olympic National Forest Plan. Hereafter, reference to the Olympic National Forest Plan (ONFP) refers to the 1990 Olympic National Forest Plan, as amended by the NWFP in 1994.

Managing ONF lands therefore requires consideration of complex geographical, climatological, ecological, and sociocultural issues. Climatic change is likely to influence the factors responsible for the Olympic Peninsula's diversity and biogeography, and numerous stakeholders and land management mandates will need to adapt to those changes to protect the natural and cultural resources on the Peninsula.

A1.2.2 Recent and Anticipated Climate Change and Impacts

The Pacific Northwest has warmed approximately 1°C (1.8°F) since 1920; most of this warming (0.9°C (1.6°F)) has been since 1950, and winter has warmed faster than summer (Mote, 2003). The trend in annual precipitation is less clear, though most sites show an increase between 1920 and 2000; decadal variability, rather than trends, best characterizes the region's 20th century precipitation (Mote, 2003). However, the winter temperature increase has caused the form of winter precipitation to change at mid- and low- elevation sites, and 30–60% declines in April 1 snow water equivalent have been observed in the Olympics and Cascade Range (Mote *et al.*, 2005). The timing of spring runoff was 10–30 days earlier in 2000 compared with 1948 (Stewart, Cayan, and Dettinger, 2004).

Proxy records indicate that climatic variability has affected ecological processes on the Olympic Peninsula for millennia (Heusser, 1974; Gavin *et al.*, 2001). For example, pollen spectra from subalpine lakes in the Olympics indicate common responses after the retreat of Pleistocene glaciers, divergent vegetation in the early Holocene, and convergent responses in the late Holocene (McLachlan and Brubaker, 1995). More recently, tree growth for many lower elevation species increased with water supply and decreased with high summer temperatures (Ettl and Peterson, 1995; Nakawatase and Peterson, 2006). A common lesson from both paleo and modern studies is that, for a given regional shift in climate, the ecological and climatic context of a particular site determines the degree and nature of the response (Holman and Peterson, 2006)—so much so that high versus low elevations and the wet versus the dry side of the Olympics may have very different responses to a uniform climatic change.

Hydrological resources also respond to climate. The timing, duration, and magnitude of stream runoff depend on the abundance of winter snowpack and winter-to-spring temperatures. The Olympic Mountains mirror regional patterns of decadal climatic variability and trends in climatic change. During the 20th century, snowpacks were smaller (especially at low elevations), temperatures were warmer (especially minimum temperatures), and precipitation varied significantly with the fluctuations of the Pacific Decadal Oscillation. Regional anadromous fish populations (Mantua *et al.*, 1997), tree growth (Peterson and Peterson, 2001), glacier mass balance (Bitz and Battisti, 1999), and forest fire activity;[6] Littell (2006) has responded to these changes.

Predictions of future climate for the Pacific Northwest are uncertain because of uncertainty about future fossil fuel emissions, global population, efficacy of mitigation, and the response and sensitivity of the climatic system. However, by comparing a range of scenarios and models for future events, climate modelers can estimate future climatic conditions. Regional climate models suggest an increase in mean temperature of 1.2–5.5°C (2.2–9.9°F), with a mean of 3.2°C (5.8°F) by 2090 (Salathé, Jr., 2005). Summer temperatures are projected to increase more than winter temperatures. Precipitation changes are less certain due to large natural variability, but slight increases in annual and winter precipitation are projected, while slight decreases in summer precipitation are possible (Salathé, Jr., 2005).

Projected changes in temperature and precipitation would lead to lower snowpacks at middle and lower elevations, shifts in timing of spring snowmelt and runoff, and increases in summer evapotranspiration (Mote *et al.*, 2005; Hamlet *et al.*, 2007). Runoff in winter (October to March) would increase, and summer runoff (April to September) would decrease (Hamlet *et al.*, 2007). For basins with vulnerable snowpack (*i.e.*, mid-elevations), streamflow would increase in winter and decrease in summer. Higher temperatures and lower summer flows would have serious consequences for anadromous and resident fish species (salmon, steelhead, bull trout). Floods may increase in frequency because the buffering effect of snowpacks would decrease and because the severity of storms is projected to increase (although less snow can decrease the maximum impacts of rain-on-snow events due to lower water storage in snow). Sea level rise would exacerbate flooding in coastal areas. Some effects, especially the timing of snowmelt and peak streamflow, are likely to vary substantially with topography.

Increased summer temperature may lead to non-linear increases in evapotranspiration from vegetation and land surfaces (McCabe and Wolock, 2002). This, in turn, would decrease the growth (Littell, 2006; Nakawatase and Peterson, 2006), vigor, and fuel moisture in lower elevation (*e.g.*, Douglas-fir and western hemlock) forests while increasing growth (Ettl and Peterson, 1995; Nakawatase and Peterson, 2006) and

[6] **Mote**, P.W., W.S. Keeton, and J.F. Franklin, 1999: Decadal variations in forest fire activity in the Pacific Northwest. In: *Proceedings of the 11th Conference on Applied Climatology,* American Meteorological Society, pp. 155-156.

regeneration in high elevation (*e.g.*, subalpine fir and mountain hemlock) forests (Woodward, Schreiner, and Silsbee, 1995). Higher temperatures would also expand the range and decrease generation time of climatically limited forest insects such as the mountain pine beetle (Logan, Regniere, and Powell, 2003), as well as increase the area burned by fire in western Washington and Oregon (Littell, 2006).

The distribution and abundance of plant and animal species would change over time (Zolbrod and Peterson, 1999), given that paleoecological data show this has always been a result of climatic variability in the range projected for future warming. This change may be difficult to observe at small scales, and would be facilitated in many cases by large-scale disturbances such as fire or windstorms that remove much of the overstory and "clear the slate" for a new cohort of vegetation. The regeneration phase will be the key stage at which species will compete and establish in a warmer climate, thus determining the composition of future vegetative assemblages and habitat for animals.

Thus, ecosystem services in ONF are likely to be affected by climatic change. Water quality for threatened fish species may decline as temperatures increase and, potentially, as increasing storm intensity causes road failures. Water quantity may decline in summer when it is most needed, as streamflow timing shifts with temperature changes. Air quality will decline if drought frequencies or durations increase and cause increased area burned by fire. The influence of climate change on habitat for threatened species is less certain, but high elevation and currently rare species would be more vulnerable (*e.g.*, Olympic Marmot, bull trout, whitebark pine).

A1.2.3 Current ONF Policy Environment, Planning Context and Management Goals

Current natural resources management in ONF is directed primarily from policy mandates and shaped by historical land use and forest fragmentation (Fig. A1.4). ONF is a "restoration forest" charged with managing large, contiguous areas of second-growth forest. Natural resource objectives include managing for native biodiversity and promoting the development of late-successional forests (*e.g.*, NWFP); restoring and protecting aquatic ecosystems from the impacts of an aging road infrastructure; and managing for individual threatened and endangered species as defined by the Endangered Species Act (ESA) or other policies related to the protection of other rare species.

Most ONF natural resources management activities are focused on restoring important habitats (*e.g.*, native prairies, old-growth forests, pristine waterways), rehabilitation or restoration of impacts related to unmaintained logging roads, invasive species control, and monitoring. Collaboration with other agencies occurs, and is a cornerstone of the NWFP. Without clear consensus on climate change, cross-boundary difficulties in solving problems may arise due to differing mandates, requirements, and strategies, but there is no evidence that this is currently a problem.

Planning guidelines for ONF are structured by mandates from the National Forest Management Act (NFMA) and the NWFP. The ONF land management plan (OLMP, to be revised in the future in coordination with other western Washington NFs) is influenced by the NWFP as well as regional Forest Service policy. Planning also is influenced by comments from the public served by ONF. Project planning is carried out at a site-specific level, so incorporating regional climatic change information into Environmental Assessment/Environmental Impact Statement documents can be difficult because assessment takes place at the site scale, while there is still substantial uncertainty surrounding climate change predictions—especially precipitation—at sub-regional scales.

Adaptation to climatic change is not yet addressed formally in the OLMP or included in planning for most management activities. Current management objectives are attempting to confer resilience by promoting landscape diversity and biodiversity and this is in keeping with adapting to climate change. To this end, tools available to ONF managers include restoration of aquatic systems (especially the minimization of the impacts of roads, bridges, and culverts); active management of terrestrial systems (through thinning and planting); and, increasingly, treatment of invasive species. Prescribed fire and wildland use fire are unlikely tools because of the low historical area burned, limitations of the Clean Air Act, and low funding levels. The range of strategies and information in using these tools varies across ONF land use designations. Late-successional reserves and wilderness have less leeway than adaptive management areas, because there are more explicit restrictions on land use and silvicultural treatment.

A1.2.4 Proactive Management Actions Anticipating Climate Change

ONF's policy and regulatory environment encompasses a great deal of responsibility, but little scientific information or specific guidance is available to guide adaptation to climatic change. The scope of possible adaptation, clear strategies for successful outcomes, and the tools available to managers are all limited. Under current funding restrictions, most tools would need to be adapted from management responses to current stresses (Table A1.1). Future impacts on ecological and socioeconomic sensitivities can result in potential tradeoffs or conflicts. For example, currently threatened species may become even more rare in the future (*e.g.*, bull trout, spotted owl, marbled murrelet, Olympic marmot) due to stress complexes, undermining the likelihood of successful protection. Another example is when short-term impacts must be weighed against long-term gains. Fish species may be vulnerable to failures of unmaintained, closed roads caused by increased precipitation/storminess, but road rehabilitation may produce temporary sedimentation and may invite invasive weeds. Ideally, triage situations could be avoided, but in the face of climate change and limited resources it may be necessary to prioritize management actions with the highest likelihood of success, at the expense of actions that divert resources and have less-certain outcomes.

Generally, success of adaptation strategies should be defined by their ability to reduce the vulnerability of resources to a changing climate while attaining current management goals. Strategies include prioritizing treatments with the greatest likelihood of being effective (resources are too limited to do otherwise) and recognizing that some treatments may cause short-term detrimental effects but have long-term benefits. For structures, using designs and engineering standards that match future conditions (*e.g.*, culvert size) will help minimize future crises. Specific strategies likely to be used in ONF terrestrial ecosystems are to increase landscape diversity, maintain biological diversity, and employ early detection/rapid response for invasive species.

Landscape diversity and resilience can be achieved by: (1) targeted thinning (increases diversity, can decrease vulnerability by increasing tree vigor, and can reduce vulnerability to disturbance); (2) avoiding a "one size fits all" toolkit, and using a variety of treatments even if new prescriptions are required; (3) creating openings large enough for elk habitat, but small enough to minimize invasive exotics; (4) considering preserves at many elevations, not just high-elevation wilderness; and (5) considering "blocking" ownerships (land trades) to reduce edges, maintain corridors, and consolidate habitat.

Biological diversity may be maintained by: (1) planting species in anticipation of climate change—using different geographical locations and nursery stock from outside current seed zones; (2) maintaining within-species diversity; and (3) providing corridors for wildlife. However, there must be credible rationale for decisions to use seed and seedlings other than local native plant species.

Early detection/rapid response focuses on solving small problems before they become large, unsolvable problems, and recognizes that proactive management is more effective than long delays in implementation. For example, the ONF strategic plan recognizes that invasive species often become established in small, treatable patches, and are best addressed at early stages of invasion. Although designed for other problems like invasives, it is also appropriate for climate change because it could allow managers to respond quickly to the impacts of extreme events (disturbances, floods, windstorms) with an eye toward adaptation.

Large-scale disturbance can cause sudden and major changes in ecosystems, but can be used as occasions to apply adaptation strategies. ONF is currently climatically buffered from chronic disturbance complexes already evident in drier forests, but age-class studies and paleoproxy evidence indicate that large-scale disturbances occurred in the past. For comparison, fire suppression and harvest practices in British Columbia played a role in the current pine beetle outbreak by homogenizing forest structure over very large areas. In ONF, the amount of young forest (as a result of 20th century harvest) is both a risk (hence ONF's "restoration" status) and an opportunity. Large disturbances that may occur in the future could be used to influence the future structure and function of forests. Carefully designed management experiments for adapting to climatic change could be implemented. There is a clear need to have concepts and plans in place in anticipation of large fire and wind events, so that maximum benefit can be realized.

Information and tools needed to assist adaptation are primarily a long-term, management-science partnership with decision-specific scientific information. ONF relayed a critical request of scientists: natural resource managers need a manager's guide with important scientific concepts and techniques. Critical gaps in scientific information hinder adaptation by limiting assessment of risks, efficacy, and sustainability of actions. Managers would also like assistance and consultation on interpreting climate and ecosystem model output so that the context and relevance of model predictions can be reconciled with managers' priorities for adaptation. Managers identified a need to determine effectiveness of prevention and control efforts for invasive species; monitoring is critical (and expensive). There is a strong need for data on genetic variability of key species, as well as recent results of hydrologic modeling relative to water supply, seasonal patterns, and temperature. In contrast, managers pointed out that ONF collects data on a large array of different topics, many of them important, but new data collection should be implemented only if it will be highly relevant, scientifically robust, and inform key decisions.

A1.2.5 Opportunities and Barriers to Proactive Management for Climate Change on the ONF

An important opportunity for adapting to climatic change at the regional scale is the coordinated development of forest plans among ONF, Mt. Baker-Snoqualmie National Forest, and Gifford Pinchot National Forest. The target date for beginning this forest planning effort is 2012. The effort would facilitate further cooperation and planning for adaptation in similar ecosystems subject to similar stressors. ONF has implemented a strategic plan that has similar capacity for guiding prioritization and can incorporate climatic change elements now, rather than waiting for the multi-forest plan effort. By explicitly addressing resilience to climatic change (and simultaneously developing any science needed to do so) in the OLMP, ONF can formalize the use of climate change information in management actions.

A second, related opportunity is to integrate climatic change into region-wide NWFP guidelines that amended Pacific Northwest forest plans. The legacy of the 20th century timber economy in the Pacific Northwest has created ecological problems, but also opportunities (Fig. A1.5). Landscapes predominately in early seral stages are more easily influenced by management actions, such as targeted thinning and planting, than are late seral forests, so there is an opportunity to anticipate climate change and prepare for its impacts with carefully considered management actions. By recognizing the likely future impacts of climatic change on forest ecosystems (such as shifts in disturbance regimes), the revised forest plans can become an evolving set of guidelines for forest managers. Specifically, will the NWFP network of late successional reserves remain resilient to climatic change and its influence on disturbance regimes? Are there specific management practices in adaptive management areas that would change given the likely impacts of climatic change?

Figure A1.5. Olympic National Forest is charged with mitigating the legacy of 20th century timber harvest. Landscape fragmentation and extensive road networks (upper left) are consequences of this legacy that influence strategies for adaptation to climate change. The old-growth forest dependent northern spotted owl (upper right) is one focus of the NWFP, which prescribes forest practices but does not address climatic change. Changes in the timing and intensity of runoff expected with climate change are likely to interact with this legacy to have negative impacts on unmaintained roads (lower left) that in turn will impact water quality for five threatened or endangered species of anadromous and resident fish. Photo Credits: All photos courtesy Olympic National Forest.

Collaboration among multiple organizations is key to successful management. ONF staff believe that the “stage is set” for continued and future collaboration among organizations and agencies on the Olympic Peninsula. Climatic change and ecosystems do not recognize political boundaries, and significant adaptive leverage can be gained by cooperation. Initiatives by coalitions and partnerships can include climatic change (*e.g.*, the Puget Sound Partnership) and are conducive to an environment in which adaptation actions are well supported. In some cases, working with other agencies can improve the likelihood of success by increasing overall land base and resources for addressing problems.

Major barriers to adaptation are (1) limited resources, (2) policies that do not recognize climate change as a significant problem or stressor, and (3) the lack of a strong management-science partnership. National and regional budget policies and processes are significant barriers to adaptation, and represent a constraint on the potential for altering or supplementing current management practices to enable adaptation to climate change. Current emphasis on fire and fuel treatments in dry forest systems has greatly reduced resources for stand density management, pathogen management, etc. in forests that do not have as much fire on the ground but may, in the future, be equally vulnerable. Multiple agency collaboration can be difficult because of conflicting legislation, mandates, and cultures, but such collaboration is likely to be a hallmark of successful adaptation to climatic change. Certainly increased collaboration between scientists and managers could streamline the process of proposing testable scientific questions and applying knowledge to management decisions and actions.

Policies, laws, and regulations that are based on a more static view of the environment do not consider the flexibility required to adapt to changing conditions outside historical observations. The NFMA puts limitations on management actions, and NEPA delays implementation of actions. The ESA requires fine-scale management for many imperiled species, which may be unrealistic in a rapidly changing climate. Given the projected future rate of climate change and the resource limitations for land management agencies, it may be more sustainable and a more efficient use of funding to protect systems and landscape diversity than to plan for and protect many individual species. The NWFP partially embraces this strategy, but does not focus specifically on climate change. The Clean Water Act could become an important barrier in the future as stream temperatures increase; this may result in unattainable standards that constrain management actions. NEPA, the ESA, the Clean Water Act, and the NWFP all focus on historical reference points in comparatively static environments, but climate change warrants looking to future impacts and the need for preparation.

Future barriers to adaptation may arise with the interaction of current policy restrictions and the potential need to adapt to climatically mediated changes in ecosystem processes. One example is the potential for using wildland fire for the benefit of forest ecosystems, which is not currently an authorized management tool on ONF. The benefits of wildland fire use (likely limited in ONF to natural ignitions within wilderness areas) would need to be weighed against the cost of authorization. Authorization to use this tool in the short term would require a Forest Plan amendment and associated NEPA process. A less costly but longer-horizon alternative is to include wildland fire use in the 2012 Forest Plan revision effort. Benefits would be limited to wildland fire use that could be approved within the confines of the ESA and other regulations. Olympic National Park recently completed a fire management plan that authorizes wildland fire use, but has restrictions related to ESA requirements. For ONF the role of wildland fire use in management would also be limited by the ESA and the adjacency of non-federal land concerns.

A1.2.6 Increasing the Adaptive Capacity to Respond to Climate Change

The ecosystem stressors ONF manages for currently (Table A1.1) are likely to be exacerbated by climatic change, but little work has focused on quantifying the direct linkages between the climate system and future ecosystem services on the Olympic Peninsula. Resilience to climate change is therefore only describable qualitatively. Past timber harvest has resulted in a very large area of lower-elevation forest consisting of second growth, in an ecosystem that was characterized by resilient old growth. This landscape homogenization has occurred in other forest types, and, at least in theory, results in less resilience to climate-mediated disturbances. However, such characterization is at the moment speculative. Aquatic ecosystems are probably less resilient, and measuring resilience there is similarly underdeveloped.

The primary conclusions of this case study are:

1. Climate change and its impacts are identifiable regionally, and adaptation to climate change is necessary to ensure the sustainability of ecosystem services.
2. ONF management priorities (Table A1.1) are consistent with adaptation to climatic change and promoting resilience to the impacts of climate change. However, available resources do not allow adaptation at sufficient scale. Moreover, scientific uncertainty remains about the best adaptation strategies and practices.
3. The current political and regulatory contexts limit adaptive capacity to current and future climatic changes by:
    a. failing to incorporate climatic change into policy, regulations, and guidelines;
    b. requiring lengthy planning processes for management actions, regardless of scope; and
    c. adopting priorities and guidelines that are not clear in intent and/or consistently applicable at national, regional, and forest levels.
4. These limitations can be overcome by:
    a. developing a manager’s guide to climate impacts and adaptation;
    b. developing an ongoing science-management partnership focused on climate change;
    c. incorporating climatic change explicitly into national, regional, and forest-level policy;
    d. re-examining the appropriateness of laws, regulations, and policies on management actions in the context of adaptation to climatic change;

e. creating clear, consistent priorities that provide guidance but allow for local/forest level strategies and management actions that increase resilience and reduce vulnerability to climatic change;
f. allocating resources sufficient for adaptation; and
g. increasing educational and outreach efforts to promote awareness of climate change impacts on ecosystem services.

ONF is at a crossroads. The effects of climatic change on forest ecosystems and natural resources are already detectable. Adapting to those changes and sustaining ecosystem services is an obvious and urgent priority, yet adaptive capacity is limited by the policy environment, current allocation of scarce resources, and lack of relevant scientific information on the effects of climate change and, more crucially, on the likely outcomes of adaptive strategies. Adaptive management is one potential strategy for learning how to predict, act on, and mitigate the impacts of climatic change on a forest ecosystem, but if there is no leeway for management actions or those actions must occur quickly, then adaptation options are limited in the current environment. ONF staff indicated that if they were managing for climate change, given what they know now and their current levels of funding and personnel, they would continue to emphasize management for biodiversity. It is possible, for example, that they might further increase their current emphasis on restoration and diversity. Another possible change, reminiscent of the earlier Forest Service priorities, would be to emphasize the role of forests as producers of hydrological commodities.

Key components of adaptation will be to (1) develop a vision of what is needed and remove as many barriers as possible; (2) increase collaboration among agencies, managers, and scientists at multiple scales; and (3) facilitate strategies (such as early detection/rapid response) that are proven to work. A functional forest ecosystem is most likely to persist if managers prioritize landscape diversity and biological diversity. Equally certain is that management actions should not, in aggregate, lead to the extirpation of rare species. Clear and consistent mandates, priorities, and policies are needed to support sustainability of ecosystem services in the face of a warmer climate and changing biophysical conditions.

We envision a future in which the policy, planning, and scientific aspects of ecosystem-based management co-evolve with changes in climate and ecosystems. This vision requires trust, collaboration, and education among policy makers, land managers, and scientists as well as the publics they serve. Climate will continue to change, effects on ecosystems will be complex, and land managers will struggle to adapt to those changes with limited resources. Collaboration with scientists is certain to produce information that relates directly to on-the-ground decision making. Less certain is how opportunities for adaptation will be realized while retaining public support for resource management actions. ONF has already transitioned from producing a few commodities to producing a broad array of ecosystem services, but the more ambitious vision of coevolution must progress rapidly in order for adaptation to keep pace with anticipated effects of climatic change.

A1.3 Uwharrie National Forest

A1.3.1 Setting and Context of the Uwharrie National Forest

The Uwharrie National Forest (originally called the Uwharrie Reservation) was first purchased by the federal government in 1931 during the Great Depression. In 1961, President John F. Kennedy proclaimed the federal lands in Montgomery, Randolph, and Davidson Counties (Fig. A1.6). The UNF is within a two-hour drive of North Carolina's largest population centers, including Winston-Salem, Greensboro, Charlotte, Raleigh, and Durham. The forest is fragmented into 61 separate parcels, which pose unique forest management challenges (Fig. A1.6). Therefore, much of UNF has been modified from a natural to a managed ecological condition. UNF has a rolling topography, with elevation ranging from 122 to 305 m above sea level. Although small by most national forest standards (20,383 ha), the UNF provides a variety of natural resources, including clean rivers and streams, diverse vegetation for scenery, wildlife habitat, and wood products. There is also a wide variety of recreational activities, and UNF is a natural setting for tourism and economic development.

Figure A1.6. Map of the Uwharrie National Forest in North Carolina.[7]

The UNF is rich in history. It is named for the Uwharrie Mountains, some of the oldest in North America. According to geologists, the Uwharries were created from an ancient chain of volcanoes. The 1,000-foot hills of today were once 20,000-foot peaks.

The UNF is located at the crossroads of both prehistoric and historic settlements. Their legacy is one of the greatest concentrations of archeological sites in the Southeast. Left undisturbed, these sites and artifacts give a record of our heritage. The first large gold discovery in the United States occurred around 1799 at the nearby Reed Gold Mine. In the early 1800s, gold was found in the Uwharries, with a later boom during the depression of the 1930s. Old mining sites still remain, and part-time prospectors still pan in the streams and find traces of gold dust.

Today, the UNF is dynamic and responsive to public needs. It continues to provide timber, wildlife, water, recreation opportunities, and a natural setting for tourism and economic development. Recreational use is growing, especially in the Badin Lake area and along the 20-mile Uwharrie National Recreation Trail. Badin Lake is one of the largest bodies of water included in the series of reservoirs within the Yadkin-PeeDee River drainage system. The entire watershed is known as the Uwharrie Lakes Region. Badin Lake is a popular setting for many different recreation activities, including camping, hiking, fishing, boating, and hunting. The area is rich game land for deer and wild turkey, and a home for bald eagles.

[7] **USDA Forest Service**, 2007: Uwharrie National Forest Uwharrie Ranger District. University of North Carolina at Asheville National Forest Service Website, http://www.cs.unca.edu/nfsnc/uwharrie_plan/maps/uwharrie_map.pdf, accessed on 7-30-2007.

A1.3.2 Current Uwharrie NF Planning Context, Forest Plan Revision and Climate Change

The National Forest Management Act of 1976 requires that all NFs periodically revise their forest management plan.[8] Existing environmental and economic situations within the forest are examined. Then plans are revised to move the forest closer to a desired future condition. The current UNF forest management plan was originally developed in 1986, and UNF is now undergoing a Forest Plan Revision (FPR).

The revised forest plan focuses on three themes. Two of the themes—restoring the forest to a more natural ecological condition, and providing outstanding and environmentally friendly outdoor recreation opportunities—will likely be affected by a changing climate. The third theme of the FPR (*i.e.*, better managing heritage (historical and archeological) resources) will likely not be significantly affected by climate change. Thus, this case study examines potential impacts on the first two UNF FPR themes.

The revised forest plan will suggest management strategies that help reduce risks to the health and sustainability of UNF associated with projected impacts of a changing climate. Therefore, the UNF case study focuses on specific recommended modifications to the forest plan. This level of specificity was not possible with either the Tahoe or Olympic National Forest case studies because neither has recently undergone a forest plan revision that incorporates climate change impacts into forest management decision making.

A1.3.2.1 Revised Forest Plan Theme 1: Restoring the Forest to a More Natural Ecological Condition

Prior to the 1940s, fires were a regular occurrence in southern U.S. ecosystems (Whitney, 1994). The reoccurrence interval varied among vegetation types, with more frequent fires being less intense than less frequent fires (Wear and Greis, 2002). Upland oak (*Quercus* sp.) and hickory (*Carya* sp.) forests would burn at an interval of 7–20 years with flame heights of less than one m (3.3 ft.). These fires would kill thin-barked tree species such as red maple (*Acer rubrum*), sweetgum (*Liquidambar styraciflua*), and tulip poplar (*Liriodendron tulipifera*), while leaving the more fire-resistant oaks and hickories alive. Pine ecosystems had a shorter fire return interval of 3–5 years, with flame heights reaching 1–2 m (3.3–6.6 ft.), thus favoring fire- and drought-resistant longleaf (*Pinus palustris*) and shortleaf (*Pinus echinata*) pines more than loblolly pines. The fires also removed much of the mid-canopy vegetation and promoted light-demanding grasses and herbs.[9] Deciduous and coniferous tree species are equally represented in UNF. However, a higher percent of the conifers are in loblolly pine (*Pinus taeda*) plantations than would have historically occurred, because of the planting emphasis of this species over the past 40 years.[9]

[8] 16 U.S.C. §1600-1614

[9] **Uwharrie National Forest**, 2007: *Proposed Uwharrie National Forest Land Management Plan*. Available from http://www.cs.unca.edu/nfsnc/uwharrie_plan/wo_review_draft_plan.pdf. USDA Forest Service, Asheville, NC.

Climate change is projected to increase the number and severity of wildfires across the southern United States in the coming years (Bachelet *et al.*, 2001). As part of its FPR, UNF plans to restore approximately 120 ha (296 acres) of loblolly pine plantation to more fire-resistant ecosystem types (*e.g.*, longleaf pine) each year.[9] This management shift will restore UNF to a more historically natural condition and reduce catastrophic wildfire risk associated with an increase in fuel loading (Stanturf *et al.*, 2002; Busenberg, 2004) and hotter climate (Bachelet *et al.*, 2001).

A1.3.2.2 Revised Forest Plan Theme 2: Provide Outstanding and Environmentally Friendly Outdoor Recreation Opportunities

Recreation opportunities provided by UNF are an important ecosystem service to the local and regional communities. The proximity to large population centers and diverse interest in outdoor activities make UNF a destination for many groups that use the trails and water bodies located within the forest. The continued quality of these trails, streams, and lakes are of very high importance to UNF's mission.

During the 20th century the frequency of extreme precipitation events has increased, and climate models suggest that rainfall intensity will continue to increase during the 21st century (Nearing, 2001). Soil erosion occurs when the surface soil is exposed to rainfall and surface runoff. Soil erosion is affected by many factors, including rainfall intensity, land cover, soil texture and structure (soil erodibility), and land topography (slope) (Toy, Foster, and Renard, 2002). Because soil erosion increases linearly with rainfall-runoff erosivity, it would be expected to increase over the next 50 years in the UNF region if no management measures are taken to control the current soil erosion problems. Soil erosion is limited to exposed (*i.e.*, without vegetative cover) soil surfaces (Pimentel and Kounang, 1998). Hiking, off-highway vehicles, and logging trails and forest harvest areas represent the major types of exposed soil surface in UNF.[9] Increased soil erosion would degrade both trail and water quality.

In response to current and projected increases in soil erosion potential, the UNF FPR proposes to repair authorized roads and trails, close unauthorized roads and trails, minimize new road construction, and reroute needed roads that increase soil erosion. In total, these measures should effectively reduce the potential impact of increased precipitation intensity on soil erosion in the UNF.

A1.3.3 Long-Term Natural Resource Services

In addition to the objectives outlined in the Uwharrie forest plan revision, forests in the United States provide valuable natural resources of clean water and wood products. While the demand for U.S. pulp and paper products has decreased in recent years, it is important to assess the long-term ability of the forests to supply wood resources if a future need should arise. The demand for clean, dependable water is increasing within the southern United States as population pressure on water resources increase. Therefore, climate change impacts on UNF water yield and timber supply were also assessed in the UNF Watershed Analysis Document of the FPR.

A1.3.3.1 Water Yield

Clean water is one of the most valuable commodities that our NFs provide. National forest lands are the largest single source of water in the United States and one of the original reasons that the NFS was established in 1891 (USDA Forest Service, 2000b). There is concern that climate change could reduce water yield from the Uwharrie. Currently, about 1,590 mm of precipitation falls in UNF every year, with close to 70% (or 1,100 mm) of it evapotranspiring back to the atmosphere. The other 30% (or 490 mm) leaves the forest as stream runoff and percolates downward becoming a part of the groundwater.[9] Climate change models suggest that precipitation may increase to 1,780 mm per year. Air temperature is also expected to increase, which will, in turn, increase forest evapotranspiration. In total, stream water flow is projected to decrease by approximately 10% by the middle of the 21st century if there is no change in forest management (Sun *et al.*, 2005).[10]

Forest water use increases with increased tree stocking density and leaf area (Hatton *et al.*, 1998; Cook *et al.*, 2002). The use of controlled fire and other forest management activities that will increase tree spacing and shift the forest toward more fire- and drought-tolerant tree species will also help to reduce forest water use (Heyward, 1939). Based on this line of research, most of the climate change-caused reductions in water yield can be compensated through this proposed change in forest management.

A1.3.3.2 Timber and Pulpwood Productivity

The southern United States has long been a major supplier of pulpwood and timber. But because an increasing amount of timber and pulpwood is being supplied to the United States by Canada, Europe, and countries in the Southern Hemisphere (USDA Forest Service, 2003), national forest managers have moved away from an emphasis on timber supply toward recreational opportunities and sustainable water (Apple, 1996).

Climate change will have variable impacts globally. Timber production in some countries, such as Canada, may benefit from warmer climate, while countries closer to the Equator may experience significant reductions in productivity (Melillo *et al.*, 1993). Although NFs are not currently major sources of wood products, this situation could change as timber production from other parts of the world shifts. Therefore, it is important to assess the impact of climate change on forest productivity in UNF. Forest productivity models suggest that although pine productivity may decrease, hardwood productivity is projected to increase and the net loss of total forest productivity would be small for the UNF over the next 40 years (National Assessment Synthesis Team, 2000). However, the analysis did not account for the potential for increased fire occurrence, which could significantly reduce overall forest volume and growth (Bachelet *et al.*, 2001). The proposed shift in forest tree types to more drought-tolerant and fire-resistant species should also help to assure that UNF remains a timber resource for future generations (Smith, Ragland, and Pitts, 1996).

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[10] See also **Sun**, G., S.G. McNulty, E. Cohen, J.M. Myers, and D. Wear, 2005: Modeling the impacts of climate change, landuse change, and human population dynamics on water availability and demands in the Southeastern US. Paper number 052219. Proceedings of the 2005 ASAE Annual Meeting, St. Joseph, MI.

A2 National Parks Case Study

A2.1 Rocky Mountain National Park

The climate is going to change continuously over at least the next 100 years. Ecosystems, species, and processes in each of the 270 natural resource parks will be affected by climate change over this time period. Therefore, it was not appropriate to select a case study based on its perceived current vulnerability to climate change. Some parks are beginning to face issues related to sea level rise; treasured species in others are at risk. Regardless of the apparent urgency in some parks, all will have to initiate adaptation actions in order to meet NPS mission and goals. Rocky Mountain National Park (RMNP), Colorado, was selected for a case study because it is a good example of the state at which most parks find themselves as they confront resource management in the face of climate change. Park managers know RMNP has some highly vulnerable and visible resources, including glaciers and alpine tundra communities, but there is high uncertainty regarding just how vulnerable they are, what specific changes might occur, how rapidly change might occur, or what to do. The following case study describes RMNP's first attempt to take stock of the Park with respect to climate change, and begin to think about management.

A2.1.1 Park Description and Management Goals

RMNP was established in 1915 and "is dedicated and set apart as a public park for the benefit and enjoyment of the people of the United States …with regulations primarily aimed at the freest use of the said park and for the preservation of natural conditions and scenic beauties."[11] The Park is located in the Front Range of the southern Colorado Rocky Mountains, the first mountain range west of the Great Plains. RMNP's wide elevation gradient—from 8,000 to more than 14,000 feet—includes montane forests and grasslands, old-growth subalpine forests, and the largest expanse of alpine tundra in the lower 48 states. More than 150 lakes and 450 miles of streams form the headwaters of the Colorado River to the west, and the South Platte River to the east. Rich wetlands and riparian areas are regional hotspots of native biodiversity. Several small glaciers and rock glaciers persist in east-facing cirque basins along the Continental Divide. The snow that accumulates in these basins each winter provides water that supports downstream cities and agricultural activities in Colorado and neighboring states. RMNP is home to populations of migratory elk, mule deer, bighorn sheep, and charismatic predators such as golden eagles, cougars, and bobcats; many plant and animal species that live in the alpine, including white-tailed ptarmigan, pika, and yellow-bellied marmot; and several endangered species, including the boreal toad and the greenback cutthroat trout.

At slightly larger than 415 square miles, RMNP is not large compared with other western national parks (Yellowstone, by comparison, is more than eight times larger). RMNP is bordered on all four sides by national forests. The Roosevelt National Forest surrounds the Park on the north and east, the Routt National Forest is to the northwest, and the Arapahoe National Forest surrounds the southwest, southern, and eastern Park

[11] 16 U.S.C. § 191-198

boundaries. Approximately half of the adjacent Forest Service land is in wilderness designation (Comanche Peak Wilderness, Neota Wilderness, Never Summer Wilderness, and Indian Peaks Wilderness), and 95% of RMNP is managed as if it was wilderness. A primary goal for RMNP, therefore, is to protect and manage the Park in its natural condition (see Box A2.1). Wilderness status has been proposed since 1974, and legislation is pending. RMNP is also designated a Clean Air Act Class I Area, meaning the superintendent has a responsibility to protect air-quality related values, including vegetation, visibility, water quality, wildlife, historic and prehistoric structures and objects, cultural landscapes, and most other elements of a park environment that are sensitive to air pollution. Several endangered species, such as the boreal toad and the greenback cutthroat trout, have management plans for enhancement and recovery. Other current management issues include fire, elk, and invasive exotic species. All told, there are more than 30 planning documents (Acts, Executive Orders, Plans, and Recommendations) that guide RMNP operations.

The towns of Estes Park and Grand Lake form gateway communities, and are connected by Trail Ridge Road which is open for traffic crossing the Continental Divide during the summer and fall months. Largely because of its spectacular vistas, the Park receives more than three million visitors each year, 25% of whom come from Colorado. Most visitor use is in the summer, when hiking, camping, mountain climbing, viewing nature, and sightseeing are common. Fall visitation is also popular, when visitors arrive to view aspen leaves and watch and listen to elk go through their mating rituals.

A2.1.2 Observed Climate Change in the Western United States

Many climate change signals have been observed in the western United States, but not all of them in the southern Rocky Mountains or in RMNP. Strong trends in winter warming, increased proportions of winter precipitation falling as rain instead of snow, and earlier snowmelt are found throughout the western United States (Stewart, Cayan, and Dettinger, 2005; Knowles, Dettinger, and Cayan, 2006; Mote, 2006). All of these trends are more pronounced in the Pacific Northwest and the Sierra Nevada than they are in the Colorado Front Range of the southern Rocky Mountains. The less pronounced evidence for RMNP compared with the rest of western U.S. mountains should not be interpreted as a lack of climate change potential within the Park. The high (and thus cold) elevations and a shift over the past 40 years from a more even annual distribution of precipitation to more winter precipitation have contributed to Front Range mountain weather going against the trend seen across much of the rest of the West (Knowles, Dettinger, and Cayan, 2006).

Summer warming has been observed in RMNP, and while a ten year record is insufficient for an understanding of cause, July temperatures increased approximately 3°C, as measured at three high elevation sites from 1991-2001 (Clow *et al.*, 2003). RMNP, along with most of the rest of the western United States, experienced record-breaking extreme March temperatures and coincident early melting of winter snowpack in 2004. While not directly attributable to climate change, extreme heat events are consistent with climate change model projections that suggest increased rates of extreme events due to the warming atmosphere (Pagano *et al.*, 2004).

A2.1.3 Observed and Projected Effects of Climate Change in the Southern Rocky Mountains and Rocky Mountain National Park

A number of studies have indicated that climatic warming is being expressed in environmental change in the southern Rocky Mountains and in RMNP: mountain glacier retreat (evidence of climatic warming) is occurring adjacent to and within RMNP. Arapahoe Glacier, located 10 miles south of the Park on the Continental Divide, has thinned by more than 40 m since 1960 (Fig. A2.1). Photograph pairs of Rowe Glacier in RMNP also show the loss of ice mass over time (Fig. A2.2). Responses to climatic change are also showing up in ecological communities: a long-term study of the timing of marmot emergence from hibernation in central Colorado found marmots emerge on average 38 days earlier than they did in 1977 (Inouye *et al.*, 2000). This is triggered by warming spring temperatures. Similarly, the spring arrival of migratory robins to Crested Butte, Colorado, is two weeks earlier now than in 1977. This also signals biological changes in response to climate (Inouye *et al.*, 2000).

Figure A2.1. Photos of Arapahoe Glacier in 1898 and 2004.[12]

Figure A2.2. Photo pair of Rowe Glacier, with permissions, NSIDC and leachfam website.[13]

A number of species of plants and animals may be vulnerable to climate change. Dwarf larkspur (*Delphinium nuttalianum*) shows a strong positive correlation between snowpack and flower production (Saavedra *et al.*, 2003). Research findings suggest that reduced snowpacks that accompany global warming might reduce fitness of this flowering plant. Local weather, as opposed to regional patterns, exerts a strong influence on several species of birds found in the Park, including white-tailed ptarmigan, *Lagopus leucurus* (Wang *et al.*, 2002b). The median hatch rates of white-tailed ptarmigan in RMNP advanced significantly from 1975–1999 in response to warmer April and May temperatures. Population numbers have been declining along Trail Ridge Road, where they are routinely monitored (Wang *et al.*, 2002a), and where population growth rates were negatively correlated with warmer winter temperatures. The Wang *et al*. (2002b) study suggests that ptarmigan may likely be extinct in RMNP within another two or three decades. Dippers (*Cinclus mexicanus*) in RMNP may also be vulnerable, as has been shown by studies of the closely related white-fronted dipper (*Cinclus cinclus*) in Scandinavia (Saether *et al.*, 2000; Wang *et al.*, 2002b).

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[12] **NSIDC/WDC for Glaciology**, Boulder, Compiler, 2006: Online glacier photograph database. *National Snow and Ice Data Center/World Data Center for Glaciology.* Available at http://nsidc.org/data/g00472.html.

[13] **Lee**, W.T., 1916: Rowe Glacier photograph. In: *Online glacier photograph database.* National Snow and Ice Data Center/World Data Center for Glaciology.

Leach, A., 1994: Rowe Glacier photograph. Available from http://www.leachfam.com/securearea/album.php. Boulder, Colorado.

Some studies of animal responses to climate change in the Park reveal positive responses. Elk populations were projected to double under climate scenarios of warmer winters and possibly wetter summers, while model results for warmer winters with drier summers projected an increase in the elk population of 50% (Wang *et al.*, 2002c). Elk populations have been increasing within RMNP due to enhanced overwinter survival, and this may be another factor in the demise of white-tailed ptarmigan, as elk are now taking advantage of warmer springs to graze on high level tundra where they compete with ptarmigan for shrubby browse.

Greenback cutthroat trout, an endangered species, have been translocated into streams and lakes in RMNP as part of a recovery effort. Water temperatures in many of the translocation streams are colder than optimal for greenback cutthroat trout growth and reproduction. Of the ten streams where the fish were reintroduced by the Colorado Division of Wildlife, only three had temperatures within the range for successful growth and reproduction at the time of translocation. A modeling scenario that postulated warmer stream temperatures suggests that three additional streams will experience sufficient temperature increases to raise the probability of translocation success to >70%. In at least one of these streams, however, temperatures are projected to also warm enough to allow the establishment of whirling disease, caused by *Myxobolus cerebralis*, a parasite that is fatal to young trout.[14]

Other studies suggest that climate warming will diminish opportunities for willow establishment along riparian areas in RMNP (Cooper *et al.*, 2006), and the occurrence of longer and more severe fire seasons will increase throughout the western United States (Westerling *et al.*, 2006).

An analysis of recreation preferences under climate change scenarios projected a relatively small increase (10-15%) in visitation to RMNP for climate-related reasons under climate warming scenarios (Richardson and Loomis, 2004). An economic study of whether such an increased visitation would affect the economy and employment outlook for Estes Park similarly did not find climate change to be very important (Weiler *et al.*, 2002). A more important driver of economic change for the Town of Estes Park was projected increases in human population numbers within the State of Colorado (Weiler *et al.*, 2002).

A2.1.4 Adapting to Climate Change

RMNP is relatively rich in information about its ecosystems and natural resources, and has benefited from long-term research and monitoring projects and climate change assessments. Examples include research and monitoring, in Loch Vale Watershed[15], and the focused assessment of the effects of climate change on RMNP and its Gateway

[14] **Cooney**, S., 2005: Modeling global warming scenarios in greenback cutthroat trout (Oncorhynchus clarki stomias) streams: implications for species recovery. M.S. thesis, Colorado State University, Fort Collins.
[15] **Natural Resource Ecology Laboratory**, 2007: Loch Vale Watershed research project. Colorado State University, www.nrel.colostate.edu/projects/lvws, accessed on 5-15-2007.

Community.[16] Even so, planning and resource management in the Park does not yet include considerations of climate change. A workshop in March 2007 provided the opportunity for Park managers and community members to begin thinking about the steps to take to increase preparedness for a climate that will be warmer and less predictable. Results of the workshop are summarized below.

In many ways, effective science-based management in RMNP has enhanced the ability of park natural resources to adapt to climate change. Most of the water rights have been purchased, dams and ditches have been removed, and many streams and lakes have been restored to free-flowing status since 1980. An exception is the Grand River Ditch. Park managers have also been proactive in removing or preventing invasive species such as leafy spurge, and invasive non-native species such as mountain goats; managing fire through controlled burns and thinning; reducing regional air pollution through partnerships with regulatory agencies; and preparing a plan to reduce elk populations to more sustainable numbers.

Despite these actions, RMNP managers are concerned over the potential for catastrophic wildfire, increasing insect infestations and outbreaks, and damage from large storm events with increasing climate change. A flooding event in the Grand River Ditch, while not necessarily caused by climate change, serves as an example of the potential effects from future storm-caused floods. The Grand Ditch diverts a significant percentage of annual Colorado River tributary streamflow into the east-flowing Poudre River. It was developed in 1894, and is privately owned and managed. A breach of the ditch during snowmelt in May 2003 caused significant erosion and damage to Kawuneechee Valley forests, wetlands, trails, bridges, and campsites.

Park managers are also concerned about the future of alpine tundra and species that live above treeline, but do not have much information about current alpine species populations and trends. Modest baseline data and monitoring programs are currently in place. Regional biogeographic models suggest that the treeline will rise and some alpine areas will diminish or disappear (Neilson and Drapek, 1998). Reduced tundra area, or its fragmentation by trees, could endanger many obligate tundra plants and animals. Species such as pika, white-tailed ptarmigan, and marmots are already known to be responsive to climate change (Inouye *et al.*, 2000; Wang *et al.*, 2002a; Beever, Brussard, and Berger, 2003).

RMNP managers have identified a strategy for increasing their ability to adapt to climate change built on their current activities, what they know, and what they do not know about upcoming challenges related to climate change. The strategy involves bringing teams of experts and regional resource managers together in a series of workshops to share information and help identify resources and processes that may be most susceptible to climate change. Support for high resolution models that project possible changes to species and processes can be used to establish scenarios of future ecological trajectories and end-states. Regularly held workshops with scientific experts offer the opportunity to

[16] **Natural Resource Ecology Laboratory**, 2002: Science to achieve results. Colorado State University, http://www.nrel.colostate.edu/projects/star/index.html, accessed on 4-6-2007.

develop planning scenarios, propose adaptive experiments and management opportunities, and keep abreast of the state of knowledge regarding climate change and its effects.

Managers also propose establishing a Rocky Mountain National Park Science Advisory Board. A Science Advisory Board could serve as a springboard for thinking strategically and enabling the Park to anticipate climate-related events. RMNP managers recognize the need to develop baselines for species or processes of highest concern (or of greatest indicator value) and plan to establish monitoring programs to track changes over time. The vital signs that have been identified for the Park need to be reviewed and possibly revised in order to capture effects that will occur with climate change.

Park managers identified a critical need to develop a series of learning activities and opportunities for all Park employees to increase their knowledge of climate change-related natural resource issues within RMNP. The Continental Divide Learning Center was recognized as an ideal venue for these activities. Managers have proposed that the Center be used as a hub for adaptive learning, articulating the value of natural resources better, and turning managers into consumers of science.

Finally, Park mangers have recognized the importance of building greater collaborations with regional partners in order to facilitate regional planning, especially for issues that cross Park boundaries. RMNP already has strong working relations with the Town of Estes Park, the Colorado Department of Public Health and Environment, the Colorado Division of Wildlife, the U.S. Fish and Wildlife Service, Larimer and Boulder Counties, and many local organizations and schools. Opportunities to work more closely with the Routt, Arapaho, and Roosevelt National Forest managers could be pursued with the objective of discussing shared management goals.

In summary, RMNP managers propose to continue current resource management activities to minimize damage from other threats, increase their knowledge of which species and ecosystems are subject to change from climate change, monitor rates of change for select species and processes, and work with experts to consider what management actions are appropriate to their protection. By developing working relations with neighboring and regional resource managers, the Park keeps its options open for allowing species to migrate in and out of the Park, considering assisted migrations, and promotes regional approaches toward fire management (Box A2.2).

A2.1.5 Needed: A New Approach Toward Resource Management

RMNP, like other national parks, often operates in reactive mode, with limited opportunity for long-term planning. Reactive management has a number of causes, only some of which are related to tight budgets and restrictive funding mechanisms. Partly because national parks are so visible to the public, there are public expectations and political pressures that trigger short-term management activities (tree thinning in lodgepole pine forest is one example of an activity that is visible to many, but of questionable value in reducing the risk of catastrophic fire). Natural resource issues are increasingly complex, and climate change adds greatly to this complexity.

RMNP managers have been proactive in addressing many of the resource issues faced by the Park. Yet they recognize there is still more to be done, particularly in human resource management. Complex issues require broad and flexible ways of thinking about them, and creative new tools for their management. Professional development programs for current resource managers, rangers, and park managers could be strengthened so that all employees understand the natural resources that are under the protection of the NPS, the causes and consequences of threats to these resources, and the various management options that are available.

The skill sets for new National Park Service (NPS) employees should reflect broad systems training. University programs for natural resource management could shift from traditional training in fisheries, wildlife, or recreational management to providing more holistic ecosystems management training. Curricula at universities and colleges could also emphasize critical and strategic thinking that embraces science and scientific tools for managing adaptively, and recognizes the need for lifelong learning. Climate change can serve as the catalyst for this new way of managing national park resources. Indeed, if the natural resources entrusted to RMNP—and other parks—are to persist and thrive under future climates, the Park Service will need managers that see the whole as well as the parts, and act accordingly.

A3 National Wildlife Refuges Case Study

A3.1 Alaska and the Central Flyway

Warming trends in Alaska and the Arctic are more pronounced than in southerly regions of the United States, and the disproportionate rate of warming in Alaska is expected to continue throughout the coming century (IPCC, 2001) (see Fig. 5.3a in the National Wildlife Refuges chapter). Migratory birds are one of the major trust species groups of the National Wildlife Refuge System (NWRS), and birds that breed in Alaska traverse most of the system as they use portions of the Pacific, Central (see Fig. A3.1), Mississippi, and Atlantic Flyways during their annual cycle. Projected warming is expected to encompass much of the Central Flyway but is expected to be less pronounced in the remaining flyways (IPCC, 2001). Historical records show strong warming in the Dakotas and a tendency toward cooling in the southern reaches of the flyway (see Fig. 5.3a in the National Wildlife Refuges chapter). Pervasive and dramatic habitat shifts (see Fig. 5.9 in the National Wildlife Refuges chapter) are projected in Alaska and especially throughout the Central Flyway by the end of the century.

Figure A3.1. Central Flyway Waterfowl Migration Corridor.[17]

[17] **U.S. Fish and Wildlife Service**, 2007: Central flyway. U.S. Fish and Wildlife Service, Pacific Flyway Council Website, http://pacificflyway.gov/Documents/Central_map.pdf, accessed on 6-2-0007.

Migration is an energetically costly and complex life history strategy (Arzel, Elmberg, and Guillemain, 2006). The heterogeneity in warming and additional stressors along migratory pathways along with their potential effects on productivity and population levels of migratory birds emphasize the importance of strong interconnections among units of the NWRS and the need for a national vision and a comprehensive management strategy to meet the challenge of climate change in the next century. The following case study examines warming and additional stressors, as well as management options in Alaska and the Central Flyway, which together produce 50–80% of the continent's ducks (Table A3.1).

A3.1.1 Current Environmental Conditions

A3.1.1.1 Changes in Climate and Growing Season Duration

Climate

In recent decades, warming has been very pronounced in Alaska, with most of the warming occurring in winter (December–February) and spring (March–May) (Serreze *et al.*, 2000; McBean *et al.*, 2005). In western and central Canada, the increases in air temperature have been somewhat less than those observed in Alaska (Serreze *et al.*, 2000). While precipitation has remained largely stable throughout Alaska and in Canada in recent decades, several lines of evidence indicate that Alaska and western Canada are experiencing increased drought stress due to increased summer water deficits (Barber, Juday, and Finney, 2000; Oechel *et al.*, 2000; Hogg and Bernier, 2005; Hogg, 2005; Hogg, Brandt, and Hochtubajda, 2005).

Growing Season Duration

The seasonal transition of northern ecosystems from a frozen to a thawed condition represents the closest analog to a biospheric "on-off switch" that exists in nature, dramatically affecting ecological, hydrologic, and meteorological processes (Running *et al.*, 1999). Several studies based on remote sensing indicate that growing seasons are changing in high-latitude regions (Dye, 2002; McDonald *et al.*, 2004; McGuire *et al.*, 2004; Smith, Saatchi, and Randerson, 2004; Euskirchen *et al.*, 2006). These studies identify earlier onset of thaw in northern North America, but the magnitude of change depends on the study. Putting together the trends in the onset of both thaw and freeze, Smith, Saatchi, and Randerson (2004) indicate that the trend for longer growing seasons in northern North America (3 days per decade) is primarily due to later freezing. However, other studies indicate that the lengthening growing season in North America is primarily due to earlier thaw (Dye, 2002; Euskirchen *et al.*, 2006). Consistent with earlier thaw of terrestrial ecosystems in northern North America, lake ice has also been observed to be melting earlier across much of the Northern Hemisphere in recent decades (Magnuson *et al.*, 2000). The study of Euskirchen *et al.* (2006) indicates that trends for earlier thaw are generally stronger in Alaska than in the Central Flyway of Canada and northern United States, but trends for later freeze are stronger in the Central Flyway of Canada and the northern United States than in Alaska.

A3.1.1.2 Changes in Agriculture

Agriculture and migratory waterfowl are intimately related because waterfowl make significant use of agricultural waste on staging and wintering areas. Much of the agricultural production in the United States is centered in the Central Flyway. Dynamic markets, government subsidies, cleaner farming practices, and irrigation have changed the mix, area, and distribution of agricultural products during the past 50 years (Krapu, Brandt, and Cox, Jr., 2004). Genetically engineered crops and resultant changes in tillage practices and the use of pesticides and herbicides, as well as development of drought resistant crop varieties, will likely add heterogeneity to the dynamics of future crop production. While corn acreage has remained relatively stable during the past 50 years, waste corn available to waterfowl and other wildlife declined by one-quarter to one-half during the last two decades of the 20th century, primarily as a result of more efficient harvest (Krapu, Brandt, and Cox, Jr., 2004). While soybean acreage has increased by approximately 600% during the past 50 years, metabolizable energy and digestibility of soybeans is noticeably less than for corn, and waterfowl consume little, if any, soybeans (Krapu, Brandt, and Cox, Jr., 2004). These changes in availability of corn and soybeans suggest that nutrition of waterfowl on migratory staging areas may be compromised (Krapu, Brandt, and Cox, Jr., 2004). If a future emphasis on bio-fuels increases acreage in corn production, the potential negative effects of the recent increase in soybean production on waterfowl energetics may be ameliorated.

A3.1.1.3 Changes in Lake Area

Analyses of remotely sensed imagery indicate that there has been a significant loss of closed-basin water bodies (water bodies without an inlet or an outlet) over the past half century in many areas of Alaska (Riordan, Verbyla, and McGuire, 2006). Significant water body losses have occurred primarily in areas of discontinuous permafrost (Yoshikawa and Hinzman, 2003; Hinzman *et al.*, 2005; Riordan, Verbyla, and McGuire, 2006) and subarctic areas that are permafrost-free (Klein, Berg, and Dial, 2005). In an analysis of approximately 10,000 closed-basin ponds across eight study areas in Alaska with discontinuous permafrost, Riordan, Verbyla, and McGuire (2006) found that surface water area of the ponds decreased by 4–31% while the total number of closed-basin ponds surveyed within each study region decreased by 5–54% (Riordan, Verbyla, and McGuire, 2006). There was a significant increasing trend in annual mean surface air temperature and potential evapotranspiration since the 1950s for all the study regions, but there was no significant trend in annual precipitation during the same period. In contrast, it appears that lake area is not changing in regions of Alaska with continuous permafrost (Riordan, Verbyla, and McGuire, 2006). However, in adjacent Canada, significant water body losses have occurred in areas dominated by permafrost (Hawkings, 1996).[18]

Warming of permafrost may be causing a significant loss of lake area across the landscape because the loss of permafrost may allow surface waters to drain into groundwater (Yoshikawa and Hinzman, 2003; Hinzman *et al.*, 2005; Riordan, Verbyla, and McGuire, 2006). While permafrost generally restricts infiltration of surface water to the sub-surface groundwater, unfrozen zones called taliks may be found under lakes because of the ability of water to store and vertically transfer heat energy. As climate warming occurs, these talik regions can expand and provide lateral subsurface drainage to stream channels. This mechanism may be important in areas that have discontinuous

[18] See also **Hawkings**, J. and E. Malta, 2000: Are northern wetlands drying up? A case study in the Old Crow Flats, Yukon. *51st AAAS Arctic Science Conference*.

permafrost such as the boreal forest region of Alaska. However, the reduction of open water bodies may also reflect increased evaporation under a warmer and effectively drier climate in Alaska, as the loss of open water has also been observed in permafrost-free areas (Klein, Berg, and Dial, 2005).

In the Prairie Pothole Region (PPR) of the Central Flyway, changes in climate accounted for 60% of the variation in the number of wet basins (Larson, 1995), with partially forested parklands being more sensitive to increasing temperature than treeless grasslands. When wet basins are limited, birds may overfly grasslands for parklands and then proceed even farther north to Alaska in particularly dry years in the pothole region. Small- and large-scale heterogeneity in lake drying may first cause a redistribution of birds and, if effects are pervasive enough, may ultimately cause changes in the productivity and abundance of birds. Fire and vegetation changes in the PPR and in Alaska may exacerbate these effects.

A3.1.2 Projections and Uncertainties of Future Climate Changes and Responses

A3.1.2.1 Projected Changes in Climate and Growing Season Duration

Climate

Projections of changes in climate during the 21st century for the region between 60^o and 90^o N indicate that air temperature may increase approximately 2^{o}C (range ~1–4^{o}C among models) and that precipitation may increase approximately 12% (range ~8–18% among models) (Kattsov and Källén, 2005). The increase in precipitation will be due largely to moisture transport from the south, as temperature-induced increases in evaporation put more moisture into the atmosphere. Across model projections, increases in temperature and precipitation are projected to be highest in winter and autumn. Across the region, there is much spatial variability in projected increases in temperature and precipitation, both within a model and among models. For any location, the scatter in projected temperature and precipitation changes among the models is larger than the mean temperature and precipitation change projected among the models (Kattsov and Källén, 2005).

In comparison with northern North America, climate model projections indicate that the Central Flyway of the United States will warm less with decreasing latitude (Cubasch *et al.*, 2001). Mid-continental regions such as the Central Flyway are generally projected to experience drying during the summer due to increased temperature and potential evapotranspiration that is not balanced by increases in precipitation (Cubasch *et al.*, 2001). Projections of changes in vegetation suggest that most of the Central Flyway (see Fig. A3.1 and Fig. 5.9d in the National Wildlife Refuges chapter) will experience a biome shift by the latter part of the 21st century (Bachelet *et al.*, 2003; Lemieux and Scott, 2005).

Growing Season Duration

One analysis suggests that projected climate change may increase growing season length in northern and temperate North America by 0.4–0.5 day per year during the 21st century (Euskirchen *et al.*, 2006), with stronger trends for more northern latitudes. This will be caused almost entirely by an earlier date of thaw in the spring, as the analysis indicated essentially no trend in the date of freeze. Analyses of this type need to be conducted across a broader range of climate scenarios to determine if this finding is robust. If so, then one inference is that lake ice would likely melt progressively earlier throughout northern and temperate North America during the 21st century.

A3.1.2.2 Changes in Lake Area

It is expected that the documented loss of surface water of closed-basin ponds in Alaska (Riordan, Verbyla, and McGuire, 2006) and adjacent Canada will continue if climate continues to warm in the 20th century. The ubiquitous loss of shallow permafrost (Lawrence and Slater, 2005) as well as the progressive loss of deep permafrost (Euskirchen *et al.*, 2006) are likely to enhance drainage by increasing the flow paths of lake water to ground water. Also, it is likely that enhanced evaporation will increase loss of water. While projections of climate change indicate that precipitation will increase, it is unlikely that increases in precipitation will compensate for water loss from lakes from increased evaporation. An analysis by Rouse (1998) estimated that if atmospheric CO_2 concentration doubles, an increase in precipitation of at least 20% would be needed to maintain the present-day water balance of a subarctic fen. Furthermore, Lafleur (1993) estimated that a summer temperature increase of 4^{o}C would require an increase in summer precipitation of 25% to maintain present water balance. These changes in precipitation to maintain water balance are higher than the range of precipitation changes (8–18%) anticipated for the 60–90^{o} N region in climate model projections (Kattsov and Källén, 2005).

A3.1.3 Non-Climate Stressors

In Alaska, climate is the primary driver of change in habitat value for breeding migrants through its effects on length of the ice-free season (U.S. Fish and Wildlife Service, 2006) and on lake drying (Riordan, Verbyla, and McGuire, 2006). Throughout the Central Flyway, projected major changes in vegetation are expected to occur by the end of the century (see Fig. 5.9d in the National Wildlife Refuges chapter) (Bachelet *et al.*, 2003; Lemieux and Scott, 2005). Additional stressors in the Central Flyway include competing land uses on staging areas outside the NWRS, changes in the distribution and mix of agricultural crops that may favor/disfavor foraging opportunities for migrants on migratory and winter ranges, and anthropogenic disturbance that may affect nutrient acquisition strategies for migrants in both spring and fall by restricting access to foraging areas. In southern regions of the Central Flyway, rising sea level and increasing urbanization may cause reductions in refuge area and increased insularity of remaining fragments. All stressors contribute to uncertainty in future distribution and abundance of birds. Climate dominates on Alaskan breeding grounds, and additional stressors complicate estimation of the net effects of climate on migrants and their use of staging and wintering areas in central and southern portions of the Central Flyway.

A3.1.4 Function of Alaska in the National Wildlife Refuge System

Alaska is a major breeding area for North American migratory waterfowl. Alaska and the adjacent Yukon Territory are particularly important breeding areas for American widgeon (~38% of total in 2006), green-winged teal (~31%), northern pintail (~31%) and greater and lesser scaup combined (~27%). Substantial proportions of the North American populations of western trumpeter swans, Brant geese, light geese (Snows) and greater sandhill cranes also breed in Alaska (U.S. Fish and Wildlife Service, 2006).

Alaska both contributes to NWRS waterfowl production and provides a vehicle to conceptually integrate most of the NWRS. Waterfowl that breed in Alaska make annual migrations throughout North America and are thus exposed to large-scale heterogeneity in potential climate warming effects. Migrants use the Pacific, Central, Mississippi, and to a lesser extent the Atlantic, Flyways on their annual spring and fall migrations. Their migration routes extend to wintering grounds as far south as Central and South America.

The spatial heterogeneity in warming, variable energetic demands among life history stages, and variable number and intensity of non-climate stressors along the migratory pathways creates substantial complexity within the NWRS. This complexity emphasizes that performance (*e.g.*, weight gain, survival, reproduction) of any species in any life history stage at any location within a region may be substantially affected by synergistic effects of climate and non-climate stressors elsewhere within the NWRS. A successful response to this complexity will require a national vision of the problems and solutions, and creative local action.

A3.1.4.1 Potential Effects of Climate Change on the Annual Cycle of Alaska Breeding Migrants

Abundance of waterfowl arriving on the breeding grounds is a function of survival and nutritional balance on the wintering grounds and on spring migration staging areas. Two types of breeding strategies are recognized. “Income” breeders obtain the energy for egg production primarily from the nesting area while “capital” breeders obtain energy for egg production primarily from wintering and spring staging areas. Regardless of whether species are income or capital breeders, food availability in the spring on breeding grounds in the Arctic is important to breeding success (Arzel, Elmberg, and Guillemain, 2006).

Breeding conditions for waterfowl in Alaska depend largely on the timing of spring ice melt (U.S. Fish and Wildlife Service, 2006). In the short term, earlier springs that result from warming likely advance green-up and ice melt, thus increasing access to open water and to new, highly digestible vegetation growth and to terrestrial and aquatic invertebrates. Such putative changes in open water and food resources in turn may influence the energetic balance and reproductive success of breeders and the performance of their offspring. Flexibility in arrival and breeding dates may allow some migrants to capitalize on earlier access to resources and increase the length of time available for re-nesting attempts and fledging of young. Some relatively late migrants, such as scaup (Austin *et al.*, 2000), may not be able to adapt to warming induced variable timing of open water and food resources, and thus may become decoupled from their primary resources at breeding.

In the long term, increased temperatures and greater length of the ice-free season on the breeding grounds may contribute to permafrost degradation and long-term reduction in the number and area of closed-basin ponds (Riordan, Verbyla, and McGuire, 2006), which may reduce habitat availability, particularly for diving ducks. Countering this potential reduction in habitat area may be changes in wetland chemistry and aquatic food resources. Reductions in water volume of remaining ponds may result in increased nutrient or contaminant concentrations, increases in phytoplankton, and a shift from an invertebrate community dominated by benthic amphipods to one dominated by zooplankton in the water column.[19] This has variable implications for foraging opportunities for waterfowl that make differential use of shallow and deep water for foraging. The net effects of lake drying on waterfowl populations in Alaska are not known at this time, but the heterogeneity in relatively local reductions and increases in lake area in relation to breeding waterfowl survey lines (see Fig. A3.2) may make it difficult to detect any effects that have occurred.

Figure A3.2. Heterogeneity in closed-basin lakes with increasing and decreasing surface area, 1950–2000, Yukon Flats NWR, Alaska. Net reduction in lake area was 18% with the area of 566 lakes decreasing, 364 lakes increasing, and 462 lakes remaining stable. Adapted from Riordan, Verbyla, and McGuire (2006).

Departure of waterfowl from breeding grounds in the fall may be delayed by later freeze-up. The ability to prolong occupancy at northern latitudes may increase successful fledging and allow immature birds to begin fall migration in better body condition. Later freeze-up may allow immature birds, particularly large species such as swans, to delay their rate of travel southward and increase their opportunities for nutrient intake during migration. Changes in the timing of arrival at various southern staging areas may affect waterfowl's access to and availability of resources such as waste grain and may result in re-distribution of birds along the migration route as they attempt to optimize foraging opportunities. The primary effect of this later departure and reduced rate of southward migration may be observed in more northerly fall distributions of species and a northward shift in harvest locations as has already been observed for some species. Later freeze-up and warmer winters may allow species to "short-stop" their migrations and winter farther north. Observations by Central Flyway biologists indicate that 1) numbers of wintering white-fronted geese numbers have increased in Kansas in recent years, evidently as a result of diminished proclivity to travel further southward to Texas and Mexico for the winter; 2) portions of the tundra swan population now winter in Ontario rather than continuing southward; and 3) the winter distribution of Canada geese has shifted to more northern latitudes. The energetic and population implications of these putative northerly shifts in distribution in winter will ultimately be determined by the interaction of migratory costs, food availability, non-climate stressors such as anthropogenic disturbance and shifting agricultural practices, and harvest risk.

Earlier spring thaw may advance the timing of spring migration and increase the amount of time that some species, such as greater sandhill cranes, spend on their staging grounds in Nebraska. Increased foraging time during spring migration should benefit larger species, which tend to accumulate nutrients for breeding on the wintering grounds and on

[19] **Corcoran**, R.M., 2005: Lesser scaup nesting ecology in relation to water chemistry and macroinvertebrates on the Yukon Flats, Alaska. Masters Thesis. Department of Zoology and Physiology, University of Wyoming, Laramie, 1-83.

spring migration stopovers, more than smaller species, which tend to obtain nutrients necessary for breeding while on the breeding ground (Arzel, Elmberg, and Guillemain, 2006) although the explicit resolution of this concept needs to be quantified on a species-by-species basis. Warming-induced changes in the timing of forage availability on spring migration routes may cause redistribution of waterfowl or dietary shifts as they attempt to maximize the results of their strategic feeding prior to breeding. Increased understanding of the relative value of spring migration staging areas to reproductive success and annual population dynamics of different waterfowl species is a critical need in order to adapt management strategies to a changing climate.

A3.1.4.2 Implications for Migrants

Climate change adds temporal and spatial uncertainty to the problems associated with accessing resources necessary to meet energy requirements for migration and reproduction. Because birds are vagile, the primary near-term expected response to climate change is redistribution as birds seek to maintain energy balance.

Lengthened ice-free periods may result in earlier arrival on breeding grounds, delayed migration (*e.g.*, trumpeter swans and greater sandhill cranes), and wintering farther north (*e.g.*, white-fronted geese) among other phenomena. Warmer conditions that result in lake drying may result in birds over-flying normal breeding areas to areas farther north (*e.g.*, pintail ducks). Warmer temperatures may reduce water levels but increase nutrient levels in warmed lakes. Community composition of the invertebrate food base may change and life cycles of invertebrates may be shortened; amphipods may be disfavored and zooplankton favored with differential implications for birds with different feeding strategies. Changes in hydrologic periods may cause nest flooding or make nesting habitats that are normally isolated by floodwater accessible to predators. Either effect may alter nest and nesting hen survival.

The primary challenge to migratory waterfowl, and all other trust species for that matter, is that the spatial timing of resource availability may become decoupled from need. For example, late nesters such as lesser scaup may be hampered by pulsed resources that appear before nesting. Other species such as trumpeter swans may benefit from increased ice-free periods that enhance the potential to fledge young and provision them on southward migrations. Earlier and longer spring staging periods may benefit energetic status of migrating sandhill cranes. Harvest may shift northward as birds delay fall migrations.

Alaska and the Central Flyway (see Fig. A3.1) encompass substantial spatial variation in documented (see Fig. 5.3 in the National Wildlife Refuges chapter) and expected climate warming. This spatial variation in warming is superimposed on the variable demands of spatially distinct seasonal life history events (*e.g.*, nesting, staging, wintering) of migrants. Variance in success in any life history stage may affect waterfowl performance in subsequent stages at remote locations, as well as the long-term abundance and distribution of migrants. Performance of migrants at one location in one life history stage may be affected by climate in a different life history stage at a different location. The superimposition of spatially variable warming on spatially separated life history events creates substantial complexity in both documenting and developing an understanding of the potential effects of climate warming on major trust species of the NWRS. This unresolved complexity does offer a vehicle to focus on the interconnection of spatially separated units of the system and to foster a national and international vision of a management strategy for accommodating net climate warming effects on system trust species.

A3.1.5 Management Option Considerations

A3.1.5.1 Response Levels

Response to climate change challenges must occur at multiple integrated scales within the NWRS and among partner entities. Individual symptomatic challenges of climate change must be addressed at the refuge level, while NWRS planning is the most appropriate level for addressing systemic challenges to the system. Flyway Councils, if they can be encouraged to include a regular focus on climate change, may provide an essential mid-level integration mechanism. Regardless of the level of response, the immediate focus needs to be on what can be done.

A3.1.5.2 Necessary Management Tools

Foremost among necessary management tools are formal mechanisms to increase inter-agency communication and long-term national level planning. This could be accomplished through the establishment of an interagency public lands council or other entity that facilitates collaboration among federal land management agencies, NGOs, and private stakeholders. Institutional insularity of agencies and stakeholders at national and regional levels needs to be eliminated. The council should foster intra- and inter-agency climate change communication networks, because *ad hoc* communication within or among agencies is inadequate. Explicit outreach, partnerships and collaborations should be identified and target dates for their implementations drafted. In addition, the council should develop and implement national and regional coordination mechanisms and devise mechanisms for integrating potential climate effects into management decisions. The council needs to increase effective communication among wildlife, habitat, and climate specialists.

Within the NWRS there needs to be adequate support to insure the development of an increased capacity to rigorously model possible future conditions, and explicit recognition that spatial variation in climate has differential effects on life cycle stages of migrants; performance in one region may be affected by conditions outside a region. Enhanced ability to assist migratory trust species when “off-refuge” and enhanced ability to facilitate desirable range expansions within and across jurisdictions are needed.

Comprehensive Plans and Biological Reviews need to routinely address expected effects of climate change and identify potential mechanisms for adaptation to these challenges. The ability to effectively employ plans and reviews as focus mechanisms for potential climate change effects will be enhanced by institutionalization of climate change in job descriptions and increased training for refuge personnel.

A3.1.5.3 Barriers to Adaptation

The primary barriers to adaptation include the lack of a spatially explicit understanding of the heterogeneity and degree of uncertainty in effects of changing climate on seasonal habitats of trust species—breeding, staging and wintering—and their implications for populations. Currently there is concern about effects of climate change on trust species, but insufficient information on which to act. This lack of understanding hampers the development of an explicit national vision of potential net effects of climate change on migrants. In addition, the lack of a secure network of protected staging areas, similar to the established network of breeding and wintering areas, limits the ability of the NWRS to provide adequate security for migratory trust species in a changing climate. More efficient use of all types of resources will be needed to minimize these national-level barriers to adaptation of the NWRS to climate change.

A3.1.5.4 Opportunities for Adaptation

One of the greatest opportunities may lie in creating an institutional culture that rewards employees for being proactive catalysts for adaptation. This would require the acceptance of some degree of failure due to the uncertain nature of the magnitude and direction of climate change effects on habitats and populations. In addition, managers and their constituencies could be energized to mount successful adaptation to climate change by emphasizing the previous successful adaptations by the U.S. Fish and Wildlife Service (USFWS) to the first three management crises of market hunting, dust bowl habitat alteration, and threatened and endangered species management.

The capacity to provide more rigorous projections of possible future states will require the creative design of inventory and monitoring programs that enhance detection of climate change effects, particularly changing distributions of migratory trust species. Monitoring programs that establish baseline data regarding the synergy of climate change and other stressors (*e.g.*, contaminants, habitat fragmentation) will especially be needed. These monitoring programs will need to be coordinated with private, NGO and state and federal agency partners.

In stakeholder meetings, refuge biologists were emphatic that they needed more biological information in order to clearly define and to take preemptive management actions in anticipation of climate change. Thus, effective adaptation to climate change will require education, training and long-term research-management partnerships that are focused on adaptive responses to climate change. The following strategy is proposed for the activities of such a research-management partnership:

- Synthesize extant biological information relevant to biotic responses to climate change;
- Educate and train refuge mangers and other staff regarding climate change, its potential ecological effects, and the changes in management and planning that may be necessary;
- Evaluate possible management and policy responses to alternative climate change scenarios in multiple regional and national workshops;
- Conduct workshops involving managers, researchers and stakeholders to identify research questions relevant to managing species in the face of climate change;

- Conduct research on questions relevant to managing species in the face of climate change. This may require the development of tools that are useful for identifying the range of responses that are likely;
- Apply management actions in response to biotic responses that emerge as likely from such research; and
- Evaluate of the effectiveness of management actions and modification of management actions in the spirit of adaptive management.

Synthesis workshops should be held every few years to identify what has been learned and to redefine questions relevant to the management of species that depend on the NWRS.

There are a number of examples of recent climate-change-related challenges and potential and implemented adaptations in Alaska and the Central Flyway:

Potential adaptations:

- The development of a robust understanding of the relative contribution of various NWRS components to waterfowl performance in a warming climate is an immediate challenge. There is a clear research need to elucidate the relative contribution of staging and breeding areas to energetics and reproductive performance of waterfowl, and to clarify the interdependence of NWRS elements and their contributions to waterfowl demography. A flyway-scale perspective is necessary to understand the importance of migratory staging areas and to assess the relative importance of endogenous/exogenous energetics to reproduction and survival. These studies should address, in the explicit context of climate warming, strategic feeding by waterfowl, temporal shifts in diets, and the spatial and temporal implications of climate induced changes in the availability of various natural and agricultural foods (Arzel, Elmberg, and Guillemain, 2006).

- Providing adequate spatial and temporal distribution of migratory foraging opportunities is a chronic challenge to the NWRS. Spring staging areas are under-represented and this problem is likely to be exacerbated by a warming climate. It will be necessary to strengthen and clarify existing partnerships with private, NGO, and state and federal entities and to identify and develop new partnerships throughout the NWRS in order to provide a system of staging areas that are extensive and resilient enough to provide security for migratory trust species. Strategic system growth through fee-simple and conservation easement acquisition will be a necessary component of successful adaptation.

Implemented adaptations:

- Indigenous communities on the Aleutian Island chain (Alaska Maritime NWR) are concerned about the potential effects of increased shipping traffic in new routes that may become accessible in a more ice-free Arctic Ocean. Previous introductions of non-endemic species to islands have had severe negative effects on nesting Aleutian Canada geese. The ecosystem management mandate of the refuge facilitates a leadership role for the refuge that has been implemented through 1) development of monitoring partnerships that are designed to detect the appearance of invasive species and of contaminants, and 2) initiation of timely prevention/mitigation programs.

- Indigenous peoples that depend on Interior Alaska NWRs are concerned about the potential effects of climate-induced lake drying and changing snow conditions on their seasonal access to subsistence resources, and on the availability of waterfowl for subsistence harvest. The refuges have promoted enhanced capacity for projecting possible future conditions, and have educated users regarding observed and expected changes while clarifying conflicting information on the magnitude and extent of observed changes in lake number and area and in snow conditions.

- Warming-induced advances in the timing of ice-out can bias waterfowl population indices that are derived from traditional fixed-date surveys. The Office of Migratory Bird Management has developed quantitative models to project the arrival date of migrants based on weather and other records. This allows the office to dynamically adjust survey timing to match changing arrival dates and thereby reduce bias in population indices.

A4 Wild and Scenic Rivers Case Studies

As emphasized throughout the Wild and Scenic Rivers (WSR) chapter, the effects of climate change on rivers will vary greatly throughout the United States depending on local geology, climate, land use, and a host of other factors. To illustrate the general “categories” of effects, we have selected three WSRs to highlight in the following case studies (Box A4.1). We selected these rivers because they span the range of some of the most obvious issues that managers will need to grapple with as they develop plans for protecting natural resources in the face of climate change. Rivers in the Southwest, such as the Rio Grande, will experience more severe droughts at a time when pressures for water extraction for growing populations are increasing. Rivers near coastal areas, such as the Wekiva, face potential impacts from sea level rise. A combination of groundwater withdrawals and sea level rise may lead to increases in salinity in the springs that feed this river. Rivers that are expected to experience both temperature increases and an increased frequency of flooding, such as the Upper Delaware, will need proactive management to prevent loss or damage to ecosystem services.

There are also key outstandingly remarkable values that the WSR program focuses on. One of those areas is anadromous fish. Box A4.2 provides an overview of potential climate change impacts to anadromous fish and offers management actions that may be taken to lessen those impacts.

A4.1 Wekiva River

The Wekiva River Basin, located north of Orlando, in east-central Florida, is a complex ecological system of streams, springs, seepage areas, lakes, sinkholes, wetland prairies, swamps, hardwood hammocks, pine flatwoods, and sand pine scrub communities. Several streams in the basin run crystal clear due to being spring-fed by the Floridan aquifer. Others are "blackwater" streams that receive most of their flow from precipitation, resulting in annual rainy season over-bank flows. (Fig. A4.1)

Figure A4.1. The Wild and Scenic portions of the Wekiva River. Data from USGS, National Atlas of the United States.[20]

In 2000, portions of the Wekiva River and its tributaries of Rock Springs Run, Wekiwa[21] Springs Run, and Black Water Creek were added to the National Wild and Scenic Rivers System. The designated segments total 66.9 km, including 50.5 km designated as Wild, 3.4 miles as Scenic, and 13 km as Recreational. The National Park Service (NPS) has overall coordinating responsibility for the Wekiva River WSR, but there are no federal lands in the protected river corridor. Approximately 60%–70% of the 0.8-km-wide WSR corridor is in public ownership, primarily managed by the State of Florida Department of Environmental Protection and the St. Johns River Water Management District (SJRWMD). The long-term protection, preservation, and enhancement are provided through cooperation among the State of Florida, local political jurisdictions, landowners, and private organizations. The designated waterways that flow through publicly owned lands are managed by the agencies that have jurisdiction over the lands. SJRWMD has significant regulatory authority to manage surface and ground water resources throughout the Wekiva Basin.

One of the main tributaries to the Wekiva River is the Little Wekiva River. Running through the highly developed Orlando area, the Little Wekiva is the most heavily urbanized stream in the Wekiva River Basin, and consequently the most heavily affected. The Orlando metropolitan area has experienced rapid growth in the last two decades, and an estimated 1.3 million people now live within a 20-mile radius of the Wekiva River.

The sections of the Wekiva River and its tributaries that are designated as WSR are generally in superb ecological condition. The basin supports plant and animal species that are endangered, threatened, or of special concern, including the American Alligator, the Bald Eagle, the Wood Stork, the West Indian Manatee, and two invertebrates endemic to the Wekiva River, the Wekiwa hydrobe and the Wekiwa siltsnail. At the location of the U.S. Geological Survey's gauging station on the Wekiva River near Sanford, the drainage area of the basin is 489 square km. Elevations for the basin range from 1.5–53 m above sea level. The climate is subtropical, with an average annual temperature of around 22°C. Mean annual rainfall over the Wekiva basin is 132 cm, most of which occurs during the June–October rainy season.

[20] **U.S. Geological Survey**, 2005: Federal land features of the United States - parkways and scenic rivers. *Federal Land Features of the United States*. http://www-atlas.usgs.gov/mld/fedlanl.html. Available from nationalatlas.gov.

[21] The term "Wekiwa" refers to the spring itself, from the Creek/Seminole "spring of water" or "bubbling water." "Wekiva" refers to the river, from the Creek/Seminole "flowing water."

The WSR management plan is being prepared with the leadership of the NPS. Based on information from the pre-legislation WSR study report,[22] and management plans for the state parks (Florida Department of Environmental Protection, 2005) and the SJRWMD (2006a), the priority management objectives for the WSR will likely include maintaining or improving: water quantity and quality in the springs, streams, and river; native aquatic and riparian ecosystems; viable populations of endangered and sensitive species; scenic values; and access and service for recreational users.

The Wekiva River was selected for a case study because it provides an example of a spring-fed WSR system, sub-tropical ecosystems, a coastal location with a history of tropical storms and hurricanes, and a system in a watershed dealing directly with large and expanding urban and suburban populations. In particular, the spring-fed systems combined with urban and suburban land uses require consideration of the relationship between groundwater and surface water and how they relate to management options in the context of climate change.

A4.1.1 Current Stressors and Management Methods Used to Address Them

The primary stressors of the Wekiva WSR are:

- water extraction for public, recreational and agricultural uses;
- land conversion to urban and suburban development;
- pollution, particularly nitrates, via groundwater pathways and surface water runoff; and
- invasive species.

The Floridan aquifer has a naturally high potentiometric surface (*i.e.*, the level that water will rise in an artesian well), which sustains the natural springs that are critical to the water regime of the Wekiva WSR. McGurk and Presley[23] cite numerous studies that show the long history of water extraction in East Central Florida and related these extractions to lowering of the potentiometric surface. Taking advantage of the high potentiometric surface, in the first half of the 20th century more than two thousands artesian (free-flowing) wells were drilled into the Upper Floridan aquifer, the water used to irrigate agriculture fields and the excess allowed to flow into the streams and rivers. Many of the artesian wells have since been plugged and otherwise regulated to reduce such squandering of the water resources.

Between 1970 and 1995, agricultural and recreational water use from the aquifer has increased nearly three fold to 958 million gallons per day (mgpd), with a significant part of the additional water supporting recreational uses (*i.e.*, golf courses). Over that same period, public (*e.g.*, city) use of water from the aquifer also increased threefold to 321

[22] **National Park Service**, 1999: *Wekiva River, Rock Spring Run & Seminole Creek Wild and Scenic River Study*. U.S. Department of Interior, pp.1-49.
[23] **McGurk**, B.E. and P.F. Presley, 2002: *Simulation of the Effects of Groundwater Withdrawals on the Floridan Aquifer System in East-Central Florida: Model Expansion and Revision*. St. Johns River Water Management District, pp.1-196.

mgpd. Projections for the year 2020 are for water extraction for agricultural and recreational uses to barely increase, while extractions for public use will nearly double.[23] The St. Johns River, Southwest Florida, and South Florida Water Management Districts have jointly determined that the Floridan Aquifer will be at maximum sustainable yield by 2013, and by that date and into the future much of the water used by people will have to come from alternative sources.

Urban development prior to modern stormwater management controls is another stressor on aquatic systems in the Wekiva Basin. In particular, the Little Wekiva River exhibits extreme erosion and sedimentation caused by high flows and velocities during major storm events (St. Johns River Water Management District, 2002). Approximately 479 drainage wells were completed in the Orlando area to control stormwater and control lake levels.[23] These drainage wells recharge the Floridan aquifer.

Declines in spring flows in the Wekiva River Basin are strongly correlated with urban development and ground water extraction (Florida Department of Environmental Protection, 2005). Projections based on current practices indicate that by 2020 water demand will surpass supply and recharge. By 2010, spring flows may decline to levels that will cause irreparable harm (Florida Department of Environmental Protection, 2005). In response to these projections, the SJRWMD has declared the central Florida region, which includes the Wekiva River Watershed, a "Priority Water Resource Caution Area" where measures are needed to protect ground water supplies and spring-dependent ecosystems. SJRWMD has developed "Minimum Flows and Levels" (a.k.a., instream flow criteria) for the Wekiva River and Blackwater Creek, and the district has identified minimum spring flows in selected major springs feeding the Wekiva and Rock Springs Run. These are an important regulatory tool to set limits on ground water withdrawals to prevent adverse reductions in spring flow.

The water management district recommends the following strategies for improving water management (St. Johns River Water Management District, 2006b):

- water conservation;
- use of reclaimed water; and
- water resource development, including:
    - artificial aquifer recharge
    - aquifer storage and recovery
    - avoidance of impacts through hydration
    - interconnectivity of water systems.

The SJRWMD, counties, and cities in the watershed are working on local water resources plans and an integrated basin-wide water plan that will guide water use and conservation land use changes for the coming decades.[24]

[24] **Florida Department of Community Affairs**, 2005: *Guidelines for Preparing Comprehensive Plan Amendments for the Wekiva Study Area Pursuant to the Wekiva Parkway and Protection Act*. pp.1-50.

Water pollution is another significant stressor of the Wekiva WSR. The causes of water pollution are closely related to the water quantity issues discussed above. In particular, unusually high concentrations of nitrates emanating from the springs of the basin are stressing the native ecosystems in the spring runs. Nitrates promote algal blooms that deplete oxygen, shade-out native species, and may negatively affect invertebrate and fish habitat. Nitrates in spring water now may reflect more distant past inputs from agricultural operations and septic systems. The sources of the nitrogen in the springs are animal waste, sewage, and fertilizers (Florida Department of Environmental Protection, 2005), which readily leach to groundwater due to the karstic geology of the basin. Future spring discharges may reflect a newer type of input from reclaimed water application for both landscape irrigation and for direct recharge via rapid infiltration basins that have increased significantly within the past 10–15 years and continue to increase. The management solutions to reduce nitrate pollution include educating the public to use fewer chemicals and apply these with greater care, development and application of agricultural best management practices, and increasing the use of central sewage treatment facilities in place of on-site systems such as septic tanks.

Recent data suggest that increases in dissolved chlorides in the springwaters may be related to sea level rise and groundwater withdrawals (Florida Department of Environmental Protection, 2005). To date, salinity changes in the Wekiva Basin springs are minor and the causes are unclear. Major increases in the salinity (increased chlorides) in the springwater would have significant impacts on the ecosystems of the WSR. Continued monitoring and further research are needed to determine the source of the chlorides (*e.g.*, recharge from polluted surface water or mixing with saltwater from below the Upper Floridan aquifer) and how to manage land and water to limit chlorides in the springflows.

Exotic plants are a major problem stressing ecosystems in the Wekiva WSR corridor. For example, wild taro (*Colocasia esculentum*) has infested Rock Springs Run and the lagoon area of Wekiwa Springs has hydrilla (*Hydrilla verticillata*), water hyacinth (*Eichhornia carssipes*), and water lettuce (*Pistia stratiotes*). The park managers use a combination of herbicides and manual labor to control invasive plant species (Florida Department of Environmental Protection, 2005).

Drought-related stress in upland areas has increased the vulnerability of trees to pest species, the Southern pine beetle (*Dendroctomus frontalis*) in particular. Infestations have prompted park managers to clear-cut infested stands and buffers to limit the spread of the beetles. Without these interventions, dead trees would contribute significant fuel, increasing the potential for destructive forest fires.

A4.1.2 Potential Effects of Climate Change on Ecosystems and Current Management Practices

For Central Florida, climate change models project average temperatures rising by perhaps 2.2–2.8°C and annual rainfall to total about the same as it does today.[25] However, the late summer and fall rainy season may see more frequent tropical storms and hurricanes, overwhelming the current stormwater management infrastructure and resulting in periodic surges of surface water with significant pollution and sedimentation loads. More runoff also means less recharge of the aquifer.

At other times of the year, droughts may be more frequent and of longer duration, leading to water shortages and increased withdrawals from the aquifer, which may reduce spring flows.

While there is only moderate confidence in projections of changes in patterns of precipitation, there is a high confidence that it will get warmer. Warmer temperatures over an extended period will change species composition in the WSR corridor. Some native species, particularly those with limited ranges, may no longer find suitable habitat, while invasive exotics, which often tolerate a broad range of conditions, would thrive. Current programs to control invasive species would face new challenges as some native species are lost and replaced by species that favor the warmer climate, particularly for terrestrial species. Where the cold spring waters can moderate water temperature in the streams and river, the current control programs for aquatic invasive species may still be successful in a moderately warmer climate. Warmer temperatures would also lead to increased evaporation and transpiration, which in turn may lead to more water used for irrigation; all of these factors combine to further reduce water available for ecosystems in the WSR. The warmer climate may also reduce or eliminate frost events that currently determine the range for some species in central Florida.

Climate change scenarios project sea level rising between 0.18–0.59 m by 2099 (IPCC, 2007b). There are two issues related to potential sea level rise relative to the Wekiva WSR: 1) how would changes in the tidal reach of the St. Johns River affect the Wekiva, and 2) how might the rising sea level affect the aquifer that supports the springflows? There are too few data available to answer these questions.

Finally, projected population increases in the Wekiva Basin and associated aquifer recharge area will add to the burden of managing for climate change impacts on water resources. Suburban expansion increases impermeable surfaces, thereby adding to polluted surface water runoff and reducing aquifer recharge. And groundwater will continue to be extracted for the public and recreational uses.

[25] **University of Arizona**, Environmental Studies Laboratory, 2007: Climate change projections for the United States. University of Arizona, http://www.geo.arizona.edu/dgesl/, accessed on 5-17-2007.

A4.1.3 Potential for Altering/Supplementing Current Management to Enable Adaptation to Climate Change

Future management adaptations for meeting ecosystem goals in the Wekiva WSR should include monitoring ecosystem health, including water quantity and quality; basin-wide modeling to protect future management needs; and implementation of management programs in advance of climatic changes. The water management district and other land management agencies have robust monitoring programs, though they may not be adequate to understand the complexity of applying reclaimed surface water in a the karst uplands. Current groundwater monitoring, which focuses on salinity, may need to be expanded to better understand how nitrates and other nutrients are transported to the springflows. Increasingly refined models are needed to understand how water and ecosystems in the Wekiva Basin respond to management.

In many ways, it appears that the SJRWMD and local government agencies are beginning to implement management programs that would be needed to maintain ecological processes in the Wekiva WSR in a climate change scenario. Aquifer management is widely recognized as among the most critical tools for ensuring public water supplies and ecological integrity of the Wekiva WSR. Most of the drinking water in and around the Wekiva Basin is extracted from the Floridan aquifer—the same water source for the springflows that are essential to ecosystems of the Wekiva WSR. The Floridan aquifer is a water reservoir that can be managed in ways analogous to a reservoir behind a dam. Like a dam, with each rain event, to the extent permitted by surface conditions, the aquifer is recharged; water otherwise runs into streams and rivers, effectively lost for most public uses and often negatively affecting riverine ecosystems. Different from a dam, aquifer recharge and replenishment operate in a delayed time frame. This characteristic makes reversal of any mitigation measures a slow process, and should be considered in adaptation planning for global climate changes. Recognizing these conditions, programs and plans are in place to minimize surface runoff and maximize groundwater recharge. Programs include, for example, minimizing impermeable surfaces (*e.g.*, roofs, driveways, and roads), and holding surface water in water gardens and artificial ponds.

Recharge water must be of sufficiently good quality in order to not adversely affect the WSR system. Current stormwater management programs, while quite good, are focused on capturing surface water runoff to prevent it from degrading water quality, but this then "re-routes" poor-quality water from a surface water load to a ground water load. The sandy soils and karst geology of the area may result in nitrate-loaded water recharged to the aquifer and then to the springs. There is a great deal to learn about the ultimate effects on groundwater quality of applying reclaimed water to land surface in the karstic uplands.

While the human population in the Wekiva Basin is expected to grow, climate change models suggest that annual rainfall will remain about the same over the next 100 years, presenting a challenge for meeting water demand. In response, programs in the basin are under development to conserve water (reduce water use per person) and to develop "new" water sources (hold and use more surface water). Similarly, programs are also being planned and implemented to reduce pollution, including educating the public and commercial users about what, when, and how to apply chemicals, including nitrate-based fertilizers.

Management adaptations to more intense rain events under climate change conditions would require more aggressive implementation of all these programs, to: maximize recharge of the aquifer during rain events, minimize withdrawals at all times and particularly during droughts, minimize pollution of surface water and groundwater, and monitor and prevent salt water intrusion in the surface water-groundwater-seawater balance system. Considering the importance of water to local residents and as a factor driving economic development, there is considerable political will to invest in water management technologies and programs in the Wekiva Basin. Through this century, current and emerging technologies will likely be adequate for meeting the water needs for human consumption and ecosystem services in the Wekiva Basin, if people are willing to make the investment in technologies and engineering and to allocate enough water to maintain ecosystems.

A4.2 Rio Grande

The Rio Grande, the second largest river in the American Southwest, rises in the snow-capped mountains of southern Colorado, flows south through the San Luis Valley, crosses into New Mexico and then flows south through Albuquerque and Las Cruces to El Paso, Texas, on the U.S.-Mexican border (see Figs. A4.2 and A4.3). A major tributary, the Rio Conchos, flows out of Mexico to join the Rio Grande below El Paso at Presidio and supplies most of the river's flow for the 1,254 miles of river corridor along the Texas-Mexico border. Since 1845, the Rio Grande has marked the boundary between Mexico and the United States from the twin border cities of Ciudad Juárez and El Paso to the Gulf of Mexico.

Figure A4.2. The Wild and Scenic portions of the Rio Grande WSR in New Mexico. Data from USGS, National Atlas of the United States.[20]

Figure A4.3. The Wild and Scenic portions of the Rio Grande WSR in Texas. Data from USGS, National Atlas of the United States.[20]

Three different segments of the Rio Grande that total 259.6 miles of stream have been designated as Wild, Scenic, and Recreational. Part of the 68.2-mile segment of the river south of the Colorado-New Mexico border was among the original eight river corridors designated as wild and scenic at the time of the system's creation in 1968. A total of 53.2 miles of this reach are designated as wild, passing through 800-foot chasms of the Rio Grande Gorge with limited development. This segment is administered by the Bureau of

Land Management (BLM) and the U.S. Forest Service (USFS).[26] About 97% of the land in the New Mexico WSR management zones is owned and managed by BLM or the USFS.

The longest segment of the Rio Grande WSR comprises 195.7 river miles in Texas (National Park Service, 2004) along the U.S.-Mexico border, with about half of this stretch classified as wild and half as scenic. This stretch, which was added to the system in 1978, is administered by the NPS at Big Bend National Park for the purpose of protecting the "outstanding remarkable" scenic, geologic, fish and wildlife, and recreational values (National Park Service, 2004). Land ownership is evenly divided between private and public (federal and state) owners on the United States side of the designated river segment.

In New Mexico, objectives for managing the WSR include (Bureau of Land Management, 2000):

- maintain water quality objectives designated by the New Mexico Environment Department;
- conserve or enhance riparian vegetation;
- preserve scenic qualities;
- provide for recreational access, including boating and fishing; and
- protect habitat for native species, particular federally listed species.

In Texas, the resource management goals for the wild and scenic river include (National Park Service, 2004):

- preserve the river in its natural, free-flowing character;
- conserve or restore wildlife, scenery, natural sights and sounds;
- achieve protection of cultural resources;
- prevent adverse impacts on natural and cultural resources;
- advocate for scientifically determined suitable instream flow levels to support fish and wildlife populations, riparian communities and recreational opportunities; and
- maintain or improve water quality to federal and state standards.

The Rio Grande WSR was selected for a case study because the distinct segments of the designated river provide examples of features typical of many rivers in the mountainous and arid Southwest. Attributes important to this paper include: significant federal and state ownership of the streamside in designated segments; an important influence of snowpack on river flow; complex water rights issues with a great deal of water being extracted upstream of the WSR; primary competition for water by agriculture; and an international component.

A4.2.1 Current Stressors and Management Methods Used to Address Them

The primary stressors of the Rio Grande WSR include (Bureau of Land Management, 2000; National Park Service, 2004; New Mexico Department of Game and Fish, 2006):

[26] **National Wild and Scenic Rivers System**, 2007: Homepage: National Wild and Scenic Rivers System. National Wild and Scenic Rivers System Website, http://www.rivers.gov, accessed on 5-30-2007.

- altered hydrology: impoundment, reservoir management and water extraction have led to flow reductions and changes in flow regime (loss of natural flood and drought cycle) and concomitant changes in the sediment regime and channel narrowing;
- altered land use: land and water use for agriculture, mining operations, and cities is leading to declines in water quality due to pollution and sedimentations;
- invasive species: non-native fish and vegetation are altering ecosystems, displacing native species and reducing biodiversity, giant reed and saltcedar are particularly problematic in the Texas WSR segment; and
- recreational users: visitors and associated infrastructure impact the riparian vegetation and protected species; subdivision and building on private lands along the Texas and Mexico segments threatens scenic values and may increase recreational users' impacts.

All segments of the Rio Grande that are designated as WSR face complex management challenges and multiple stressors on river health, most notably from dams, diversions and other water projects that dot the river and its tributaries, reducing and altering natural flows for much of the river's length. (Fig. A4.4) Although there are no dams on the main stem of the river upstream of the New Mexico WSR corridor, dams and other water projects on major tributaries affect flows downstream. For example, two Bureau of Reclamation projects in Colorado—the Closed Basin (groundwater) Project and the Platoro Dam and Reservoir on the Conejos River—influence downstream flows into New Mexico. Flow regime of the WSR in New Mexico is largely managed by the Bureau of Reclamation, which manages upstream dam and diversion projects based on a century of water rights claims and seasonal fluctuations in available water. The water rights and dams are considered integral to the baseline condition for the WSR, as they were in place prior to the river's designation.

Figure A4.4. Dams and diversions along the Rio Grande.[27]

Downstream from El Paso, Texas, the channel of the Rio Grande is effectively dry from diversion for about 80 miles. Because of this "lost reach," the river is more like two separate rivers than one, with management of the Colorado and New Mexico portion having little effect on flows downstream of El Paso. In the past, the river in Colorado and New Mexico normally received annual spring floods from the melting snowpack while the river below Presidio, Texas received additional flood events in the summer through fall from rains in the Rio Conchos Basin, Mexico. However, throughout the Rio Grande these natural cycles of annual floods have been severely disrupted by dams and water extraction.

[27] **Middle Rio Grande Bosque Initiative**, 2007: Dams and diversions of the Middle Rio Grande. Middle Rio Grande Bosque Initiative Website, http://www.fws.gov/southwest/mrgbi/Resources/Dams/index.html, accessed on 5-17-2007.

Management of the Texas Rio Grande WSR still depends on flows entering from Mexico—including the Rio Conchos, which provides 85% of the water to this WSR segment—and which is managed by the International Boundary and Water Commission according to the Rio Grande Compact. Instream flows in Texas segments of the WSR have decreased 50% in the past 20 years (National Park Service, 2004). During drought years of the late 1990s and into 2004, Mexico did not meet its obligations to the United States under the compact and water levels reached critical lows (Woodhouse, 2005). In 2003, the combination of dams, water extraction and drought were particularly hard on the river, flow essentially ceased, the river became a series of pools in Texas WSR segments and the river failed to reach the ocean.[28]

Inefficient regulation of groundwater contributes to these impacts on the river's flow. The primary source of household water in central New Mexico is groundwater, for which the rate of extraction currently exceeds recharge.[29] Aquifers in the region may not be able to meet demand in twenty years, which will further stress an overburdened surface water resource.

Changes in the flow regime of the river are affecting the channel, the floodplain, and the associated aquatic and riparian ecosystems. In the past 90 years, overall stream flow has been reduced more than 50%, and periodic flooding below Presidio has been reduced by 49% (Schmidt, Everitt, and Richard, 2003). Dams in the lower Rio Grande prevent fish migrations so that Atlantic Sturgeon and American Eel no longer reach the WSR.[30] Where native species were dependent on or tolerant of the periodic floods, the new flow regime is apparently giving an edge to invasive, non-native species (National Park Service, 1996). Garrett and Edwards[28] suggest that changes in flow and sedimentation, pollution, simplification of channel morphology and substrates, and increased dominance of non-native plant species can explain recent changes in fish diversity and critical reductions and local extinctions of fish species. Giant reed *(Arundo donax*) and salt cedar *(Tamarix* sp.) are particularly problematic as these exotic species invade the channelized river and further disrupt normal sedimentation, thereby reducing habitats critical to fish diversity.[28] The problems of dams and irregular flows are complicated by local and international water rights issues, and the ecological health of WSR is only one of the many competing needs for limited water resources.

To address pollution issues, BLM, USFS, and NPS managers have reduced pollution to the river from their operations by reducing or eliminating grazing and mining near the river, improving management of recreation sites, and increasing education and outreach. However, as with flow regime, most of the water quality problems are tied to decreases in

[28] **Garrett**, G.P. and R.J. Edwards, forthcoming: Changes in fish populations in the Lower Canyons of the Rio Grande. *Proceedings of the Sixth Symposium on Natural Resources of the Chihuahuan Desert Region, Chihuahuan Desert Research Institute*.
[29] **New Mexico Office of State Engineer** and Interstate Stream Commission, 2006: *The Impact of Climate Change on New Mexico's Water Supply and Ability to Manage Water Resources*. New Mexico Office of State Engineer/Interstate Stream Commission.
[30] **National Park Service**, 2007: Floating the lower canyons. National Park Service, http://www.nps.gov/rigr/planyourvisit/lower_cyns.htm, accessed on 4-14-2007.

water quantity and discharge from large-scale agricultural, industrial and urban upstream users.

Federal land managers are making a difference where they can with site-level management. For example, riparian zones are being withdrawn from grazing and mineral leases and are being protected via limited access to sensitive sites and education of backcountry visitors about the values of protected streamside vegetation. Programs are also underway to control erosion in recreation areas and river access points and to improve habitat for protected species (Bureau of Land Management, 2000).

A4.2.2 Potential Effects of Climate Change on Ecosystems and Current Management Practices

According to Schmidt *et al*. (2003) the primary drivers of ecosystem change of the Rio Grande are:

- climatic changes that change runoff and influx of sedimentation;
- dam management and water extraction that lead to changes in flow regime (loss of natural flood and drought cycle) and sedimentation;
- changes to the physical structure of the channel and floodplain;
- introduction of exotic species; and
- ecosystem dynamics that cause species to replace other species over time.

The American Southwest in general, including the Rio Grande watershed, seems likely to experience climate extremes in the form of higher temperature, reduced precipitation (including reduced snowpacks), earlier spring melts, and recurring droughts on top of population growth and other existing stressors.[29] While global climate models are inconclusive regarding changes in precipitation for this region, and for the Upper Rio Grande Basin in particular, it seems likely that the projected increase in temperature will result in evaporation rates that more than offset any possible increase in precipitation.[29] In this scenario, the New Mexico WSR segment of the Rio Grande might experience earlier spring floods, with reduced volume and more erratic summer rains.[29] Projections of perhaps 5% decrease in annual precipitation for the middle and lower Rio Grande (see Fig. 6.13 in the Wild and Scenic Rivers chapter) combined with higher temperatures (see Fig. 6.12 in the Wild and Scenic Rivers chapter) suggest that annual flows in the Texas WSR segment may be further reduced, and during severe droughts the water levels may decline to critical levels as has been the case in recent years (National Park Service, 2004). Water quality may be further reduced as the shallower water is susceptible to increased warming due to higher temperatures driven by climate change (Poff, Brinson, and Day, Jr., 2002). These conditions would negatively affect many native species and may favor invasive non-native species, further complicating existing programs to manage for native riparian vegetation and riverine ecosystems (National Park Service, 2004).[29]

A4.2.3 Potential for Altering/Supplementing Current Management to Enable Adaptation to Climate Change

The incorporation of climate change impacts into the planning and management of the WSR corridors of the Rio Grande is complicated by the river's international character, the numerous dams, diversions, and groundwater schemes that already affect its flow regime, and the multiple agencies involved in the river's management within the WSR corridors as well as upstream and downstream. Sustaining the Rio Grande's wild and scenic values under these circumstances will require planning, coordination, monitoring of hydrological trends, and scenario-based forecasting to help river managers anticipate trends and their ramifications. For example, given the probability of reduced snowpack in the headwaters of the Rio Grande, sustaining flows through the New Mexico WSR corridor will likely depend on coordination among the USFS and BLM, which administer this WSR stretch, the Bureau of Reclamation, which manages upstream water projects (both groundwater and surface water) that influence downstream flows, and owners of local and international water rights. Long standing water rights complications make it difficult to predict needed water releases to mimic natural flow regime. In this region, required water deliveries might be met by transferring water rights between watersheds or through credits for future water delivery.

Similarly, the NPS, which administers the Rio Grande WSR corridor in Texas, needs to coordinate with the International Boundary and Water Commission to extract ecological services from regulated flows. This may prove more difficult than securing water for the river in New Mexico. During recent years of drought, Mexico did not meet its obligations to the United States under the compact. With droughts of greater duration expected as temperatures warm, more years of difficulty meeting treaty obligations may arise.

Economic incentives are another approach to securing sufficient clean water needed to meet management objectives of the WSR. Recognizing the value of ecological services, one potential measure, for instance, is to purchase or lease water rights for the river. Additionally, technical assistance and incentives could also be provided to users who improve water efficiency, reduce pollution, and release surplus clean water to the river. Water deliveries could mimic natural flows, including scouring floods to build the channel.

Improving efficiency of agricultural and urban water use and increasing re-use to conserve water and reduce pollution are probably the most cost-effective strategies to make more clean water available in the Rio Grande. If improved water efficiency results in "new" water, the challenge for WSR managers will be to negotiate, purchase or lease water for the river when it is most needed for ecological flows.

A4.3 Upper Delaware River

The Delaware River runs 330 miles from the confluence of its East and West branches at Hancock, New York to the mouth of the Delaware Bay. Established by Congress in 1978, the Upper Delaware Scenic and Recreational River consists of 73.4 miles (32.1 miles designated as scenic and 50.3 miles as recreational) of the Delaware River between Hancock and Sparrow Bush, New York, along the Pennsylvania-New York border. Although this case study focuses on the Upper Delaware, there are also 35 miles designated as scenic in the Middle Delaware River in the Delaware Water Gap National Recreational Area and 67.3 miles of Delaware River and tributaries (25.4 scenic and 41.9 recreational) in the Lower Delaware Scenic and Recreational River (Fig. A4.5).

Figure A4.5. Map of Wild and Scenic stretches in the Delaware River basin. Courtesy of Delaware River Basin Commission.[31]

The Upper Delaware Scenic and Recreational River boasts hardwood forests covering over 50% of the river corridor (Conference of the Upper Delaware Townships, 1986). These forests provide lush habitat for diverse fauna including at least 40 species of mammals, such as many of Pennsylvania's remaining river otters and one of the largest populations of black bear in the state. It is one of the most important inland bald eagle wintering habitats in the northeastern United States. Water quality in the Upper Delaware is exceptional and supports abundant cold- and warm-water fish. As the last major river on the Atlantic coast undammed throughout the entire length of its mainstem, the Delaware provides important habitat for migratory fish such as American eel and America shad. In the upper reaches of the Delaware system, rainbow and brown trout are highly sought by anglers. The river and its surrounding ecosystems provide a beautiful setting for recreation including fishing, boating, kayaking, sightseeing and hiking.

The Upper Delaware Scenic and Recreational River includes a 55,575 acre ridge-top-to-ridge-top (approx. ½ mile wide) corridor, nearly all privately held. The NPS has jurisdiction over 73.4 miles of the river, including a "strand" area along its banks (up to the mean high water mark), but owns only 31 acres within the corridor (Conference of the Upper Delaware Townships, 1986). While the Delaware's main stem remains free flowing, New York City has constructed three reservoirs on major tributaries (the East and West Branches of the Delaware River and the Neversink River) to provide drinking water for more than 17 million people. New York City gets the majority of its water—in fact, its best quality water—from these Catskill reservoirs.

The negligible public ownership, complex private ownership, and significant extraction of water for New York City require that the Upper Delaware be managed as a "Partnership River." The NPS, the Upper Delaware Council (*e.g.*, local jurisdictions), the Delaware River Basin Commission (DRBC, which manages the water releases), the Commonwealth of Pennsylvania, and the State of New York collaborated in preparing the River Management Plan (Conference of the Upper Delaware Townships, 1986) and collaborate in managing the river.

The goals described in the River Management Plan include maintaining or improving water quality and aquatic ecosystems, providing opportunities for recreation, and maintaining scenic values of river corridor and selected historic sites. The rights of private land owners are described in great detail and heavily emphasized throughout the plan, while management actions essential to maintain ecosystem services are more generalized.

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[31] **Delaware River Basin Commission**, 2007: Wild and Scenic Rivers map. Delaware River Basin Commission Website, http://www.state.nj.us/drbc/wild_scenic_map.htm, accessed on 7-20-2007.

The Upper Delaware was chosen as a case study because it exemplifies river ecology for the northeast and management challenges typical of the region, including a significant human population, intense water extraction for enormous urban centers, and its status as a "Partnership River."

A4.3.1 Current Stressors of Ecosystems and Management Methods Used to Address Them

The primary ecosystem stressors in the Upper Delaware include water extraction and unnatural flow regimes associated with reservoir management. Water quality, water temperature, fish and other river biota are negatively affected by these stressors (Mid-Atlantic Regional Assessment Team, 2000). In 2004 to 2006 unusually frequent and severe flooding—three separate hundred-year flood events in a 22-month period—further stressed the river system and added to the management challenges.[32]

Water managers in the Delaware Basin are addressing at least four priority issues: (1) provision of drinking water for major metropolitan areas, (2) flood control, (3) biotic integrity and natural processes of the WSR, and (4) recreation activities, including coldwater fisheries. New York City takes about half of the water available in the Upper Delaware River Basin above the designated WSR. Hence, the primary mechanism remaining to manage the flow regime, water quality, and river ecology and processes in the WSR is dam management, and the secondary mechanism is improved surface water management throughout the Upper Basin. Considering the volume of water extracted, water released from the reservoirs is, overall, significantly below historic flows. Furthermore, while goals for *annual* average releases are met, they do not always conform to the periodicity that stream biologists and anglers say are required for native species and ecological processes. When too little water is released, particularly in the spring and summer, water temperature increases beyond optimal conditions for many species, and pollutants are more concentrated. Aquatic invertebrates decline, trout and other species up the food chain are negatively affected and tourism based on river boating and anglers suffers (Parasiewicz, undated).

Water is also released from the Upper Delaware reservoirs to help maintain river levels adequate to prevent saltwater intrusion from Delaware Bay up river. During droughts in the past 50 years, the "salt front" has moved up river considerably. This intrusion may play a role in the conversion of upland forest areas to marshes, which could affect adjacent river ecosystems.[33] The saltwater is problematic for industries using water along the river front and increases sodium in the aquifer that supplies water to Southern New Jersey. Water conservation in the Delaware Basin and New York City has significantly helped address drought-related water shortages.

[32] **Delaware River Basin Commission**, 2006: *Water Resource Program FY2006 – FY 2012*. Available at http://www.state.nj.us/drbc/WRP2006-12.pdf. Delaware River Basin Commission, pp.1-9.
[33] **Partnership for the Delaware Estuary**, 2007: Partnership for the Delaware Estuary, a National Estuary Program homepage. Partnership for the Delaware Estuary Website, http://www.delawareestuary.org/, accessed on 7-12-2007.

Flood control and water quality in the Upper Basin are managed through restoration of stream banks, riparian buffers and floodplain ecosystems and through improved land and water management. The DRBC sets specific objectives for ecosystem management in the basin (Delaware River Basin Commission, 2004). Land use along the river is regulated by Township (PA) and Town (NY) zoning regulations, which are influenced by state regulations and requirements to qualify for FEMA flood insurance. The NPS and other partners work with the towns and townships to promote, through planning and zoning, maintenance of native vegetation in the floodplain and river corridor and to improve stormwater management throughout the watershed.

The NPS and state agencies also manage river recreation, providing access to boaters and hikers and regulating their impacts. Following recent floods, agencies assisted with evacuation of residents in low-lying flood-prone areas; evacuated their own boats, vehicles, and equipment to higher ground; and mobilized post-flood boat patrols to identify hazardous materials (*e.g.,* propane tanks, etc.) left in the floodway and hazards to navigation in the river channel.

NPS and others are beginning to work more closely with the National Weather Service to provide them with data on local precipitation amounts, snowpack, and river ice cover, and to coordinate with their Advanced Hydrologic Prediction Service to enable better forecasting and advanced warning to valley residents of flood crests and times.

A4.3.2 Potential Effects of Climate Change on Ecosystems

Climate in the Delaware Basin can be highly variable, sometimes bringing severe winter ice storms and summer heat-waves. However, there has been a steady increase in mean temperature over the last 50 years as well as an increase in precipitation (Lins and Slack, 1999; Rogers and McCarty, 2000; Najjar *et al.*, 2000). The expectations are for this pattern to continue and, in particular, for there to be the potential for less snowpack that melts earlier in the spring, and rain in the form of more intense rain events that may create greater fluctuations in river levels and greater floods. Severe flood events will likely continue to disrupt the river channel and impact floodplain ecosystems. Furthermore, during periodic droughts there will be increased potential for combinations of shallower water and warmer temperatures, leading to significantly warmer water that cold be especially damaging to coldwater invertebrates and fish. It is possible that dam management could offset this warming if water can be drawn from sufficient depths in the reservoir (*e.g.*, with a temperature control device on the dam).

As with any river system, such climate-induced changes in environmental conditions may have serious ecological consequences, including erosion of streambanks and bottom sediments that may decrease the availability of suitable habitat, shifts in the growth rate of species due to thermal and flood-related stresses, and unpredictable changes in ecological processes such as carbon and nitrogen processing (see section 6.4.3 in the Wild and Scenic Rivers chapter).

A4.3.3 Potential for Altering or Supplementing Current Management to Enable Adaptation for Climate Change

Management of the reservoir levels and dam releases are the most direct methods to maintain riverine ecosystems under increased burdens of climate change. The DRBC Water Resource Program report for 2006–2012[32] identifies the current water management issues for the Basin and their program to address the challenges, including a river flow management program to ensure human and ecosystem needs.[32] A major thrust of the Commission's program is research and modeling to help find a balanced approach to managing the limited water resources. This approach of establishing flow regime based on sound scientific data, with models and projects extended over decades will serve well in a future impacted by climate change.

Improved watershed management to reduce aberrant flood events and minimize water pollution is one of the most useful long-term tools for managing river resources in a changing climate (Mid-Atlantic Regional Assessment Team, 2000). Federal, state and local authorities can create incentives and pass ordinances to encourage better water and land use that protect the river and its resources. For example, improved efficiency of water use and stormwater management (*e.g.*, household rain barrels and rain gardens, holding ponds), improved use of agrochemicals and soil management, and restoration of wetlands and riparian buffers would combine to reduce severity of floods, erosion damage and water pollution.

Finally, continual improvements in municipal and household water conservation are among the most promising approaches to manage water in the Delaware River Basin. Populations in and around the Delaware Basin will grow, increasing demand on water supplies and river access for recreational uses. Per capita water use in New York City has declined from more than 200 gallons per capita per day around 1990 to 138 gallons per capita per day in 2006.[34] Water pricing can be use to promote further conservation (Mid-Atlantic Regional Assessment Team, 2000). An important component of this approach is educating the public so that consumers better understand the important role that water conservation plays in protecting river ecosystems and future water supplies.

A5 National Estuaries Case Study

A5.1 The Albemarle-Pamlico Estuarine System

A5.1.1 Introduction

We chose the Albemarle-Pamlico Estuarine System (APES) for our case study. APES provides a range of ecosystem services, extending over a diversity of ecosystem types, which provide the basis for the management goals of the Albemarle-Pamlico National Estuary Program (APNEP). Like other estuaries, the ecosystem services of APES are climate sensitive, and this sensitivity affects the ability to meet management goals. A range of adaptation options exist for climate-sensitive management goals. Many of these

[34] **New York City Department of Environmental Protection**, 2006: Water Conservation Program. pp.1-54.

adaptation options are applicable across estuarine ecosystems generally. Furthermore, because APNEP represents one of the first national estuaries, documentation of management successes and failures (Korfmacher, 1998; Korfmacher, 2002) exists for its 20-year history. Extensive data and decision support information are available for the system and are likely to continue to be gathered into the future. We highlight a few key climate-related issues in this case study, including warming and altered precipitation patterns, but especially accelerated sea level rise and increased frequency of intense storms.

The rationale for selecting the APES for the in-depth case study is based upon several unique characteristics of this system in addition to the scope of its management challenges related to climate change. First, the shores of the Albemarle and Pamlico Sounds are so gradually sloped that this system possesses more low-lying land within 1.5 m of sea level than any other national estuary. Within the United States, wetlands and coastal lands inundated by sea level rise will be exceeded only on the Louisiana coast of the Mississippi River delta and the Everglades region of South Florida (Titus, 2000; U.S. Climate Change Science Program, 2007). Thus, the incentives here for management adaptation are high. Second, the State of North Carolina passed a Fisheries Reform Act in 1997, which mandated development of a Coastal Habitat Protection Plan (CHPP) for fisheries enhancement. This plan at the state level represents a working example of ecosystem-based management because it engages all the diverse and usually independent state agencies whose mandates involve aspects of the environment that affect fish and their habitat. Consequently, there exists a model opportunity for integrating climate change into an ecosystem-based plan for management adaptation. Third, the Albemarle-Pamlico Sound system faces the daunting management challenges associated with projected disintegration of the protective coastal barrier of the Outer Banks of North Carolina (Riggs and Ames, 2003). As a result, the general problem of responding to erosion risk on coastal barriers is of higher urgency here because what is estuary now could become converted to an oceanic bay if the integrity of the banks is breached.

A5.1.2 Historical Context

Like many important estuaries, the Albemarle-Pamlico ecosystem has experienced a long history of human-induced changes including species depletion, habitat loss, water quality degradation, and species invasion (Lotze *et al.*, 2006). About 800 years ago, indigenous Native Americans initiated agriculture in the basin, and approximately 400 years ago Europeans began to colonize and transform the land. Since then, the human population around the estuary has increased by two orders of magnitude from that in 1700 (Lotze *et al.*, 2006). Before European colonization, North Carolina had about 11 million acres of wetlands, of which only 5.7 million remain today. About one-third of the wetland conversion, mostly to managed forests and agriculture, has occurred since the 1950s.[35] Since 1850, the amount of cropland has increased 3.5-fold. More recent land use patterns show that 20% of the basin area consists of agricultural lands, 60% is forested, and relatively little is urbanized (Stanley, 1992). Over the last three decades, the production

[35] **U.S. Geological Survey**, 1999: National water summary on wetland resources: state summary highlights. USGS, http://water.usgs.gov/nwsum/WSP2425/state_highlights_summary.html, accessed on 3-23-2007.

of swine has tripled and the area of fertilized cropland has almost doubled (Cooper *et al.*, 2004). These changes in land-use patterns and increases in point and non-point nutrient loading have induced multiple changes in water quality, with the greatest changes appearing during the last 50–60 years (Cooper *et al.*, 2004).

Over the last two to three centuries in the Albemarle and Pamlico Sounds, overexploitation, habitat loss, and pollution have resulted in the depletion and loss of many marine species that historically have been of economic or ecological importance (Lotze *et al.*, 2006). Of the 44 marine mammals, birds, reptiles, fish, invertebrates, and plants for which sufficient time series information exists, 24 became depleted (<50% of former abundance), 19 became rare (<90%), and 1 became regionally extinct by 2000 (Lotze *et al.*, 2006). Great losses also occurred among the subtidal bottom habitats. Historical accounts from the late 1800s indicate that bays and waterways near the mainland once had extensive beds of seagrass, while today seagrass is limited to the landward side of the barrier islands (Mallin *et al.*, 2000). Oyster reef acreage has been diminished over the last 100 years as a consequence of overharvesting, habitat disturbance, pollution, and most recently Dermo (*Perkinsus marinus*) infections.[36]

A5.1.3 Geomorphological and Land Use Contexts and Climate Change

Climate change impacts on APES may take numerous forms. Warming in and of itself can alter community and trophic structure through differential species-dependent metabolic, phenological, and behavioral responses. Changes in precipitation patterns also may have species-specific consequences. In combination, warming and precipitation patterns affect evapotranspiration, soil moisture, groundwater use and recharge, and river flow patterns. The current rate of relative rise in mean sea level in this geographic region is among the highest for the Atlantic coast, with estimates commonly over 3 mm per year and in at least one study as high as 4.27 mm per year (Zervas, 2001). The anticipated scenario of increasing frequency of intense storms in combination with rising sea levels creates a likelihood of dramatic physical and biological changes in ecosystem state for APES because the very integrity of the Outer Banks that create the protected estuaries behind them is at risk (Riggs and Ames, 2003; Paerl *et al.*, 2006).

APES is a large and important complex of rivers, tributary estuaries, extensive wetlands, coastal lagoons and barrier islands. Its 73,445 km^2 watershed (Stanley, 1992) is mostly in North Carolina but extends into southern Virginia (Fig. A5.1). The largest water body is Pamlico Sound to the southeast, with two major tributaries, the Neuse and the Tar-Pamlico Rivers. Both rivers empty into drowned river estuaries, the Neuse River Estuary (NRE) and the Pamlico River Estuary (PRE), which connect to Pamlico Sound. Albemarle Sound is farther north with two major tributaries, the Chowan and the Roanoke Rivers, and a number of local tributary estuaries. Other smaller sounds connect the Albemarle and the Pamlico (Roanoke and Croatan Sounds), and the Currituck Sound extends along the northeastern portion of the complex.

[36] **North Carolina Department of Environmental and Natural Resources**, 2006: Stock status of important coastal fisheries in North Carolina. North Carolina Department of Environmental and Natural Resources, North Carolina Department of Environmental and Natural Resources, Division of Marine fisheries, http://www.ncfisheries.net/stocks/index.html, accessed on 3-23-2007.

Figure A5.1. The Albemarle-Pamlico National Estuary Program region.[37]

The geological framework for coastal North Carolina, including APES has recently been summarized by Riggs and Ames (2003). The system represents several drowned river valley estuaries that coalesce into its large coastal lagoon (Fig. A5.1). The coastal plane, estuaries and sounds have a very gentle slope in which Quarternary sediments are underlain largely by Pliocene sediments. Much of this sediment is organic rich mud arising from eroding peat of swamps and marshes (Riggs, 1996). The gentle slope has allowed major shifts in position of the shoreline and barrier islands as sea level has risen and fallen. Furthermore, the position and number of inlets has changed along the barrier islands, promoting or limiting the exchange of fresh and seawater.

Much of the watershed is within the coastal plain with low elevations that affect land use. Moorhead and Brinson (1995) estimate that 56% of the peninsula between the Albemarle Sound and PRE is less than 1.5 m in elevation. Fifty-three percent of the peninsula's area is composed of wetlands, and 90% contains hydric soils. Thus, this region of the watershed is sparsely populated and largely rural. In contrast, other regions are more highly developed. The barrier islands, the famous "Outer Banks" of North Carolina, are a mosaic of highly developed lands for tourism and protected natural areas. The southeastern portion of Virginia in the APES basin is highly urbanized, and the piedmont origins of the Neuse and Tar Rivers in North Carolina are highly populated. Agriculture and silvaculture are important land uses and economic drivers in the region. Urban economies dominate much of southeastern Virginia. And a relatively new trend is the development of high-end and retirement subdivisions along the "Inner Banks," the mainland shore zone of the complex. The watershed's population exceeds 3,000,000 people including Virginia. However, only about 25% are found in coastal counties of North Carolina, based on estimates for 2000.[38] A significant portion of this population is considered "vulnerable" to strong storms and thus faces risks from climate change (*i.e.*, people who live in evacuation zones for storm surge or who are subject to risks from high winds by living in mobile homes). The low-lying lands and basic nature of services and infrastructure of the rural environment pose growing risks of flood damage as sea level and storm intensities rise to land uses, infrastructure (*e.g.*, water delivery from aquifers, waste water treatment facilities, roads, and buildings) and even human lives.

Another characteristic of the system's geomorphology makes it uniquely susceptible to climate change drivers. The exchange of water between the ocean and the sounds is restricted by the few and small inlets that separate the long, thin barrier islands (Giese,

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[37] **Albemarle-Pamlico National Estuary Program**, 2007: Albemarle-Pamlico Sounds region. Albemarle-Pamlico National Estuary Program Website, http://www.apnep.org/pages/regions.html, accessed on 7-25-2007.

[38] **Federal Emergency Management Agency**, 2007: Chapter 01 - description of study area. Comprehensive Hurricane Data Preparedness, FEMA Study Web Site, http://chps.sam.usace.army.mil/USHESDATA/NC/Data/chapter1/chapter01_description.html, accessed on 3-23-2007.

Wilder, and Parker, 1985; Riggs and Ames, 2003). This restricted connectivity greatly dampens amplitude of astronomical tides and limits the degree to which seawater is mixed with freshwater. Temperature increases may have significant impacts on the APES because its shallow bays have limited exchange with ocean waters, which serve as a cooling influence in summer.

Water quality has been a recurring management concern for APES and APNEP. The tributary rivers generally have high concentrations of dissolved nutrients. This fosters high primary productivity in tributary estuaries, but under most circumstances nutrient concentrations in the sounds remain relatively low (Peierls, Christian, and Paerl, 2003; Piehler *et al.*, 2004). Most nutrient loading derives from non-point sources, although nitrogen loading from point sources may account for up to 60–70% in summer months (Steel and Carolina, 1991). Nitrogen deposition from the atmosphere may account for an additional 15–32% (Paerl, H.W., Dennis, and Whitall, 2002). Phosphorus loading to the Pamlico River Estuary was greatly enhanced by phosphate mining, which accounts for about half of the total point source phosphorus loadings to this estuary and officially began in 1964 (Copeland and Hobbie, 1972; Stanley, 1992). Loading has decreased dramatically in recent years as treatment of mine wastes has improved. High surface sediment concentrations of the toxic heavy metals arsenic, chromium, copper, nickel, and lead are found in the Neuse River Estuary, possibly associated with industrial and military operations, while high cadmium and silver levels in PRE most likely result from phosphate mining discharges (Cooper *et al.*, 2004). In 1960, hypoxia was first reported in the Pamlico River Estuary (Hobbie, Copeland, and Harrison, 1975). Since then, hypoxic and anoxic waters in the PRE and NRE were mostly of short duration (days to weeks) but have resulted in death of benthic invertebrates on the bottom and fish kills (Stanley and Nixon, 1992; Buzzelli *et al.*, 2002; Cooper *et al.*, 2004). Nuisance and toxic algal blooms are reported periodically (Burkholder *et al.*, 1992; Bricker *et al.*, 1999), and about 22 aquatic plants and 116 aquatic animals, of which 22 occur in marine or marine-freshwater habitats, have been identified as non-indigenous species in North Carolina.[39] Increases in temperatures are expected to enhance hypoxia and its negative consequences, through the combined effects of increased metabolism and, to a lesser degree, decreased oxygen solubility.

The interactions between relative sea level rise, shoreline morphology, and bay ravinement could have significant impacts on estuarine water quality and ecosystem function in the APES. Losses of wetlands to inundation could lead to a large shift in function from being a nitrogen sink to being a nitrogen source. Both planktonic and benthic primary producers may be affected by, and mediate, changes in water quality, nutrient and material fluxes across the sediment-water interface that may result from sea level rise (Fig. A5.2). Changes in the water column productivity affect particle composition and concentration, which in turn increases turbidity and feedback to modify further the balance between water column and benthic productivity. Inundated sediments will then be subject to typical estuarine stressors (*e.g.*, salinity, changes in water table, isolation from atmosphere) that can lead to dissolution of particulates, desorption of

[39] **U.S. Geological Survey**, 2005: Nonindigenous aquatic species search page. U.S. Geological Survey, http://nas.er.usgs.gov/queries/default.asp, accessed on 4-9-2007.

nutrients or organic matter, and altered redox states. These changes result in fluxes of nutrients and DOC that could radically transform the proportion of productivity and heterotrophic activity in the water above the sediment and in the rest of the estuary. Nutrient management plans generally assume that the frequency and magnitude of bottom water hypoxia will decrease by reducing watershed inputs of dissolved inorganic nitrogen and organic matter that either indirectly or directly fuel water column and benthic respiration (Kemp *et al.*, 1992; Conley *et al.*, 2002). However, factors such as the nutrient and sediment filtration capacity of wetlands under flooded conditions of higher sea levels, and the potential for a large organic matter input from erosion and disintegration of now inundated wetlands, create uncertainty about progress in containing eutrophication across different scales and render the determination of management targets and forecasting of hypoxia extremely difficult.

Figure A5.2. Feedbacks between nutrient and sediment exchange and primary production in the benthos and water column. A plus symbol indicates enhancement and a minus symbol suppression.

Because of the large fetch of the major sounds and tributary estuaries, wind tides control water levels and wave energy can be quite high. Wind tides can lead to extended flooding and high erosion rates, especially within the eastern and southern parts of the complex (Brinson, 1991; Riggs and Ames, 2003). Furthermore, the barrier islands are prone to breaching during storms, and geological history demonstrates the fragility of this thin strip of sand and reveals the locations of highest risk of breaching. Formation of persistent inlets within the barrier islands would increase oceanic exchange and thereby the amplitude of astronomical tides. This, in turn, could profoundly alter the ecology of both aquatic and wetland ecosystems in the APES.

The size, geomorphology, and location of the APES complex make it an important source of ecosystem services for the region and the nation. The largest economic contribution of APES today derives from tourism and recreation. The Outer Banks attract people from around the world. Populations during the prime summer season considerably exceed winter populations. The Outer Banks include the most economically important acreage of the complex along with ecologically important natural areas. These coastal barriers are also the most sensitive to the combination of sea level rise and increased frequency of intense storms. Barrier island geomorphology is constantly changing on short and long time scales, increasing and decreasing in width with sand movement and both forming and closing inlets during storms. Inlets have broken through the Outer Banks repeatedly over the past century and paleo records from the past few thousand years demonstrate dramatic movements in location and character of the barriers as sea level has changed (Riggs and Ames, 2003). But human structures on the islands and human uses of the barrier islands' natural resources have now changed the degree to which natural geological processes occur. Construction and maintenance of Route 12 along the Outer Banks has restricted washover and the movement of sand from the seaward side of the islands to the sound side. Furthermore, the presence of houses, condominiums, hotels, etc. produces conflicts between maintaining the natural geomorphic processes that allow island migration landwards as sea level rises and protecting human infrastructure. Rising sea level and increased frequency of intense storms enhances the potential beach erosion, thereby increasing costs of beach nourishment, and increases risk of island disintegration, leading to increased political pressure to legalize hard structures on the ocean shoreline.

Beaches are a major natural resource and drive many coastal economies. Because the presence of houses, condominiums, and roads and other infrastructure leads to defense of the shoreline position and prevents natural recession, beach erosion now reduces beach widths as sea level is rising. North Carolina prohibits hard structures (*e.g.*, bulkheads, jetties, and permanent sand bags) on the ocean shoreline. Instead, erosion is countered by beach nourishment, in which sand is dredged from offshore. This is a temporary and expensive solution. It also has potentially significant impacts on the living resources of the beach, such as shorebirds and resident invertebrates (Peterson and Bishop, 2005; Peterson *et al.*, 2006). Erosion of beaches tends to occur with the major axis parallel to the islands (*i.e.*, meters or tens of meters of erosion of beach along hundreds to thousands of meters along the beach face). Breaching of new inlets and overwash events penetrate more into the islands. A recent breach occurred on Hatteras Island during Hurricane Isabel, but it was quickly closed by the U.S. Army Corps of Engineers to permit road reconstruction and automobile travel along the Outer Banks. Riggs and Ames (2003) have projected that under higher stands of sea level, future hurricanes may create numerous large, new inlets and break the chain of coastal barriers that forms the eastern edge of the entire APES system. They mapped locations of the paleochannels along the islands and identified these as the most likely locations for such breaches. Such events represent the most dramatic consequences of climate change to APES. Extensive new inlets would lead to an entirely new tidal, salinity, wave, and hydrodynamic regime within APES, and in turn drastically change the ecology of the complex. Wise management for the future must include preparation for the possibility of events such as these and their consequences.

Natural areas in APES have been recognized for their significance as wildlife habitat, nurseries for aquatic species, stop-over sites (flyways) for migratory birds, and important spawning areas for anadromous fish. Recreational fishing and boating add to the attraction of the beaches, barrier islands, and natural areas within the watershed. The nursery services of the complex are also important to fisheries, both locally and along the entire eastern coast of the United States. Cape Hatteras sits at the biogeographic convergence of populations of northern and southern species, and many of these species use the sounds during their life cycles. Thus, the location of APES makes it particularly sensitive to any climate-related changes that alter migratory patterns of both birds and marine organisms.

The wetlands of the Albemarle Pamlico Sound complex are largely non-tidal and subject to irregular wind tides, as described above. In freshwater regions along the rivers and flood plains, swamp forests dominate. Pocosins—peat-forming ombrotrophic wetlands—are found in interstream divides. As sea level rises in oligohaline regions, swamp forests may continue to dominate or be replaced by brackish marshes. Irregularly flooded marshes, dominated by *Juncus roemerianus*, extend over much of the higher-salinity areas. Back barrier island marshes are dominated by *Spartina alterniflora*. The ability of these wetlands to respond to sea level rise is becoming compromised by increased human infrastructure. Roads, residential and urban developments, hard structures for shoreline stabilization, and agricultural ditching are preventing horizontal transgression of wetlands and promoting erosion of edges throughout the complex. Furthermore, development of the barrier islands has prevented natural overwash and inlet-forming processes that promote salt marsh development (Christian *et al.*, 2000; Riggs and Ames, 2003).

A5.1.4 Current Management Issues and Climate Change

The APES became part of the NEP (APNEP) in 1987. Initial programmatic efforts focused on assessments of the condition of the system through the Albemarle-Pamlico Estuarine Study. The results of these efforts were used in the stakeholder-based development of a Comprehensive Conservation and Management Plan (CCMP) in 1994. The CCMP presented objectives for plans in five areas: water quality, vital habitats, fisheries, stewardship, and implementation (Box A5.1).[40] For each objective, issues of concern were identified and management actions proposed. None of the issues or proposed actions explicitly included climate change. In 2005, NEP Headquarters conducted its most recent triennial implementation review of APNEP. APNEP passed the implementation review and was found eligible for funding through FY 2008.

Although no management objective explicitly identifies climate change or its consequences, water quality, vital habitats, and fisheries are likely to be substantially affected by changes in climate. Recent efforts by APNEP and the State of North Carolina led to more direct consideration of the impacts of climate change. APNEP has identified indicators of condition of the system and begun the process for implementing their use. Multiple indicators assess condition of atmosphere, land, wetland, aquatic, and human components of the system. While some indicators focus on short-term changes in these components, many have meaning only in their long-term trends. Given a changing climate and associated impacts, these indicators place APNEP in position to assess these impacts for wise management. On a broader front, the legislature of North Carolina in 2006 established a commission on climate change to assess how climate change will affect the state and to propose actions to either minimize impacts or take advantage of them.

In 1987 North Carolina passed the Fisheries Reform Act, requiring both development of formal species management plans for each commercially and/or recreationally harvested fishery stock and the development of a CHPP. The CHPP development and implementation process resembles an EBM at the state level because it requires consideration and integrated management of all factors that affect the quality of fish habitats in a synthetic, integrative fashion. To achieve this goal, staff from all appropriate state resource and environmental commissions came together to map coordinated approaches to achieve sustainability of habitat quantity and quality for fishery resources.

[40] **Albemarle-Pamlico National Estuary Program**, 1994: Albemarle-Pamlico NEP Comprehensive Conservation and Management Plan.

This partnership among agencies, while only at the state level, addresses one of the biggest goals of EBM (Peterson and Estes, 2001). Commissions and agencies responsible for fisheries management (Marine Fisheries Commission), water quality and wetlands (Environmental Management Commission), and coastal development (Coastal Resources Commission) are the major entities, but the Sedimentation Control Commission and Wildlife Resources Commission also contribute. The CHPP does contemplate several aspects of climate change and human responses to threats such as beach and shoreline erosion, although long-term solutions are elusive. Now that a plan exists, the implementation of its short-term goals has yet to begin and may become contentious.

Other innovative programs and initiatives within North Carolina are the Ecosystem Enhancement Program (EEP), Clean Water Management Trust Fund (CWMTF), and the designation of estuaries as nutrient sensitive. EEP is an agency that coordinates wetland mitigation efforts to maximize their effectiveness. The North Carolina Department of Transportation's mitigation needs are largely met through EEP. The program uses a watershed approach in planning mitigation projects. This allows a broad and comprehensive perspective that should be reconciled with climate change expectations. The CWMTF provides financial support for activities that improve or protect water quality. It offers an opportunity to link consideration of climate change to such activities, although no such link has been an explicit consideration. The designation of nutrient sensitivity allows enhanced controls on nutrient additions and total maximum daily loadings to the Neuse and Tar-Pamlico systems. In fact, regulations have been designed to not only curb expansion of nutrient enrichment but to roll it back with restrictions to both point- and non-point sources.

A5.1.5 Recommendations for Environmental Management in the Face of Climate Change

We make three overarching recommendations for management of estuaries in the face of climate change: (1) maintain an appropriate environmental observing system; (2) educate a variety of audiences on long-term consequences; and (3) pursue adaptation and adaptive management. Each of these is described specifically for APES but has application to other estuaries in whole or part. Furthermore, each involves coordination of multiple initiatives and programs. It is this coordination that should be a major focus of APNEP in particular and NEP in general.

An appropriate observing system involves a network of programs that detects, attributes and predicts change at multiple scales. It includes sustained monitoring, data and information management, predictive model production, and communication of these products to users. The users include environmental managers, policy makers, and members of the public over a range of economic positions and status. Regulatory and policy needs require a variety of measurements to be made in a sustained way. These measurements extend to variables of physical, chemical, biological, and socioeconomic attributes of APES. Many have been identified by APNEP with its indicator program. These measurements must be made to respond to drivers at different time scales; while these time scales include short-term variation, the most important to this report are long-term trends and infrequent but intense disturbances.

There are other observing system initiatives within coastal North Carolina. These include the North Carolina Coastal Ocean Observing System and Coastal Ocean Research and Monitoring Program. Both have their emphases on the coastal ocean and near real-time products of physical conditions. However, their efforts need to be more directed toward the APES and other estuarine ecosystems to be more valuable to the people of North Carolina. More effort is needed to assess and understand the physical dynamics of the estuarine systems. Observations and analyses should be extended to characterize the physical and geochemical processes of catchment and riverine inflows, which are likely to change dramatically under changing climatic conditions. The systems also need to broaden their observations to include ecological and socioeconomic measurements. These measurements are less likely to be near real-time, but user needs do not require such quick reporting. We recommend that the coastal observing systems be linked explicitly to APNEP indicator activities.

Education is needed across the spectrum of society to produce informed stakeholders and thus facilitate enlightened management adaptations. The need for K–12 education on climate change is obvious, but there is also a lack of general understanding among adults. Education efforts are needed for the general public, policy makers, and even environmental managers. North Carolina has several significant programs that can promote this general understanding. APNEP and the Commission on Climate Change have been mentioned above. Public television and radio have a general mission to educate and have contributed time to the topic. Two other programs are (1) the Partnership for the Sounds, including the Estuarium in Washington, North Carolina, and (2) the North Carolina Aquariums. The latter includes three aquaria along the coast. These programs are in a unique position to teach the general public about climate change. We recommend that coordination among these different programs be fostered to promote education within the state.

Finally, adaptive management and adaptation strategies are essential to respond to the complex implications of climate change. Adaptive management recognizes the need for both sustained monitoring associated with observing systems and adaptive justification of intervention plans that reflect advances in our understanding of impacts of climate change and new insights on what experimental interventions are needed. Adaptive management also recognizes the important role of education that promotes better appreciation of a changing and uncertain world. Adaptive management is explicit within APNEP, CHPP, and EEP. It also is incorporated into controls on nutrient additions to alleviate the impacts of cultural eutrophication. It acknowledges the importance of the ecosystem perspective and breaks the regulatory mold of being specific to an issue, species, single source of pollution, etc. This enhances the ability to meet the challenges of climate change. One aspect of this change is the expectation that landscape units that are controlled by sea level will migrate. Beaches and wetlands will move shoreward. Regulations and policies that foster the ability to retreat from these landscape migrations are part of this adaptive approach. Adaptive management is an established approach in North Carolina, which can serve as a successful example nationally.

A5.1.6 Barriers and Opportunities

APNEP possesses environmental and social barriers to effective implementation of management adaptation to climate change, yet at the same time various social and environmental characteristics represent favorable opportunities for adaptation. Indeed, APNEP was chosen for a case study because it could illustrate both significant barriers and opportunities. Perhaps its greatest single barrier to successful adaptation to climate change is the intractable nature of the challenge of preserving the integrity of the coastal barrier complex of the Outer Banks over the long time scales of a century and longer. These coastal barriers are responsible for creating the APNEP estuarine system, and a major breach in the integrity would ultimately convert the estuary into a coastal ocean embayment (Riggs and Ames, 2003). Current management employs beach nourishment to fortify the barrier, but this method will become increasingly expensive as sea level rises substantially, and thus would be politically infeasible. Construction of a seawall along the entire extent of the barrier complex also does not appear to be a viable option because of financial costs and loss of the beach that defines and enriches the Outer Banks.

Special opportunities for implementation of adaptive management in APNEP include the existence of the CHPP process, a legislatively mandated ecosystem-based management plan for preserving and enhancing coastal fisheries. This plan involves collaborative attentions by all necessary state agencies and thereby can overcome the historic constraints of compartmentalization of management authorities. This plan sets an admirable example for other states. Similarly, the novel state commission on effects of climate change that was legislated in 2005 also provides opportunity for education and participation of legislators in a process of looking forward, well beyond the usual time frames of politics, to serve as an example of proactivity for other states to emulate. Sparse human populations and low levels of development along much of the interior mainland shoreline of the APNEP complex provide opportunities for implementation of policies that protect the ability of the salt marsh and other shallow-water estuarine habitats to be allowed to retreat as sea level rises. Implementing the policies required to achieve this management adaptation would not be possible in places where development and infrastructure are so dense that the economic and social costs of shoreline retreat are high. Special funding to support purchase of rolling easements or other implementation methods can come from the Clean Water Management Trust Fund and the Ecosystem Enhancement Program of North Carolina, two facilitators of large coordinated projects. The State of North Carolina was among the first to establish basin-scale water quality management and has established novel methods of basin-wide capping of nutrient delivery to estuaries, such the NRE, involving ecosystem-based management through participation of all stakeholders. This too facilitates actions required to manage consequences of climate change to preserve management goals of a national estuary.

A6 Marine Protected Area Case Studies

This section includes three U.S. case studies along with an Australian case study for comparison. This report focuses on U.S. federally managed lands and waters to frame the question of adaptation, the goal is to review all types of adaptation options including those developed by non-governmental organizations and internationally that may be implemented to benefit U.S. resources. With regard to climate change impacts and adaptation, coral reefs are the best studied marine system. Because the Great Barrier Reef Marine Park (GBRMP) in Australia is an international leader in addressing climate change impacts to coral reefs, a case study of how this issue is being addressed there is of great value for examining adaptation options that may be transferable to U.S. coral reefs and other U.S. marine systems. Each case study discusses existing management approaches, threats of climate change, and adaptation options. The case studies are located in Florida (Florida Keys National Marine Sanctuary (FKNMS)), Australia (GBRMP), Hawaii (Papahānaumokuākea Marine National Monument (PMNM)), and California (Channel Islands National Marine Sanctuary (CINMS)). These MPAs range in size, species composition, and levels of protection; no-take designations, for example, are 6% (FKNMS), 10% (CINMS), 33% (GBRMP), and 100% (PMNM).

A6.1 The Florida Keys National Marine Sanctuary

A6.1.1 Introduction

The Florida Keys are a limestone island archipelago extending southwest over 320 km from the southern tip of the Florida mainland (see Fig. 8.3 in the MPA chapter). The FKNMS surrounds the Florida Reef Tract, one of the world’s largest systems of coral reefs and the only bank-barrier reef in the coterminous United States. The FKNMS is bounded by and connected to Florida Bay, the Southwest Florida Continental Shelf, and the Straits of Florida and Atlantic Ocean. It is influenced by the powerful Loop Current/Florida Current/Gulf Stream system to the west and south, as well as a weaker southerly flow along the West Florida Shelf (Lee *et al.*, 2002). The combined Gulf of Mexico and tropical Atlantic biotic influences make the area one of the most diverse in North America.

The uniqueness of the marine environment and ready access from the mainland by a series of bridges and causeways draws millions of visitors to the Keys, including many from the heavily populated city of Miami and other metropolitan areas of South Florida. Also, in recent years Key West has become a major destination for cruise liners, attracting more than 500 stop-overs annually. The major industry in the Florida Keys has become tourism, including dive shops, charter fishing, and dive boats and marinas as well as hotels and restaurants. There also is an important commercial fishing industry.

National Marine Sanctuaries established at Key Largo in 1975 and Looe Key in 1981 demonstrated that measures to protect coral reefs from direct impacts could be successful using management actions such as mooring buoys, education programs, research and monitoring, restoration efforts, and proactive, interpretive law enforcement. In 1989, mounting threats to the health and ecological future of the coral reef ecosystem in the Florida Keys prompted Congress to take further protective steps. The threat of oil drilling in the mid- to late-1980s off the Florida Keys, combined with reports of deteriorating water quality throughout the region, occurred at the same time as adverse effects of coral bleaching,[41] the Caribbean-wide die-off of the long-spined urchin (Lessios, Robertson, and Cubit, 1984), loss of living coral cover on reefs (Porter and Meier, 1992), a major seagrass die-off (Robblee *et al.*, 1991), declines in reef fish populations (Bohnsack, Harper, and McClellan, 1994; Ault, Bohnsack, and Meester, 1998), and the spread of coral diseases (Kuta and Richardson, 1996). These were already topics of major scientific concern and the focus of several scientific workshops when, in the fall of 1989, three large ships ran aground on the Florida Reef Tract within a brief 18-day period. On November 16, 1990, President Bush signed into law the Florida Keys National Marine Sanctuary and Protection Act. Specific regulations to manage the sanctuary did not go into effect until July 1997, after the final management plan (U.S. Department of Commerce, 1996) had been approved by the Secretary of Commerce and the Governor and Cabinet of the State of Florida. The FKNMS encompasses approximately 9,800 km^2 of coastal and oceanic waters surrounding the Florida Keys (Keller and Causey, 2005) (see Fig. 8.3 in the MPA chapter), including the Florida Reef Tract, all of the mangrove islands of the Florida Keys, extensive seagrass beds and hard-bottom areas, and hundreds of shipwrecks.

Visitors spent $1.2 billion[42] over 12.1 million person-days[43] in the Florida Keys between June 2000 and May 2001. Over that period, visitors and residents spent 5.5 million of the person-days on natural and artificial reefs. Significantly, visitors (and residents) perceive significant declines in the quality of the marine environment of the Keys.[44]

A6.1.2 Specific Management Goals and Current Ecosystem Stressors Being Addressed

Goal and Objectives of the Florida Keys National Marine Sanctuary

The goal of the FKNMS is "To preserve and protect the physical and biological components of the South Florida estuarine and marine ecosystem to ensure its viability for the use and enjoyment of present and future generations" (U.S. Department of Commerce, 1996). The Florida Keys National Marine Sanctuary and Protection Act as well as the Sanctuary Advisory Council identified a number of objectives to achieve this goal (Box A6.1). FKNMS management was designed during the 1990s to address local stressors; the subsequent recognition of the significance of regional and global stressors requires that future planning efforts incorporate these larger-scale factors.

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[41] **Causey**, B.D., 2001: Lessons learned from the intensification of coral bleaching from 1980-2000 in the Florida Keys, USA. In: *Proceedings of the Workshop on Mitigating Coral Bleaching Impact Through MPA Design, Volume 102* [Salm, R.V. and S.L. Coles (eds.)]. Asia Pacific Coastal Marine Program Report #0102, Coral Bleaching and Marine Protected Areas Conference, Honolulu, Hawaii, pp. 60-66.

[42] **Leeworthy**, V.R. and P.C. Wiley, 2003: *Profiles and Economic Contribution: General Visitors to Monroe County, Florida 2000-2001*. National Oceanic and Atmospheric Administration, National Ocean Service, Office of Management and Budget, Special Projects Division, Silver Spring, MD, pp.1-24.

[43] **Johns**, G.M., V.R. Leeworthy, F.W. Bell, and M.A. Bonn, 2003: *Socioeconomic Study of Reefs in Southeast Florida*. Final Report October 19, 2001 as Revised April 18, 2003 for Broward County, Palm Beach County, Miami-Dade County, Monroe County, Florida Fish and Wildlife Conservation Commission, National Oceanic and Atmospheric Administration, Hollywood, FL.

[44] **Leeworthy**, V.R., P.C. Wiley, and J.D. Hospital, 2004: *Importance-Satisfaction Ratings Five-Year Comparison, SPA and ER Use, and Socioeconomic and Ecological Monitoring Comparison of Results 1995-96 to 2000-01*. National Oceanic and Atmospheric Administration, National Ocean Service, Office of Management and Budget, Special Projects Division, Silver Spring, MD, pp.1-59.

Coral Reef and Seagrass Protection

The management plan (U.S. Department of Commerce, 1996) established a channel and reef marking program that coordinated federal, state, and local efforts to mark channels and shallow reef areas. These markers help prevent damage from boat groundings and propeller-scarring.

A mooring buoy program is one of the most simple and effective management actions to protect sanctuary resources from direct impact by boat anchors. By installing mooring buoys in high-use areas, the sanctuary has prevented damage to coral from the thousands of anchors dropped every week in the Keys.

Marine Zoning

The management plan implemented marine zoning with five categories of zones. The relatively large "no-take" Ecological Reserve at Western Sambo (see Fig. 8.3 in the MPA chapter) was designed to help restore ecosystem structure and function. A second Ecological Reserve was implemented in the Tortugas region in 2001 as one of the largest no-take areas in U.S. waters (U.S. Department of Commerce, 2000; Cowie-Haskell and Delaney, 2003; Delaney, 2003). In addition to the larger Ecological Reserves, there are 18 small, no-take Sanctuary Preservation Areas (SPAs) that protect over 65% of shallow, spur and groove reef habitat. These areas displaced few commercial and recreational fishermen and resolved a user conflict with snorkeling and diving activities in the same shallow reef areas. Four small Research-Only Areas are also no-take; only scientists with permits are allowed access.

In addition, 27 Wildlife Management Areas (WMAs) were established to address human impacts to nearshore habitats such as seagrass flats and mangrove-fringed shorelines. Most of these WMAs only allow no-motorized access. Finally, because the FKNMS Act called for the two existing sanctuaries to be subsumed by the FKNMS, a final type of marine zone, called Existing Management Areas, was used to codify both Key Largo and Looe Key NMS regulations into FKNMS regulations. This was a way to maintain the additional protective resource measures that had been in effect for the Key Largo and Looe Key NMSs since 1975 and 1981, respectively. Those areas prohibited spearfishing, marine life collecting, fish trapping, trawling, and a number of other specific activities that posed threats to coral reef resources.

Improvement of Water Quality

The FKNMS Act directed the U.S. Environmental Protection Agency to work with the State of Florida and NOAA to develop a Water Quality Protection Program (WQPP) to address water quality problems and establish corrective actions. The WQPP consists of four interrelated components: 1) corrective actions that reduce water pollution directly by using engineering methods, prohibiting or restricting certain activities, tightening existing regulations, and increasing enforcement; 2) monitoring of water quality, seagrasses, and coral reefs to provide information about status and trends in the sanctuary; 3) research to identify and understand cause-and-effect relationships involving pollutants, transport pathways, and biological communities; and 4) public education and outreach programs to increase public awareness of the sanctuary, the WQPP, and pollution sources and impacts on sanctuary resources.

Research and Monitoring

The FKNMS management plan established a research and monitoring program that focused research on specific management needs. In 2000, staff convened a panel of external peers to review the sanctuary's science program and provide recommendations for improvements.[45] Based on the panel's recommendation that sanctuary managers identify priority research needs, staff prepared a Comprehensive Science Plan to identify priority research and monitoring needs explicitly linked to management objectives (Florida Keys National Marine Sanctuary, 2002).

The three monitoring projects of the WQPP[46] are developing baselines for water quality, seagrass distribution and abundance, and coral cover, diversity, and condition. Such a baseline of information is particularly important to have as the Comprehensive Everglades Restoration Plan (CERP)[47] is implemented just north of the FKNMS. The CERP is designed so that managers can be adaptive to ecological or hydrological changes that are taking place within or emanating from the Everglades, with possible positive or negative influences on communities in the FKNMS (Keller and Causey, 2005).

Additional monitoring comprises the Marine Zone Monitoring Program, which is designed to detect changes in populations, communities, and human dimensions resulting from no-take zoning (Keller and Donahue, 2006). Coupled with environmental monitoring using data buoys,[48] routine cruises,[49] remote sensing,[50] and paleoclimatic analyses of coral skeletons,[51] the FKNMS is a relatively data-rich environment for detecting presumptive climate change effects.

Education and Outreach

The management plan for the FKNMS includes an education and outreach program that lays out ways that education efforts can directly enhance the various programs to protect sanctuary resources. Public awareness and understanding are essential to achieve resource protection through cooperation and compliance with regulations.

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[45] **Florida Keys National Marine Sanctuary**, 2007: Year 2000 Florida Keys National Marine Sanctuary advisory panel meeting. NOAA Website, http://floridakeys.noaa.gov/research_monitoring/sap2000.html, accessed on 7-27-2007.

[46] **Fish and Wildlife Research Institute**, 2007: Florida Keys National Marine Sanctuary water quality protection program. Fish and Wildlife Research Institute Website, http://ocean.floridamarine.org/fknms_wqpp/, accessed on 7-27-0007.

[47] **U.S. Army Corps of Engineers**, 2007: Official website of the comprehensive Everglades restoration plan. Comprehensive Everglades Restoration Plan Website, http://www.evergladesplan.org/index.aspx, accessed on 5-23-2007.

[48] **National Oceanic and Atmospheric Administration**, 2006: NOAA's coral health and monitoring homepage. NOAA Website, http://www.coral.noaa.gov/seakeys/index.shtml, accessed on 7-27-2007.

[49] **National Oceanic and Atmospheric Administration**, 2007: NOAA's south Florida ecosystem research and monitoring program. NOAA Website, http://www.aoml.noaa.gov/sfp/data.shtml, accessed on 7-27-2007.

[50] **NOAA Coast Watch Program**, 2007: Harmful algae bloom bulletin home page. NOAA Website, Harmful Algae Bloom Bulletin, http://coastwatch.noaa.gov/hab/bulletins_ms.htm, accessed on 7-27-2007.

[51] **Eakin**, C.M., P.K. Swart, T.M. Quinn, K.P. Helmle, J.M. Smith, and R.E. Dodge, 2006: Application of paleoclimatology to coral reef monitoring and management. *Proceedings of the 10th International Coral Reef Symposium*, 588-596.

Regulations and Enforcement

The FKNMS management plan includes regulations that have helped managers protect resources of the sanctuary while having the least amount of impact on those who enjoy and utilize sanctuary resources in a conscientious way. In order to maximize existing enforcement programs, the management plan contains an enforcement plan that has served to help focus enforcement on priority problems within the sanctuary. The program also coordinates all the enforcement agencies in the Keys. Enforcement complements education and outreach in efforts to achieve compliance with regulations.

A6.1.3 Potential Effects of Climate Change on Management

Coral Bleaching

The potential effects of climate change on coral reefs are generally well known (*e.g.*, Smith and Buddemeier, 1992; Hoegh-Guldberg, 1999; Buddemeier, Kleypas, and Aronson, 2004; Hoegh-Guldberg, 2004; Sheppard, 2006), but the fate of individual reef systems such as the Florida Reef Tract will vary based on a combination of factors related to history, geography, and an understanding of processes that explain the patchiness of coral bleaching and subsequent mortality that occurs on reefs. Coral bleaching was first reported in the Florida Keys in 1973 (Jaap, 1979), with at least seven other episodes documented prior to 2000[41] and a major bleaching event in 2005 that also affected the Caribbean (Miller *et al.*, 2006; Donner, Knutson, and Oppenheimer, 2007). Unfortunately, before-during-and-after sampling has not been conducted during major bleaching events in the Florida Keys (but see Lang *et al.*, 1992 for during- and after-surveys at four sites), which makes assumptions about coral mortality caused by bleaching at best correlative. Hurricanes are an especially confounding factor when they occur during bleaching years, as they did in 1997–98 and 2005. Still, anecdotal evidence suggests that large numbers of corals were killed in 1997–98 when corals remained bleached for two consecutive years.[41] Long-term temperature records do not exist that reveal trends of increasing surface seawater temperature for the Florida Keys, but Williams, Jackson, and Kutzbach (2007), using climate models and IPCC greenhouse gas estimates to forecast how climate zones may change in the next 100 years, identified the southeastern United States as a region with the greatest likelihood of developing novel regional climate conditions that would be associated with temperature increases of several degrees. The consequences of such changes on coral reefs in Florida will be dramatic unless significant adaptation or acclimatization occurs.

Governments and agencies have responded to the crisis of coral bleaching with detailed management plans (Westmacott *et al.*, 2000; Marshall and Schuttenberg, 2006), workshops to develop strategies that support response efforts,[52] and research plans (Marshall and Schuttenberg, 2006; Puglise and Kelty, 2007). Two themes have emerged from these efforts. First, effort is needed at local and regional levels to identify and protect bleaching-resistant sites—if they exist. Second, management plans should be developed or modified in the case

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[52] **Salm**, R.V. and S.L. Coles, 2001: Coral bleaching and marine protected areas. In: *Proceedings of the Coral Bleaching and Marine Protected Areas, Volume 102* [Salm, R.V. and S.L. Coles (eds.)]. Asia Pacific Coastal Marine Program Report #0102. Workshop on Mitigating Coral Bleaching Impact Through MPA Design, Honolulu, Hawaii, pp. 1-118.

of the FKNMS to restore or enhance the natural resilience (Hughes *et al.*, 2003; West and Salm, 2003) of coral reefs.

Response plans to coral bleaching events depend upon increasingly accurate predictions to help guide resource assessment and monitoring programs, and the NOAA Coral Reef Watch program has increasingly accurate capability to predict the severity, timing, and geographic variability of mass bleaching events, largely using remote sensing technologies.[53] Scientists and managers in Florida have not fully implemented an assessment and monitoring program that specifically addresses bleaching events, including the critical before-during-after sampling that is necessary to quantify the distribution, severity, and consequences of mass bleaching. While such monitoring programs do nothing to prevent coral bleaching, they do provide data that may identify bleaching-resistant sites that, if not already protected, can be considered high priority for management action and protection against local stressors.

Currently in Florida, status and trends monitoring has identified habitat types with higher than average coral cover and abundance, but it is unknown whether these areas are more or less prone to bleaching because only baseline assessments have been conducted.[54] Deeper reefs (to 35 meters) may also exhibit less evidence of mortality caused by coral bleaching (Miller *et al.*, 2001), but even less is known about these habitats—especially related to the distribution and abundance of coral diseases, which can confound assessments of factors causing mortality because the temporal scale of monitoring is sufficient to only assess disease prevalence and not incidence or mortality rates.

No-Take Protection and Zoning for Resistance or Resilience

The use of marine reserves (Sanctuary Preservation Areas, Research-Only Areas, and Ecological Reserves) in the FKNMS has already been adopted as a tool to manage multiple user groups throughout the Sanctuary (U.S. Department of Commerce, 1996), and in the Dry Tortugas to enhance fisheries where positive results have been obtained after only a few years (Ault *et al.*, 2006). Potential exists to use a range of options to identify bleaching-resistant reefs in the Keys, from simply identifying the best remaining sites left and using a decision matrix based on factors that may confer resilience to establish priority sites for protection, to the Bayesian approach of Wooldridge and Done (2005). Only recently have coral community data been obtained at the relevant spatial scales and across multiple habitat types (Smith *et al.*, forthcoming). Whatever approach is used, the results are likely to include sites with high coral cover and abundance, high diversity, connectivity related to current regimes with the potential to transport larvae,

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[53] **NOAA Satellite and Information Service**, 2007: NOAA coral reef watch satellite bleaching monitoring datasets. NOAA Website, National Oceanic and Atmospheric Administration, http://coralreefwatch.noaa.gov/satellite/ge/, accessed on 7-27-2007.

[54] **Miller**, S.L., M. Chiappone, L.M. Rutten, D.W. Swanson, and B. Shank, 2005: *Rapid Assessment and Monitoring of Coral Reef Habitats in the Florida Keys National Marine Sanctuary: Quick Look Report: Summer 2005 Keys-Wide Sampling*. National Undersea Research Center, University of North Carolina at Wilmington, Wilimington, NC.

and protection from local stressors including overfishing and pollution (Done, 1999; Hughes *et al.*, 2003).[55]

In the Florida Keys, marine protected areas date to 1960 for John Pennekamp Coral Reef State Park, 1975 for the Key Largo National Marine Sanctuary, 1981 for Looe Key National Marine Sanctuary, and 1990 for expansion of these sites to include 2,800 square nautical miles of coastal waters that are now designated as the Florida Keys National Marine Sanctuary. The Tortugas Ecological Reserve was added in 2001, and six years later a 46-square-mile Research Natural Area was also established within Dry Tortugas National Park.[56] While spatial resolution among habitat types from Miami to the Dry Tortugas is not as extensive as in the Great Barrier Reef, work similar to Wooldridge and Done (2005) should be evaluated for application to the Florida Keys. For example, a combination of retrospective sea-surface temperature studies using NOAA Coral Reef Watch products, combined with *in situ* temperature data, water quality monitoring data,[57] and detailed site characterizations[58] might help identify bleaching-resistant sites (if temporally- and spatially-relevant sampling is conducted before, during, and after a bleaching event), identify candidate sites for protection based on resilience criteria, and in general validate the concept of marine reserve networks in the region as a management response to coral bleaching threats.

Geographic Range Extensions of Coral Reefs in Florida

Coral reefs in south Florida represent the northern geographic limit of reef development in the United States. It is reasonable to assume that some northward expansion of either the whole reef community or individual species may occur as a result of warming climate. Indeed, such a northward expansion may already be in progress, but caution is necessary before assigning too much significance to what might be an anomalous event. Specifically, *Acropora cervicornis* was discovered growing in large thickets off Fort Lauderdale in 1998 (Vargas-Ángel, Thomas, and Hoke, 2003) and *A. palmata* was discovered off Pompano Beach in northern Broward county (Precht and Aronson, 2004). It is possible that these populations—over 50 km northward of their previously known

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[55] See also **Salm**, R.V., S.E. Smith, and G. Llewellyn, 2001: Mitigating the impact of coral bleaching through Marine Protected Area design. In: *Coral Bleaching: Causes, Consequences and Response* [Schuttenberg, H.Z. (ed.)]. Proceedings of the Ninth International Coral Reef Symposium on Coral Bleaching: Assessing and linking ecological and socioeconomic impacts, future trends and mitigation planning, Coastal Management Report 2230, Coastal Resources Center, University of Rhode Island, Narragansett, pp. 81-88.
And **West**, J.M., 2001: Environmental determinants of resistance to coral bleaching: implications for management of marine protected areas. In: *Coral Bleaching and Marine Protected Areas, Volume 102* [Salm, R.V. and S.L. Coles (eds.)]. Asia Pacific Coastal Marine Program Report #0102. Proceedings of the Workshop on Mitigating Coral Bleaching Impact Through MPA Design, Honolulu, Hawaii, pp. 40-52.

[56] **National Park Service**, 1-18-2007: Dry Tortugas National Park - research natural area will be effective January 19, 2007. National Park Service Website, http://www.nps.gov/drto/parknews/researchnaturalarea.htm, accessed on 7-26-2007.

[57] **Boyer**, J.N. and H.O. Briceño, 2006: *FY2005 Annual Report of the Water Quality Monitoring Project for the Water Quality Protection Program of the Florida Keys National Marine Sanctuary*. Southeast Environmental Research Center, Florida International University, Miami, FL, pp.1-83.

[58] **Miller**, S.L., D.W. Swanson, and M. Chiappone, 2002: Multiple spatial scale assessment of coral reef and hard-bottom community structure in the Florida Keys National Marine Sanctuary. In: *Proceedings of the 9th International Coral Reef Symposium*, pp. 69-74.

northern limit—are a result of recent climate warming known to have occurred in the western Atlantic (Hoegh-Guldberg, 1999; Levitus *et al.*, 2000; Barnett, Pierce, and Schnur, 2001). It is also possible that these reefs represent a remnant population or a chance recruitment event based on a short-term but favorable set of circumstances that will disappear with the next hurricane, cold front, disease epizootic, or bleaching event. Still, the presence of these acroporid reefs is suggestive of what might happen as climate warms. Interestingly, the presence of these northern acroporid populations matches the previous northern extension of reef development in the region during the middle Holocene (Lighty, Macintyre, and Stuckenrath, 1978), when sea surface temperatures were warmer. Reefs up to 10 m thick grew off Palm Beach County in the middle Holocene (Lighty, Macintyre, and Stuckenrath, 1978) and when temperatures started to cool 5,000 years before present reef development moved south to its current location (Precht and Aronson, 2004).

Despite these northern extensions in the geographic distributions of corals seen in the fossil record, predicting future geographic expansions in Florida is complicated by factors other than temperature that influence coral reefs, including light, carbonate saturation state, pollution, disease (Buddemeier, Kleypas, and Aronson, 2004), and a shift from a carbonate to siliciclastic sedimentary regime along with increasing nutrient concentrations as latitude increases up the east coast of Florida (Precht and Aronson, 2004). One thing, however, is certain: geographic shifts of reefs in Florida that result from global warming will not mitigate existing factors that today cause widespread local and regional coral reef decline (Precht and Aronson, 2004). Further, if we assume that the reefs of the mid-Holocene were in better condition than today's reefs, they may not prove to be a good analogue for predicting the future geographic trajectory of today's reefs. Because corals in Florida are already severely impacted by disease, bleaching, pollution, and overfishing, expansion at best will be severely limited compared to what might occur if the ecosystem were intact.

At the global scale and across deep geological time, range extensions to higher latitudes occurred for hard corals that survived the Cretaceous warming period (Kiessling, 2001; Kleypas, 2006), and some coral species today that are found in the Red Sea and Persian Gulf can survive under much greater temperature ranges than they experience throughout the Indo-Pacific (Coles and Fadlallah, 1991). Both of these examples, however, probably reflect long-term adaptation by natural selection and not short-term acclimatization (Kleypas, 2006). At shorter times scales (decades), corals that survive rapid climate warming may be those that are able to quickly colonize and survive at higher latitudes where maximum summer temperatures may be reduced compared to their previous geographic range. An alternative to migration is the situation where corals adapt to increasing temperatures at ecological time scales (decades), and there is some evidence to suggest that this might occur (Guzmán and Cortés, 2001; Podestá and Glynn, 2001). However, the ability to predict if corals will acclimate is complicated because absolute values and adaptive potential are likely to vary across species (Hughes *et al.*, 2003;

Kleypas, 2006).[59] Acclimation without range expansion is a topic of great significance related to coral bleaching.

Another question related to the potential for coral reef migration to higher latitudes in Florida is related to understanding factors that currently limit expansion northward. Cold-water temperature tolerances for individual corals are not well known; however, their present-day global distribution generally follows the 18 °C monthly minimum seawater isotherm (Kleypas, McManus, and Mendez, 1999; Kleypas, Buddemeier, and Gattuso, 2001; Buddemeier, Kleypas, and Aronson, 2004). South Florida is located between the 18 and 20°C isotherm and is thus significantly affected by severe winter cold fronts, especially for corals in shallow water (Burns, 1985; Walker, Rouse, and Huh, 1987).[60] Well documented coral die-offs due to cold water fronts have occurred repeatedly throughout the Florida Keys (Davis, 1982; Porter, Battey, and Smith, 1982; Walker *et al.*, 1982; Roberts, Rouse, and Walker, 1983; Shinn, 1989); and as far south as the Dry Tortugas (Porter, Battey, and Smith, 1982; Jaap and Hallock, 1990).[61] Porter and Tougas (2001) documented a decreasing trend in generic coral diversity along the east coast of Florida, but a number of coral species extend well beyond the 18°C isotherm with at least two species surviving as far north as North Carolina, likely due to the influence of the Gulf Stream. Thus, climate warming that has the potential to influence the impact of winter cold fronts may influence the range expansion of corals in Florida.

Finally, the above examples have focused mostly on the acroporid corals, which represent only two species out of more than forty that are found regionally (Jaap, 1984). Obviously, when considering range expansion of the total reef system, and not just two coral species, models designed to optimize or anticipate management actions that conserve existing habitat or predict future locations for habitat protection are likely to be exceedingly complicated. In Florida, if reefs are in sufficiently good condition in the future to act as seed populations for range expansion, one management action to anticipate the effects of climate change would be to protect habitats similar to those that thrived during the middle Holocene when coral reefs flourished north of their current distribution (Lighty, Macintyre, and Stuckenrath, 1978). However, existing declines in the acroporids throughout Florida and the Caribbean (Gardner *et al.*, 2003; Precht and Miller, 2006) suggest that at least for these two species, the major framework building species in the region, expansion will not occur unless factors such as disease and coral bleaching are mitigated.

[59] See also **Ware**, J.R., 1997: The effect of global warming on coral reefs: acclimate or die. In: *Proceedings of the 8th International Coral Reef Symposium, Volume 1*, pp. 527-532.
[60] See also **Jones**, J.A., 1977: Morphology and development of southeastern Florida patch reefs. In: *Proceedings of the 3rd International Coral Reef Symposium, Volume 2.* University of Miami, Miami, Florida, pp. 232-235.
[61] See also **Jaap**, W.C. and F.J. Sargent, 1994: The status of the remnant population of *Acropora cervicornis* (Lamarck, 1816) at Dry Tortugas National Park, Florida, with a discussion of possible causes of changes since 1881. In: *Proceedings of the Colloquium on Global Aspects of Coral Reefs: Health, Hazards and History* [Ginsburg, R.N. (ed.)] Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida pp. 101-105.

A6.1.4 Adapting Management to Climate Change

The Sanctuary Advisory Council (SAC) is a committee of stakeholder representatives that provides advise to sanctuary managers across a broad range of topics and issues (Keller and Causey, 2005), particularly regarding new issues as they arise. The SAC has a climate change working group, which can work with sanctuary managers to help develop adaptation approaches best suited for the Florida Keys (see also section 8.4.4.2 of the Marine Protected Areas chapter).

Little has been done to restore mangrove habitat in the Florida Keys, where many shorelines were cleared for development. In addition to supporting critical nurseries, mangroves produce tannins and other dissolved organic compounds that absorb ultraviolet radiation. Dependable sources of these compounds from intact mangrove coastlines can provide reefs with some protection from photo-oxidative stress that contributes to bleaching. Mangrove restoration should be considered as a management strategy that may become increasingly important in the context of climate change - for shoreline protection as well as the benefits noted above.

The Great Barrier Reef Marine Park Authority (next section) has a Climate Change Response Program and an action plan (section 8.4.4 of the Marine Protected Areas chapter) that is a model for the FKNMS, which is completing a bleaching response plan, but has not yet developed a broader plan about responding to climate change. Such a plan is a logical next step. At the same time, The Nature Conservancy is leading the Florida Reef Resilience Program[62] to investigate possible patterns of resilience along the Florida Reef Tract and recommend actions.

A6.2 The Great Barrier Reef Marine Park

A6.2.1 Introduction

The Great Barrier Reef (GBR) is a maze of reefs and islands spanning an area of 348,000 km^2 off the Queensland coast in northeast Australia (Fig. A6.1). It spans 14 degrees of latitude, making it the largest coral reef ecosystem in the world and one of the richest in biological diversity. The GBR supports 1,500 species of fish, 350 species of hard corals, more than 4,000 species of mollusks, 500 species of algae, six of the world's seven species of marine turtles, 24 species of seabirds, more than 30 species of whales and dolphins, and the dugong. The GBR was chosen as a case study because it is a large marine protected area that has moderate representation of no-take areas (33%) and has been under a management regime since 1975.

Figure A6.1. Map of the Great Barrier Reef Marine Park showing the adjacent catchment in Queensland. Modified from Haynes (2001) and courtesy of the Great Barrier Reef Marine Park Authority.

[62] http://www.nature.org/wherewework/northamerica/states/florida/preserves/art17499.html

The GBR already appears to have been affected by climate change. The first reports of coral bleaching in the GBR appeared in the literature in the 1980s[63] and have continued to increase in frequency since then (Hoegh-Guldberg, 1999; Done *et al.*, 2003). Coral-coring work done at the Australian Institute of Marine Science detected the earliest growth hiatus associated with mass coral bleaching in 1998 (Lough, 2007). There have been nine bleaching events on the GBR, with three major events in the last decade correlating with elevated sea temperatures and causing damage to parts of the reef. These early signs of climate change, and the extensive research and monitoring data that are available for the GBR, make it a suitable case study for this report.

The conservation values of the GBR are recognized in its status as a World Heritage Area (listed in 1981), and its resources are protected within the Great Barrier Reef Marine Park. The enactment of the Great Barrier Reef Marine Park Act in 1975 established the legal framework for protecting these values. The goal of the legislation is "…*to provide for the protection, wise use, understanding and enjoyment of the Great Barrier Reef in perpetuity through the care and development of the Great Barrier Reef Marine Park*."

A6.2.2 Managing the Great Barrier Reef Marine Park

The Great Barrier Reef Marine Park Authority has management strategies in place to address current stresses on the GBR. Stressors include terrestrial inputs of sediment, nutrients, and pesticides from coastal catchments; fisheries extraction; tourism and recreational activities; and changes to coastal hydrology as a result of coastal development and climate change. Sustainability of the environmental and social values of the Great Barrier Reef depend largely (and in most cases, entirely) on a healthy, self-perpetuating ecosystem. Reducing pressures on this system has been a focus of management activities over the last decade.

The Great Barrier Reef Marine Park was rezoned in 2003 to increase the area of highly protected no-take zones to 33%, with at least 20% protected in each habitat bioregion. These no-take areas aim to conserve biodiversity, increasing the potential of maintaining an intact ecosystem, with larger no-take areas including more representative habitats.[64]

Current Approaches to Management

There are 26 major catchments that drain into the GBR (Fig. A6.1) covering an area of 425,964 km^2. Cropping (primarily of sugar cane), grazing, heavy industry and urban settlement are the main land uses. The *Reef Water Quality Protection Plan* (The State of Queensland and Commonwealth of Australia, 2003) is a joint state and federal initiative that aims to *halt and reverse the decline in the quality of water entering the Reef by 2013*.

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[63] **Oliver**, J., 1985: Recurrent seasonal bleaching and mortality of corals on the Great Barrier Reef. In: *Proceedings of the 5th International Coral Reef Symposium, Volume 4*, pp. 201-206.

[64] **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, Volume 2, 23, October 2000, Bali, Indonesia, pp. 687-696.

Day, J., L. Fernandes, A. Lewis, and J. Innes, 2004: Representative areas program - an ecosystem approach to biodiversity protection planning. In: Proceedings of the Second International Tropical Ecosystems Management Symposium, March 2003, Manila, Philippines.

Under this initiative, diffuse sources of pollution are targeted through a range of voluntary and incentive-driven strategies to address water quality entering the GBR from activities in the catchments.

Important commercial fisheries in the GBR include trawling that mainly targets prawns and reef-based hook-and-line that targets coral trout and sweetlip emperor, inshore fin fish, and three crab fisheries (spanner, blue, and mud). None of these fisheries is considered overexploited; however, there is considerable unused (latent) effort in both the commercial and recreational sectors. Commercial fisheries contribute A$251 million to the Australian economy (Great Barrier Reef Marine Park Authority, 2007). Fisheries management is undertaken by the Queensland Government and includes a range of measures such as limited entry, management plans, catch and effort limits, permits, and industry accreditation. Recreational activities (including fishing) contribute A$623 million per annum to the region (Great Barrier Reef Marine Park Authority, 2007), and recreational fishing is subject to size and bag limits for many species.

Over 1 million tourists visit the GBR annually, contributing A$6.1 billion to the Australian economy (Great Barrier Reef Marine Park Authority, 2007). The Great Barrier Reef Marine Park Authority manages tourism using permits, zoning, and other planning tools such as management plans and site plans (Smith *et al.*, 2004). Visitation is concentrated in the Cairns and Whitsunday Island areas, and an eco-certification program encourages best practices and sustainable tourism (Skeat, 2003).

As one of the fastest growing regions in Australia, the GBR coast is being extensively developed through the addition of tourist resorts, urban subdivisions, marinas, and major infrastructure such as roads and sewage treatment plants. All levels of government regulate coastal development depending on the scale and potential impacts of the development. Local government uses local planning schemes and permits, state government uses the Integrated Planning Act,[65] and in the case of significant developments, the federal government uses the Environment Protection and Biodiversity Conservation Act[66] to assess the environmental impacts of proposals. These efforts have resulted in an increase in biodiversity protection, a multi-stakeholder agreement to address water quality, and a well-managed, multiple-use marine protected area.

Vulnerability of the Great Barrier Reef to Climate Change

Despite these landmark initiatives, the ability of the ecosystem to sustain provision of goods and services is under renewed threat from climate change (Wilkinson, 2004). Climate change is rapidly emerging as one of the most significant challenges facing the GBR and its management. While MPA managers cannot directly control climate, and climate change cannot be fully averted, there is an urgent need to identify possibilities for reducing climate-induced stresses on the GBR (Marshall and Schuttenberg, 2006). The GBR Climate Change Response Program has undertaken an assessment of the vulnerability of the GBR to climate change and is developing strategies to enhance

[65] Number 69 of 1997
[66] Number 91 of 1999

ecosystem resilience, sustain regional communities and industries that rely on the GBR, and provide supportive policy and collaborations.

The Climate Change Response Program used regional GBR climate projections to assess the vulnerability of species, habitats, and key processes to climate change. Some relevant projections emerged. Regional GBR sea temperatures have increased by 0.4^{o}C since 1850 and are projected to increase by a further 1–3^{o}C above present temperatures by 2100 (Fig. A6.2). Sea level rise is projected to be 30–60 cm by 2100, and ocean chemistry is projected to decrease in pH by 0.4–0.5 units by 2100 (Lough, 2007). There is less certainty about: changes to tropical cyclones, with a 5–12% increase in wind speed projected; rainfall and river flow, with projected increases in intensity of droughts and rainfall events; and ENSOs, which will continue to be a source of high interannual variability (Lough, 2007).

Figure A6.2. Sea surface temperature (SST) projections for the Great Barrier Reef (GBR) (Lough, 2007).

Coral Bleaching

The key threats to the GBR ecosystem from climate change manifest in impacts to all components of the ecosystem, from species to populations to habitats and key processes. Although coral reefs represent only 6% of the Great Barrier Reef, they are an iconic component of the system and support a diversity of life. Unusually warm summers caused significant coral bleaching events in the GBR in 1998, 2002, and 2006. More than 50% of reefs were affected by bleaching in the summers of 1998 and 2002, following persistent high sea temperatures throughout the GBR. Fortunately, temperatures cooled soon enough to avoid catastrophic impacts, yet approximately 5% of reefs suffered long-term damage in each year. Stressful temperatures were confined to the southern parts of the GBR in the summer of 2006 and persisted long enough to cause over 40% of the corals to die. Future warming of the world's oceans is projected to increase the frequency and severity of coral bleaching events, making further damage to the GBR inevitable (Hoegh-Guldberg *et al.*, 2007). Continued monitoring efforts—such as those proposed in the GBR Coral Bleaching Response Plan—will be essential for understanding this ecosystem change.

Impacts to Species

Mass mortalities of seabirds and failures of nesting (death of all chicks) have been observed at several key seabird rookeries during anomalously warm summers on the GBR (coinciding with mass coral bleaching). New research is showing that provisioning failure, resulting when adults have to travel too far to find food for their chicks, causes these deaths (Congdon *et al.*, 2007). This is thought to be due to decreased availability of food fish caused by changes in circulation patterns (location and depth of cool water bodies preferred by these fish). Marine turtles are also at risk from climate change, with increasing air temperatures projected to alter the gender ratio of turtle hatchlings; during periods of extremely high temperatures in the past, complete nesting failures have been observed. Sea level rise also poses a threat to seabirds and turtles, as nesting islands and beaches become inundated and suitability of alternative beaches is reduced by coastal development.

Fish, shark, and ray populations will be most affected by reductions in reef habitat, with resultant decreases in diversity and abundance and changes in community composition (Munday *et al.*, 2007; Chin *et al.*, 2007). Conversely, small increases in sea temperature may benefit larval fish by accelerating embryonic and larval growth and enhancing larval swimming ability. This shows that climate change will not affect all organisms equally, and some populations or groups (such as macroalgae) may in fact benefit by increasing their range or growth rate. However, this will change the distributions of species as they migrate southward or offshore. This in turn would likely result in population explosions of fast growing, 'weed-like' species to the detriment of other species, thereby reducing species diversity. As species and habitats decline, so too does the productivity of the system and its ability to respond to future change.

Impacts to Key Processes

The reef matrix itself is at risk from climate change through loss of coral—not only from coral bleaching but also physical damage from more intense storms and cyclones and reduced coral calcification rates as ocean pH decreases. This is critical from the perspective of the structural integrity of the GBR as well as the services reefs provide to other organisms, such as habitat and food.

Primary productivity, through changes to microbial, plankton, and seagrass communities, is likely to be affected as changes in the carbon cycle occur. Changes in rainfall patterns, runoff, and sea temperature also are likely to change plankton, seagrass, and microbial communities. These changes reduce trophic efficiency, which decreases food quality and quantity for higher trophic levels with a resultant decline in abundance of animals at higher trophic levels. Productivity is also likely to be sensitive to changes in ocean circulation as nutrient transport patterns change, thereby reducing nutrient availability and primary production.

Connectivity is at risk from changes to ocean circulation patterns and ENSO; as ocean currents and upwelling are affected, so too will be the hydrological cycles that transport material latitudinally and across the shelf. Connectivity will also be affected by coastal changes such as sea level rise and altered rainfall regimes, which are likely to have the most influence on coastal connectivity between estuaries and the inshore lagoon of the GBR. As temperature-induced stratification reduces wind-driven upwelling, offshore hydrological cycles are affected, potentially reducing connectivity between offshore reefs. All these changes could interact to affect the survival and dispersal patterns of larvae between reefs.

As biodiversity and connectivity are lost, the system becomes less complex, which initiates a cascade of events that results in long-term change. Simplified systems are generally less resilient and therefore less able to absorb shocks and disturbances while continuing to maintain their original levels of function. Reducing biodiversity and connectivity reduces the number of components and networks that can buffer against poor water quality, overfishing, and climate change. Maintaining a healthy ecosystem requires that ecological processes be preserved and that there is sufficient biodiversity to respond to changes. Larger marine protected areas that include representative habitats and protect biodiversity and connectivity may be more resilient to climate change (Roberts *et al.*, 2006).

A6.2.3 Adapting Management to Climate Change

In the face of these potential climate change impacts, the GBR Climate Change Response Program developed a Climate Change Action Plan in 2006. The action plan has five main objectives:

1. Address climate change knowledge gaps
2. Communicate with and educate communities about climate change implications for the GBR
3. Support greenhouse gas emissions mitigation strategies in the GBR region
4. Enhance resilience of the GBR ecosystem to climate change
5. Support GBR communities and industries to adapt to climate change

Key strategies within the action plan include assessing the vulnerability of the GBR ecological and social systems to climate change; developing an agency-wide communication strategy for climate change; facilitating greenhouse gas emissions reductions using the Reef Guardian incentive project; undertaking resilience mapping for the entire GBR and reviewing management arrangements in light of the relative resilience of areas of the GBR; and working with industries to promote industry-led initiatives to address climate change.

Addressing Information Gaps

The Great Barrier Reef Marine Park Authority (GBRMPA) has been working with scientists to assess the vulnerability of the different components of the GBR ecosystem, industries, and communities to climate change. A resultant publication identifies the key vulnerabilities for all components of the ecosystem, from plankton to corals to marine mammals, and makes management recommendations that aim to maximize the ability of the system to resist or adapt to climate changes (Johnson and Marshall, 2007). Examples of management recommendations include addressing water quality in inshore areas where primary productivity is high (*e.g.*, areas with extensive seagrass meadows or with critical plankton aggregations). Another example is conserving landward areas for migration of mangroves and wetlands as sea level rises, including possible land acquisitions and removal of barrier structures. Finally, protecting sites of specific importance from coral bleaching through shading or water mixing in summer months is an option. Reducing other impacts on critical habitats or species is also recommended (*e.g.*, improving shark fisheries management, reducing disturbance of seabird nesting sites during breeding season, reducing boat traffic and entanglement of marine mammals, protecting key turtle nesting beaches, enhancing resilience of coral reefs by improving water quality, protecting herbivores, and managing other destructive activities such as anchoring and snorkeling). These recommendations will be used to review existing management strategies and incorporate climate change considerations where needed.

Raising Awareness and Changing Behavior

The Climate Change Response Program developed a communication strategy in 2004 that aims to increase public awareness of the implications of climate change for the GBR. This strategy is being amended to include all GBRMPA activities and ensure that all groups consistently present key climate change messages. This is particularly important for groups that are addressing those factors that confer resilience to the ecosystem, such as water quality and fisheries. The key messages of the agency-wide communication strategy are that climate change is real, climate change is happening now, climate change is affecting the GBR, the GBRMPA is working to address climate change, and individuals' actions can make a difference.

The Reef Guardian program is a partnership with schools and local governments in GBR catchments. The program is voluntary and provides resources for schools and councils to incorporate sustainability initiatives into their everyday business. A sustainability and climate change syllabus has been developed for primary schools and will teach students about climate change and the implications for the GBR, as well as provide greenhouse gas emission reductions projects for the schools. The local council participants have been provided with similar information, and in order to be a recognized Reef Guardian, a council must implement a minimum number of sustainability modules. This partnership currently has 180 schools and is incrementally working toward having 20 local councils participating by 2010.

Toward Resilience-Based Management

One of the most significant strategies that coral reef managers can employ in the face of climate change is to enhance the resilience of the ecosystem (West *et al.*, 2006). Working with researchers, the Climate Change Response Program has identified resilience factors that include water quality, coral cover, community composition, larval supply, recruitment success, herbivory, disease, and effective management. These will be used to identify areas of the GBR that have high resilience to climate change and should be protected from other stresses, as well as areas that have low resilience and may require active management to enhance their resilience. Recognized research institutes have provided essential science that has formed the basis of this project and will continue collaborations between GBRMPA and researchers. Ultimately, it is hoped that this information can be used to review existing management regimes (such as planning and permit tools) to protect areas with high resilience as source sites and actively work in areas with low resilience to improve their condition.

Partnering with Stakeholders

The GBRMPA has been working with the GBR tourism industry to facilitate development of the GBR Tourism and Climate Change Action Strategy. This initiative was the result of a workshop with representative tourism operators that generated the GBR Tourism and Climate Change Action Group. This industry-led group has developed the action strategy to identify how climate change will affect the industry, how the industry can respond, and what options are available for the industry to become climate sustainable. The marine tourism industry considers reef-based activities particularly susceptible to the effects of climate change. Loss of coral from bleaching and changes to the abundance and location of fish, marine mammals, and other iconic species are likely to have the greatest impact on the industry. Increasing intensity of cyclones and storms will affect trip scheduling, industry seasonality, tourism infrastructure (particularly on islands), and future tourism industry development. Potential strategies for adapting to climate change include product diversification, new marketing initiatives, and targeting eco-accredited programs.

Managing Uncertainty

A critical component of all these strategies is the ability to manage flexibly and respond to change rapidly. This is important to enable managers to shift focus as new information becomes available or climate impact events occur. In reviewing existing management regimes, there will be a focus on ways of making management more flexible and drawing on management tools as they are needed. This type of adaptive management is essential for addressing the uncertain and shifting climate change impacts on the GBR. Given the scale of the issue and the fact that the cause and many of the solutions lie outside the jurisdiction of GBRMPA managers, effective partnerships with other levels of government and stakeholders to work cooperatively on climate change have been developed and will continue to be integral to adapting management to the climate change challenge.

A6.3 Papahānaumokuākea (Northwestern Hawaiian Islands) Marine National Monument

A6.3.1 Introduction

The Hawaiian Islands are one of the most isolated archipelagos in the world and stretch for over 2,500 km, from the island of Hawaii in the southeast to Kure Atoll (the world's highest-latitude atoll) in the northwest (Grigg, 1982; 1988; Friedlander *et al.*, 2005). Beginning at Nihoa and Mokumanamana Islands (~7 and 10 million years old, respectively) and extending to Midway and Kure Atolls (~28 million years old), the Northwestern Hawaiian Islands (NWHI) represent the older portion of the emergent archipelago (Grigg, 1988). The majority of the islets, shoals, and atolls are low-lying and remain uninhabited, although Midway, Kure, Laysan Island, and French Frigate Shoals have all been occupied for extended periods over the last century by various government agencies (Shallenberger, 2006). Because of their location in the central Pacific, the NWHI are influenced by large-wave events resulting from extratropical storms passing across the North Pacific each winter that have a profound influence on the geology and biology of the region (Grigg, 1998; Dollar and Grigg, 2004; Jokiel *et al.*, 2004; Friedlander *et al.*, 2005).

Ecosystem Structure

With coral reefs around the world in decline (Jackson *et al.*, 2001; Bellwood *et al.*, 2004; Pandolfi *et al.*, 2005), it is extremely rare to be able to examine a coral reef ecosystem that is relatively free of human influence and consisting of a wide range of healthy coral reef habitats. The remoteness and limited reef fishing and other human activities that have occurred in the NWHI have resulted in minimal anthropogenic impacts (Friedlander and DeMartini, 2002; Friedlander *et al.*, 2005). The NWHI therefore provide a unique opportunity to assess how a “natural” coral reef ecosystem functions in the absence of major localized human intervention.

One of the most striking and unique components of the NWHI ecosystem is the abundance and dominance of large apex predators such as sharks and jacks (Friedlander and DeMartini, 2002; DeMartini, Friedlander, and Holzwarth, 2005). These predators exert a strong top-down control on the ecosystem (DeMartini, Friedlander, and Holzwarth, 2005; DeMartini and Friedlander, 2006) and have been depleted in most other locations around the world (Myers and Worm, 2003; 2005). Differences in fish biomass between the main Hawaiian Islands (MHI) and NWHI represent both near-extirpation of apex predators and heavy exploitation of lower-trophic-level fishes on shallow reefs of the MHI (Friedlander and DeMartini, 2002; DeMartini and Friedlander, 2006).

The geographic isolation of the Hawaiian Islands has resulted in some of the highest endemism of any tropical marine ecosystem on earth (Jokiel, 1987; Kay and Palumbi, 1987; Randall, 1998) (Fig. A6.3). Some of these endemics are a dominant component of the community, resulting in a unique ecosystem that has extremely high conservation value (DeMartini and Friedlander, 2004; Maragos *et al.*, 2004). With species loss in the sea accelerating, the irreplaceability of these species makes Hawaii an important biodiversity hotspot (Roberts *et al.*, 2002; DeMartini and Friedlander, 2006).[67] The coral assemblage in the NWHI contains a large number of endemics (~30%), including at least seven species of acroporid corals (Maragos *et al.*, 2004). Acroporids are the dominant reef-building corals in the Indo-Pacific, but are absent from the MHI (Grigg, 1981; Grigg, Wells, and Wallace, 1981). Kure Atoll is the world’s most northern atoll and is referred to as the Darwin Point, where coral growth, subsidence, and erosion balance one another (Grigg, 1982).

Figure A6.3. Endemic species from the Hawaiian Islands. A. Masked angelfish, *Genicanthus personatus* (Photo courtesy of J. Watt), B. Rice coral, *Montipora capitata*, and finger coral, *Porites compressa* (photo courtesy of C. Hunter), C. Hawaiian hermit crab, *Calcinus laurentae* (photo courtesy of S. Godwin), D. Red alga, *Acrosymphtyon brainardii* (photo courtesy of P. Vroom).

The NWHI represent important habitat for a number of threatened and endangered species. The Hawaiian monk seal is one of the most critically endangered marine mammals in the United States (1,300 individuals) and depends almost entirely on the islands of the NWHI for breeding and the surrounding reefs for sustenance (Antonelis *et al.*, 2006). Over 90% of all sub-adult and adult Hawaiian green sea turtles found throughout Hawaii inhabit the NWHI (Balazs and Chaloupka, 2006). Additionally, seabird colonies in the NWHI constitute one of the largest and most important assemblages of seabirds in the world (Friedlander *et al.*, 2005).

[67] See also **Allen**, G.R., 2002: Indo-Pacific coral-reef fishes as indicators of conservation hotspots. In: *Proceedings of the Ninth International Coral Reef Symposium, Volume 2,* 23, October 2000, Bali, Indonesia, pp. 921-926.

In contrast to the MHI, the reefs of the NWHI are relatively free of major human influences. The few alien species known from the NWHI are restricted to the anthropogenic habitats of Midway Atoll and French Frigate Shoals (Friedlander *et al.*, 2005). Disease levels in corals in the NWHI were much lower than those reported from other locations in the Indo-Pacific (Aeby, 2006).

Existing Stressors

Although limited in scale, a number of past and present human activities have negatively affected the NWHI. Marine debris is currently one of the largest threats to the reefs of the NWHI (Boland *et al.*, 2006; Dameron *et al.*, 2007). Marine debris has caused entanglement of a number of protected species and damage to benthic habitats and is a potential vector for invasive species in the NWHI (Dameron *et al.*, 2007). An extensive debris removal effort between 1999 and 2003 has now surpassed the accumulation rate, resulting in a reduction in overall accumulation levels (Boland *et al.*, 2006). However, much of this debris originates thousands of kilometers away in the north Pacific, making the solution to the problem both a national and international issue. Other direct human stresses such as pollution, coastal development, and ship groundings, have had negative consequences in localized areas but have been limited to a small number of locations.

The NWHI are influenced by a dynamic environment that includes large annual water temperature fluctuations, seasonally high wave energy, and strong inter-annual and inter-decadal variations in ocean productivity (Polovina *et al.*, 1994; Grigg, 1998; Polovina *et al.*, 2001; Friedlander *et al.*, 2005). As a result of these influences, natural stressors play an important role in the structure of the NWHI ecosystem. Large swell events generated every winter commonly produce waves up to 10–12 m in vertical height and between 15–20 m about once every decade (Grigg *et al.*, 2007). This limits the growth and abundance of coral communities, particularly on the north and western sides of all the islands. The best-developed reefs on all the islands exist either in the lagoons or off southwestern exposures (Grigg, 1982).

Summer sea surface temperatures (SSTs) along the island chain are generally similar, peaking at about 28ºC; however, winter SSTs are much cooler at the northern end of the chain, dipping down to 17ºC in some years (Grigg, 1982; Grigg *et al.*, 2007). This represents a 10ºC intra-annual difference at the northern end of the chain, while that at the southern end of the NWHI is only half as great: 5ºC (22–27ºC). Compared with most reef ecosystems around the globe, the annual fluctuations of SST of about 10°C at these northerly atolls is extremely high. Cooler water temperatures to the north restrict the growth and distribution of a number of coral species (Grigg, 1982). In addition, the biogeographic distribution of many fish species in the NWHI is influenced by differences in water temperatures along the archipelago (DeMartini and Friedlander, 2004; Mundy, 2005).

Climate Sensitivity

The NWHI ecosystem is sensitive to natural climate variability at a number of spatial and temporal scales. The Pacific Decadal Oscillation (PDO) results in changes in ocean productivity at large spatial and long temporal scales and has been attributed to changes in monk seal pup survival, sea bird fledging success, and spiny lobster recruitment in the NWHI (Polovina *et al.*, 1994; Polovina, Mitchem, and Evans, 1995). Inter-annual variation in the Transition Zone Chlorophyll Front is also known to affect the distribution and survival of a number of species in the NWHI (Polovina *et al.*, 1994; Polovina *et al.*, 2001).

Because of their high latitude location in the central Pacific, the NWHI were thought to be one of the last places in the world to experience coral bleaching (Hoegh-Guldberg, 1999). Hawaiian reefs were unaffected by the 1998 mass bleaching event that affected much of the Indo-Pacific region (Hoegh-Guldberg, 1999; Reaser, Pomerance, and Thomas, 2000; Jokiel and Brown, 2004). The first documented bleaching event in the MHI was reported in 1996 (Jokiel and Brown, 2004). The NWHI were affected by mass coral bleaching in 2002 and again in 2004 (Aeby *et al.*, 2003; Kenyon *et al.*, 2006). Bleaching was most acute at the three northern-most atolls (Pearl and Hermes, Midway, and Kure) and was most severe on backreef habitats (Kenyon and Brainard, 2006). Of the three coral genera that predominate at these atolls, *Montipora* and *Pocillopora* spp. were most affected by bleaching, with lesser incidences observed in *Porites* (Kenyon and Brainard, 2006). The occurrence of two mass bleaching episodes in three years lends credence to the projection of increased frequency of bleaching with climate change.

SST data derived from both remotely sensed satellite observations (Fig. A6.4a) as well as in situ Coral Reef Early Warning System (CREWS) buoys suggest that prolonged, elevated SSTs combined with a prolonged period of anomalously light wind speed led to decreased wind and wave mixing of the upper ocean (Hoeke *et al.*, 2006) (Fig. A6.4b). The reefs to the southeast of the archipelago show smaller positive temperature anomalies compared with the reefs towards the northwest. Research and monitoring efforts should target this pattern to better understand dispersal, bleaching, and other events that might be affected by it.

Figure A6.4. a) NOAA Pathfinder SST anomaly composite during summer 2002 period of NWHI elevated temperatures, July 28–August 29. b) NASA/JPL Quikscat winds (wind stress overlayed by wind vector arrows) composite during summer 2002 period of increasing SSTs, July 16–August 13. The Hawaii Exclusive Economic Zone (EEZ) is indicated with a heavy black line; all island shorelines in the archipelago are also plotted (adapted from Hoeke *et al.*, 2006).

Potential Impacts of Climate Change

Climate change may increase the intensity of storm events as well as result in changes in ocean temperature, circulation patterns, and water chemistry (Cabanes, Cazenave, and Le Provost, 2001; IPCC, 2001; Caldeira and Wickett, 2003). Warmer temperatures in Hawaii have been shown to cause bleaching mortality (Jokiel and Coles, 1990) and negatively affect fertilization and development of corals.[68] Annual spawning of some species in Hawaii occurs at temperatures near the upper limit for reproduction,[68] so increases in ocean temperature related to climate change may have a profound effect on coral populations by causing reproductive failure. The rate and scale at which bleaching has been increasing in recent decades (Glynn, 1993) points to the likelihood of future bleaching events in Hawaii (Jokiel and Coles, 1990).

Coral disease is currently low in the NWHI (Aeby, 2006), but increases in the frequency and intensity of bleaching events will stress corals and make them more susceptible to disease (Harvell *et al.*, 1999; Harvell *et al.*, 2002). Acroporid corals are prone to bleaching and disease (Willis, Page, and Dinsdale, 2004) and are restricted in range and habitat within the Hawaiian Archipelago to a few core reefs in the NWHI (Grigg, 1981; Grigg, Wells, and Wallace, 1981; Maragos *et al.*, 2004). This combination could lead to the extinction of this genus from Hawaii if mortality associated with climate change becomes severe.

Most of the emergent land in the NWHI is low-lying, highly vulnerable to inundation from storm waves, and therefore vulnerable to sea level rise (Baker, Littnan, and Johnston, 2006). The limited amount of emergent land in the NWHI is critical habitat for the endangered Hawaiian monk seal (Antonelis *et al.*, 2006), the threatened green sea turtle (Balazs and Chaloupka, 2006), and numerous terrestrial organisms and land birds that are found nowhere else on Earth (Rauzon, 2001). The emergent land in the NWHI may shrink by as much as 65% with a 48 cm rise in sea level (Baker, Littnan, and Johnston, 2006). Efforts such as translocation or habitat alteration might be necessary if these species are to be saved from extinction.

At the northern end of the chain, lower coral diversity is linked to lower winter temperatures and lower annual solar radiation (Grigg, 1982). Increases in ocean temperature could therefore change the distribution of corals and other organisms that might currently be limited by lower temperatures. Many shallow-water fish species that are adapted to warmer water are restricted from occurring in the NWHI by winter temperatures that can be as much as 7°C cooler than the MHI (Mundy, 2005). Conversely, some shallow-water species are adapted to cooler water and can be found in deeper waters at the southern end of the archipelago. This phenomenon—known as tropical submergence—is exemplified by species such as the yellowfin soldierfish (*Myripristis chrysonemus*), the endemic Hawaiian grouper (*Epinephelus quernus*), and the masked angelfish (*Genicanthus personatus*), which are found in shallower water at Midway and/or Kure atolls, but are restricted to deeper depths in the MHI (Randall *et al.*, 1993; DeMartini and Friedlander, 2004; Mundy, 2005).

Level/Degree of Management

Administrative jurisdiction over the islands and marine waters is shared by NOAA/NMSP, U.S. Fish and Wildlife Service, and the State of Hawaii. Eight of the 10

[68] **Krupp**, D.A., L.L. Hollingsworth, and J. Peterka, 2006: Elevated temperature sensitivity of fertilization and early development in the mushroom coral, *Fungia scutaria*. In: *Proceedings of the 10th International Coral Reef Symposium, Okinawa, Japan*, 28, June 2004, pp. 71-77.

NWHI (except Kure and Midway Atolls) have been protected by what is now the Hawaiian Islands National Wildlife Refuge (HINWR) established by President Theodore Roosevelt in 1909. The Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve was created by Executive Orders 13178 and 13196 in December 2000 and amended by Executive Order 13196 in January of 2001 to include the marine waters and submerged lands extending 1,200 nautical miles long and 100 nautical miles wide from Nihoa Island to Kure Atoll.

In June 2006, nearly 140,000 square miles of the marine environment in the NWHI was designated as the Papahānaumokuākea (Northwestern Hawaiian Islands) Marine National Monument (PMNM). This action provided immediate and permanent protection for the resources of the NWHI and established a management structure that requires extensive collaboration and coordination among the three primary co-trustee agencies: the State of Hawaii, the U.S. Fish and Wildlife Service, and NOAA.

Proclamation 8031 states that the monument will:

- Preserve access for Native Hawaiian cultural activities;
- Provide for carefully regulated educational and scientific activities;
- Enhance visitation in a special area around Midway Island;
- Prohibit unauthorized access to the monument;
- Phase out commercial fishing over a five-year period; and
- Ban other types of resource extraction and dumping of waste.

Preservation areas have been established in the PMNM in sensitive areas around all the emergent reefs, islands, and atolls. Vessels issued permits to operate in the PMNM are required to carry approved Vessel Monitoring Systems (VMS).

Program of Monitoring and Research

Long-term monitoring relevant to climate change has been conducted in the NWHI dating back to the 1970s by a variety of agencies (Grigg, 2006). Since 2000, a collaborative interagency monitoring program led by the Coral Reef Ecosystem Division (CRED) of the NOAA Pacific Islands Science Center has conducted integrated assessment and monitoring of coral reef ecosystems in the NWHI and throughout the U.S. Pacific (Wadell, 2005; Friedlander *et al.*, 2005). In conjunction with various state, federal, and academic partners, this program has integrated ecological studies with environmental data to develop a comprehensive ecosystem-based program of assessment and monitoring of U.S. Pacific coral reef ecosystems.

Ocean currents are measured and monitored in the NWHI using shipboard acoustic Doppler current profilers (ADCP), Surface Velocity Program (SVP) current drifters, and APEX profiling drifters (Friedlander *et al.*, 2005; Firing and Brainard, 2006). Spatial maps of ocean currents in the vicinity of the NWHI are also computed from satellite observations of sea surface height from the TOPEX-Poseidon and JASON altimetric satellites (Polovina, Kleiber, and Kobayashi, 1999). Moored ADCPs have been deployed by CRED at several locations to examine temporal variability of ocean currents over submerged banks and reef habitats in the NWHI.

Because of the significant influence of temperature on coral reef ecosystem health, observations of temperature in the NWHI are collected by a wide array of instruments and platforms, including satellite remote sensing (AVHRR) of SST (Smith and Reynolds, 2004), moored surface buoys and subsurface temperature recorders, closely spaced shallow water conductivity-temperature-depth profiles (CTD casts) in nearshore reef habitats, broadly spaced shipboard deep water CTD casts to depths of 500 m, and satellite-tracked SVP drifters. These data are integrated in the Coral Reef Ecosystem Integrated Observing System (CREIOS) as described below.

A6.3.2 Managing the Papahānaumokuākea Marine National Monument

Current Approaches to Research and Monitoring in Support of Management and How Climate Change is Being Examined

Over the past several years, the NOAA Coral Reef Conservation Program has established the Coral Reef Ecosystem Integrated Observing System (CREIOS), which is a cross-cutting collaboration between four NOAA Line Offices (NMFS, OAR, NESDIS, and NOS) focused on mapping, monitoring, and observing ecological and environmental conditions of U.S. coral reefs. At present, the ocean observing system in the NWHI consists of surface buoys measuring SST, salinity, wind, atmospheric pressure, and air temperature (enhanced systems also measure ultraviolet-B (UV-B) and photosynthetically available radiation); surface SST buoys; subsurface Ocean Data Platforms measuring ocean current profiles, wave energy and direction, temperature and salinity; subsurface current meters measuring bottom currents and temperature; and subsurface temperature recorders. Many of the surface platforms provide near real-time data telemetry to the Pacific Islands Fisheries Science Center and subsequent distribution via the World Wide Web. Time series data from subsurface instruments (without telemetry) are typically available every 12 to 24 months, after the instrument has been recovered and the dataset uploaded. Information about available datasets such as geo-location, depth, data format, and other metadata are available for both surface and subsurface instruments at the NOAA Coral Reef Information System (CoRIS) website.[69]

Another component of CREIOS is Coral Reef Watch (NESDIS, Office of Research and Applications) which uses remote sensing, computational algorithms, and artificial intelligence tools in the near real-time monitoring, modeling, and reporting of physical environmental conditions that adversely influence coral reef ecosystems. Satellite remotely sensed data products include near real-time identification of bleaching "hotspots" and identification of low-wind (doldrums) areas over the world's oceans. The CRED long-term moored observing stations are part of the Coral Reef Early Warning System (CREWS) network initiated by the NOAA Coral Health and Monitoring Program, which provides access to near real-time meteorological and oceanographic data from major U.S. coral reef areas. The CREWS buoys deployed by CRED in the NWHI record and telemeter data pertaining to sea-surface temperature, salinity, wind speed and

[69] **National Oceanic and Atmospheric Administration**, 2007: NOAA's coral reef information system. NOAA Website, http://www.coris.noaa.gov/, accessed on 7-27-2007.

direction, air temperature, barometric pressure, UV-B, and photosynthetically available radiation (Kenyon *et al.*, 2006).[70]

Information from CREIOS serves to alert resource managers and researchers to environmental events considered significant to the health of the surrounding coral reef ecosystem, allowing managers to implement response measures in a timely manner, and allowing researchers to increase spatial or temporal sampling resolution, if warranted. Response measures might include focused monitoring to determine the extent and duration of the event and management actions could include limiting access to these areas until recovery is observed. Information from the Coral Reef Watch Program in summer 2002 indicated conditions favorable for bleaching and resulted in assessments focused on potential bleaching areas during the subsequent research cruise.

Potential for Altering or Supplementing Current Management Practices to Enable Adaptation to Climate Change

To more fully address concerns about the ecological impacts of climate change on coral reef ecosystems and the effect of reef ecosystems on climate change, a number of agencies have proposed a collaborative effort to establish a state-of-the-art ocean observing system to monitor the key parameters of climate change impacting reef ecosystems of the Pacific and Western Atlantic/Caribbean. This proposed system includes:

- Expanding the existing array of oceanographic platforms across the remainder of the U.S. Pacific Islands
- Installing pCO_2 and UV-B sensors to examine long-term changes in carbon cycling and UV radiation
- Establish long-term records of coral reef environmental variability to examine past climate changes using paleoclimatic records of SST and other parameters from coral skeletons. This will allow us to determine if current and future SST stresses are unusual, or part of natural climatic variability.
- Develop/expand integrated *in situ* and satellite based bleaching mapping system
- Continue the development of the Coral Reef Early Warning System, which can be used to develop timely research activities to determine the extent and duration of any climate event and management actions that can potentially be implemented to mitigate these events.

In order to better understanding the impact of sea level rise on low-lying emergent areas in the NWHI, data are needed on hydrodynamic and geological characteristics of the region. Detailed information on elevation, bathymetry, waves, wind, tide, etc. is needed to develop predictive models of shoreline change relative to climate change. One possible management measure to counter loss of habitat for monk seals and turtles in the NWHI due to sea level rise might be beach nourishment (Baker, Littnan, and Johnston, 2006). Given the small size of the islets in the NWHI, local sand resources might be sufficient to mitigate sea level rise, but a great deal of research and planning would be required given

[70] **NOAA National Marine Fisheries Service**, 2007: Coral reef ecosystems - ecological assessment, marine debris removal, oceanography, habitat mapping. NOAA Website, http://www.pifsc.noaa.gov/cred/, accessed on 5-24-2007.

the remoteness and sensitive nature of the ecosystem (Baker, Littnan, and Johnston, 2006).

A6.3.3 Adapting Management to Climate Change

The draft Monument Management Plan does not address climate and ocean change management actions specifically, but by integrating strategies that focus on climate through research and monitoring, education and outreach, and review and syntheses, management will be better informed and prepared to deal with issues related to climate and ocean change. A comprehensive understanding of the effects of climate change on the NWHI is needed in order to provide managers with the information and tools needed to address these effects. Specific attention should be given to the effects on habitats critical to endemic and protected species.

The continued development and expansion of the Coral Reef Early Warning System and the Ocean Observing System are critical to improve understanding of climate change in the PMNM and the scale and capabilities of these systems should be enhanced. Investigations directed at examining the physiological, ecological, and genetic responses of the entire ecosystem to climate change should be conducted. Continuation and expansion of monitoring programs are important to better understand the ecosystem in time and space and higher-intensity spatial and temporal monitoring and assessment should be initiated in conjunction with disturbance events (*e.g.*, coral bleaching, disease outbreaks, elevated water temperatures).

The draft PMNM science plan calls for a number of specific research activities to examine the effects of climate change on the NWHI ecosystem.

- Determine the effect of climate change on nesting sites of protected species, *e.g.* the effect of sea level rise on nesting site of the green sea turtle and Hawaiian monk seal.
- Determine specific habitats, communities, and populations that will be affected by global climate change (ocean acidification, sea level, temperature, chlorophyll fronts, etc.).
- Understand habitat changes that will result from sea level rise.
- Map areas that will be most affected by extreme wave events.
- Discern anthropogenic impacts from natural variability of the physical environment.

PMNM constituency building and outreach plans should emphasize climate change in its various venues of information dissemination (*e.g.*, websites, brochures, fact sheets, school presentations, meetings, workshops, etc.). Building upon existing NWHI-based curricula developed under the Navigating Change Partnership and the new Hawaii Marine Curriculum, specific study units on climate change should be developed and impacts of climate change incorporated into other study units, where appropriate. By increasing the public’s awareness of climate change impacts, the PMNM can provide a societal benefit that extends beyond the boundaries of the monument.

A6.3.4 Conclusions

The nearly pristine condition of the NWHI results in one of the last large-scale, intact, predator-dominated reef ecosystems remaining in the world (Friedlander and DeMartini, 2002; Pandolfi *et al.*, 2005). Top predators can regulate the structure of the entire community and have the potential to buffer some of the ecological effects of climate change (Sala, 2006). Intact ecosystems such as the NWHI are hypothesized to be more resistant and resilient to stressors, including climate change (West and Salm, 2003). Owing to its irreplaceable assemblage of organisms, it possesses extremely high conservation value. The Papahānaumokuākea Marine National Monument is the largest marine protected area (MPA) in the world and provides a unique opportunity to examine the effects of climate change on a nearly intact large-scale marine ecosystem.

A6.4 The Channel Islands National Marine Sanctuary

A6.4.1 Introduction

Ecosystem Structure

Designated in 1980, the Channel Islands National Marine Sanctuary (CINMS) consists of an area of approximately 1,243 nm^2 of coastal and ocean waters and submerged lands off the southern coast of California (Fig. A6.5). CINMS extends 6 nm offshore from the five northern Channel Islands, including San Miguel, Santa Cruz, Santa Rosa, Anacapa, and Santa Barbara islands. The primary objective of the sanctuary is to conserve, protect, and enhance the biodiversity, ecological integrity, and cultural legacy of marine resources surrounding the Channel Islands for current and future generations. State and federal agencies with overlapping jurisdiction in the CINMS, including the California Department of Fish and Game, the Channel Islands National Park, and the National Marine Fisheries Service, are working together to manage impacts of human activities on marine ecosystems.

Figure A6.5. Map of the Channel Islands National Marine Sanctuary showing the location of existing state and proposed federal marine reserves and marine conservation areas.[71]

The Channel Islands are distributed across a biogeographic boundary between cool temperate waters of the Californian Current and warm temperate waters of the Davidson Current (or California Countercurrent). The California Current is characterized by coastal upwelling of cool, nutrient-rich waters that contribute to high biological productivity. Intertidal communities around San Miguel, Santa Rosa, and part of Santa Cruz islands are characteristic of the cool temperate region, whereas those around Catalina, San Clemente, Anacapa, and Santa Barbara islands are associated with the warm temperate region (Murray and Littler, 1981). Fish communities around the Channel Islands also show a distinctive grouping based on association with western islands (influenced strongly by the

[71] **Channel Islands National Marine Sanctuary**, 2007: Marine reserves environmental review process. NOAA Website, NOAA, http://channelislands.noaa.gov/marineres/main.html, accessed on 7-1-2007.

California Current) and eastern islands (influenced by the Davidson Current). Rockfish (*Sebastes* spp.), embiotocid species, and pile perch occur more in western islands while Island kelpfish (*Alloclinus holderi*), opaleye (*Girella nigricans*), garibaldi (*Hypsypops rubicundus*), blacksmith (*Chromis punctipinnis*), and kelp bass (*Paralabrax clathratus*) occur more often in the eastern islands (Halpern and Cottenie, 2007).

From Monterey Bay to Baja California, including the Channel Islands, giant kelp (*Macrocystis pyrifera*) is the dominant habitat-forming alga. Giant kelp grows in dense stands on hard rocky substrate at depths of 2–30 m (Foster and Schiel, 1985). Kelp is among the fastest growing of all algae, adding an average of 27 cm/day (in spring) and a maximum of 61 cm/day and reaching lengths of 60 m (200 ft). Giant kelp forests support a diverse community of associated species including marine invertebrates, fishes, marine mammals and seabirds (Graham, 2004). Kelp stocks and fronds may support thousands of invertebrates including amphipods, decapods, polychaetes, and ophiuroids. Some invertebrates such as sea urchins (*Strongylocentrotus* spp.) and abalone (*Haliotis* spp.) rely on bits of drifting kelp as their primary source of food. Fish in the kelp forest community specialize in life at different depths: kelp, black and yellow, and gopher rockfish are found at the base of kelp stocks, while olive, yellowtail, and black rockfish swim in mid-water. Drifting kelp mats at the sea surface provide cover for young fishes that are vulnerable to predation. Marine mammals and seabirds are attracted to abundant fish and invertebrate populations (which serve as their primary prey) associated with kelp forests. Because of their high diversity, California kelp forests are thought to be more resistant and resilient to disturbance than kelp forests elsewhere (Steneck *et al.*, 2002).

Stressors on Marine Ecosystems in the Channel Islands

Kelp forest communities are vulnerable to an array of stressors caused by human activities and natural environmental variation. Using data gathered by the Channel Islands National Park over a period of 20 years, Halpern and Cottenie (2007) documented overall declines in abundance of giant kelp communities over time. These declines were linked with commercial and recreational fishing in the Channel Islands. Overfishing reduces density and average individual size of targeted populations and, consequently, targeted species are more vulnerable to the effects of natural environmental variation. Overfishing also has cascading effects through the marine food web. In areas of the Channel Islands where lobster (*Panulirus interruptus*) and other top predators were fished, purple sea urchin (*Strongylocentrotus purpuratus*) populations were more abundant, overgrazing stands of giant kelp and other algae and resulting in barren reefs devoid of kelp and its associated species (Behrens and Lafferty, 2004).

Kelp forest communities also respond to natural environmental variations, such as increased storm intensity, ocean warming, and shifts in winds associated with ENSO events (Dayton *et al.*, 1992; Ladah, Zertuche-Gonzalez, and Hernandez-Carmona, 1999; Edwards, 2004). Storm intensity, which is known to increase during periods of ocean warming, damages kelp stocks and rips kelp holdfasts from their rocky substrate (Dayton *et al.*, 1992; 1999). In addition to the physical damage from storms, kelp growth may be suppressed by lower levels of nutrients due to relaxation of coastal wind activity and reduction of upwelling during ENSO events. Giant kelp forests were decimated during the intense ENSO event of 1982–83 and did not recover to their previous extent for almost two decades. Several other ENSO events, in 1992–93 and 1997–98 also diminished kelp growth. The effects of these ENSO events may have been compounded by a shift (Pacific Decadal Oscillation) in 1977 to a period of slightly warmer waters in the northeastern Pacific Ocean.

Dramatic declines of giant kelp communities are likely the consequence of cumulative impacts of human activities and natural environmental variation. Giant kelp forests in one marine reserve (where fishing has been prohibited since 1978) were more resilient to ocean warming, shifts in winds, and increased storm activity associated with ENSO (Behrens and Lafferty, 2004). Giant kelp forests in the reserve persisted over a period of 20 years, including several intense ENSO events. Kelp forests at all study sites outside of the reserve were overgrazed by dense populations of sea urchins, and their growth was further inhibited by warmer water, increased storm intensity, and lower levels of nutrients, leading to periodic die-backs to a barren reef state. These observations suggest that marine reserves can be used as a management tool to increase resilience of kelp forest communities.

Current Management of the Channel Islands

In 1999, the CINMS and the California Department of Fish and Game (CDFG) developed a partnership and public process (modeled after the Florida Keys National Marine Sanctuary) to consider the use of fully protected marine reserves to protect natural biological communities (Box A6.2). The cooperating agencies engaged a working group of stakeholders through the Sanctuary Advisory Council to evaluate the problem and develop potential solutions. The “Marine Reserves Working Group” developed a problem statement acknowledging that human activities and natural ecological changes contributed to the decline of marine communities in southern California. The working group determined that marine reserves should be established to protect marine habitats and species, to achieve sustainable fisheries and maintain long-term socioeconomic viability, and to protect cultural heritage. The stakeholders, working with marine scientists and economists, created a range of options for marine reserves to meet these goals. Subsequently, the CINMS and CDFG used the two most widely supported options to craft compromise solution that addressed the interests of a broad array of stakeholders.

In 2003, the CDFG established a network of 10 fully protected marine reserves and two conservation areas that allow limited commercial and recreational fishing (Fig. A6.5). The total area protected was 102 nm^2, approximately 10% of sanctuary waters. The marine reserves and conservation areas included a variety of representative marine habitats characteristic of the region, such as rocky intertidal habitats, sandy beaches, kelp forests, seagrass beds, soft bottom habitats, submerged rocky substrate, and submarine canyons. In 2006, the Pacific Fisheries Management Council designated Essential Fish Habitat to protect benthic communities from bottom contact fishing gear within and adjacent to the state marine protected areas, up to 6 nm offshore. In the same year, the CINMS released a Draft Environmental Impact Statement proposing complementary marine reserves and a marine conservation area extending into federal waters (Fig. A6.5). The Essential Fish Habitat designated by the Council and the marine protected areas proposed by the sanctuary increase the total area of protected marine zones to 19% of the CINMS.

In 2008, data from relevant monitoring programs will be prepared for a review by the California Fish and Game Commission of the first five years of monitoring the Channel Islands state marine reserves. Expectations are that species that were targeted by commercial or recreational fisheries will increase in density and size within marine reserves (Halpern, 2003). Some species are expected to decline if their predators or competitors increase in abundance.

Potential Effects of Climate Change on Ecosystems in the Channel Islands Region

Coastal SST has increased steadily (by approximately 2°C) since 1950 and is expected to increase further in the coming centuries (IPCC, 2007a). Water temperature affects metabolism and growth (Bayne, Thompson, and Widdows, 1973; Phillips, 2005), feeding behavior (Petraitis, 1992; Sanford, 1999; 2002), reproduction (Hutchins, 1947; Philippart *et al.*, 2003), and rates of larval development (Hoegh-Guldberg and Pearse, 1995; Anil, Desai, and Khandeparker, 2001; Luppi, Spivak, and Bas, 2003; O'Connor *et al.*, 2007) of intertidal and subtidal animals. Shifts in species ranges already have occurred in California with the steady increase of coastal sea surface temperature. The range boundary of *Kelletia kelletii* has shifted north from the late 1970s to the 2000s (Herrlinger, 1981; Zacherl, Gaines, and Lonhart, 2003). Southern species of anthozoans, barnacles, and gastropods increased in Monterey Bay, while northern species of anthozoans and limpets decreased between the 1930s (Hewatt, 1937) and the 1990s (Barry *et al.*, 1995; Sagarin *et al.*, 1999). Holbrook, Schmitt, and Stephens, Jr. (1997) documented an increase of 150% in southern species of kelp forest fish in southern California, and a decrease of 50% in northern species since the 1970s.

Increased ocean temperatures have been linked with outbreaks of marine disease (Hofmann *et al.*, 1999). Populations of black abalone (*Haliotis cracherodii*) in the Channel Islands and north along the California coast to Cambria suffered mass mortalities from “withering syndrome” caused by the intracellular prokaryote *Xenohaliotis californiensis*, between 1986 and 2001. Healthy populations of black abalone persist north of Cambria, where cool waters suppress the disease. Samples of red abalone (*Haliotis rufescens*) from populations around San Miguel Island in 2006 indicated that approximately 58% of the population carries *X. californiensis*, but the red abalone population persists in a thermal refuge within which temperatures are low enough to suppress the expression of the disease. The disease may be expressed during prolonged periods of warming (*e.g.*, over 18°C for several days) associated with ENSO or other warm-water events. In 1992, an ENSO year, an urchin-specific bacterial disease entered the Channel Islands region and spread through dense populations of purple sea urchin (*Strongylocentrotus pupuratus*). Sites located in a marine reserve where fishing was prohibited had more lobster (which prey on urchins), smaller populations of urchins, persistent forests of giant kelp, and a near absence of the disease.[72] During several warm-water events, including the ENSO of 1997–98, scientists observed and documented

[72] **Lafferty**, K.D. and D. Kushner, 2000: Population regulation of the purple sea urchin, *Strongylocentrotus purpuratus*, at the California Channel Islands. In: *Fifth California Islands Symposium*, Minerals Management Service, Santa Barbara, California, pp. 379-381.

declines of sea star populations at the Channel Islands due to epidemics of "wasting disease," which disintegrates the animals.

Increased temperature is expected to lead to numerous changes in currents and upwelling activity. As the sea surface warms, thermal stratification will intensify and become more stable, leading to reduced upwelling of cool, nutrient-rich water (Soto, 2001; Field *et al.*, 2001). Reduced upwelling will lead to a decline in primary productivity (McGowan *et al.*, 1998), suppression of kelp growth, and cascading effects through the marine food web.

Introductions of non-native species (such as the European green crab *Carcinus maenas* on the U.S. West Coast) are associated with rising temperatures and altered currents associated with ENSO events (Yamada *et al.*, 2005). The Sanctuary Advisory Council identified non-indigenous species as an emerging issue in the revised Sanctuary Management Plan (U.S. Department of Commerce, 2006). The sanctuary participated in the removal of a non-indigenous alga (*Undaria pinnatifida*) from the Santa Barbara Harbor, but the sanctuary does not support systematic monitoring or removal of non-indigenous species. Introduction of non-indigenous species can disrupt native communities, potentially leading to shifts in community structure.

Sea level may rise up to three feet in the next 100 years, depending on the concentrations of greenhouse gases during this period (Cayan *et al.*, 2006a; IPCC, 2007a). Projections of sea level rise around the Channel Islands indicate little encroachment of seawater onto land due to steep rocky cliffs that form the margins of the islands; however, projections of sea level rise indicate potential saltwater intrusion into low-lying coastal areas such as the Santa Barbara Harbor (where the CINMS Headquarters is located) and the Channel Islands Harbor (where the sanctuary's southern office is located). Changes in sea level may affect the type of coastal ecosystem (Hoffman, 2003). Graham, Dayton, and Erlandson (2003) suggested that sea level rise transformed the Southern California Bight from a productive rocky coast to a less productive sandy coast more than 18,000 years ago.

The severity of storm events is likely to increase with climate change (IPCC, 2001). As described above, storm activity damages kelp stocks and pulls kelp holdfasts from the substrate (Dayton *et al.*, 1992; 1999). Frequent and intense storm activity during the 1982–83 ENSO event decimated populations of giant kelp that once formed extensive beds attached to massive old kelp holdfasts in sandy areas along the mainland coast. Since the old kelp holdfasts were displaced from the mainland coast, young kelp plants have been unable to attach to the sandy substrate and the coastal kelp forests have not returned. At the Channel Islands, kelp forests that were destroyed during the same ENSO event have slowly returned to the rocky reefs around the Channel Islands, particularly following a Pacific Decadal Oscillation to cooler waters in 1998.

A Shared Vision for the Channel Islands

The CINMS manager and staff work closely with the Sanctuary Advisory Council to identify and resolve resource management issues. As noted above, the Sanctuary Advisory Council consists of representatives from local, state, and federal agencies, which share jurisdiction of resources within the Channel Islands region, and stakeholders with interests in those resources. The Sanctuary Advisory Council offers a unique opportunity to focus attention of regional agencies and stakeholders on the potential threats associated with climate change and to develop a shared vision for how to respond.

The Sanctuary Management Plan (U.S. Department of Commerce, 2006) describes a strategy to work in a coordinated, complementary, and comprehensive manner with other authorities that share similar or overlapping mandates, jurisdiction, objectives, and/or interests. The sanctuary is poised to take a leading role to bring together the relevant agencies and stakeholders to discuss the issue of climate change. The sanctuary can initiate an effort to develop regional plans to adapt to a modified landscape and seascape predicted from climate change models, and mitigate the negative impacts of climate change.

A6.4.2 Management of the Channel Islands National Marine Sanctuary

The Sanctuary Management Plan (U.S. Department of Commerce, 2006) for the CINMS mentions but does not fully address the issue of climate change, with one exception in the strategy for offshore water quality monitoring. The strategy is to better evaluate and understand impacts on water quality from oceanographic and climatic changes and human activities. The proposed actions include continued vessel and staff support for monitoring projects related to water quality. To evaluate the potential impacts of climate change, the sanctuary staff could expand monitoring of—or collaborate with researchers who are monitoring—ocean water temperature, currents, dissolved oxygen, and pH at different depths.

The Sanctuary Management Plan (U.S. Department of Commerce, 2006) describes a strategy to identify, assess, and respond to emerging issues. The plan explicitly identifies noise pollution, non-indigenous species, and marine mammal strikes as emerging issues. Other emerging issues that are not addressed by the management plan, but should be, include ocean warming, sea level rise, shifts in ocean circulation, ocean acidification, spread of disease, and shifts in species ranges.

The Sanctuary Management Plan (U.S. Department of Commerce, 2006) outlined a potential response to emerging issues through consultation with the Sanctuary Advisory Council and local, state, or federal agencies with a leading or shared authority for addressing the issue. With the elevated level of certainty associated with climate change projections (IPCC, 2007a), it is appropriate to bring the topic of climate change to the Sanctuary Advisory Council and begin working with local, state, and federal agencies that share authority in the region to plan for potential impacts of climate change. Regional agency managers may consider and develop strategies to respond to the potential impacts of:

- Ocean warming (contributing to potential shifts in species ranges, changes in metabolic and physiological processes, and accelerated spread of disease);
- Ocean acidification (leading to breakdown of calcareous accretions in corals and shells);

- Shifts in ocean circulation (leading to changes in upwelling activity and possible formation of low oxygen zones); and
- Sea level rise (shifting jurisdictional boundaries, displacing terrestrial and intertidal organisms, leading to salt-water inundation of coastal marshes, lagoons and estuaries, and increasing coastal flood events).

Monitoring and Research in the Channel Islands Region

Monitoring and research are critical for detecting and understanding the effects of climate and ocean change. The Sanctuary Management Plan (U.S. Department of Commerce, 2006) outlines strategies for monitoring and research in the coming years, but the plan does not address climate and ocean change specifically. The current strategies for monitoring and research can be refocused slightly to capture important information about climate and ocean change.

Monitoring of algae, invertebrates, and fishes is needed within and around marine reserves to detect differences between protected and targeted populations in their responses to climate change. One hypothesis is that populations within marine reserves will be more resilient to the effects of climate change than those that are altered by overfishing and other extractive uses. In addition, scientists have determined that local environmental variation causes different populations to respond in different ways to ocean warming (*e.g.*, Helmuth *et al.*, 2006). For example, a population of red abalone at San Miguel Island lives in a “thermal refuge” where waters are cooled by upwelling, preventing spread of disease that is carried in the population. Sustained ocean warming is likely to increase thermal stress of individuals in this population and accelerate the spread of disease through affected populations. Monitoring can be used to detect such changes at individual, population, and regional levels. The CINMS has the capacity to support subtidal monitoring activities from the *RV Shearwater*, aerial surveys of kelp canopy from the sanctuary aircraft, and collaborative research projects with scientists and fishermen.

In addition to the ecological monitoring in marine reserves, it will be critical to monitor environmental variables, including ocean water temperature, sea level, currents, dissolved oxygen, and pH at different depths. Any change in these variables should trigger more intensive monitoring to evaluate the ecological impacts of ocean warming, sea level rise, shifts in current patterns, low oxygen, and increased acidification. The sanctuary could benefit from partnerships with scientists who are monitoring ocean changes and who have the capability of ramping up research activities in response to observed changes. For example, before 2002, scientists at Oregon State University, Corvallis, routinely monitored temperature and salinity at stationary moorings off the coast of Oregon. When they detected low oxygen during routine monitoring in 2002, the scientists intensified their monitoring efforts by increasing the number of temperature and salinity sensors and adding oxygen sensors (which transmit data on a daily basis) near the seafloor at a number of locations along the coast. In this way, the scientists can quantify the scope and duration of hypoxic events, which have recurred off the coast of Oregon during the past five years (Barth *et al.*, 2007).

The Sanctuary Management Plan (U.S. Department of Commerce, 2006) describes the need for analysis and evaluation of information from sanctuary monitoring and research. Working with local educational institutions and the National Center for Ecological Analysis and Synthesis, the sanctuary could develop the capacity to catalog and analyze spatial data (maps) that characterize the coastline of the sanctuary and the extent of kelp canopy within the sanctuary, among other types of information. To detect the ecological impacts of climate change, the information from sanctuary monitoring and research should be reviewed at regular intervals (at least annually) by collaborating scientists (such as the Sanctuary Advisory Council's Research Activities Panel), sanctuary staff, and the sanctuary manager. The annual review should compare data from the current year with previous years, from areas inside marine reserves and in surrounding, fished areas. Ecological changes should be placed within the context of El Niño-Southern Oscillation and La Niña cycles and shifts associated with the Pacific Decadal Oscillation. Changes in fisheries or other management regulations also should be considered as part of the evaluation. Any significant shifts away from predictable trends should trigger further evaluation of the data in an effort to understand local and regional ecosystem dynamics and any possible links to climate change.

Communication in the Channel Islands Region

Public awareness and understanding are paramount in the discussion about how to adapt to climate change. The education and outreach strategies described in the Sanctuary Management Plan (U.S. Department of Commerce, 2006) do not focus on the issue of climate change but, with a slight shift in focus, the existing strategies can be used to increase public awareness and understanding of the causes and impacts of climate change on ocean ecosystems. Key strategies are to educate teachers, students, volunteers, and the public using an array of tools, including workshops, public lectures, the sanctuary website and weather kiosks, and a sanctuary publication and brochure, among others. Opportunities to focus the sanctuary education program's activities and products on the issue of climate change include the following:

- Integrate information about climate change into volunteer Sanctuary Naturalist Corps and adult education programs;
- Update the sanctuary website and weather kiosks with information about causes and impacts of climate change;
- Produce a special issue of the sanctuary publication, *Alolkoy*, about the current scientific understanding of climate change and potential impacts on sanctuary resources;
- Develop a brochure about climate change to help members of the community identify opportunities to reduce their contributions to greenhouse gases and other stressors that exacerbate the problem of climate change;
- Expand the sanctuary's Ocean Etiquette program[73] to include consideration and mitigation of individual activities that contribute to climate change;
- Host a teacher workshop on the subject of climate change;

[73] http://sanctuaries.noaa.gov/protect/oceanetiquette.html

- Prepare web-based curriculum with classroom exercises and opportunities for experiential learning about climate change; and

Partner with local scientists who study climate change to give public lectures and engage students in monitoring climate change.

A6.5 Conclusions about Marine Protected Area Case Studies

The Great Barrier Reef Marine Park has been examined along with the National Marine Sanctuary case studies because it is an example of an MPA that has a relatively highly developed climate change program in place. A Coral Bleaching Response Plan is part of its Climate Change Response Program, which is linked to a Representative Areas Program and a Water Quality Protection Plan in a comprehensive approach to support the resilience of the coral reef ecosystem. In contrast, the Florida Keys National Marine Sanctuary is only now developing a bleaching response plan. The Florida Reef Resilience Program, under the leadership of The Nature Conservancy, is implementing a quantitative assessment of coral reefs before and after bleaching events. The recently established Papahānaumokuākea (Northwestern Hawaiian Islands) Marine National Monument is the largest MPA in the world and provides a unique opportunity to examine the effects of climate change on a nearly intact large-scale marine ecosystem. These three MPAs consist of coral reef ecosystems, which have experienced coral bleaching events over the past two decades.

The Sanctuary Management Plan for the Channel Islands National Marine Sanctuary mentions, but does not fully address, the issue of climate change. The Plan describes a strategy to identify, assess, and respond to emerging issues through consultation with the Sanctuary Advisory Council and local, state, or federal agencies. Emerging issues that are not yet addressed by the management plan include ocean warming, sea level rise, shifts in ocean circulation, ocean acidification, spread of disease, and shifts in species ranges.

Barriers to implementation of adaptation options in MPAs include lack of resources, varying degrees of interest in and concern about climate change impacts, and a need for basic research on marine ecosystems and climate change impacts. National Marine Sanctuary Program staff are hard-pressed to maintain existing management programs, which do not yet include explicit focus on effects of climate change. While the Program's strategic plan does not address climate change, the Program has recently formed a Climate Change Working Group that will be developing recommendations. Although there is considerable research on physical impacts of climate change in marine systems, research on biological effects and ecological consequences is not as well developed.

Opportunities with regard to implementation of adaptation options in MPAs include a growing public concern about the marine environment, recommendations of two ocean commissions, and an increasing dedication of marine scientists to conduct research that is relevant to MPA management. References to climate change as well as MPAs permeate both the Pew Oceans Commission and U.S. Commission on Ocean Policy reports on the state of the oceans. Both commissions held extensive public meetings, and their findings reflect changing public perceptions and attitudes about protecting marine resources from threats of climate change. The interests of the marine science community have also evolved, with a shift from “basic” to “applied” research over recent decades. Attitudes of MPA managers have changed as well, with a growing recognition of the need to better understand ecological processes in order to implement science-based adaptive management.

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A8 Boxes

Box A2.1. Definition of Wilderness

A wilderness, in contrast with those areas where man and his own works dominate the landscape, is hereby recognized as an area where the earth and its community of life are untrammeled by man, where man himself is a visitor who does not remain. For the purposes of this chapter, an area of wilderness is further defined to mean an area of undeveloped Federal land retaining its primeval character and influence, without permanent improvements or human habitation, which is protected and managed so as to preserve its natural conditions and which (1) generally appears to have been affected primarily by the forces of nature, with the imprint of man's work substantially unnoticeable; (2) has outstanding opportunities for solitude or a primitive and unconfined type of recreation; (3) has at least five thousand acres of land or is of sufficient size as to make practicable its preservation and use in an unimpaired condition; and (4) may also contain ecological, geological, or other features of scientific, educational, scenic, or historical value.[74]

[74] 16 U.S. C. 1131-1136 P.L. 88-577

Box A2.2. Opportunities and Barriers for Rocky Mountain National Park in Adapting to Climate Change

Opportunities:

- Cadre of highly trained natural resource professionals
- Extensive scientifically grounded knowledge of many natural resources and processes
- Continental Divide Learning Center serves as hub of learning and training
- Plan to establish a Science Advisory Board
- Climate Friendly Parks Program has enhanced climate change awareness
- Good working relations with city, county, state, and federal land and resource managers
- RMNP is surrounded on nearly all sides by protected national forest lands, including wilderness.
- Regionally, mountain and high valley lands to the north, west, and south of RMNP are mostly publicly owned and protected, or sparsely populated ranch and second home developments.
- RMNP is a headwater park and controls most of the water rights within its boundaries. As such, it has direct control over its aquatic ecosystems and water quality.

Barriers:

- Insufficient knowledge about individual species' status and trends
- Limited opportunity for long-term strategic planning
- Limited interagency coordination of management programs
- The large and growing urban, suburban, exurban Front Range urban corridor may hinder migration of species into or out of RMNP from the Great Plains and Foothills to the east.

Box A4.1. Climate Change, Multiple Stressors and WSRs

Examples are provided to illustrate categories of change and common complicating factors; however, a very large number of combinations are expected around the United States and some of the complicating factors may be present in all regions (*e.g.*, invasive species). See the WSR Case Studies for literature citations.

Dominant Climate Change	*Examples of Climate Change Impacts*	*Common Complicating Stressors*	*Example of Region*	*Case study*
More flooding	Flood mortality, channel erosion, poor water quality	Development in watershed	Northeast, Upper Midwest	Upper Delaware
Droughts, intense heat	Drought mortality, shrinking habitat, fragmentation	Over-extraction of water Invasive Species	Southwest	Rio Grande
Little change in rainfall, moderately warmer	Impacts modest unless complicating stressors	Development in watershed	Northern Florida, Mississippi, parts of middle and western states	Wekiva River

Box A4.2. Migratory Fish

Many fish species are anadromous and adapted to cooler waters—living much of their lives in oceans, but migrating inland to spawn in colder reaches of freshwaters. Several species of salmon and sturgeon reproduce in the rivers of Alaska and the Pacific Northwest, while others, including Atlantic salmon, sturgeon, and striped bass, spawn in eastern seaboard rivers from the Rio Grande to the Canadian coast. Many of these species were also introduced to the Great Lakes, where they migrate up many of Michigan's WSRs. Such species played a significant role in the establishment of the Wild and Scenic Rivers Act and continue to be a primary focus in the management of WSRs. The life cycles of most of these species are determined largely by water temperatures and flows, driven by snowmelt or low water in the summer and fall.

Anadromous fish in the United States are exposed to several anthropogenic stressors that may be exacerbated by climate change. Dams impede or prevent fish migrations, including dams upstream of river stretches designated "wild and scenic." Water withdrawals and reservoir management have affected flow regimes, and water temperatures and pollutants—combined with increased sediment loads—have made many rivers uninhabitable for some migratory fish.

Climate change effects, including reduced streamflows, higher water temperatures, and altered frequencies and intensities of storms and droughts, will further degrade fish habitat (Climate Impacts Group, University of Washington, 2004). Battin et al. (2007) estimate a 20–40% decline in populations of Chinook salmon by 2050 due to higher water temperatures degrading thermal spawning habitat, and winter and early spring floods scouring riverbeds and destroying eggs. This may be a conservative estimate since the analysis did not address the effects that increased sea levels and ocean temperatures would have on Chinook during the oceanic phase of their life cycle, and the study focused on the run of Chinook salmon that spawns in late winter or spring and migrates to the sea by June. Yearlings that remain in freshwater throughout the summer months may be even more vulnerable.

Fish habitat restoration efforts are widespread throughout the United States. However, the models used to guide restoration efforts rarely include projected impacts of climate change. Nevertheless, Chinook salmon studies suggest that habitat restoration in lower elevation rivers (including reforesting narrow reaches to increase shade and decrease water temperatures) may reduce the adverse impacts of climate change (Battin *et al.*, 2007). Galbraith *et al.*(forthcoming) also identify the potential importance of releases of cool water from existing dams for the preservation of thermal spawning and rearing habitat. Also, mitigating watershed-level anthropogenic stressors that could exacerbate climate change impacts (*e.g.*, water withdrawals, pollutants) could be an effective adaptation option.

Ultimately, management of anadromous fish in WSR will need to reflect species and local circumstances. However, including climate change projections in habitat restoration plans, working to mitigate human-induced stressors, and implementing effective monitoring programs will likely be three of the most important actions managers can take to facilitate the adaptation of anadromous fish to climate change.

Box A5.1. CCMP Objectives for the Albemarle-Pamlico National Estuary Program

Water Quality Plan
GOAL: Restore, maintain or enhance water quality in the Albemarle-Pamlico region so that it is fit for fish, wildlife and recreation.

- Objective A: Implement a comprehensive basinwide approach to water quality management.
- Objective B: Reduce sediments, nutrients and toxicants from nonpoint sources.
- Objective C: Reduce pollution from point sources, such as wastewater treatment facilities and industry.
- Objective D: Reduce the risk of toxic contamination to aquatic life and human health.
- Objective E: Evaluate indicators of environmental stress in the estuary and develop new techniques to better assess water quality degradation.

Vital Habitats Plan
GOAL: Conserve and Protect Vital Fish and Wildlife Habitats and Maintain the Natural Heritage of the Albemarle-Pamlico Sounds Region.

- Objective A: Promote regional planning to protect and restore the natural heritage of the A/P Sounds region.
- Objective B: Promote the responsible stewardship, protection and conservation of valuable natural areas in the A/P Sounds region.
- Objective C: Maintain, restore and enhance vital habitat functions to ensure the survival of wildlife and fisheries.

Fisheries Plan
GOAL: Restore or Maintain Fisheries and Provide for Their Long-Term, Sustainable Use, Both Commercial and Recreational.

- Objective A: Control overfishing by developing and implementing fishery management plans for all important estuarine species.
- Objective B: Promote the use of best fishing practices that reduce bycatch and impacts on fisheries habitats.

Stewardship Plan
GOAL: Promote Responsible Stewardship of the Natural Resources of the Albemarle-Pamlico Sounds Region.

- Objective A: Promote local and regional planning that protects the environment and allows for economic growth.
- Objective B: Increase public understanding of environmental issues and citizen involvement in environmental policy making.
- Objective C: Ensure that students, particularly in grades K-5, are exposed to science and environmental education.

Implementation Plan
GOAL: Implement the Comprehensive Conservation and Management Plan in a way that protects environmental quality while using the most cost-effective and equitable strategies.

- Objective A: Coordinate public agencies involved in resource management and environmental protection to implement the recommendations of the CCMP.
- Objective B: Assess the progress and success of implementing CCMP recommendations and the status of environmental quality in the Albemarle-Pamlico Sounds region.

Box A6.1. Goal and Objectives of the Florida Keys National Marine Sanctuary (U.S. Department of Commerce, 1996)

Goal:
To preserve and protect the physical and biological components of the South Florida estuarine and marine ecosystem to ensure its viability for the use and enjoyment of present and future generations.

Objectives Required by the FKNMS Act:

Objective 1. Facilitate all public and private uses of the Sanctuary consistent with the primary objective of resource protection.

Objective 2. Consider temporal and geographic zoning to ensure protection of Sanctuary resources.

Objective 3. Incorporate regulations necessary to enforce the Water Quality Protection Program.

Objective 4. Identify needs for research and establish a long-term ecological monitoring program.

Objective 5. Identify alternative sources of funding needed to fully implement the management plan's provisions and supplement appropriations authorized under the FKNMS and National Marine Sanctuaries Acts.

Objective 6. Ensure coordination and cooperation between Sanctuary managers and other federal, state, and local authorities with jurisdiction within or adjacent to the Sanctuary.

Objective 7. Promote education among users of the Sanctuary about coral reef conservation and navigational safety.

Objective 8. Incorporate the existing Looe Key and Key Largo National Marine Sanctuaries into the FKNMS.

Objectives Developed by the FKNMS Sanctuary Advisory Council:

Objective 1. Encourage all agencies and institutions to adopt an ecosystem and cooperative approach to accomplish the following objectives, including the provision of mechanisms to address impacts affecting Sanctuary resources, but originating outside the boundaries of the Sanctuary.

Objective 2. Provide a management system that is in harmony with an environment whose long-term ecological, economic, and sociological principles are understood, and which will allow appropriate sustainable uses.

Objective 3. Manage the FKNMS for the natural diversity of healthy species, populations, and communities.

Objective 4. Reach every single user of and visitor to the FKNMS with information appropriate to his or her activities.

Objective 5. Recognize the importance of cultural and historical resources, and managing these resources for reasonable, appropriate use and enjoyment.

Box A6.2. Timeline for Establishment of Marine Reserves in the Channel Islands National Marine Sanctuary (CINMS)

- 1998: Sportfishing group initiates discussions about marine reserves in the Channel Islands National Marine Sanctuary
- 1999: California Department of Fish and Game and NOAA develop partnership and initiate community-based Marine Reserves Working Group process
- 2001: Working Group recommendations delivered to California Department of Fish and Game and NOAA
- 2003: California Fish and Game Commission established 10 state marine reserves and 2 state marine conservation areas established in state waters of the CINMS
- 2006: Pacific Fisheries Management Council designated Essential Fish Habitat and Habitat of Areas of Particular Concern in adjacent federal waters of the CINMS prohibiting bottom fishing
- 2006: Sanctuary released Draft Environmental Impact Statement to propose marine reserves in federal waters of the CINMS.
- 2007: Pending - NOAA will release Final Environmental Impact Statement and final rule to complete the marine reserves in federal waters
- 2007: Pending - California Fish and Game Commission will take regulatory action to close gaps between state and federal marine protected areas

A9 Tables

Table A1.1. Case Study Outline Foci for the ONF: current ecosystem stresses, management goals, current management methods, and climate change impacts

Current ecosystem stresses	Management goal(s)	Current methods	Climate impacts on ecosystems and management practices
Historical timber harvest impacts on landscape	Promote species and landscape biodiversity Increase late seral habitat Protect old-growth dependent species	Silvicultural treatment to achieve a broad range of habitats for native species Silvicultural treatments to increase rate of "old growth" structure development Same as above	Depends on how area and frequency of disturbances changes (windthrow, fire, endemic/exotic insect/pathogen outbreaks). Increases in the above, and their interactions, in ONF per se are understudied because they have not been large problems. All are climate mediated, and could become so, but unknown impact on management practices. Currently, the main disturbance legacy on ONF is 20th century logging.
Aquatic ecosystem degradation	Restore aquatic ecosystems to conditions that support endangered species	Riparian restoration, culvert rehabilitation	Warming waters, changes in timing of seasonal snow/rain/runoff will increase need for restoration, but potentially limit its success rate as well.
Impacts of unmaintained, closed roads	Remove potential effects of unmaintained roads	Road restoration / rehabilitation; occasionally removal	If intense storms, flooding, or rain-on-snow events increase in frequency, closed road failures will likely increase in frequency. Multiple failures on the same road limit response/access. This will require substantial investment in new management efforts.
Invasive exotic species	Limit spread of new invasives Treat established invasive species	Preventive educ./strategies Treatment limited to hand pulling in most locations; herbicide where permitted.	If disturbances or recreational travel increase or if climate changes the competitive balance between natives and exotics , efficacy of current strategies uncertain
Endemic Insects	Currently none	Monitoring	Uncertain
Fire	Currently none	Suppression (rare)	Depends on interplay between climate-mediated fire and climate-mediated regeneration

Table A3.1. The annual cycle of migratory waterfowl that breed in Alaska may serve as an integrative focus for development of a national vision of climate effects and management adaptation options for the National Wildlife Refuge System. The complexity of potential interactions among locations, life history stages, climate mechanisms, non-climate stressors, and options for management adaptation for migratory waterfowl that breed in Alaska demonstrates that inter-regional assessment and timely communication will be essential to the development of a national vision.

Location	**Life History**	**Climate Mechanisms**	**Non-Climate Stressors**	**Adaptation Options**
Alaska	Production: *Breeding* *Fledging*	Early Thaw: *Resource access* *Habitat area* *Season length*	Minimal	Assess System Predict Collaborate Facilitate
Prairie Potholes (*Central Flyway*)	Staging: *Energy reserves*	Late Freeze: *Habitat distribution* *Migration timing* *Harvest distribution*	Land use Crop mix Disturbance Alternate Energy Sources	Assess System Predict Partnerships Secure Network
Southern United States	Wintering: *Survival* *Nutrition*	Sea Level: *Habitat access* Storms: *Frequency, Intensity*	Urbanization Fragmentation Pollution	Partnerships Education Acquisition Adaptive Mgmt.

A10 Figures

Figure A1.1. Map and location of the Tahoe National Forest, within California (a) and the Forest boundaries (b).[1]

a)

1 b)


Tahoe NF
District Boundary
Major Road
Pacific Crest Trail
Ranger Station
Visitor Center
Sierraville
Sierraville District
Camptonville
Yuba River District
Truckee
Big Bend
Truckee District
Nevada City
American River District
Foresthill

2

Figure A1.2. Thinned stands for fuel reduction and resilience management, part of the Herger-Feinstein Quincy Library Pilot Project. Photo courtesy of Tahoe National Forest.

Figure A1.3. Former salmon habitat (rivers marked in bold black) of the Sierra Nevada. Tahoe National Forest (TNF) rivers are scheduled to have salmon restored to them in current national forest planning. Adaptive approaches suggest that future waters may be too warm on the TNF for salmon to survive, and thus, restoration may be inappropriate to begin. Map adapted from (Sierra Nevada Ecosystem Project Science Team, 1996).

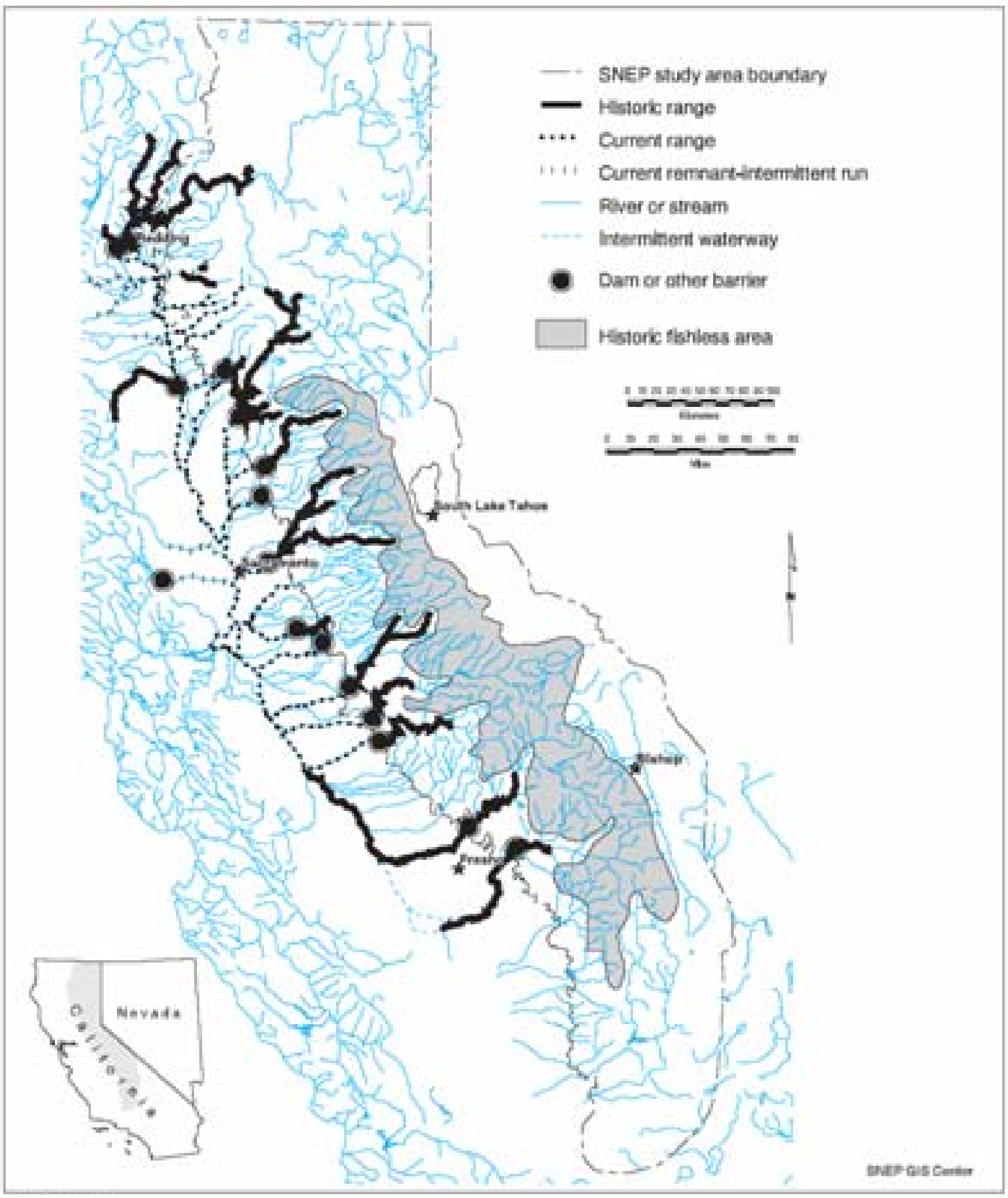

FIGURE 33.1

Figure A1.4. Olympic Peninsula land ownership and Northwest Forest Plan allocation map. Olympic National Forest contains lands (dark boundary) with different land use mandates and regulations. These include adaptive management areas, late-successional reserves, and Wilderness areas. Map courtesy of Robert Norheim, Climate Impacts Group, University of Washington.

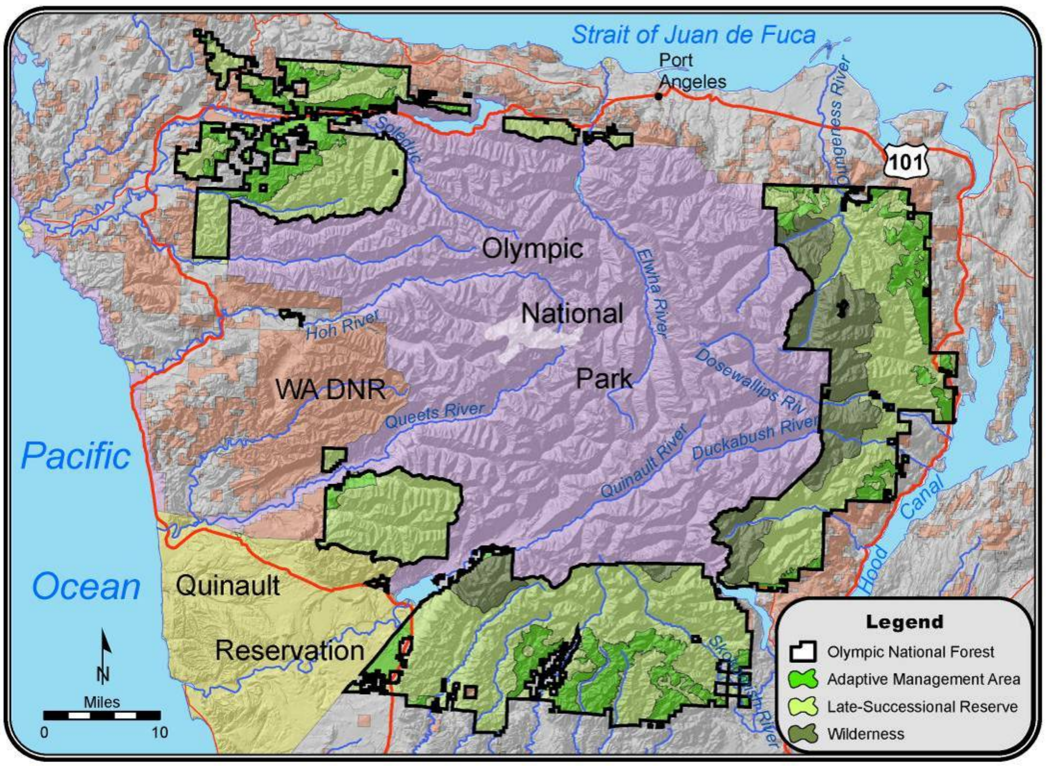

Figure A1.5. Olympic National Forest is charged with mitigating the legacy of 20th century timber harvest. Landscape fragmentation and extensive road networks (upper left) are consequences of this legacy that influence strategies for adaptation to climate change. The old-growth forest dependent northern spotted owl (upper right) is one focus of the NWFP, which prescribes forest practices but does not address climatic change. Changes in the timing and intensity of runoff expected with climate change are likely to interact with this legacy to have negative impacts on unmaintained roads (lower left) that in turn will impact water quality for five threatened or endangered species of anadromous and resident fish. Photo Credits: All photos courtesy Olympic National Forest.

1 **Figure A1.6.** Map of the Uwharrie National Forest in North Carolina.[7]

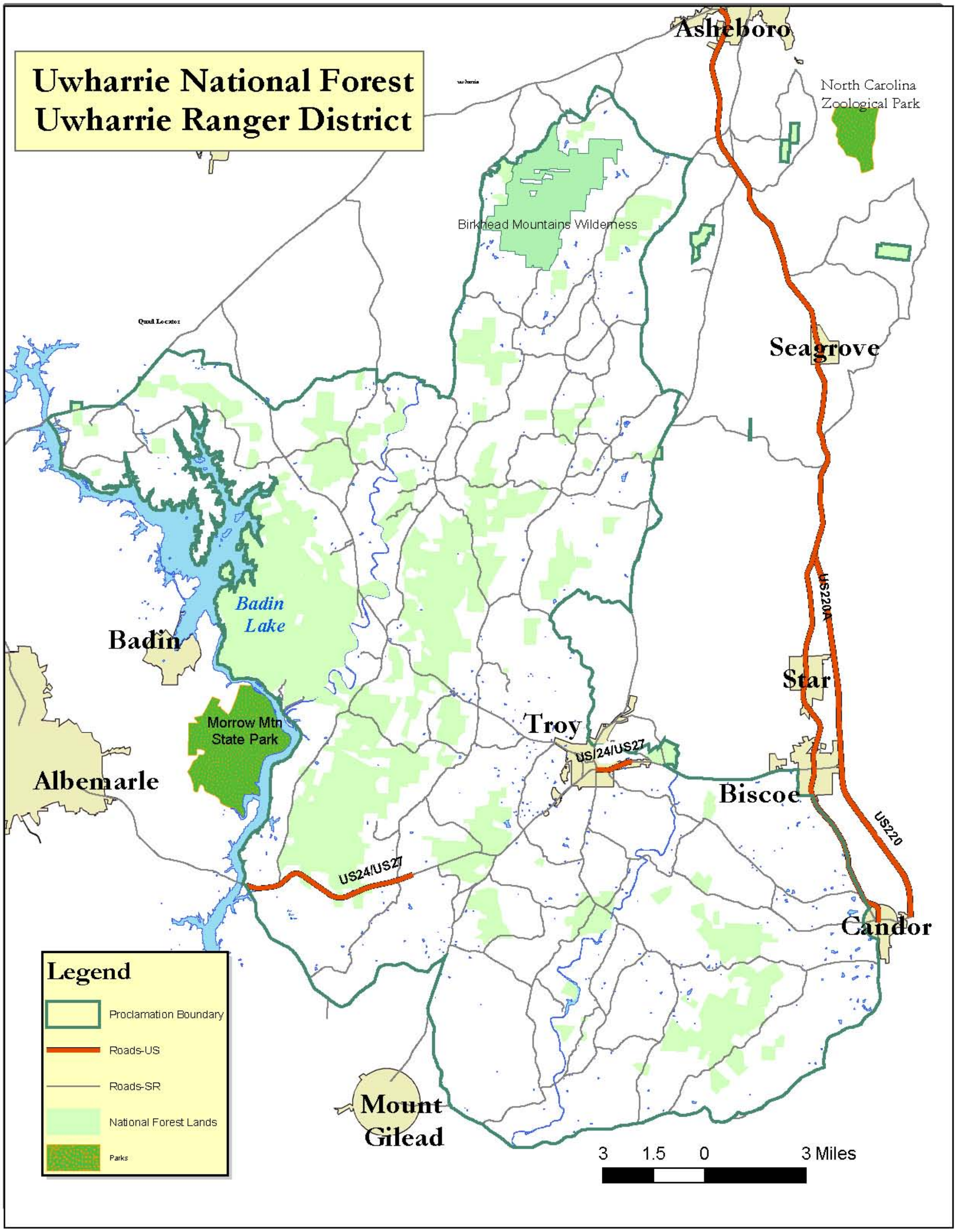

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Figure A2.1. Photos of Arapahoe Glacier in 1898 and 2004.[12]

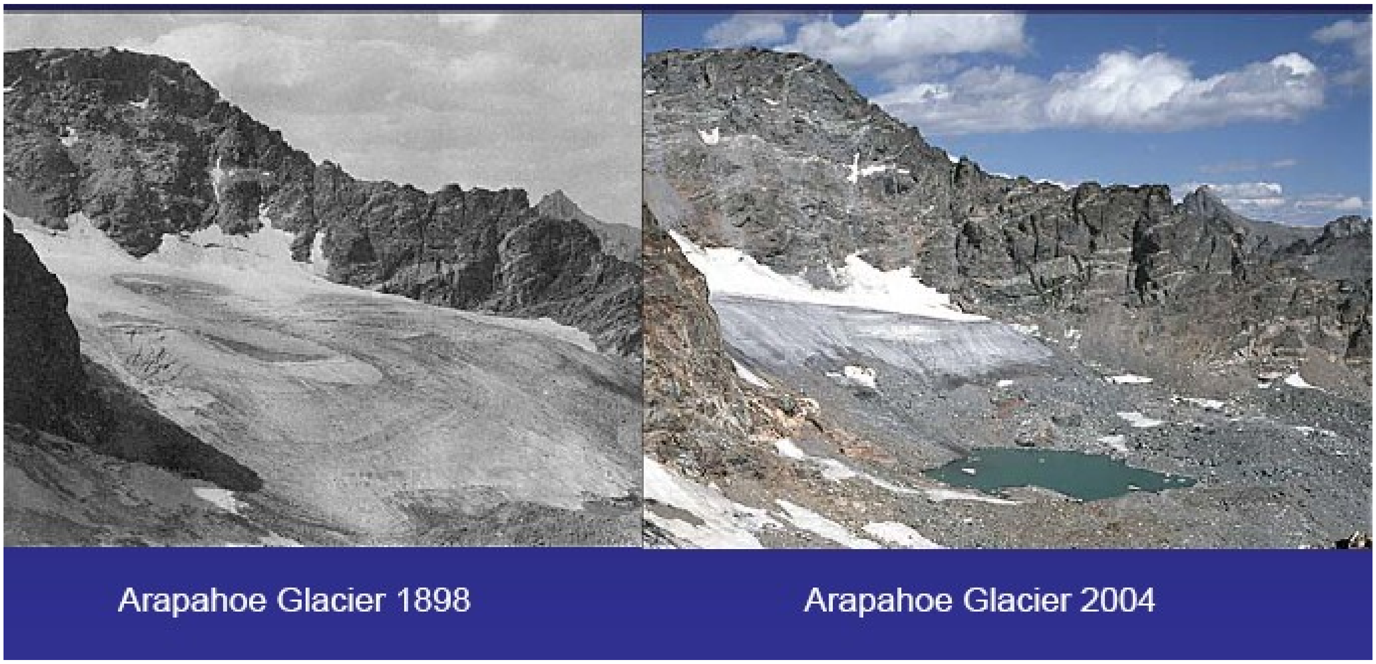

Figure A2.2. Photo pair of Rowe Glacier, with permissions, NSIDC and leachfam website.[13]

1 **Figure A3.1.** Central Flyway Waterfowl Migration Corridor.[17]

2

Figure A3.2. Heterogeneity in closed-basin lakes with increasing and decreasing surface area, 1950–2000, Yukon Flats NWR, Alaska. Net reduction in lake area was 18% with the area of 566 lakes decreasing, 364 lakes increasing, and 462 lakes remaining stable. Adapted from Riordan, Verbyla, and McGuire (2006).

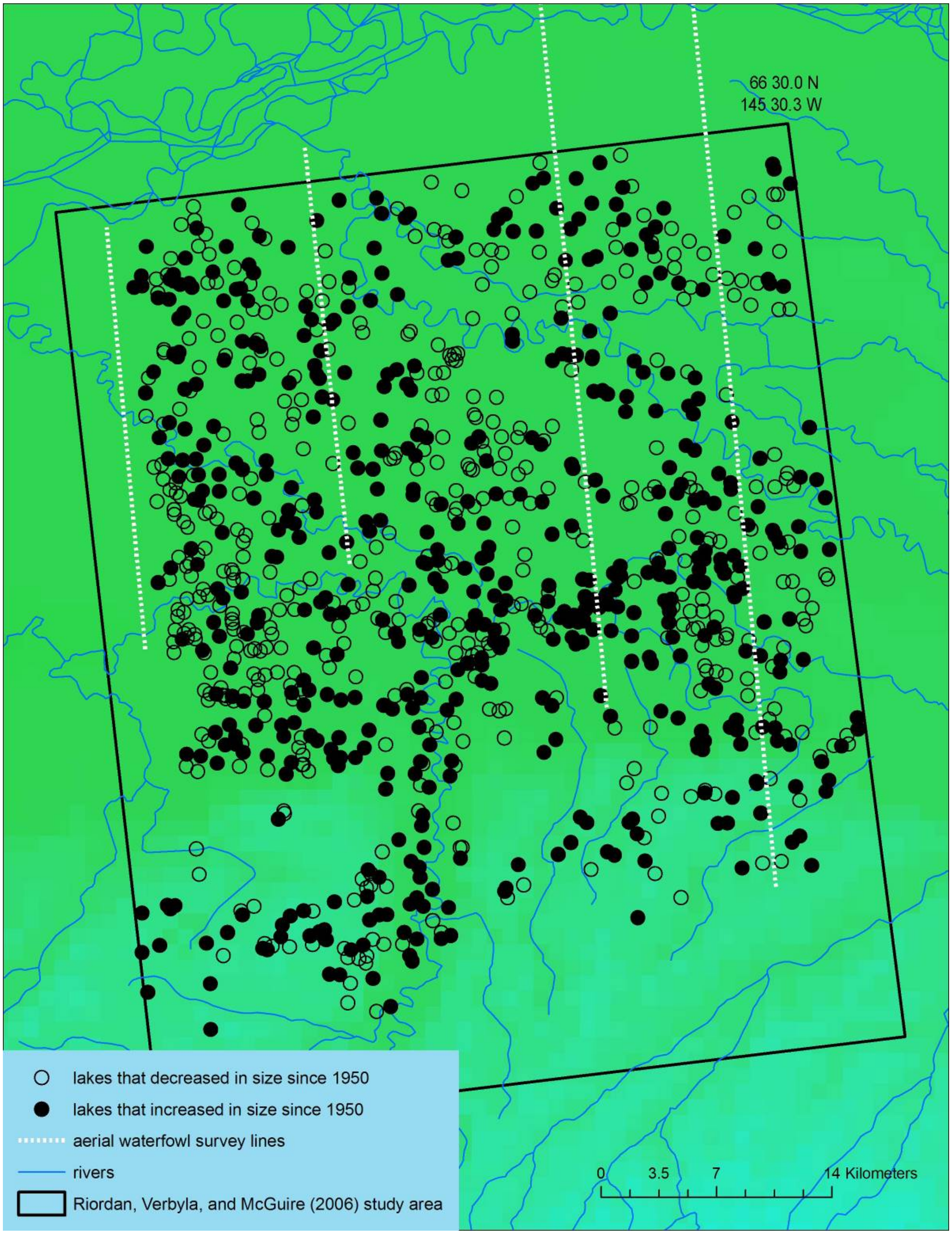

Figure A4.1. The Wild and Scenic portions of the Wekiva River. Data from USGS, National Atlas of the United States.[20]

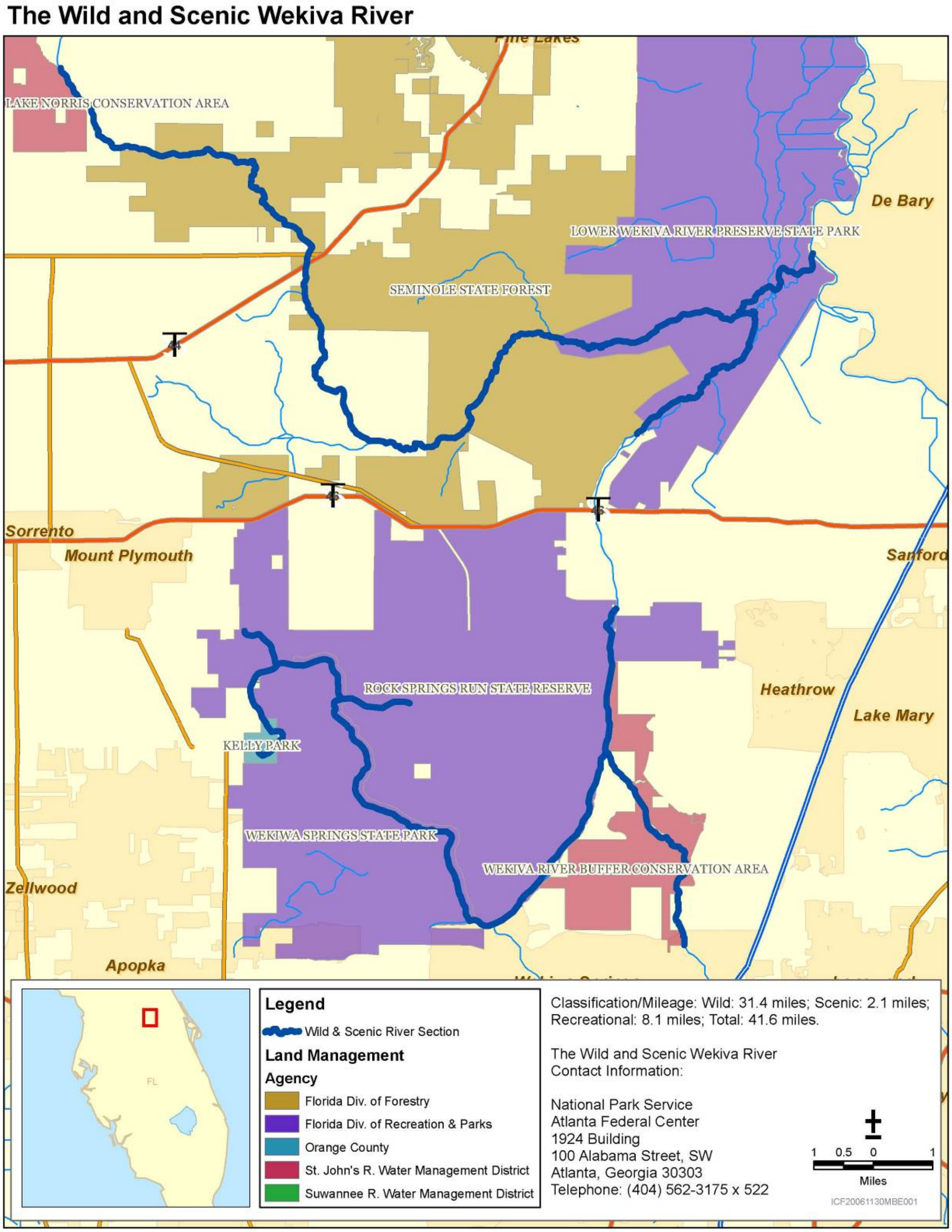

Figure A4.2. The Wild and Scenic portions of the Rio Grande WSR in New Mexico. Data from USGS, National Atlas of the United States.[20]

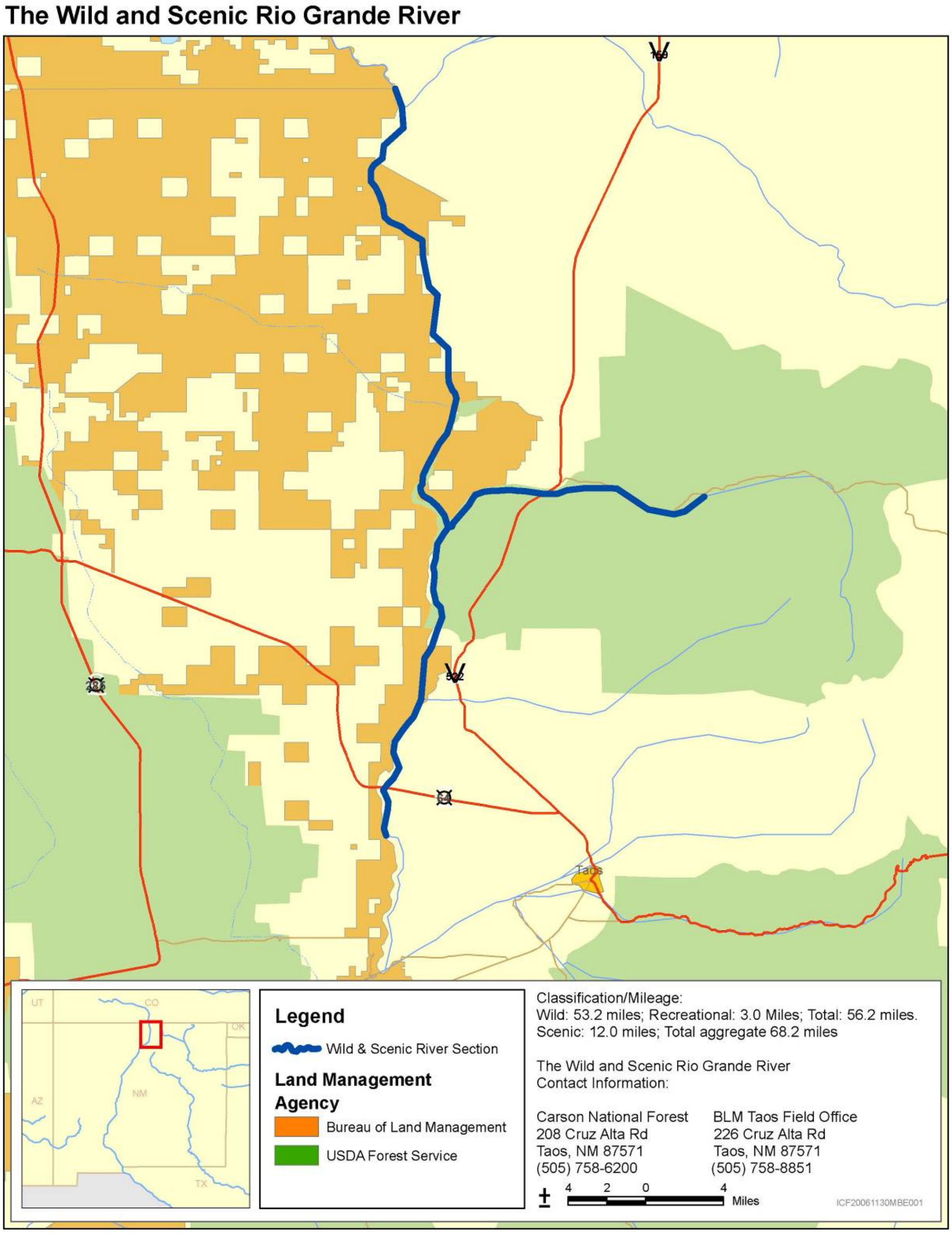

Figure A4.3. The Wild and Scenic portions of the Rio Grande WSR in Texas. Data from USGS, National Atlas of the United States.[20]

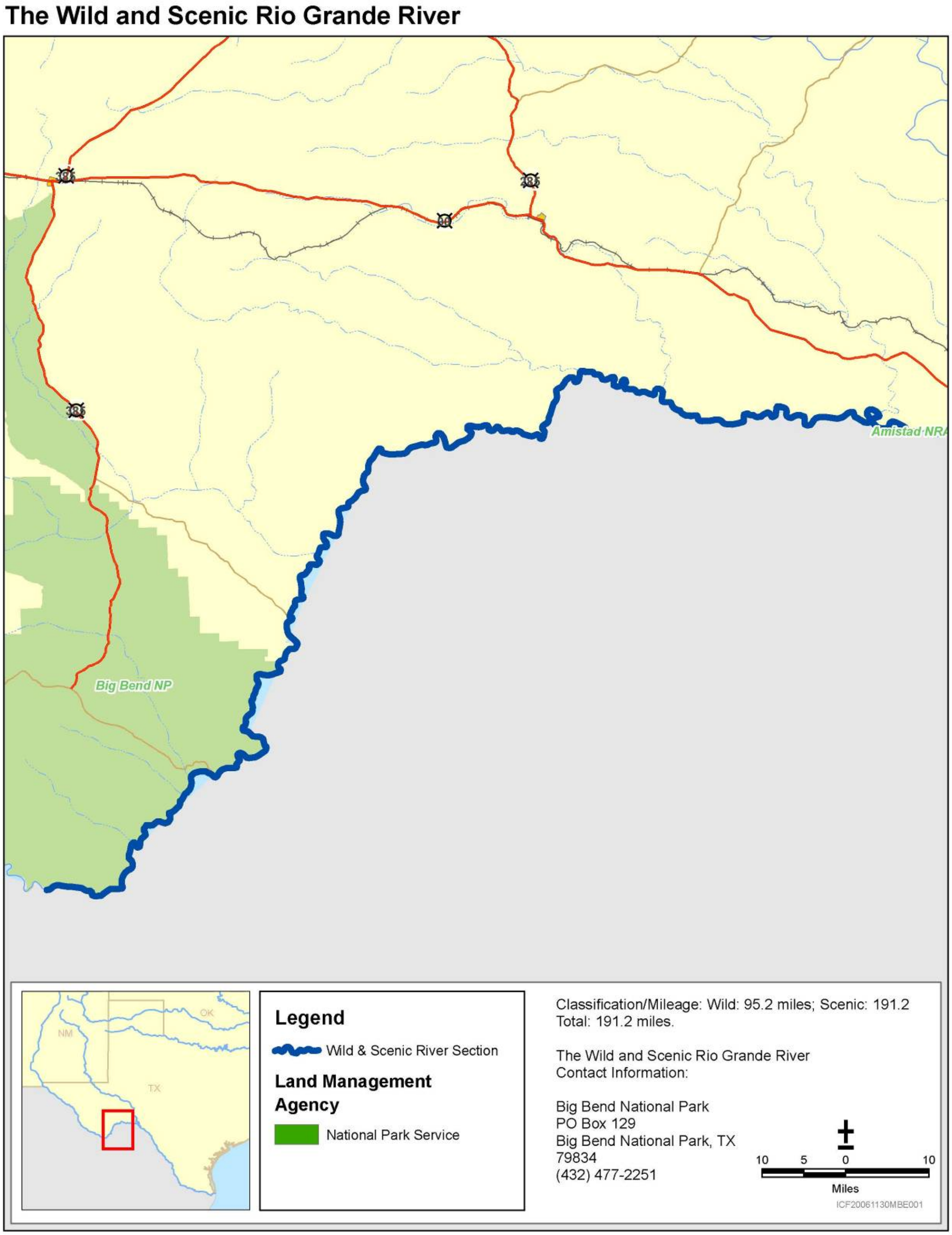

Figure A4.4. Dams and diversions along the Rio Grande.[27]

Figure A4.5. Map of Wild and Scenic stretches in the Delaware River basin. Courtesy of Delaware River Basin Commission.[31]

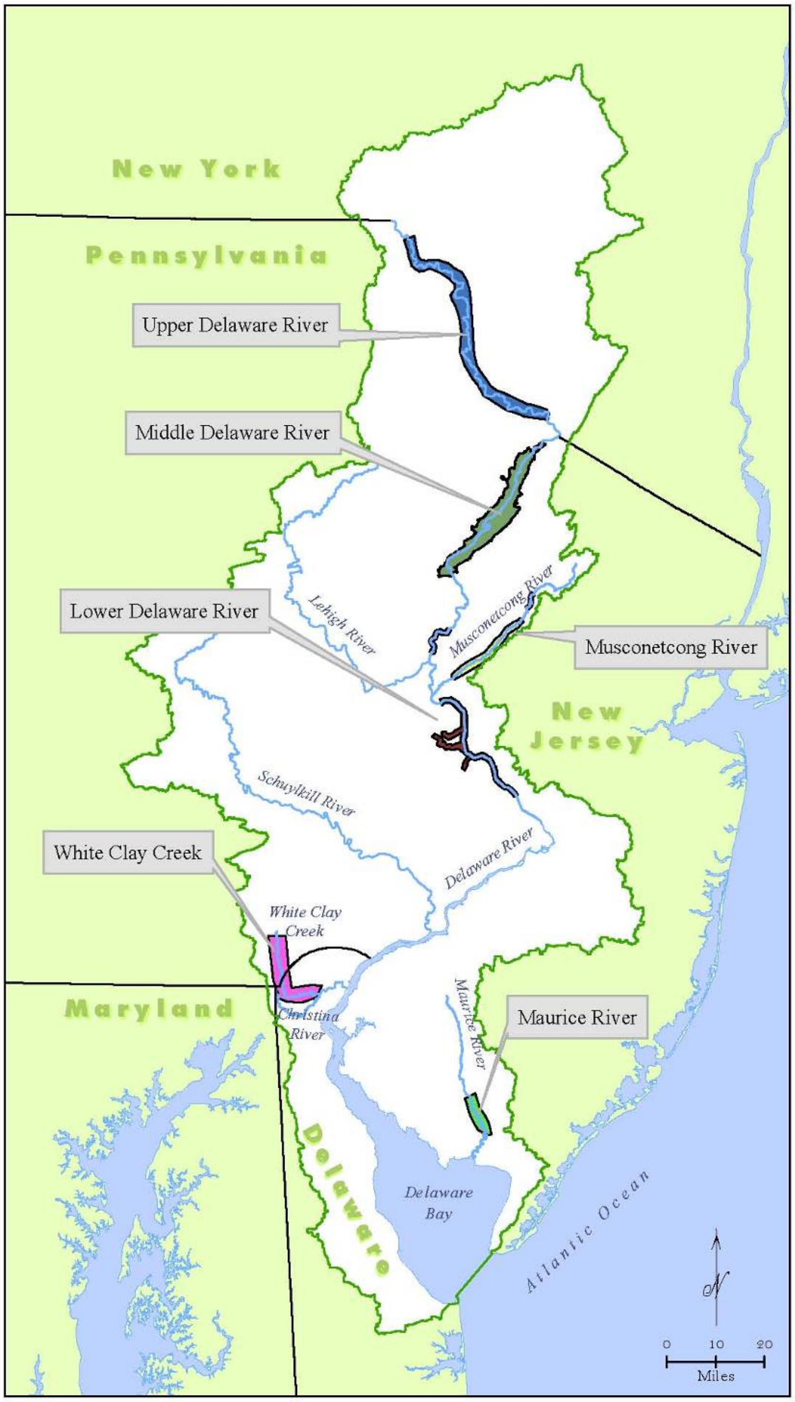

Figure A5.1. The Albemarle-Pamlico National Estuary Program region.[37]

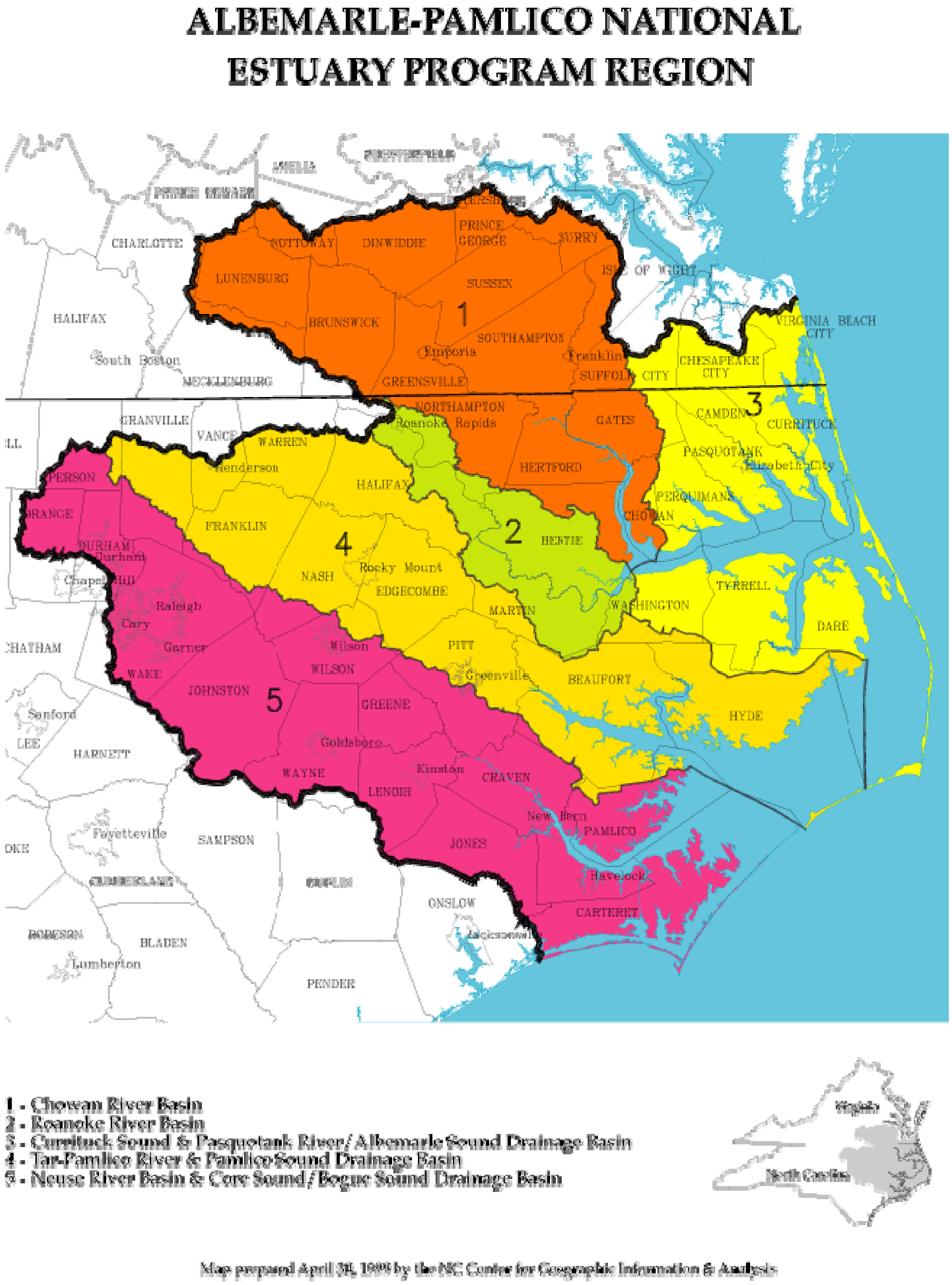

Figure A5.2. Feedbacks between nutrient and sediment exchange and primary production in the benthos and water column. A plus symbol indicates enhancement and a minus symbol suppression.

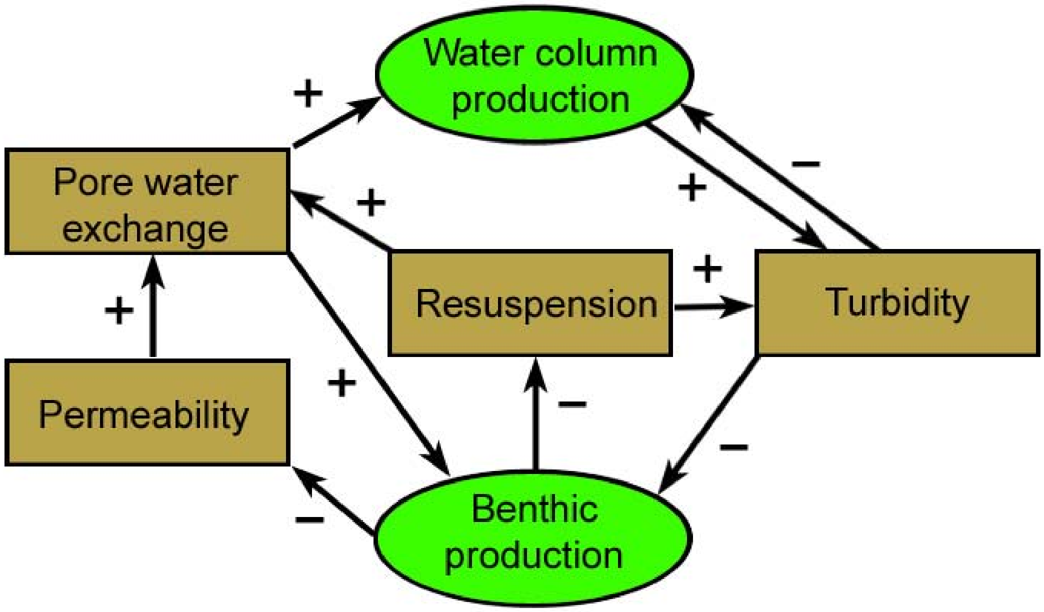

Figure A6.1. Map of the Great Barrier Reef Marine Park showing the adjacent catchment in Queensland. Modified from Haynes (2001) and courtesy of the Great Barrier Reef Marine Park Authority.

Figure A6.2. Sea surface temperature (SST) projections for the Great Barrier Reef (GBR) (Lough, 2007).

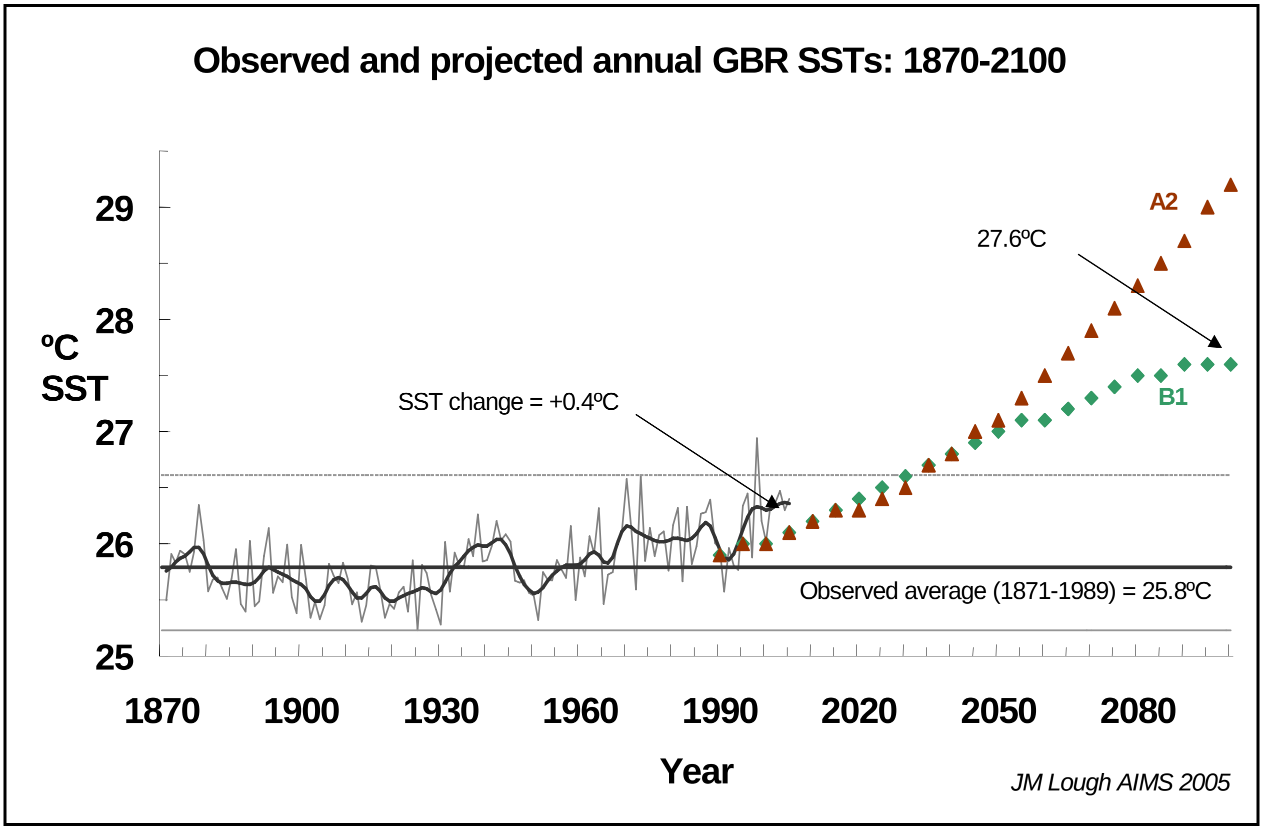

Figure A6.3. Endemic species from the Hawaiian Islands. A. Masked angelfish, *Genicanthus personatus* (Photo courtesy of J. Watt), B. Rice coral, *Montipora capitata*, and finger coral, *Porites compressa* (photo courtesy of C. Hunter), C. Hawaiian hermit crab, *Calcinus laurentae* (photo courtesy of S. Godwin), D. Red alga, *Acrosymphtyon brainardii* (photo courtesy of P. Vroom).

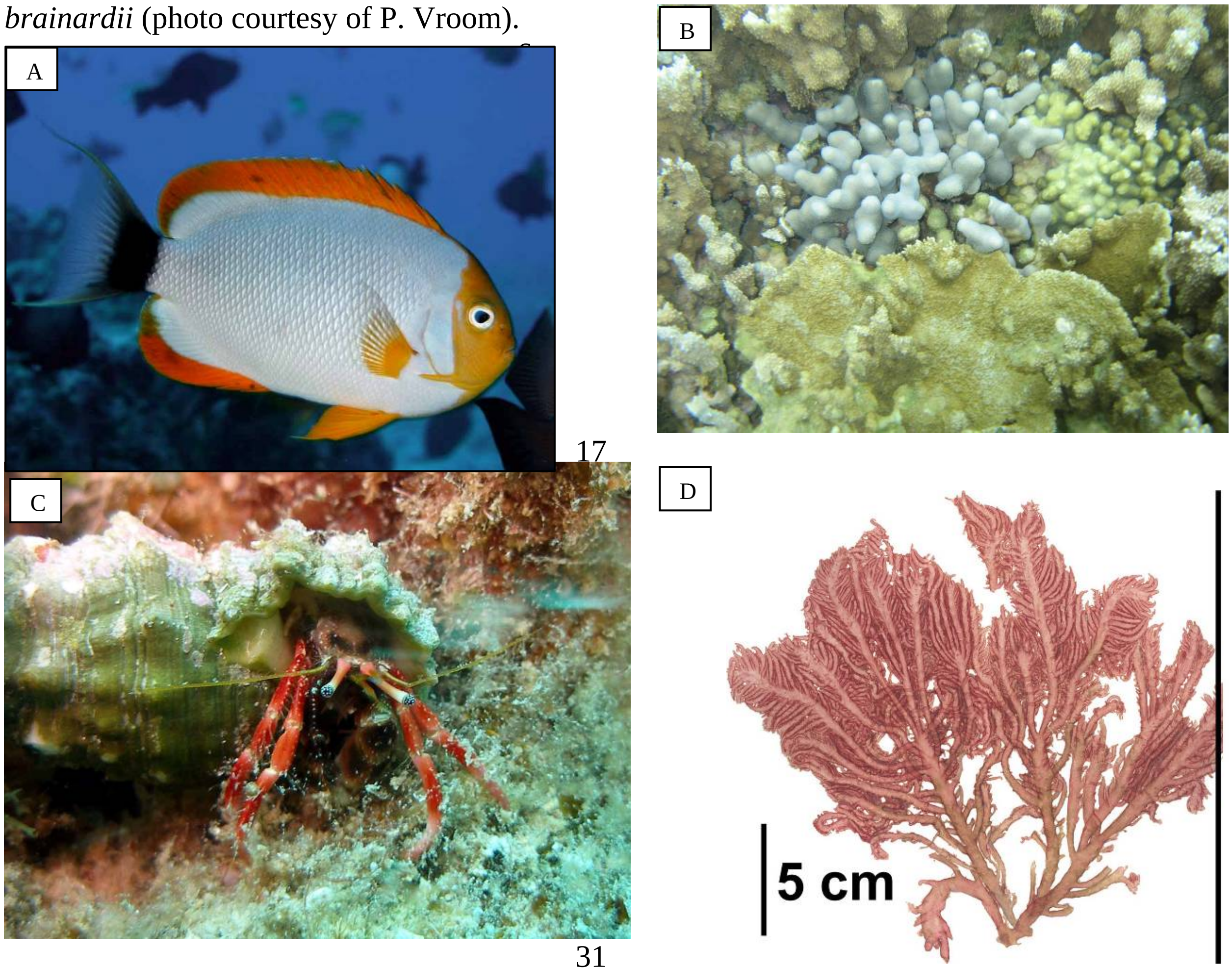

Figure A6.4. a) NOAA Pathfinder SST anomaly composite during summer 2002 period of NWHI elevated temperatures, July 28–August 29. b) NASA/JPL Quikscat winds (wind stress overlayed by wind vector arrows) composite during summer 2002 period of increasing SSTs, July 16–August 13. The Hawaii Exclusive Economic Zone (EEZ) is indicated with a heavy black line; all island shorelines in the archipelago are also plotted (adapted from Hoeke *et al.*, 2006).

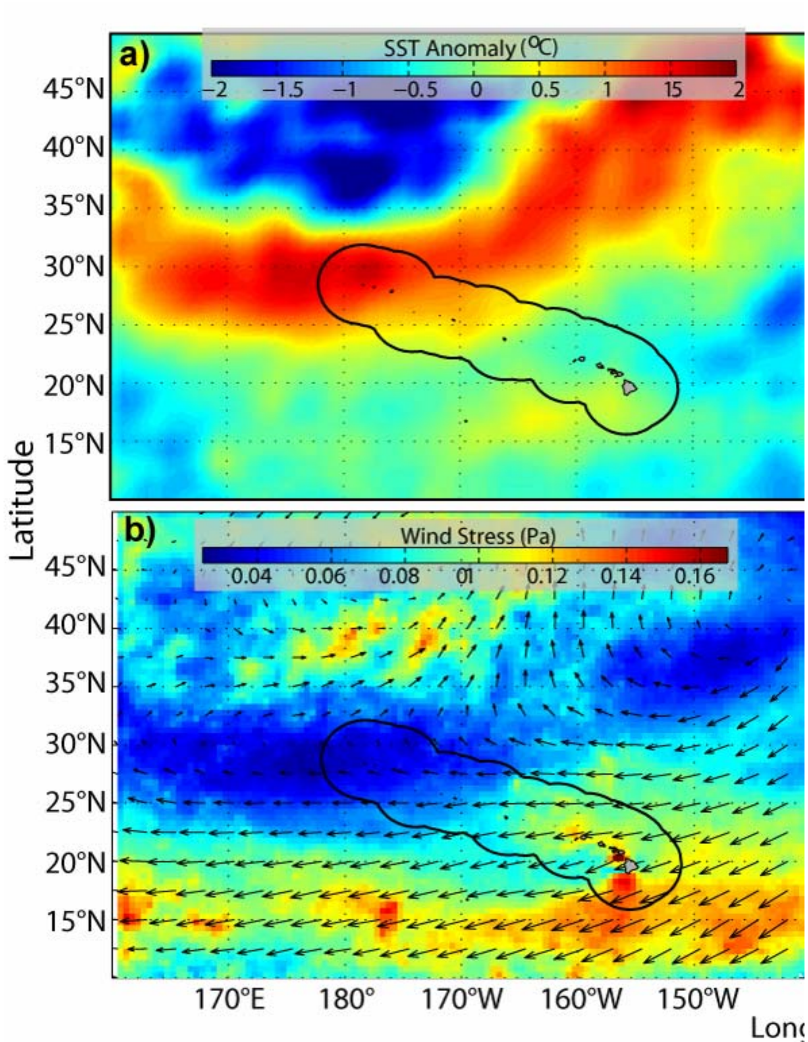

Figure A6.5. Map of the Channel Islands National Marine Sanctuary showing the location of existing state and proposed federal marine reserves and marine conservation areas.[71]