Scanning the Conservation Horizon

A Guide to Climate Change Vulnerability Assessment

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A Guide to Climate Change Vulnerability Assessment

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This guidance document is a product of an expert workgroup on climate change vulnerability assessment convened by the National Wildlife Federation in collaboration with the U.S. Fish and Wildlife Service.

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Contents

Michael D. Peterson

Executive Summary

Rapid climate change is the defining conservation issue of our generation. The effects of climate change are increasingly apparent, from drowned coastal marshes and drying prairie potholes to melting glaciers. These climate-driven changes will profoundly affect our ability to conserve fish and wildlife and the habitats on which they depend. Indeed, preparing for and coping with the effects of climate change—an endeavor referred to as climate change adaptation—is emerging as the overarching framework for conservation and natural resource management.

The ecological impacts associated with climate change do not exist in isolation, but combine with and exacerbate existing stresses on our natural systems. Understanding those interactions will be critical to designing effective conservation measures. Conservation in an era of climate change will require that we not only acknowledge and address the environmental problems of the past but also anticipate and prepare for those of an increasingly uncertain future.

Developing and implementing effective adaptation strategies first requires an understanding of the potential impacts of climate change on our natural world. To provide the best possible chance for conserving species and ecosystems in a rapidly changing climate, it is essential that managers have the ability to both identify what we need to do differently in the future, as well as which existing strategies and activities continue to make sense from a climate adaptation perspective.

Vulnerability assessments are a key tool for informing adaptation planning and enabling resource managers to make such judgments. *Scanning the Conservation Horizon* is designed to assist fish and wildlife managers and other conservation and resource professionals to better plan, execute, and interpret climate change vulnerability assessments.

Alan D. Wilson

Climate change vulnerability assessments provide two essential contributions to adaptation planning. Specifically, they help in:

- Identifying ***which*** species or systems are likely to be most strongly affected by projected changes; and

- Understanding ***why*** these resources are likely to be vulnerable, including the interaction between climate shifts and existing stressors.

Determining *which* resources are most vulnerable enables managers to better set priorities for conservation action, while understanding *why* they are vulnerable provides a basis for developing appropriate management and conservation responses.

Vulnerability to climate change, as the term is used in this guide, has three principle components: sensitivity, exposure, and adaptive capacity.

Vulnerability to climate change, as the term is used in this guide, has three principal components: ***sensitivity, exposure, and adaptive capacity.*** Vulnerability assessments are, therefore, structured around assessments of these distinct components. *Sensitivity* generally refers to innate characteristics of a species or system and considers tolerance to changes in such things as temperature, precipitation, fire regimes, or other key processes. *Exposure*, in contrast, refers to extrinsic factors, focusing on the character, magnitude, and rate of change the species or system is likely to experience. *Adaptive capacity* addresses the ability of a species or system to accommodate or cope with climate change impacts with minimal disruption.

Key Steps for Assessing Vulnerability to Climate Change

Determine objectives and scope

- Identify audience, user requirements, and needed products
- Engage key internal and external stakeholders
- Establish and agree on goals and objectives
- Identify suitable assessment targets
- Determine appropriate spatial and temporal scales
- Select assessment approach based on targets, user needs, and available resources

Gather relevant data and expertise

- Review existing literature on assessment targets and climate impacts
- Reach out to subject experts on target species or systems
- Obtain or develop climatic projections, focusing on ecologically relevant variables and suitable spatial and temporal scales
- Obtain or develop ecological response projections

Assess components of vulnerability

- Evaluate climate sensitivity of assessment targets
- Determine likely exposure of targets to climatic/ecological change
- Consider adaptive capacity of targets that can moderate potential impact
- Estimate overall vulnerability of targets
- Document level of confidence or uncertainty in assessments

Apply assessment in adaptation planning

- Explore why specific targets are vulnerable to inform possible adaptation responses
- Consider how targets might fare under various management and climatic scenarios
- Share assessment results with stakeholders and decision-makers
- Use results to advance development of adaptation strategies and plans

Although climate change vulnerability assessments can be applied to human infrastructure as well as natural systems, our focus here is on approaches designed to support wildlife conservation and ecosystem-based adaptation. Such assessments can target various levels of ecological or biological diversity. Because of their relevance to most wildlife management and conservation practitioners, this guidance focuses on assessments of ***species, habitats, and ecosystems,*** detailing approaches for assessing sensitivity, exposure, and adaptive capacity at each of these biological levels. Understanding likely future change is central to these assessments, and we also provide an overview and guidance for the use of climate and ecological response models relevant to conducting fish and wildlife vulnerability assessments.

Climate change vulnerability assessments are, first and foremost, intended to support decision-making, and as such they should be designed from the start with an eye toward the needs of the end users, whether they be on-the-ground managers, policy-makers, or others in the management or scientific communities. A critical first step is to identify the scope and objectives of the assessment based on the intended user, their information needs, and existing decision processes. We also provide guidance on successful approaches for engaging stakeholders. Designing assessments requires attention to several other key considerations, including selection of the appropriate geographic and temporal scales, the features to be assessed (e.g., species or ecosystems), and level of detail and complexity. Given the inherent uncertainties associated with various aspects of climate projections and vulnerability assessments, we provide specific guidance on understanding, addressing, and documenting uncertainty. Finally, climate change is not occurring in a vacuum, and assessments must be carried out in the context of existing stresses on our species and systems—from the fragmentation and loss of habitat to the on-going deluge of invasive species.

Vulnerability assessments can provide a factual underpinning for differentiating between species and systems likely to decline and those likely to thrive, but do not in themselves dictate adaptation strategies and management responses. Indeed, a continuum of possible adaptation approaches exists ranging from: (1) building *resistance* to climate-related stressors as a way of maintaining high-priority species or systems; (2) enhancing *resilience* in order to provide species and systems with a better chance for accommodating and weathering changes; and (3) anticipating and facilitating ecological *transitions* that reflect the changing environmental conditions.

To help bring the concepts behind vulnerability assessment alive, the guide concludes with a series of seven case studies, profiling efforts of varying scope and complexity. These examples include assessments that employ different analytical approaches (e.g., expert opinion vs. computer models), conservation targets (e.g., species vs. habitats), and spatial scales (e.g., states vs. regions) among other variables. Collectively, these case studies represent many of the leading examples of wildlife and ecosystem-oriented climate change vulnerability assessments.

Mike Brake

There is no single right approach to vulnerability assessment that applies to all situations. Rather, the design and execution of an assessment must be based on a firm understanding of the user needs, the decision processes into which it will feed, and the availability of resources such as time, money, data, and expertise. *Scanning the Conservation Horizon* is intended to provide resource managers and conservationists with much-needed guidance for understanding the basic concepts behind vulnerability assessments, and for identifying which approaches may best serve their specific needs as together we rise to the challenge of conserving our fish and wildlife resources in an era of rapid climate change.

Preface

"I skate to where the puck is going to be, not where it has been."
– Hockey great, Wayne Gretzky.

Preparing for and coping with the effects of a changing climate—known as climate change adaptation—rapidly is becoming the dominant framework for conservation and natural resource management. Developing sound adaptation strategies requires that managers understand which of the resources they are managing are most likely to be affected, and what options may be available to sustain them into the future. Climate change vulnerability assessments provide an essential tool for informing the development of such adaptation plans, and a variety of approaches for assessing vulnerability are now in use or are under development.

Scanning the Conservation Horizon is designed to help fish and wildlife professionals and other conservation practitioners understand how vulnerability assessments can help them in responding to the challenges of managing natural resources in an era of rapid climate change. Developed by a collaborative working group of conservation professionals and conservation scientists (see below), the document provides guidance for agencies and organizations to consider in developing and conducting vulnerability assessments in support of their conservation and management missions and as a tool in the development of climate change adaptation strategies. The guidance document has three primary objectives:

- Provide an overview of the general principles of climate change vulnerability as it relates to species, habitats, and ecosystems

- Describe the various approaches available for assessing the components of vulnerability and address key issues and considerations related to these tools and practices

- Highlight examples of climate change vulnerability assessment in practice among government agencies, non-governmental organizations, academic institutions, and other stakeholders

Because the needs and challenges facing conservation and resource management agencies and organizations are so variable, this document offers a framework and general guidelines for assessing climate change vulnerability rather than provide a step-by-step "cookbook" for conducting assessments. Similarly, the intent is not to identify and promote a single "best" approach for assessing vulnerability, but rather to help readers understand the range of approaches available and enable them to identify the best match for their particular conservation requirements, decision processes, and available resources. Guidance documents, no matter how well written, are no substitute for in-person training and hands-on experience, and this guide is designed to support future training sessions to be held on the topic of vulnerability assessment and adaptation planning.

Acknowledgements

This guidance document is a product of an expert workgroup on vulnerability assessment convened by the National Wildlife Federation in collaboration with the U.S. Fish and Wildlife Service. This workgroup includes many of the leading thinkers and practitioners in this rapidly evolving field and draws from state and federal agencies, non-governmental conservation organizations, and universities. We are grateful to the workgroup members listed on page iii who have given unstintingly of their time and expertise to participate in this workgroup and collaboratively develop this guidance document.

We are also grateful to the following individuals who collaborated with workgroup members to co-author case studies: Jennifer Newmark and Kristin Szabo (Nevada Natural Heritage Program), Jeff Price (World Wildlife Fund), Megan Friggens and Karen Bagne (U.S. Forest Service), Michael Wilson (Center for Conservation Biology), Patrick McCarthy (The Nature Conservancy), and Michael Case (University of Washington).

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Finally, we dedicate this publication to the memory of Dr. Stephen H. Schneider, whose lifelong pursuit of scientific knowledge and steadfast commitment to effective communication set the stage for the tremendous contribution that the science of climate change has made for the public good.

I. Introduction

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Our Rapidly Changing World

Rapid changes in the earth's **climate*** are well underway, and more and larger shifts are expected, even under the best-case scenarios for **greenhouse gas** emissions reductions. It is clear from current trends and future projections that the planet's living resources—humans, plants, and animals alike—will exist in an environment in the future that will be vastly different from the one we have experienced over the past century, during which our conservation traditions evolved.

Since the release of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) in 2007 (IPCC 2007a, 2007b, 2007c, 2007d), new evidence that our planet is experiencing significant and irreversible changes has underscored reasons for concern (Smith, et al. 2009). In the United States, we are seeing a multitude of changes consistent with a rapidly warming climate. Climate change impacts in the United States summarized by the U.S. Global Change Research Program in *Global Change Impacts in the United States* (USGCRP 2009, p. 27) include:

Lead authors: Bruce A. Stein and Patty Glick.

*Terms highlighted in blue are defined in the Glossary.

- U.S. average temperature has risen more than 2 degrees Fahrenheit over the past 50 years and is projected to rise more in the future; how much more depends primarily on the amount of heat-trapping gases emitted globally and how sensitive the climate is to those emissions.

- Precipitation has increased an average of about 5 percent over the past 50 years. Projections of future precipitation generally indicate that northern areas will become wetter, and southern areas, particularly in the West, will become drier.

- The amount of rain falling in the heaviest downpours has increased approximately 20 percent on average in the past century, and this trend is very likely to continue, with the largest increases in the wettest places.

- Many types of extreme weather events, such as heat waves and regional droughts, have become more frequent and intense during the past 40 to 50 years.

- The destructive energy of Atlantic hurricanes has increased in recent decades. The intensity of these storms is likely to increase in this century.

- In the eastern Pacific, the strongest hurricanes have become stronger since the 1980s, even while the total number of storms has decreased.

- Sea level has risen along most of the U.S. coast over the last 50 years, and will rise more in the future.

- Cold-season storm tracks are shifting northward and the strongest storms are likely to become stronger and more frequent.

- Arctic sea ice is declining rapidly and this is very likely to continue.

These changes are already having a considerable impact on species and natural systems, including changes in the timing of biological events (i.e., phenological changes), such as the onset and end of breeding seasons, migration, and flowering; shifts in geographic ranges; and changes in community dynamics and populations (U.S. CCSP 2008a). For example:

- Across North America, plants are leafing-out and blooming earlier; birds, butterflies, amphibians, and other wildlife are breeding or migrating earlier; and species are shifting or expanding their ranges, often northward and to higher elevations (Parmesan and Galbraith 2004; Kelly and Goulden 2008; Root et al. 2005).

- Increased water temperatures in coral reefs in southern Florida, the Caribbean, and Pacific Islands have contributed to unprecedented bleaching and disease outbreaks (Donner et al. 2006; Harvell et al. 2007).

- Severe storm events, sea-level rise, and saltwater intrusion have led to a decline in coastal wetland habitats from the Atlantic Coast to the Gulf of Mexico (Janetos et al. 2008; Kennedy et al. 2002).

- Salmonids throughout the Pacific Northwest are now challenged by global warming–induced alteration of habitat conditions throughout their complex life cycles (ISAB 2007).

USFWS

- Forest and grassland systems throughout the West have been stressed by drought, catastrophic wildfires, insect outbreaks, and expansion of invasive species (Ryan et al. 2008).

These and other changes are bellwethers for what scientists project will be even more dramatic impacts for many species, habitats, and ecosystems in the decades to come. Even with the acknowledgement that there is considerable uncertainty in climate change projections, the underlying message is clear: widespread changes already are occurring, they will continue, they will expand in scope and scale in the next few decades due to greenhouse gases already in the atmosphere, and they will expand even more over longer time horizons if greenhouse gas emissions continue unabated or increase.

Adaptation is rapidly becoming the primary lens for conservation and natural resource planning and management.

Climate Change Adaptation—Putting Vulnerability Assessment in Context

The potential for far-reaching impacts of **climate change** are driving a fundamental shift in conservation and natural resource management. Managers can no longer look exclusively to the past to guide their conservation and restoration goals, but instead must anticipate an increasingly different and uncertain future (Milly et al. 2008). We will need to make conservation decisions based on longer time frames (e.g., over several decades) than we have traditionally considered. Addressing climate change will also require us to design and implement research and conservation efforts at larger landscape and biogeographical scales, often spanning multiple institutional and political jurisdictions (Opdam and Wascher 2004). Further complicating matters, climate change does not occur in a vacuum. Indeed, it is the combined effects of climate change and existing problems such as habitat fragmentation that ultimately pose the greatest threat to our natural systems and the fish, wildlife, and people they support (Root and Schneider 2002).

Climate change adaptation is the emerging discipline that focuses on helping people and natural systems prepare for and cope with the impacts of climate change (Glick et al. 2009). Indeed, adaptation is rapidly becoming the primary lens for conservation and natural resource planning and management.

Until recently the human response to climate change has focused largely on efforts to reduce the greenhouse gas emissions that are the underlying driver of climate change and global warming. Adaptation efforts serve as an essential complement to such climate change "mitigation" efforts. Adaptation, however, has only recently begun to be widely acknowledged and embraced as a response to the challenges of climate change. As a result, the adaptation science and practice is still in an early developmental stage and is evolving rapidly (Heller and Zavaleta

2009). Additionally, much of the early thinking and work on adaptation has been targeted, understandably, toward protecting human communities and infrastructure from climate impacts, with limited attention to date on safeguarding the natural systems that sustain both people and wildlife.

Developing meaningful adaptation strategies requires an understanding of, first, the impacts, risks, and uncertainties associated with climate change, and second, the vulnerability of the different components of our natural world to those changes. In this context, **vulnerability** to climate change refers to the extent to which a species, habitat, or ecosystem is susceptible to harm from climate change impacts (Schneider et al. 2007). More vulnerable species and systems are likely to experience greater impacts from climate change, while less vulnerable species and systems will be less affected, or may even benefit. Accordingly, climate change adaptation can be defined as "initiatives and measures designed to reduce the vulnerability of natural systems to actual or expected climate change effects" (IPCC 2007d).

Adaptation refers to measures designed to reduce the vulnerability of systems to the effects of climate change.

Key Adaptation Concepts

A considerable body of knowledge is now emerging focusing on ecosystem or natural resource-based adaptation (Groves et al. 2010; West et al. 2009; Lawler 2009; Mawdsley et al. 2009; Glick et al. 2009). Adaptation efforts generally fall under one or more of the following approaches: (1) building *resistance* to climate-related stressors as a way of maintaining high-priority species or systems; (2) enhancing *resilience* in order to provide species and systems with a better chance for accommodating and weathering changes; and (3) anticipating and facilitating ecological *transitions* that reflect the changing environmental conditions. In the climate change adaptation literature, **resistance** typically refers to the ability of a system (e.g., and ecosystem, species, population, etc.) to withstand a disturbance or change without significant loss of ecological structure or function (U.S. CCSP 2008b; Heller and Zavaleta 2009; Nyström et al. 2008; Williams et al. 2008; Walker et al. 2004; Easterling et al. 2004; Hansen and Biringer 2003). In other words, the species or ecosystem can tolerate or avoid the impacts of altered air or water temperatures, extreme events, and/or other climate change variables altogether. **Resilience**, in an adaptation context, generally refers to the ability of a system to recover from a disturbance or change without significant loss of function or structure, and to return to a given ecological state, rather than shift to a different state (Gunderson 2000).

Susan Stein

Coral reefs provide a useful illustration of these concepts. One of the primary ways in which climate change is affecting coral reefs is through higher average sea surface temperatures, which is contributing to an increase in the frequency and extent of

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coral bleaching events around the world (Hoegh-Guldberg et al. 2007). A coral reef may be able to avoid bleaching and its associated mortality if, for example, local upwelling draws cooler water to the surface where that reef is located (Grimsditch and Salm 2006). Similarly, a coral reef may be resilient to a coral bleaching event if, after experiencing bleaching during a period of high ocean temperatures, the coral ecosystem recovers and continues to function as a coral-dominated system. On the other hand, conditions may be such that the reef system may not be able to withstand or recover from a major bleaching event (e.g., adverse temperature conditions may be prolonged and/or multiple climate and non-climate stressors may be at play). Recently, the conversion of coral-dominated reefs to algal-dominated reefs in some areas following mass bleaching and mortality is a strong indication of decreased resilience of these systems (Hughes et al. 2003).

Managing for ecological transitions will be an increasingly significant part of our conservation agenda.

While efforts to promote or maintain ecosystem resilience are among the most commonly recommended strategies for climate change adaptation, it will also be important to develop strategies that actually enable or facilitate the ability of a species or ecosystem to change in response to global warming, not just avoid or bounce back from the impacts (Heller and Zavaleta 2009; Galatowitsch et al. 2009).). In all likelihood, measures to manage for ecological transitions are going to be an increasingly significant part of our conservation agenda.

Although relevant adaptation strategies will vary considerably based on specific circumstances, several general adaptation principles are broadly applicable:

- **Reduce existing stressors.** Climate change will exacerbate many existing threats to our wildlife and natural ecosystems, such as the loss of habitat and spread of invasive species. Reducing those existing stressors that interact negatively with climate change will often be key to promoting ecosystem resilience.

- **Manage for ecosystem function.** Healthy and biologically diverse ecosystems will be better able to withstand or bounce back from the impacts of climate change.

- **Protect refugia and improve habitat connectivity.** Identifying and protecting both existing and possible future strongholds of wildlife populations and wildlife corridors will be important for helping sustain the full array of species, ecosystems, and their human benefits. Ensuring connectivity among these core habitat areas will facilitate the ability of species to shift ranges in response to changing climates.

- **Implement proactive management and restoration.** Efforts that actively *facilitate* the ability of species, habitats, and ecosystems to accommodate climate change—for example, beach nourishment, enhancing marsh accretion, and planting climate change-resistant species—may be necessary to protect highly valued species or ecosystems when other options are insufficient.

Vulnerability Assessment: A Tool for Adaptation Planning

The conservation and resource management community is now being challenged to take the type of general principles described above and develop climate change adaptation plans that address specific on-the-ground needs. Ensuring that these plans are truly "climate-smart" and do not simply represent relabeled business-as-usual will require that managers go through an explicit process for bringing climate data and ecological understanding to bear on their planning.

Climate change vulnerability assessment represents a key tool for providing adaptation planning efforts with such explicit climate input. Vulnerability assessments can provide two essential types of information needed for adaptation planning:

1. Identifying ***which*** species or systems are likely to be most strongly affected by projected changes

2. Understanding ***why*** they are likely to be vulnerable

Determining *which* resources are most vulnerable enables managers to better set priorities for conservation action, while understanding *why* they are vulnerable provides a basis for developing appropriate management and conservation responses.

Figure 1.1 offers an overall framework for adaptation planning, indicating how vulnerability assessments can fit into and support that process. Elements of this framework should look familiar to many conservationists because it draws from a number of existing conservation planning frameworks, such as The Nature Conservancy's *Conservation by Design* (TNC 2006) and the U.S. Fish and Wildlife Service's Strategic Habitat Conservation framework (U.S. FWS 2009a).

Kim Matticks

Kyle Barrett

Element 1: The framework starts with identifying conservation targets, whether they be species, habitats, ecosystems, or some other unit. **Element 2:** These conservation targets are then assessed for their vulnerability to climate change in order to determine which are likely to be most at risk and which are more likely to persist. **Element 3:** Based on an understanding of why the species or systems are regarded as vulnerable to climate change and other stressors, an array of management options can be identified and evaluated based on technical, financial, and legal considerations. **Element 4:** Selected management strategies can then be implemented, with the activities and outcomes subject to monitoring in order to feed into a regular cycle of evaluation, correction, and revision. Climate change is not occurring in a vacuum, and the elements of the adaptation planning process must also take existing stressors into consideration as well as other relevant factors affecting the system.

This guide focuses on how vulnerability assessment (Element 2) can support conservationists and natural resource managers as we move into a future that does not necessarily have past analogs. For although these assessments must be strongly science based, they are not simply scientific assessments; rather, they must be viewed as an integral part of a broader adaptation planning and implementation framework.

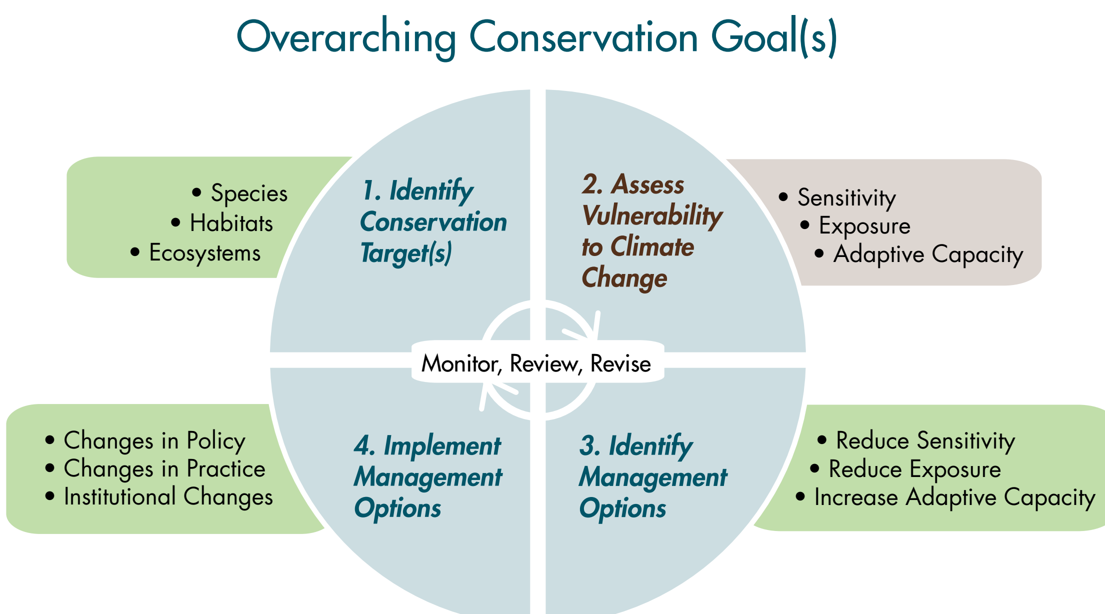

Figure 1.1. Framework for Developing Climate Change Adaptation Strategies

Box 1.1 "Top-Down" vs. "Bottom-Up" Approaches to Adaptation Planning

The process of developing a climate change adaptation strategy can be approached from either a "top-down" or "bottom-up" perspective, or some combination of these. The most appropriate approach will depend on the scale and goals of your strategy, which in turn will help guide the design of your vulnerability assessment (Hansen and Hoffman 2011). A top-down approach generally starts with looking at one or more scenarios for shifts in climate (e.g., projections for sea-level rise, temperature changes, or extreme rainfall events); assessing what the future landscape might look like under those scenarios (e.g., what are the plausible ecological effects of the projected physical changes); and finally setting specific conservation objectives and management priorities designed to address those projected future changes. This approach is particularly useful for broad-scale efforts, such as those conducted at regional or national levels, focused on regional ecosystem or biomes, or that have multiple species as conservation targets. A bottom-up approach, on the other hand, usually starts with an organization or agency's specific conservation or management goals (e.g., protecting critical habitat for a particular endangered species, managing a specific wildlife refuge, or setting maximum allowable pollutant levels); identifying how climatic variables influence those conservation goals (e.g., the influence of temperature on species' health and reproduction or on the toxicity of pollutants); determining plausible physical and ecological changes under a range of climate scenarios; and finally identifying and evaluating options for reducing the vulnerability of the agency's goals to those projected changes.

Why Assess Vulnerability?

As described above, vulnerability assessments are key tools for the development of climate change adaptation strategies. We would like to highlight in particular three key motivations for carrying out vulnerability assessments:

- Help in setting management and planning priorities
- Assist in informing and crafting adaptation strategies
- Enable more efficient allocation of scarce resources

Mark Karrass

Set Management and Planning Priorities

Vulnerability assessments help resource managers better understand the relative susceptibility of the species, habitats, ecosystems, or special places they are working to protect to the likely future impacts of climate change. They help answer two related questions regarding setting priorities. First, they help us identify answers to the question: "What should we be doing differently in light of climate change?" Just as important, however, they also help clarify answers to the question: "Which of our existing activities and management actions continue to make sense in a climate change context?" Focusing our conservation efforts with an explicit climate perspective will give us a greater chance of success in evaluating current conservation and management objectives to determine if they should be adjusted and if so, how, and in designing effective approaches for reaching our objectives. In cases where the potential impacts of climate change are highly uncertain, managers may initially focus on so-called “no regrets” strategies, which provide conservation benefits whether or not the projected magnitude of climate changes actually occur.

The following are simplified examples of how climate change vulnerability assessments might help inform conservation plans:

1. A coastal organization concerned about preserving an important sea turtle nesting site commissions a study that shows that the region is at substantial risk of being inundated due to rising sea levels. Although there is uncertainty about how much sea-level rise will occur and when at their site, loss of most or all of the nesting site is considered highly likely. The organization can then plan to acquire or secure a long-term easement for land inland of the current site to provide an additional habitat “buffer” (i.e., protect a greater amount of existing habitat area than is considered sufficient under current conditions) or perhaps accommodate potential habitat migration (i.e., the transformation of “new” areas inland into habitat with suitable conditions for nesting). Without an understanding of the potential impacts of sea-level rise, the organization’s resources might have been spent in other directions, and the option of conserving habitat for a new nesting site may have been ultimately lost to development or other uses.

2. Land managers are concerned about an invasive plant or insect species that has been spreading across areas to the south of their current location. Model simulations project that these species will expand into their region due to higher temperatures and increased disturbances from wildfires. They decide to proactively devote additional resources toward halting the spread of this invasive before it arrives in the region. Such efforts may not have been viewed as a priority if those new areas were not identified as a viable habitat in which the particular invasive species might thrive. In other areas, land managers may decide to lessen or abandon efforts to fight invasive species where studies suggest climate change may do the job for them—for example, as models project drier conditions that will no longer support the invader.

Inform and Craft Adaptation Strategies

Vulnerability assessments can also inform the development of effective management strategies for meeting a conservation goal that considers climate change as an added stressor. As will be elaborated on later, vulnerability consists of three components—sensitivity, exposure, and adaptive capacity—and adaptation strategies can be designed either to reduce the sensitivity and/or exposure of a species or system, or to increase its adaptive capacity. For example:

1. Climate change may be contributing to an increase in average water temperatures in an important trout stream. Targeted measures to help moderate those temperatures, such as expanding riparian

Box 1.2. Adaptation and Adaptive Management: Complementary but Distinct Concepts

Adaptation and adaptive management are distinct concepts that are frequently confused with one another. As described earlier, adaptation refers to strategies designed to prepare for and cope with the effects of climate change. Because of the uncertainties associated with predicting the effects of future climates on species and ecosystems, flexible management will almost certainly be a component of well-designed adaptation strategies.

In contrast, adaptive management is one particular approach to management in the face of uncertainty, and is not necessarily tied to climate change. Adaptive management has been described as an iterative learning process producing improved understanding and management over time (Williams et al. 2007). Most portrayals of adaptive management describe a cyclical process in which: management goals are defined based on current understanding and predictive models but with key uncertainties explicitly highlighted; management actions are carried out and monitored, and outcomes are compared to predictions; and refinements are made to goals and actions based on real-time learning and knowledge generation.

While it is a common complaint that current environmental rules and regulations lack the flexibility needed for true adaptive management, the Department of the Interior's technical guide to adaptive management (Williams et al. 2007) provides both suggestions for and examples of effective adaptive management in the federal context.

Adaptation to climate change is characterized by making decisions in the face of uncertainty. While the adaptive management framework is structured to enable managers to act in the face of uncertainty, other management approaches and philosophies, as discussed in Chapters V and VI, are also designed to address different levels of uncertainty.

To summarize, adaptive management can be an important component of adaptation efforts, but not all adaptive management is climate change adaptation, nor is all climate change adaptation necessarily adaptive management.

vegetation, protecting cold-water refugia, or increasing cold-water spill from existing reservoirs, could become an important part of trout conservation in the area. Such actions would help reduce that species' exposure to adverse conditions.

2. Coastal marshes may be in danger of being flooded by rising sea levels. A conservation action that may not have been considered without knowledge of likely impacts of climate change is the use of proactive measures to assist in the accretion of sediments as a means for the marsh to keep up with rising waters. Chapter VI provides more detail about how to use the results of vulnerability assessments in the context of developing climate change adaptation strategies.

Allocate Scarce Resources

It follows from the aforementioned reasons that the results of vulnerability

Cheryl Empey

assessments can help wildlife managers allocate scarce conservation resources more efficiently (Marsh et al. 2007). For example:

1. Vulnerability assessments may steer managers away from potentially costly conservation measures that may have a low likelihood of being efficacious due to climate change, such as restoration of a particular habitat type in an area where assessments indicate continued habitat suitability is highly unlikely.

The choice of whether to focus conservation efforts on the most vulnerable or most viable will be based not only on science, but also on social, economic, and legal values.

2. Managers may decide to spend more of their budget on increased and well-designed monitoring efforts, which will be particularly important to help fill knowledge gaps and reduce uncertainty about climate change impacts over time. Long-term, appropriately designed monitoring is a critical component of **adaptive management,** which is likely to play an important role in the development and implementation of climate change adaptation strategies (see Box 1.2).

What Vulnerability Assessments Won't Do

It is equally important to understand what climate change vulnerability assessments will not do. Although these assessments can provide information about the levels and sources of vulnerability of species or systems to help in setting priorities, the assessments alone do not dictate what those priorities should be. Managers increasingly will be faced with the dilemma of deciding how to invest scarce resources to address various conservation needs. Vulnerability assessments can provide a factual underpinning for differentiating between species and systems likely to decline and those likely to thrive. The choice of whether to focus conservation efforts on the most vulnerable, the most viable, or a combination of the two, will of necessity be based not only on scientific factors, but also social, economic, and legal values. Although uncomfortable to consider, policy-makers, managers, and society as a whole increasingly will be called upon to make

Box 1.3. The Evolution of Climate Change Vulnerability Assessments

Vulnerability assessments have been used for decades in a wide range of sectors to address a wide range of risks. They may target a single risk (e.g., terrorism) or multiple risks (e.g., assessing all sources of vulnerability for an endangered species). The development of climate change vulnerability assessments is part of this ongoing history, adding a new suite of risks for regulators, managers, businesses, and others to consider. Vulnerability to climate change may be investigated in a stand-alone assessment, but in many cases it will be more effective to include it as part of broader vulnerability assessments addressing a range of risks.

As the scientific understanding of the potential and observed impacts of climate change has grown over the past two decades, so too has the interest in developing useful definitions and frameworks for conducting climate change vulnerability assessments (Füssel and Klein 2005). Earlier efforts tended to focus on developing frameworks for assessing the vulnerability of agriculture, public health, and other human systems to climate change, building on approaches used in addressing problems such as poverty, famine, and natural hazards (e.g., Bohle et al. 1994; Handmer et al. 1999; Kelly and Adger 2000; Downing and Patwardhan 2003). More recently, attention also has been placed on assessing the vulnerability of natural systems (species, habitats, and ecosystems) to climate change (Nitschke and Innes 2008; Zhao et al. 2007), as well as multi-disciplinary efforts to assess the vulnerability of ecosystem services to humans (Metzger et al. 2005) and the interactions between multiple stressors (Turner et al. 2003).

Within each of these areas, however, different definitions and concepts for climate change vulnerability have emerged, which often has led to misunderstandings and challenges in assessment efforts (Füssel 2007). In this guide, we followed the general framework adopted by the IPCC (2001a, 2007c), and subsequently by many others, in which vulnerability assessments are founded on evaluations of exposure, sensitivity, and adaptability to climate changes. The information in this guide provides a general framework for assessing vulnerability of natural systems to climate change, drawing from and building on some of the major concepts gleaned from the literature and attained in practice.

difficult triage choices. Conservation long has been described as a marriage of art and science and that will continue to hold true. Making decisions in the face of climate change will depend on a combination of sound science and practical experience modulated by societal values.

Climate change vulnerability assessments will not provide an estimate of extinction risk or provide the sole basis for determining whether a species ought to receive protection under the Endangered Species Act (ESA). The types of information used in climate change vulnerability assessments can, however, provide information useful in considering the status of a species in relation to the ESA's requirements. For example, information about vulnerability of species and their habitats to climate change, including uncertainty, has been one of the key

Mary Graham

elements considered in several U.S. Fish and Wildlife Service decisions recently under the ESA. These have included: listing the polar bear under the ESA as a threatened species (U.S. FWS 2008a); identifying the Rio Grande cutthroat trout as a candidate of listing (U.S. FWS 2008b); revising critical habitat designated for the Quino checkerspot butterfly (U.S. FWS 2009b); and determining that the American pika, both at the species and subspecies levels, does not warrant listing under the ESA (U.S. FWS 2010).

Finally, there is a permeable boundary between where climate change vulnerability assessments stop and where later components of adaptation planning begin. In this document we focus on the role of vulnerability assessments in providing insights into the relative vulnerabilities of species, habitats, and ecosystems, and understanding the factors involved in those vulnerabilities and other stressors, some of which may be exacerbated by climate change. Adaptation planning also requires the identification, evaluation, and selection of potential management responses to address those vulnerabilities. In practice, some vulnerability assessment efforts go to this next level to identify management responses (e.g., Case Study 6), while others do not. This guidance document does not attempt to address detailed techniques and approaches for identifying, evaluating, and selecting such adaptation responses. However, one increasingly common technique for taking the process to the next step is the use of scenario-based management planning, a technique for decision-making in the face of high uncertainty, which is discussed in Chapter VI.

II. Vulnerability Assessment Basics

This chapter highlights the overarching principles of climate change vulnerability assessments in the context of fish and wildlife management and discusses general considerations in the design of an assessment, including the critical first step of determining scope and objectives. The next chapter (Chapter III) provides more detailed guidance on how to conduct a vulnerability assessment once those goals and objectives have been established. Although the specifics may vary, Box 2.1 summarizes the key steps to carrying out a climate change vulnerability assessment as: (1) determining objectives and scope, (2) gathering relevant data and expertise, (3) assessing the various components of vulnerability, and (4) applying the assessment in adaptation planning and resource management.

Components of Vulnerability

The IPCC defines vulnerability as a function of the *sensitivity* of a particular system to climate changes, its *exposure* to those changes, and its *capacity to adapt* to those changes (IPCC 2007c). **Sensitivity** is a measure of whether and how a species or system is likely to be affected by a given change in climate. **Exposure** is a measure of how much of a change in climate and

Box 2.1. Key Steps for Assessing Vulnerability to Climate Change

Determine objectives and scope

- Identify audience, user requirements, and needed products
- Engage key internal and external stakeholders
- Establish and agree on goals and objectives
- Identify suitable assessment targets
- Determine appropriate spatial and temporal scales
- Select assessment approach based on targets, user needs, and available resources

Gather relevant data and expertise

- Review existing literature on assessment targets and climate impacts
- Reach out to subject experts on target species or systems
- Obtain or develop climatic projections, focusing on ecologically relevant variables and suitable spatial and temporal scales
- Obtain or develop ecological response projections

Assess components of vulnerability

- Evaluate climate sensitivity of assessment targets
- Determine likely exposure of targets to climatic/ecological change
- Consider adaptive capacity of targets that can moderate potential impact
- Estimate overall vulnerability of targets
- Document level of confidence or uncertainty in assessments

Apply assessment in adaptation planning

- Explore why specific targets are vulnerable to inform possible adaptation responses
- Consider how targets might fare under various management and climatic scenarios
- Share assessment results with stakeholders and decision-makers
- Use results to advance development of adaptation strategies and plans

Lead authors: Bruce A. Stein, Patty Glick, and Jennie Hoffman.

associated problems a species or system is likely to experience. **Adaptive capacity** refers to the opportunities that may exist to ameliorate the sensitivity or exposure of that species or system. The relationship among these three components is outlined schematically in Figure 2.1. Considering the degree of change (i.e., exposure) that a species or system is projected to experience along with its likely response (i.e., sensitivity) to those changes determines the potential impact. Understanding the likely consequences (i.e., vulnerability), however, requires further consideration of the ability for the species or system to reduce or moderate those potential impacts (i.e., its adaptive capacity).

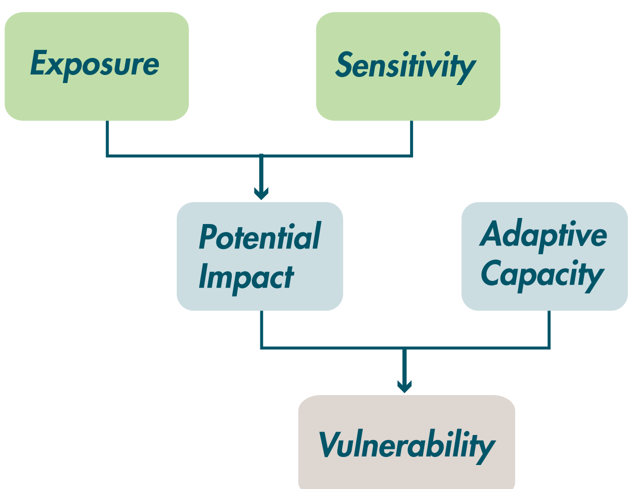

Figure 2.1. Key components of vulnerability, illustrating the relationship among exposure, sensitivity, and adaptive capacity.

Sensitivity

The sensitivity of a species, habitat, or ecosystem to climate change reflects the degree to which that system is or is likely to be affected by or responsive to those changes. Sensitivity may depend on innate physiological or biological variables. For example, a species that is already living at the upper end of its biological temperature range may not be able to tolerate increases in the average temperature in its habitat due to climate change. That species is therefore considered to be "sensitive" to at least one element of climate change, higher average temperatures. Conversely, a population already living in hot conditions may have adapted evolutionarily to high temperatures, and may be less vulnerable to warming than other populations of that species adapted to cooler conditions.

Sensitivity also may be a factor of specific physical or ecological factors. For example, a local river habitat that depends on snowmelt to maintain sufficient instream flows for fish and wildlife is likely to be sensitive to projected reductions in average snowpack due to climate change, as well as to changes in the timing and intensity of precipitation. Finally, sensitivity to climate change impacts may be highly influenced by the existence and extent of other human-related stressors, such as habitat fragmentation due to roads and other development, which can limit the ability of a species to shift ranges in response to changing climate conditions and associated shifts in habitats or ecosystem processes important for the life cycle of the species. In addition, a problem such as unsustainable harvest may increase the sensitivity of a species to climate change by reducing the genetic diversity of individuals within that population. Some of these factors may be considered part of the *adaptive capacity* of a species or system, rather than an element of sensitivity (see below). Additional details on aspects of sensitivity and methods for assessing it are provided in Chapter III.

Exposure

Even if a particular species or system is inherently sensitive to climate change, its vulnerability also depends on the character, magnitude, and rate of changes to which it is exposed. This includes exposure to not only the physical climate changes (e.g., temperature and precipitation) but also to related factors such as altered fire regimes, shifts in vegetation types, increased salinity due to sea-level rise, location of the species or system on the landscape (e.g., latitude and elevation), etc. For example, a specific population of a temperature-sensitive species may inhabit an area likely to be sheltered from rapid temperature increases, such as a north-facing, highly vegetated forest or a high-elevation headwater stream (i.e., refugia). In such instances, the population may have a lower vulnerability than others of its species given its lower level of exposure.

Box 2.2. A Burning Example of Vulnerability

Sunburn is an easily grasped (albeit sometimes painful) example of how the components of vulnerability relate to one another.

- **Sensitivity.** Fair-skinned individuals are usually more sensitive to sunburn than those with deeper skin tones. This sensitivity has a clear biological basis: the skin pigment melanin absorbs ultraviolet (UV) radiation, which is the primary cause of sunburn. As a result, the skin of individuals with lower melanin levels is innately more prone to burning than that of individuals with higher concentrations of melanin.

- **Exposure.**. Depending on one's exposure to UV rays, even individuals with high levels of melanin can burn. In this instance, exposure is related to both the strength of the sun's rays, which varies by latitude, season, and weather conditions, as well as the number of hours in the sun.

- **Adaptive Capacity.** A variety of intrinsic and extrinsic means exist for ameliorating a person's likelihood of burning, and therefore reducing vulnerability. Options for reducing exposure to UV radiation range from protective clothing and sunscreen to remaining indoors and out of direct sunlight. A person's intrinsic sensitivity to UV rays can also be reduced through graduated exposure to sunlight, leading to a temporarily increased concentration of melanin – a process otherwise known as tanning.

Use of climate change projections at various scales can help managers get a sense for where and how much change might be expected to affect a given conservation target. Depending on availability, vulnerability assessments can take advantage of regional climate change projections (i.e., changes in average temperature or precipitation projected across an entire region) or more geographically explicit (but not necessarily more accurate) data from downscaled climate projections. Both originate from simulations by **climate models,** driven by a range of future scenarios. The climate system can be represented by models of varying complexity, that is, for any one component or combination of components a spectrum or hierarchy of models can be identified. Models differ in such aspects as the number of spatial dimensions, the extent to which physical, chemical, or biological processes are explicitly represented, or the level at which empirical parameterizations are involved.

It is also possible to identify the potential ecological effects associated with climate change through the use of so-called **ecological response models,** which provide ways to assess the sensitivity and potential adaptability or resilience of species, habitats, and ecosystems exposed to climate change impacts (Wormworth and Mallon 2007). There are numerous types of response models, ranging from simple to complex. Some of the most commonly used types of response models are the "habitat and occupancy" models, which can project changes in habitat suitability for one or more species over large geographic areas based on specific habitat criteria (e.g., optimal temperature regimes) and biophysical attributes that a species or community can occupy. Other types include conceptual models, general characterization models, expert opinion models, vegetation/habitat response models, physiologically based models, and ecological models. Chapter IV provides a more detailed discussion of climate and response models and how they may be used in vulnerability assessments.

Adaptive Capacity

The adaptive capacity of a species, habitat, or ecosystem refers to the ability of that particular system to accommodate or cope with climate change impacts with minimal disruption. Broadly, adaptive capacity may be considered a factor of particular internal traits, such as the ability of a species to physically move in search of more favorable habitat conditions, adapt evolutionarily, or modify its behavior as climate changes. Adaptive capacity may also be a factor of external conditions such as the existence of a structural barrier such as urban areas, seawalls, or dikes that may limit the ability of that species or habitat to move, or overharvest that limits the genetic diversity available for evolutionary adaptation.

As mentioned above, some factors could equally well be included as part of adaptive capacity, sensitivity, and exposure, particularly in the case of species-based assessments. However, while there is no hard-and-fast rule about where each of these elements should fit in as part of the overall vulnerability assessment, the distinction may be useful for informing management responses. For example, a species that is highly sensitive to climate change but also has a high adaptive capacity may be considered less vulnerable than a moderately sensitive species with little or no adaptive capacity.

Adaptive capacity is different from specific adaptation measures; it can be considered a "pre-existing condition."

It is important to recognize, as well, that the adaptive capacity of a given conservation target is different from the specific adaptation measures to reduce vulnerability. Essentially, it can be considered as a "pre-existing condition" of that species or system that subsequent adaptation measures can address. For example, some adaptation measures, such as removal of seawalls, may serve to enhance the adaptive capacity of a coastal habitat, thereby reducing its vulnerability to sea-level rise.

Components of Biodiversity

Devising a useful vulnerability assessment not only requires an understanding of the components of vulnerability, but also the components of biodiversity and natural systems so that the most appropriate features can serve as targets of the assessment. Such targets can include species, habitats, or ecosystems, and several sections of this guidance document are structured around those biological levels. The definitions of and terminology for these biological units, however, is often the subject of considerable discussion and debate, and terms like "habitat" can have multiple meanings. For that reason, this section provides a brief summary of the various components of biodiversity and discusses how these concepts and terms are used in the context of vulnerability assessments in this guidance document.

Levels of Biological Diversity

The concept of biological diversity—or biodiversity—has become an overarching framework for characterizing the full variety of life on earth (Wilson 1992; Stein et al. 2000). Although many people think of biodiversity in terms of the array of species that exist in a particular place, the concept is considerably broader and includes at least three biological levels of organization—***genes, species, and ecosystems.*** Most vulnerability assessments focus at either species or ecosystem levels, or include some combination of the two (although genetic factors can come into play in assessing species vulnerabilities). Terminology and application is often widely divergent, however, especially for ecologically defined features (e.g., ecosystem, natural community, vegetation type, habitat type). Usage often differs markedly between academic researchers and land or wildlife managers, and also differs based on regional variations in ecological classification and mapping efforts.

Each biological level can be viewed as having three attributes— composition, structure, and function.

Bruce Stein

Each biological level, in turn, can be viewed as having three primary attributes: ***composition, structure, and function*** (Noss 1990). As an example, a specific forest type can be viewed in terms of its composition (the different species of plants and animals making up and inhabiting the forest), its structure (e.g., overstory trees, midstory shrubs, understory forbs), and its functions (e.g., key ecological processes such as periodic fire or nutrient cycles).

Distinguishing among these three attributes may seem an abstract exercise, but can be important for distinguishing among the climate impacts to a particular species or habitat type. In a particular forest type, for instance, shifting climate may eliminate or decrease the frequency of certain species, translating into an change in composition. Depending upon the affected species, however, that change can also represent a shift in ecosystem structure or function. Pine rocklands in the lower Florida Keys, for example, are characterized by open stands of slash pine with a scrubby understory of palms and shrubs. In 2005 saltwater inundation from hurricane-associated storm surge covered large portions of this habitat on the National Key Deer Refuge on Big Pine Key, causing mortality of the overstory pines (Sah et al. 2010). As a result, this portion of the refuge has been converted from an open woodland to a scrubland, with consequent affects on wildlife values and ecological functioning.

Box 2.3. How Does "Resilience" Fit In?

As discussed in Chapter I, one of the most prominent concepts in the field of climate change adaptation today is resilience. A number of factors can determine whether and to what extent a particular species or ecosystem is resilient to climate change. For example, studies show that diversity at multiple levels (i.e., among different functional groups, species within functional groups, and within species and populations of those species, in addition to species richness itself) is particularly critical for ecosystem resilience (Kareiva et al. 2008; Worm et al. 2006; Folke et al. 2004; Luck et al. 2003; Elmqvist et al. 2003). Essentially, such diversity is like climate "insurance"—if one element of a system is compromised, it is more likely that other elements will still be available to support key ecological processes (Peterson et al. 1998). However, while a more resilient ecosystem might be considered less vulnerable to climate change, where and how to incorporate the concept into a vulnerability assessment is not necessarily clear cut (Gallopin 2007). For example, a system that is considered sensitive to climate change, such as a coral reef, may or may not be resilient (e.g., return to a coral-dominant system after a major bleaching event) (Nyström et al. 2000). It is likely that, in most cases, the concept of resilience in a climate change vulnerability assessment will be considered an element of the adaptive capacity of an ecosystem.

Species and Populations

Individual species of fish, wildlife, and plants often constitute the focus of conservation efforts, and similarly are frequent targets for climate change vulnerability assessments. Such assessments can consider a species at the "full taxon" level, that is, across its entire range, or focus on a geographically defined portion of the species. The geographic subsets may simply be that portion of a species that exists within the area of interest for the assessment, or may reflect biologically defined populations (including subpopulations or metapopulations). Most vulnerability assessments are geographically limited in scope (e.g., a state, region, or place) and will therefore usually consider one or more populations, rather than the species as a whole. Common exceptions include assessments mandated by federal statutes such as the ESA.

In practice, most vulnerability assessments are geographically limited and will consider one or more populations, rather than a species as a whole.

The implication of this is significant in assessing the individual components of vulnerability with respect to a species. Many aspects of *sensitivity* relate to innate characteristics of a species, and would be expected to hold relatively constant across its full range. These might includes factors such as reproductive rate or physiological thresholds. On the other hand, *exposure* is by definition variable depending on location. Given the same level of innate sensitivity a species may be exposed to more change in some portions of its range than others. For example, a temperature-sensitive species may be at risk of exceeding its temperature threshold in the southern portion of its range but not along the northern range boundary. As a result, its overall vulnerability may differ significantly between southern and northern populations. It is also possible that *adaptive capacity* can vary across a species geographic range. In this instance, genetic variation across the species' range may render the plant or animal more or less capable of dealing with climate or ecosystem variability and perturbations.

Habitats and Ecosystems

Terminology related to ecological levels of biodiversity is complex and contentious and tends to provoke interminable discussions and debates about appropriate usage. Among the many terms and concepts involved are: habitat, natural community, biotic community, biological assemblage, ecological community, ecological system, ecosystem, ecoregion, biome, and landscape. It is not the purpose of this guidance document to attempt to define and distinguish among these various terms and concepts, and there are many articles and texts in ecology, wildlife biology, and conservation biology that address aspects of this topic (e.g., Bailey 2009; Jax 2006). Because of the significance of ecologically defined units to the practice of vulnerability assessment, though, it is important to draw a few key distinctions, as well as to clarify the sense in which key terms are used in this guidance document.

In this document, the term "habitat" should be interpreted in its most inclusive and general sense.

Defining "Habitat"

Fish and wildlife managers are accustomed to thinking about habitat in relation to their work, and many if not most conservation activities focus on habitat protection, management, or restoration. In practice, *habitat* generally refers either to the place in which an organism exists, or more specifically, to the biophysical features that provide such things as food, water, and shelter necessary to sustain an organism. In a strict sense, habitats are species specific. That is, habitat is viewed through the prism of a particular organism, constituting those things that are needed by and used by that particular species. Different organisms may have similar or overlapping habitat requirements, but these requirements will virtually always differ either subtly or more conspicuously.

Notwithstanding this organism-centric view of habitat, the term is perhaps even more commonly used to describe and communicate about natural ecosystems and landscapes more generally. In this

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sense, the usage can be extremely broad—referring for instance to natural cover providing some wildlife benefit—or very narrow, applying to a specific and precisely defined vegetation type. Usage of the term in terrestrial systems and for terrestrial organisms most commonly is based on a combination of vegetation cover and physical features (e.g., cliff faces, soil types). In aquatic systems the term commonly is based on physical features such as geomorphology, bottom substrate, and water current velocity.

Habitat classifications are, not surprisingly, highly variable and give rise to an exceptional range of habitat mapping efforts based on different attributes and standards. Habitat classifications and mapping have been standardized in some disciplines and in some states or regions, but not in others. For example, in the northeastern United States, the states have collaborated on the development of a regional habitat classification designed to cross-walk the state-specific habitat types that were the focus of individual state wildlife action plans (Gawler et al. 2008).

Despite variability in usage and meaning, habitat is such a central concept in the practice of conservation—and to key audiences for this guide—that we use the term extensively throughout this guidance document. Unless otherwise noted, in this document the term should be interpreted in its most inclusive and general sense. Habitat-oriented vulnerability assessments can be very powerful tools, but given the varied usage and interpretations of this term, it is essential that when they are used as targets of assessments the basis for the habitats (both in concept and execution) be clearly identified and documented.

Defining "Ecosystem"

Just as the term *habitat* has multiple meanings, so too does the term *ecosystem*. In its classical sense, the term refers to a natural unit consisting of the interaction of living organisms and the physical environment (Odum 1953). This traditional concept of an ecosystem is scaleless in the sense that it can refer to the interaction among biotic and abiotic elements contained within a tiny water-filled depression, or across a million-acre landscape.

As noted above, however, there is a host of terms of varying technical specificity that refer to different types of ecological units. Some focus on the interactions that exist among organisms themselves (e.g., biological communities), some on particular classes of organisms (e.g., vegetation types), while others take a more geographic or landscape-level perspective (e.g., Greater Yellowstone Ecosystem). It is not our intent to descend into the bottomless pit of debating the appropriateness of one set of terms over another. In this document, where the term "ecosystem" is used, it can be taken to refer in a general sense to ecological features or units, and indeed, we often simply refer to "systems."

There are, however, several ecosystem-related concepts that have great applicability for adaptation planning and vulnerability assessment. First, there is a wide gradation in spatial scales for different types of units. As an example, the U.S. National Vegetation Classification provides a fine-scale means of characterizing and mapping vegetation types in a nationally consistent way based primarily on vegetation structure and composition (Grossman et al. 1998). At a somewhat coarser scale, the "Ecological Systems" classification that supports U.S. Geological Survey's Gap Analysis Program (GAP) and the U.S. Forest Service's LANDFIRE effort are based on vegetation structure and composition, as well as underlying ecological processes (Comer et al. 2003). Another promising approach from a climate adaptation standpoint is a focus on conserving the ecological "arena" rather than specific biological "actors" through the use of "land facets"—recurring landscape units with uniform topographic and soil attributes (Beier and Brost 2010; Anderson and Ferree 2010).

Setting Goals and Engaging Stakeholders

Climate change vulnerability assessments are, first and foremost, intended to support decision-making, and as such they should be designed from the start with an eye toward the needs of the end users, whether they be on-the-ground managers, policy-makers, or others in the management or scientific communities. This concept is so important that the National Research Council (2009) lists "begin with users' needs" as its first principle for effective decision support in the face of a changing climate.

Assessments should be designed from the start with an eye toward the needs of the end users.

A critical first step then in conducting a vulnerability assessment is to identify the scope and objectives of the assessment based on the intended audience and uses of the assessment. More than anything else, the audience and decision process the assessment is intended to inform will help shape the contours of the analysis.

In this section we discuss the importance of identifying the audience for and stakeholders in the assessment, determining the appropriate level of stakeholder engagement for your particular assessment, clarifying up-front goals and objectives, and addressing some key considerations that logically relate to meeting those objectives within available time and resources. There are a number of different approaches to assessing climate change vulnerability, which vary in the input requirements and type of outputs. Some approaches are more quantitative and other more qualitative, some are modeling-intensive while others rely more on expert knowledge. There is no one single best approach for conducting a vulnerability assessment. Rather, the right approach for any particular effort will depend on user goals and requirements, including the question being asked and the level of resources—data, expertise, time, and funding—available.

Who Is Your Audience?

Execution of a climate change vulnerability assessment should be geared toward the particular user (which we refer to as the *audience*) who will be using the results. Different audiences will likely warrant different assessment targets, levels of complexity, and approaches to communicate the findings. If the primary goal of conducting a vulnerability assessment is to raise greater public awareness of the threat that climate change poses to fish and wildlife at a regional or national level, it may be sufficient to conduct a review of existing literature on climate change impacts or conduct relatively broad and general assessments and then synthesize that information in understandable and accessible outreach tools. On the other hand, if the intended audience is a refuge or park manager who will be using the data to target specific land acquisitions and restoration investments, then much more fine-scale data and assessment results will be necessary. For example, creating simplistic “bathtub” models of sea-level rise, which are based primarily on coastal land elevation data, can be enormously effective in raising awareness of the potential impacts of sea-level rise. Such simple models, however, are not likely to be particularly informative for targeting specific on-the-ground management actions, since they don’t take into account important fine-scale processes, such as the effects of tides or sediment accretion. On the other hand, while conducting a more sophisticated and fine-scale analysis and assessment may require additional time and resources, it can ultimately produce a more actionable set of results for managers of specific places. Similarly, if your target audience is a federal or state agency developing an adaptation plan that aimed at conserving a particular endangered species, more complex assessments that consider detailed biological information about the species and involve projecting ecosystem-level changes to its habitat might be the most valuable approach if resources allow.

What Are Your Objectives?

Clearly establishing the goals and objectives is an essential step in designing a successful vulnerability assessment. First, consider relevant mandates, goals, and objectives that already exist for your organization, agency, refuge, or other such unit. Particularly for state and federal actors, these may constrain the degree of flexibility they have when it comes to the vulnerability assessment itself. However, how those goals and objectives are described is important from the standpoint of ensuring they are framed in ways that are clear and meaningful to those who will conduct the assessment. Consequently, the description of the goals and objectives should be a collaborative endeavor that includes the prospective end users as well as scientific and technical staff involved in carrying out the assessment. All too often, managers and researchers speak in different terms and have different expectations and understandings. Time spent at the beginning of a project to ensure that all participants have a common understanding of intended outcomes, technical requirements, resource needs, and timelines will maximize the likelihood of the assessment helping achieve the conservation goals. (See National Research Council [2009] for a detailed discussion of linking information producers and users.)

Ultimately, the purpose of conducting a vulnerability assessment in support of adaptation planning is to help increase the likelihood that you can achieve your conservation goals and objectives given the added impacts and complexities of climate change in conjunction with other stressors. The objective may be to restore and protect populations of a particular species or group of species. Or, it may be to ensure that a given ecosystem will continue to support sustainable levels of a natural resource such as timber, or provide certain ecosystem services such as clean water. In some cases, the goal may be to facilitate a substantial change in conditions, including changes in habitat and in the composition of plant and animal species, so that as much "naturalness" as possible can be maintained. Consider the vulnerability of your goal itself to climate change.

It will be important to get climate change adaptation principles embedded into established planning and decision-making processes.

Although vulnerability assessments can feed directly into stand-alone climate adaptation planning efforts, there will be other times when this information will need to inform existing agency and organizational planning or decision processes. Indeed, in many instances it will be more important to get climate change adaptation principles embedded into established planning and decision-making processes, many of which have the force of the law.

In some cases, the goals of a vulnerability assessment may depend on factors such as the management jurisdiction or mandate of the agency or agencies conducting the analysis. Many state wildlife agencies, for example, are focused on managing "species of greatest conservation need" (SGCN) as defined under their state wildlife action plans. While they may also be interested in assessing the vulnerability of habitats and ecosystems, targeting efforts toward those species will likely be important to inform the agency's relevant adaptation decisions. Federal agencies are required to utilize their programs in furtherance of achieving the conservation of species under the ESA. Some agencies or organizations may be responsible for managing a particular park or other protected area, or an area available for use for various purposes of high interest to the public—for them, regionally specific information about climate change will be of greatest interest and importance.

Regardless of the application and focus, coping with climate change will require fundamental shifts in the way conservation and natural resource management are carried out. The traditional approach of using past conditions and trends as a benchmark and goal for conservation will become increasingly problematic in a rapidly changing climate. While many of our conservation tools and principles will remain the same, it is likely that some of our goals and priorities will need to change as we look at protecting native species of fish, wildlife, and plants in a changing environment.

Gary Tischer/USFWS

Why Engage Stakeholders?

Engaging the right stakeholders in the right way and at the right times can be the critical factor in determining the success of an assessment under some circumstances. We address three important categories for decisions about stakeholder engagement in a climate change vulnerability assessment: why, who, and how. The goals and context of a particular assessment will, in turn, determine the kind and amount of effort directed to involve stakeholders.

First, consider what you hope to gain from stakeholder engagement. Engaging and informing stakeholders can help to accomplish the following:

1. Provide Data. While there is a large amount of relevant data available in public contexts such as on-line databases and the published literature, there are even more data available from less easily accessible sources such as site-specific monitoring programs or long-term citizen science projects. Less formal or accessible data sources can be particularly useful for understanding local or regional climatic or ecological systems and patterns and for providing information at a finer scale than is available elsewhere. For example, local observers and resource users can help to identify which particular climate variables (timing of first rainfall, minimum annual temperature, etc.) are likely to be most important for the ecosystem under consideration. The number and type of stakeholders that need to be engaged as providers of climatic or ecological information depends on various factors such as how well characterized is the system being assessed, the quality, size, and availability of existing data sets, and the degree of finer scale variation within the system.

2. Refine Scope and Focus. To maximize the usefulness of a vulnerability assessment, it is also important to engage stakeholders in determining the scope or focus of the assessment. If the goal is to inform resource management over a wide area involving multiple jurisdictions, for instance, you need the input of a broad array of resource managers as to how they make decisions—the timing of decision cycles, the variables they use, etc. Defining the scope or focus may happen in two stages. A smaller group of individuals may conduct an exploratory vulnerability assessment that is used to inform decisions about who needs to be engaged at a broader level. Again, the approach taken will depend on the specific circumstances.

3. Provide Sociopolitical Context. Because the sociopolitical setting influences the climate vulnerability of natural systems, it is important to engage stakeholders who can explain and integrate important components of the sociopolitical system into the assessment. These components may include national, regional, or local laws, regulations, rules, and plans; important subsistence or cultural uses of the natural environment; and value systems that may determine how human systems in the region in question respond to climate change. While ecological and sociopolitical elements of vulnerability are often considered separately, some level of integration is likely to produce more robust and useful results. Local stakeholder engagement is especially important when there are ethnographic considerations. Cultural and/or spiritual information is often poorly documented or resides entirely in oral histories and traditions.

4. Build Support for Adaptation. Finally, if the goal is to use the vulnerability assessment for climate change adaptation planning, it is worth engaging individuals and organizations that will be important for developing and implementing the adaptation plan (Vogel et al. 2007). They may not need to be full participants in the vulnerability assessment, but they may need to know that it is happening and understand how it will feed into the adaptation planning process. This is particularly relevant if one's goal is to support adaptive management plans that accompany or are part of climate change adaptation plans or other conservation plans, since such plans may require broad public support to achieve the needed level of flexibility.

Box 2.4. Steps to Identify the Appropriate Scope of Stakeholder Participation

- Create an initial list of organizations, interest groups, and individuals who may wish to be involved in the process or whose buy-in may contribute to project success or failure.
- Meet with representatives of these groups separately in informal settings that are familiar to the people with whom you are meeting.
- Explain clearly the principles of vulnerability assessment and adaptation and the goals of the project with which you are asking them to engage.
- Emphasize the importance of public participation, and that you are asking them to decide among a range of options for engagement, both in terms of the level of involvement and the mechanism.
- Ask group members to express their interests or concerns, and request the selection of a group representative to participate in an initial joint meeting of all the groups.
- Ask these interested parties if they know of others who should be involved in the process.
- Once all interested groups, sectors, and individuals have been approached individually, hold an initial meeting with representatives from all interested groups and sectors to agree on the details of the participation process. Depending on funding and the degree of trust among participants, it may be useful for participants to select a mediator for the stakeholder engagement process, someone who is widely respected and viewed as neutral. It may also be necessary to provide some background information or training for stakeholder groups, for instance if they will be asked to interpret the results of climate models.

Source: Integrated Resource Planning Committee (1993).

Whom to Engage?

The variety of individuals and organizations that may need to be involved is as great as the variety of reasons to engage them at all. Categories to consider include:

- Decision-makers (e.g., regulators and managers), in addition to those who may be requesting or directing that a vulnerability assessment be conducted

- Decision implementers (e.g., managers)

- End users of resources/lands (e.g., hunters, birders, oil and gas developers)

- Opinion leaders (influential and respected individuals within the region or sector of interest)

- Climate change adaptation planners

- Providers of information (e.g., scientists, holders of traditional knowledge, sociologists, etc.; will usually overlap with other groups)

Time allocated to thoughtfully identifying and engaging stakeholders in the vulnerability assessment will usually be more than worth the effort if the vulnerability assessment is to be part of a longer-term engagement on climate change issues.

How to Engage Stakeholders?

The degree of stakeholder engagement in a vulnerability assessment may vary widely. At one end of the spectrum, it may involve simply providing information along the way, while at the other end of the spectrum it can involve guiding the entire process. It is generally the case that the more deeply engaged stakeholders are, the more committed they will be to a climate change vulnerability assessment and to using the results in subsequent adaptation planning and projects. The expected scale of the assessment and of the subsequent adaptation planning will help determine the most desirable level of involvement by specific stakeholders. Engaging too many stakeholders or engaging stakeholders too intimately can lead to a quagmire in which little is accomplished; engaging too few stakeholders or engaging stakeholders too shallowly can lead to inaccurate or incomplete assessments and lack of buy-in for subsequent adaptation projects.

The more deeply engaged stakeholders are, the more committed they will be to using the results.

One important element of engaging stakeholders is to be clear with them about their role. This may vary depending on the circumstances and on the stakeholders involved (e.g., in some circumstances you may want the selection of assessment targets to be determined entirely or largely by stakeholders, while in other circumstances the selection of targets may be dictated by the organization or agency conducting or commissioning the assessment).

Another important element is to let stakeholders know about any decisions that already have been made about assessment targets and processes. For example, there may be situations in which resource managers identify target species or habitats for climate change vulnerability assessments due to legal or policy considerations, and that while stakeholders may be asked for input about additional species to assess, some targets may be set *a priori.*

Finally, it is important to acknowledge the value of stakeholders' time and offer constructive ways to ensure that both you and they benefit from their engagement in the assessment process.

Selecting Assessment Targets

Species

Given that a significant portion of the conservation work at the state and federal levels are focused on individual species of plants and animals, species are and will likely continue to be one of the primary targets for climate change vulnerability assessments. A wide variety of traits and processes can make a species more or less vulnerable to climate change. The effects of a changing climate tend to exacerbate the effects of other threats, such as habitat loss or pressure from invasive species that may have already made a species susceptible to population declines or even extinction.

The World Conservation Union (IUCN) has described five categories of biological traits that can make species more vulnerable to climate change (Foden et al. 2008):

- Specialized habitat or microhabitat requirements
- Narrow environmental tolerances or thresholds that are likely to be exceeded under climate change
- Dependence on specific environmental triggers or cues that are likely to be disrupted by climate change (phenological responses—e.g., rainfall or temperature cues for migration, breeding, or hibernation)
- Dependence on interactions between species that are likely to be disrupted
- Inability or poor ability to disperse quickly or to colonize a new, more suitable range

Target species may be selected for a wide array of reasons. Some species may not have any of the biological traits that match the list above, but an assessment of their vulnerability to climate change may be of interest for other reasons. For example, the vulnerability of species that are of high economic, social, or cultural value in an area may be of interest to resource managers, business people, and others who want projections to help them gauge whether regional populations are likely to be sustained or to move elsewhere as a result of a changing climate, even though they are not at risk of becoming extinct. The first three case studies in Chapter VII are examples of climate change vulnerability assessments targeted to species.

Habitats

As described earlier, the term habitat is used in a variety of ways. Nonetheless, because many wildlife conservation actions are delivered on the ground based on a habitat framework, using habitats as the target of a vulnerability assessment can be a helpful way to ensure that the results will support the needs of managers. Focusing on specific habitats as a target for vulnerability assessments may occur as an objective in and of itself, or may be in tandem with efforts to assess species vulnerability.

Climate change can affect habitats in a number of ways (e.g., it can alter their species composition, their location and/or their size, or their functioning). For example, areas that are currently managed as important shrub–steppe habitat may become more suitable for piñon–juniper habitat or may be likely to undergo changes due to fire and invasive species under future climate conditions. Further analysis (both quantitative and qualitative) can help determine how these habitat changes might affect associated species, such as greater sage-grouse, various species of migratory songbirds, and numerous other animals and plants associated with shrub–steppe habitat.

As with species analysis, climate change vulnerability assessments for habitats can range in levels of complexity. There are a number of modeling tools and resources that can assist habitat managers in conducting vulnerability studies. For terrestrial systems, scientists frequently rely on models that can project shifts in the range of vegetation or other organisms due to changes in climatic variables, usually at relatively large regional scales. Some of the more basic models project vegetation changes under steady-state conditions. Specifically, they relate the current distribution of a species to current climate conditions, such as temperature and precipitation, and then project a potential future range under scenarios of future climate conditions (Botkin et al. 2007). It is also possible to apply more complex models that can simulate habitat responses and project potential changes in ecosystem structure and function.

For aquatic habitats, wider availability of spatially and temporally downscaled climate models have allowed for more localized projections on likely changes in temperatures and precipitation to a scale relevant for hydrological impact studies, which can help inform watershed planning and other management efforts under climate change (Wood et al. 2004).

Ecosystems

The use of ecosystems as the basis for climate change vulnerability assessment will depend largely on the availability of ecological characterization and mapping efforts in the region of concern, and on the way in which ecosystems (or related concepts) fit into prevailing management and planning regimes. Some assessments may focus entirely on a single large-landscape "ecosystem," in which case the assessment targets will not actually be the ecosystem itself, but rather subcomponents such as species or particular biological communities or habitats, or an examination of ecological processes.

Of particular concern in assessing ecosystem vulnerabilities are the potential for disruptions in ecological interactions and compromises to key ecosystem functions and processes (Shaver et al. 2000). In turn, impacts to ecosystem functions can have profound consequences for the services that are provided by the particular system. The concept of ecosystem services (e.g., water production, carbon sequestration) increasingly is serving as an important framework for human valuation of natural systems (Millennium Ecosystem Assessment 2005). Because many ecological assemblages (e.g., the connection between pollinators and the flowers they fertilize, or breeding birds and the insects on which they feed) will likely be disassembled under future climate change as their component species respond to changes differently, a combined strategy of targeting both species and ecosystems may be desirable in many situations (Root and Schneider 2002).

Further complicating matters is the fact that the ecological impacts of climate change do not occur in isolation, but combine with and exacerbate other stresses on our natural systems. Leading threats to biodiversity include habitat destruction, alteration of key ecological processes such as fire, the spread of harmful invasive species, and the emergence of new pathogens and diseases. The health and resilience of many of our species and natural systems are already seriously compromised by these "traditional" stressors and changes in climate will have the effect of increasing their impact, often in unpredictable ways. As noted earlier in this document, some aspects of sensitivity, exposure, and adaptive capacity take other stressors into account to some degree. For some systems and situations (again, depending on users' needs), it may be important to take an assessment approach that more specifically integrates the intersecting effects of all the important stressors.

Although assessing the vulnerability of ecosystems to climate change is inherently complex, advances in modeling have made such assessments more accessible. For example, some dynamic global vegetation models (DGVM) can simulate ecosystem processes such as carbon dioxide (CO_2) uptake and fluxes in nutrients and water (Bachelet et al. 2001).

Chapter IV provides more detail about the use of these and other models in conducting a climate change vulnerability assessment for species, habitats, and ecosystems.

Space and Time: Selecting the Right Scales

Setting the appropriate geographic scale for your vulnerability assessment and determining over what time scale the analysis should cover are two key factors in designing a successful assessment.

Geographic Extent

Climate change vulnerability assessments can be done at local, regional, and national scales. As with the identification of the relevant assessment targets, a number of factors can determine the spatial scale on which you will focus. By its very nature, however, climate change will require that we think and plan within the context of larger landscapes, even when our management needs are very local. For example, many species are expected to shift ranges in response to shifting climates,

An inverse relationship exists between the geographic scale of an assessment and the certainty of projections.

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and as a result, our existing portfolio of protected areas and wildlife management areas may no longer support the suite of species for which they had originally been established (Hannah et al. 2007). This is especially true for migratory species, whose habitat range may span several states, countries, or even continents. Accordingly, selecting an appropriate geographic scale for an assessment must consider not only the organization's management jurisdiction, but also the geographic requirements of the species or ecosystems that are the target of the assessment.

Clearly defining the spatial scale of the assessment early can help keep the process as efficient as possible. If an assessment is conducted at the state level, it is important to consider how it will take into account species that cross state boundaries, including species that may move into or out of the state or region under future climate conditions. In some cases, conducting a multi-state vulnerability assessment or coordinating with neighboring states can help resolve these problems (see, for example, Case Studies 6 and 7).

Much adaptation planning and implementation will, of necessity, be conducted at the level of individual land management units, whether parks, preserves, military installations, national forests, or other managed landscapes. Ideally, such local-scale planning will be able to draw from vulnerability assessments conducted at broader geographic scales. Nonetheless, some local-scale managers will be interested in conducting their own vulnerability assessments. To the extent possible, these should be structured to build from and take advantage of assessments covering the state or multi-state region in which the landscape rests.

Vulnerability assessments for individual protected areas should identify the likely effectiveness of those areas to support a given species, habitat, or ecosystem under scenarios of climate change. Beyond considering the species or habitats that may be lost from an area, however, they should consider what species or habitats may be likely to move into the area that may be of management interest. In general, it is important to consider the scale of projections from climate models and the scales desired for projections of biological responses, to ensure they match appropriately (Wiens and Bachelet 2009). There is often an inverse relationship between the geographic scale of an assessment and the level of certainty regarding projections of both climate and ecological response. Climate projections, for instance, are most robust at coarser scales, and even with the availability of downscaled climate projections, less so at finer scales. As a result, in carrying out vulnerability assessments at local scales, it is particularly important to understand uncertainties and refrain from overinterpreting fine-scale projections.

Time Frame

Another key consideration is which climate change scenarios to use, and over what time frame. As described in detail in Chapter IV, there are multiple scenarios available based on a range of assumptions, including future emissions trends, levels of economic activity, and other factors. Identifying the potential impacts of climate change under multiple scenarios and time steps (e.g., 10 years, 25 years, 100 years) will be important to inform a range of possible management strategies. In determining the appropriate time frame for an assessment, consider that near-term projections of climate change scenarios tend to have a higher degree of certainty than those that look farther out. This is the case because it is difficult to anticipate how greenhouse gas emissions might change in the future, whereas the climate change we experience over the next few decades will be primarily caused by past emissions. However, it may be appropriate for some vulnerability assessments to consider a longer time frame, acknowledging the higher level of uncertainty in long-term climate projections.

Complexity: More Isn't Always Better

Climate change vulnerability assessments for species and ecosystems use a range of methodologies, from qualitative assessments based on expert knowledge to highly detailed, quantitative analysis using ecological models. Selecting an approach may depend on a host of factors, including the availability of already existing information, the level of expertise, time and budget constraints, and so on. For example, while there are a growing number of models available that can project the impacts of climate change on plant and animal ranges, the availability to conduct more detailed analyses such as modeling the dynamic ecological responses among diverse species within and among ecosystems is still relatively limited. In some cases, focusing quantitative assessments more broadly on habitat changes and then applying qualitative assessments of potential species responses may be the best approach given existing information. Additional studies can then be undertaken as information and resources allow.

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Embracing Uncertainty

Assessing the vulnerability of species, habitats, or ecosystems to most stressors, and certainly to climate change, is complex, and there are different levels of certainty and confidence in each piece of scientific information and expert knowledge that are integrated together to produce a vulnerability assessment. Uncertainty is a reality: No one knows exactly how climate may change or how ecological or human systems may respond to change, in any particular location.

Management decisions can proceed in the face of uncertainty. A useful way to characterize uncertainty in the assessment process is the level of confidence in a given input or outcome. In some instances we will have a high level of confidence in some or all of the parts determining climate change vulnerability, and in other cases we may be less certain in one or more vulnerability factors. It is important to understand the level of certainty about the different components of vulnerability, to identify the range of potential vulnerability given the uncertainties, and to determine what we can and cannot say about the vulnerability of the system. At the same time, lingering uncertainty about climate change need not paralyze us in making decisions and developing strategies for adapting to climate change. Chapter V provides a more detailed discussion of the nature of uncertainty, presents a language for addressing certainties and uncertainties, and provides methods for incorporating uncertainty into vulnerability assessments.

III. Assessing the Components of Vulnerability

This chapter provides a more detailed treatment of how to apply the sensitivity, exposure, and adaptive capacity framework presented in the previous chapter for conducting a vulnerability assessment. Depending on the objective of the analysis, whether it focuses on a single species, specific habitat, ecosystem, or geographic place—different components will be more or less useful. Some elements will be useful for assessing the vulnerability of a wide range of targets (species, habitats, or ecosystems). Below, we first describe these "universal" elements, that is, aspects that are relevant to most any vulnerability analysis. We then provide descriptions of some of the elements that are better suited to assessing the vulnerability of particular targets.

Many of the sensitivity elements that apply across biological levels are associated with physical systems and processes.

Assessing Sensitivity

Universal Elements of Sensitivity

Many of the critical sensitivity elements that apply across biological levels—that is, to species, habitats, and ecosystems—are associated with the earth's physical systems and processes such as hydrology, fire, and wind. Although there are other sensitivity factors that affect all three levels of ecological organization, they tend to do so through their effects on individuals or species. Thus, most sensitivity factors are described in the species subsection, below.

Hydrology

Both terrestrial and aquatic species, habitats, and ecosystems can be sensitive to changes in hydrology. For example, salmon spawning and migration are sensitive to the timing and the volume of stream flows; the composition and structure of forest stands are sensitive to the availability of ground water; and dissolved oxygen levels, water temperatures, decomposition rates, and other wetland attributes are sensitive to the amount of water flowing into and out of the wetland. Other species are sensitive to reductions in snowpack, such as the American wolverine, which requires persistent spring snow cover for its natal dens (Copeland et al. 2010; Aubry et al. 2007).

Fire

Individual species as well as habitats and ecosystems can be sensitive to changes in the frequency, severity, and extent of fires. For example, plant species that depend

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on fire for germination and conversely species that are intolerant of intense fires are sensitive (albeit in different ways) to changes in fire regimes. The degree to which a plant community type is sensitive to changes in fire regimes will depend not only on the individual sensitivities of its component species, but also on any synergistic effects that particular combination of species and their spatial arrangement has on fire behavior (e.g., the structure of the vegetation, the ground-level accumulation of fine fuels, and the invasion of habitat by plant species, such as cheatgrass or buffelgrass, that can alter a system's fire regime) (Young and Blank 1995). Similarly, an ecosystem's sensitivity to fire will be affected by the sensitivities of its component species and habitats, but also by topography, hydrology, and potentially by the spatial arrangement of habitat types and the sensitivities of neighboring ecosystems.

Wind

Sensitivities to changes in wind and storm events also may apply across multiple biological levels. For example, individual tree species will be more or less sensitive to wind based on their physiologies. Habitats and ecosystems will be more or less sensitive depending on their component species but also the arrangement and composition of those species and potential interactions between wind events, insect outbreaks, and fire. Longleaf pine trees, for example, are considered to be less sensitive to wind storms than are loblolly pine and slash pine (McNulty 2002). When encountering hurricane-force winds, longleaf pine trees are more likely than these other species to have minimal damage or be blown over, rather than snapping midstem or becoming completely uprooted, as their large taproot and widespread lateral root system provide them with greater stability. For another example, wind can transport dust from lower-elevation deserts to higher-elevation snowfields, increasing the rate of snowmelt (Steltzer et al. 2009). This can, in turn, lead to early germination in many plant species, leaving them susceptible to frost damage and, in some cases, mortality (Inouye 2008).

Species-Level Sensitivities

Physiological Factors

Species-level sensitivities often are characterized by physiological factors such as changes in temperature, moisture, CO_2 concentrations, pH, or salinity. These physiological sensitivities can be thought of as direct sensitivities to climate change. Examples of sensitivities to changes in temperature are cold-water fish species with maximum temperature tolerances (e.g., bull trout), turtles with temperature-dependent sex ratios, and trees with frost tolerances or required growing-season lengths (Dunham et al. 2003; Janzen 1994; Luedeling et al. 2009). Examples of direct physiological sensitivities to changes in moisture include germination requirements in plants, moisture requirements for some amphibians, nest microclimate requirements for incubation or nestling survival in birds, and snowpack-insulation effects on high-elevation plants and animals (e.g., the American pika, which exhibits high temperature sensitivity during the summer months) (Fay et al. 2009; Blaustein et al. 2010; Rauter et al. 2002; Smith and Weston 1990). Increases in atmospheric CO_2 concentrations can increase water use efficiency in plants and therefore increase growth through "CO_2 fertilization" (Belote et al. 2003). Increasing CO_2 concentrations are also affecting the pH of marine and, in some cases, freshwater systems. For example, many corals and other species with calcareous exoskeletons or shells will be sensitive to changes in pH (Kuffner and Tihansky 2008).

Dependence on Sensitive Habitats

In many cases, individual species' sensitivity is likely to be influenced by the sensitivity of its habitat to climate change (McCarty 2001). For example, species that breed in vernal pools, ephemeral wetlands, intermittent streams, and species that live in alpine environments or low-lying coastal zones are all likely to be highly susceptible to climate impacts such as rising temperature regimes; winter precipitation arriving more frequently as rain than snow; shifts in the timing of snowmelt, runoff, and peak flows in streams; and sea-level rise. In some cases, it may suffice to highlight species that are linked to highly sensitive habitats such as those listed above. In other cases, one might want to conduct a detailed habitat sensitivity assessment (based on some of the factors listed below in the section on habitat-specific sensitivities).

Ecological Linkages

Species' sensitivities also likely depend on the effects of climate change on predators, competitors, prey, forage, host plants, diseases, parasites, and other groups of species that affect the focal species (Parmesan 2006). For example, there may be changes in the occurrence or abundance of predators or prey that subsequently affect the focal species (Visser and Both 2005). There may also be changes in the interspecific relationships themselves. CO_2-driven increases in water use efficiency have the potential to change the competitive relationship among species. Likewise, an increase in temperature could increase the feeding efficiency of a warm-water fish species, allowing it to better compete with a cool-water species.

Other key examples of changes in ecological linkages might include changes in the community of invasive species (e.g., new invaders), changes in the frequency or intensity of pest outbreaks, and changes in the prevalence, spread, and susceptibility to disease. For example, increases in temperature have allowed mountain pine beetles to complete their life cycles within a single year at higher elevations, exposing previously isolated whitebark pine to beetle outbreaks (Logan et al. 2003; Logan and Powell 2001). Similarly, changes in climate have been implicated in the range shift of the disease-causing chytrid fungus, potentially affecting previously isolated amphibian populations and species (Pounds et al. 2006; Bosch et al. 2007).

Phenological Changes

Phenology refers to recurring plant and animal life-cycle stages, such as leafing and flowering of plants, maturation of agricultural crops, emergence of insects, and migration of birds. Many of these events are sensitive to climatic variation and change (Parmesan and Yohe 2003), and when the timing and sequence of these events are altered, loss of species and certain ecological functions (e.g., pollination) can occur (Root et al. 2003; Visser and Both 2005). For example, climate change can reduce the amount of food available to birds during migration and the breeding season (Both et al. 2006; Leech and Crick 2007). It can also alter fundamental interactions between species that affect competition and survivorship (Root and Hughes 2005). However, the scale of response can depend on the life history of the individual species. For example, sea birds with high dispersal capacity have been shown to respond to broader-scale cues (e.g., the North Atlantic Oscillation) whereas permanent residents tend to response to local-scale cues (e.g., sea surface temperature) (Frederikson et al. 2004). Similarly, the timing of spring migration by long-distance migrants is more attuned to regional- to continental-scale climates while timing of spring migration by short-distance migrants responds much more strongly to the local climate (MacMynowski and Root 2007). Information on phenology can be found at http://www.usanpn.org/.

Population Growth Rates

Species that can quickly recover from low population numbers are more likely to be able to withstand rapidly changing climates as well as colonize new locations following climate disruption (Kinnison and Hairston 2007). In addition, rapid population growth can also help maintain genetic variability. This trait favors colonization of extant and novel habitats by early-successional and invasive species (Cole 2010). As a result, conservation practitioners and managers will be challenged by deciding which species have conservation value as species reassemble and populations grow.

Degree of Specialization

Generalist species are likely to be less sensitive to climate change than are specialists (Brown 1995). Species that use multiple habitats, for example, have multiple prey or forage species, or have multiple host plants are likely to be less sensitive to climate change than are species with very narrow habitat needs, single-forage or -prey species, or single-host-plant species (Thuiller et al. 2005). In addition, specialist species are likely to have specific evolutionary factors (e.g., low genetic variation for heat resistance) that limit their ability to adapt to changing conditions over time (Kellermann et al. 2009).

Reproductive Strategy

The reproductive strategy of species may also make them sensitive to climate change. Some studies suggest that species with long generation times and fewer offspring (e.g., "K-selected" species) are likely to be at greater risk of extinction under long-term climate change than those whose life history is characterized by short generation times and many offspring (e.g., "r-selected" species) (Isaac 2009; Chiba 1998). For example, more opportunistic, rapidly reproducing species may be better able to take advantage of major climate change–related disturbances such as wildfires and hurricanes.

Interactions with Other Stressors

The existence of other stressors has the potential to exacerbate the effects of climate change on individuals and populations. For example, research suggests that exposure to pollutants such as heavy metals, oil, and pesticides may act synergistically with ocean warming to induce coral bleaching events in some instances (Brown 2000). Studies have also found that the existence of pollution can significantly reduce the recovery rate of corals after major bleaching events and disease outbreaks (Carilli et al. 2009).

Habitat-Level Sensitivities

Sensitivity of Component Species

The sensitivity of a given habitat type will largely be determined by the sensitivities of its component species. The sensitivity of dominant species, ecosystem engineers, keystone species, and “strong interactors” are likely to have large influences on the sensitivity of a habitat type.

Community Structure

Plant and animal communities depend in part on a delicate balance of multiple, interspecific interactions. Some communities will be more sensitive to climate change than others. For example, the presence of algae-grazing species of fish and invertebrates can help limit the overgrowth of harmful, opportunistic algae on coral reef habitats damaged by coral bleaching, facilitating their ability to recover (Nyström et al. 2000). Coral reefs in regions where problems such as overfishing have reduced the population of algae-grazing species are therefore likely to be more sensitive to climate change than those with such functional communities intact.

The level of diversity of component species and functional groups in a habitat also may affect the sensitivity of that habitat to climate change impacts. For example, research suggests that restoring heterogeneity in vegetation structure, composition, density, and biomass to rangelands such as the tallgrass prairie of the Great Plains is likely to be an important strategy to improve the resilience of these systems to climate change (Fuhlendorf and Engle 2001). Increased homogeneity in some rangeland systems due to livestock production has made these systems much more vulnerable to disturbances such as widespread wildfires, which are different from the more patchwork-type burn patterns and associated grazing patterns of a more diverse tallgrass prairie system.

Ecosystem-Level Sensitivities

Sensitivity of Component Species

The sensitivity of a given ecosystem will largely be determined by the sensitivities of the ecological function and biological diversity of that system, as well as the sensitivities of the component species/habitats.

As with habitats, the sensitivities of dominant, keystone, and indicator species are likely to have large influences on the sensitivity of an ecosystem. For example, the ochre sea star is a keystone species in rocky intertidal ecosystems of the Pacific Northwest, in that it maintains community diversity through predation on mussels. Research has found that such predation is sharply reduced by decreases in water temperature (such as during the seasonal upwelling of cold, nutrient-rich water from the ocean floor) (Sanford 2002). Upwelling is sensitive to climate, and its frequency and intensity may be reduced by future climate change. As a result, predation by the ochre sea star may become more regular, transforming the community dynamics by reducing mussel populations.

Sensitivity of Ecosystem Processes to Temperature or Precipitation

Many ecosystem processes, such as decomposition, nutrient transport, sedimentation, fire, etc., are sensitive to changes in temperature or precipitation. Changes in river flow and water temperatures, for instance, are likely to have an impact on eutrophication and oxygen depletion in estuarine systems such as the Chesapeake Bay. If climate change leads to an increase in the frequency or extent of heavy downpours, as some models suggest, increased runoff will flush greater amounts of nutrients and other pollutants into coastal waters (Hagy et al. 2004). Heavy runoff also decreases water mixing as less dense fresh water rides over the top of denser salt water, inhibiting the mixing of water and the replenishment of oxygen in deep waters. Higher water temperatures also may affect oxygen levels in some systems because warm water holds less dissolved oxygen than cool water (Najjar et al. 2000). Further, higher water temperatures can accelerate the bacterial decay of organic matter present in the water, thereby consuming oxygen and exacerbating hypoxia (Varekamp et al. 2004).

Assessing Exposure

Universal Elements of Exposure

Most of the following exposure elements apply to all three levels of ecological organization. This section provides a general overview of the various elements of exposure. The following chapter (Chapter IV) offers more detailed information about specific tools available to evaluate exposure in climate change vulnerability assessment.

Historic versus Future Projected Change

Vulnerability assessment can be conducted either based on historic observed changes in climate (retrospective assessment), future modeled projections (prospective assessment), or a combination of the two. Historic changes will generally indicate the current vulnerability as compared with the past, while the future climate projections will give an assessment of future vulnerability. Depending on the objectives of the assessment, one or the other may be more appropriate. If the resources and data are available, a combination of both retrospective and prospective assessments provides the most complete picture in terms of the current status and the likely future status.

Basic Climate

The most basic and direct types of exposure are from changes in climate: temperature, precipitation, wind, humidity, cloud cover, and solar radiation. Although these variables often increase vulnerability indirectly—such as by changing hydrology, fire, or distribution of interacting species (e.g., competitors, predators, prey, etc.)—they can also directly increase vulnerability. The change in the mean values of these basic climate variables can be used in vulnerability analyses (e.g., changes in average annual temperature or total annual precipitation). However, it may be changes to the extreme values of these variables (e.g., daily minimum or daily maximum temperatures) that are most important for determining vulnerability. The ability for plant species to exist in a certain area is often related to the temperature of the coldest day of the year in that location.

These basic climate variables can be measured for different time periods—annually, seasonally, within specific months, or even within a day (e.g., nocturnal/diurnal extremes). Understanding which of these time periods and climate measures are biologically relevant is key for determining climate vulnerability. For example, changes to springtime temperatures may be the most important factor determining climate sensitivity for organisms or ecosystems dependent on the timing of specific spring events such as flowering or hatching. In contrast, wintertime temperature changes might be most important for a species with chilling requirements for seed production (Luedeling et al. 2009).

Drought

Changes in temperature and precipitation can influence drought frequency and/or severity. In general, it is thought that under climate change there will be an increase in the incidence, intensity, and duration of droughts, but this will certainly differ by location. There are drought indices available for quantifying the exposure to drought (Trenberth et al. 2003). Two of the most commonly used indices are the Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Index (SPI). For a good overview of drought indices see: http://drought.unl.edu/whatis/indices.htm. The U.S. Drought Monitor Program (http://drought.unl.edu/DM/MONITOR.html) provides current and recent historic maps of drought severity in the United States. The National Oceanic and Atmospheric Administration provides current drought maps at: http://lwf.ncdc.noaa.gov/oa/climate/research/prelim/drought/palmer.html.

Hydrologic Changes

There are many hydrologic changes that may occur to both terrestrial and aquatic systems in a changing climate. For terrestrial systems, the types of hydrologic exposure will generally relate to the amount of available soil moisture through changes in precipitation, water runoff, and evapotranspiration (ET). In general, increasing temperatures will result in increased rates of ET causing decreases in soil moisture. Increases in precipitation can offset this increase in ET, but it must come in sufficient amounts and at the right time of year. If temperature increases and precipitation does not change or decreases, it can be fairly safely assumed

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that soil moisture will decrease. There are various methods of calculating changes to ET. The simplest methods are based only on temperature and number of daylight hours (e.g., the Hamon method) (Hamon 1961). The assessment approach used in the Four Corners case study (Case Study 6) included application of the Hamon method. More complex methods for computing ET need information about temperature, wind speed, relative humidity, and solar radiation (e.g., Penman-Monteith) (Allen et al. 1998). Once ET is estimated, various related metrics can be calculated by subtracting it from ET from precipitation: actual ET, moisture deficit, and moisture surplus.

Macroscale hydrologic models provide an even more complex and generally more accurate but computationally intensive method for estimating hydrologic responses to climate change. One such model is the Variable Infiltration Capacity (VIC) model developed by researchers at the University of Washington (http://www.hydro.washington.edu/Lettenmaier/Models/VIC/). These models explicitly track the movement of water through the landscape, and so are generally more accurate and complete than the other methods for estimating ET. In addition to the metrics mentioned above, these models can also model other hydrologic changes, such as snowpack depth and water runoff. The changes in water runoff can be used to estimate changes in river flow. Depending on how climate changes, river flow may change in different ways, but with warming temperature there are some changes that are more likely to occur, such as earlier spring runoff and lower summertime base flows in snow-fed rivers.

Changes in Fire Regimes

Climate change is expected to contribute to significant changes in fire regimes in some regions, including shifts in the timing, intensity, and frequency of wildfire events (Flannigan et al. 2000). For example, research shows that wildfires in western forests have become more frequent and larger since the mid-1980s, a trend that corresponds with warmer springs and an expansion of summer dry periods (Westerling et al. 2006). Studies project that the overall acreage burned could double in size across parts of the west by mid- to late century as average temperatures continue to rise (Spracklen et al. 2009; McKenzie et al. 2004).

Changes in CO_2 Concentrations

There is no doubt that atmospheric CO_2 concentrations have already increased from approximately 280 parts per million (ppm) in the recent historic past to around 385 ppm today. Future atmospheric CO_2 concentrations could range from 500 ppm to close to 1000 ppm based on emissions scenarios used in the IPCC AR4 (2007b). The concentrations will continue to rise through at least the late part of this century, and depending on the emissions scenario considered, concentrations may continue to increase beyond the end of the century. These changes in CO_2 concentrations can have physiological effects on plant species. For example, increases in atmospheric CO_2 concentrations can result in increased water use efficiency in some plants. In an atmosphere with enriched CO_2, these plants may be able to grow in drier climates than they currently occupy. Changes in water use efficiency can also lead to higher-level ecological impacts such as changes in species competitive interactions and changes to community composition (Cramer et al. 2001).

Changes in Vegetation

Changes in climate have the potential to alter the distribution of plant species and hence alter plant associations and plant communities. Dynamic global vegetation models and other less complex models can be used to project how "plant functional types" such as conifers, broad-leafed deciduous trees, and grasses are likely to change in the future (Bachelet et al. 2001; Cramer et al. 2001; Sitch et al. 2003). Projected shifts in vegetation types or biomes can provide an idea of how much specific plant community types might change.

Changes in Species Distributions

Species distributions will shift as climate changes. In some cases, it will be useful to understand how a specific species might move in response to climate change. For example, maps of projected range shifts for invasive species, keystone species or ecosystem engineers, or predators, competitors, or diseases of a focal species may serve as useful exposure elements for individual species, habitats, or ecosystems. Species distribution modeling can be used to project how species' ranges will shift due to the many different factors affected by climate change (Lawler et al. 2006, 2009).

Changes in Salinity

Climate change is altering salinity concentrations in the world's oceans. In the Atlantic Ocean, there has been an increase in salinity observed between latitude 20 and 50 degrees north (Stott et al. 2008), while increasing water runoff from melting glaciers and polar ice caps are causing a decrease in salinity in oceans near the poles (Curry et al. 2003). For a good overview of ocean salinity see: http://nasascience.nasa.gov/earth-science/oceanography/physical-ocean/salinity. Data and maps on changes to salinity can be found at: http://aquarius.jpl.nasa.gov/AQUARIUS/index.jsp.

Changes in pH

As the oceans absorb atmospheric CO_2, they become more acidic. If CO_2 concentrations in the atmosphere continue to increase at the current rate, then the oceans will become relatively more acidic (i.e., will have a lower pH) than they have been in millions of years (Caldeira and Wickett 2003). This lower pH will erode the basic mineral building blocks for the shells and skeletons of calcareous, reef-building organisms such as shellfish and corals, as well as a number of important microorganisms that are a foundation for the marine food web (Kuffner and Tihansky 2008; Orr et al. 2005).

Changes in Storm Frequency and Intensity

In general, the frequency and magnitude of intense storms is projected to increase. This is at least in part due to increased temperatures causing greater evaporation. For example, modeling studies have projected an increase in tropical cyclone (hurricane) intensity, and there is evidence that the number of Category 4 and 5 hurricanes has increased over the past 30 years (Trenberth 2007; Webster et al. 2005; Emanuel 2005).

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Assessing Adaptive Capacity

The IPCC defines adaptive capacity as "the potential, capability, or ability of a system to adjust to climate change, to moderate potential damages, to take advantage of opportunities, or to cope with the consequences" (IPCC 2007c). In the context of assessing the vulnerability of human communities, adaptive capacity often refers to the potential to implement planned adaptation measures to cope with change, including factors such as economic wealth, institutional capacity, and equity (Metzger et al. 2005). For natural systems, adaptive capacity is often considered to be an intrinsic trait that may include evolutionary changes as well as "plastic" ecological, behavioral, or physiological responses (Williams et al. 2008). This is not to say, however, that only the intrinsic factors of adaptive capacity are relevant in assessing the vulnerability of species, habitats, or ecosystems to climate change. Certainly, there are likely to be a number of external factors (both natural and anthropogenic) that will influence the ability of a species or system to adjust to or cope with climate change (see Box 3.1). This section provides some examples of adaptive capacity within both of these contexts.

As mentioned earlier in this report, it is important to note that some of these examples may be considered as factors that contribute to a species or system's sensitivity to climate change, rather than as adaptive capacity.

Species-Level Adaptive Capacity

Plasticity

The ability for a species to modify its physiology or behavior to synchronize with changing environmental conditions or coexist with different competitors, predators, and food sources (a characteristic called *plasticity*) can be considered a factor of adaptive capacity (Running and Mills 2009; Nylin and Gotthard 1998; Gotthard and Nylin 1995). In general, plasticity increases the likelihood that a species will be able to respond effectively to both climate change itself and to effects of climate change, such as phenological mismatch (Parmesan 2005; Parmesan and Galbraith 2004; Parmesan et al. 1999). There is evidence that recent climate change has already elicited these types of adaptive responses across a wide range of plant and animal species (Walther et al. 2002). Over time, it is possible that these traits may become a genetic, evolutionary component (see below).

Dispersal Abilities

Dispersal refers to the movement of a species away from an existing, typically natal, population (Fahrig 2007). Some species may be able to disperse over long distances (e.g., seeds may be carried to different areas by birds or other hosts).

Other species, such as those that have evolved in patchy or rare habitats, may have lower dispersal ability. In general, species that are poorer dispersers may be more susceptible to climate change as they will be less able to move from areas that climate change renders unsuitable and into areas that become newly suitable. Berg et al. (2010) reviewed dispersal distances across broad taxonomic groups, noting especially that below-ground organisms tend to have an extremely limited ability to disperse. Barriers to dispersal may increase the vulnerability of some species with high innate dispersal ability.

Evolutionary Potential

Some species and some populations will be better able to adapt (evolutionarily) to climate change. Relevant traits include generation time, genetic diversity, and population size (Skelly et al. 2007; Bradshaw and Holzapfel 2006). For example, species with shorter generation times, in general, have faster evolutionary rates than species with longer generation times, and may be able to evolve behavioral or physiological traits that allow them to withstand climatic changes more rapidly than will than long-lived species with long generation times. Likewise, populations with high genetic diversity for traits related to climate tolerance are more likely to contain individuals with heritable traits that increase the tolerance of the species to climate change. Several recent studies have already discovered heritable, genetic changes in populations of some animals, including the Yukon red squirrel (Réale, et al. 2003), the European blackcap (Bearhop et al. 2005), and the great tit (Nussey et al. 2005), in response to climate change, most often associated with adaptation to the timing of seasonal events or season length.

Maintaining the evolutionary potential for species to adapt will be key in designing climate change adaptation strategies. Among the best approaches for retaining this potential is ensuring that protected area networks harbor a well-distributed representation of species found in a region.

Habitat-Level Adaptive Capacity

Permeability of the Landscape

The degree to which species, propagules, and processes can move through the landscape will affect the sensitivity of species, habitats, and ecosystems to climate change. More permeable landscapes with fewer barriers to dispersal and/or seasonal migration will likely result in greater adaptive capacity for species, habitats, and ecosystems. However, the degree to which a landscape is permeable

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Box 3.1. Assessing Adaptive Capacity: Insights from a Coastal System

Both natural and anthropogenic factors can affect the adaptive capacity of a system, as illustrated in the case of coastal vulnerability to sea-level rise (Klein and Nicholls 1999). The impacts of sea-level rise on a coastal system depends on the global rate of eustatic sea-level rise, which refers to the change in volume of the oceans due to thermal expansion and the addition of water from land-based ice melt, as well as localized factors that affect the relative amount of sea-level rise in a particular area. Relative sea level rise is affected by such variables as rates of geological uplift and deposition of sediments: marsh sediment accretion, for instance, can lessen the amount of localized sea-level rise, while land subsidence can exacerbate the problem. In deltaic systems, for example, the release of river sediments downstream can help habitats such as coastal wetlands keep pace with sea-level rise (Reed 2002; Morris et al. 2002). Similarly, coastal habitats such as wetlands and beaches might be able to occupy new areas farther inland as rising sea levels inundate or erode those habitats along the shore. Essentially, these variables can be considered elements of the adaptive capacity of a coastal ecosystem.

A number of factors can either enhance or reduce this adaptive capacity. For example, altered river flows (due to climate change, upstream water uses, and/or other stressors) or the existence of dams or levees can reduce or eliminate the amount of sediments that reach the coast, contributing to a higher rate of relative sea-level rise. Similarly, the existence of upland barriers, either natural (e.g., rocky cliffs) or anthropogenic (e.g., seawalls), can limit or prevent the ability of coastal habitats to migrate inland. Ultimately, understanding the multiple factors that can affect the adaptive capacity of a coastal ecosystem can help inform relevant management decisions, such as finding ways to restore the deposition of sediments or removing coastal barriers.

depends on the process or organism that is being considered, and thus a permeable landscape for one species may not be very permeable for another species. The relative permeability of a landscape may depend on both natural and anthropogenic factors. In particular, fragmentation of habitat due to urban development, agriculture, dams, and other human activities is likely to be an important factor in reducing the adaptive capacity of some otherwise highly dispersible and migratory species (Vos et al. 2002).

Ecosystem-Level Adaptive Capacity

Redundancy and Response Diversity within Functional Groups

Within any community, there is a range of functional groups present. In ecological communities, this includes groups such as primary producers, herbivores, carnivores, and decomposers. In systems where each functional group is represented by multiple species and the response to any given environmental change varies significantly among the species that make up the functional group, system resilience to environmental change is likely to be higher (Nystrom et al. 2008; Naeem 1998; Petchey and Gaston 2009). In other words, if a particular species or decomposer responds negatively to a climate change but others respond positively, decomposition function within the system may not be disrupted.

IV. Peering into the Future: Climate and Ecological Models

Assessing the exposure of species to climate change requires the ability to peer into the future and identify likely or potential changes in ecologically relevant variables. These variables can be both direct climatic factors, such as changes in temperature or precipitation, or indirect factors, such as shifts in ecosystem processes or interactions with other species. Models provide an important means for forecasting possible future conditions. A model constitutes a representation of a system, which enables researchers to investigate and understand the properties of that system. Depending on their design, models can also be used to simulate future conditions and outcomes. Although models can be powerful, they also have limitations. The statistician George Box famously has been quoted as saying "all models are wrong, but some are useful" (Box and Draper 1987). Considerable progress has been made over the past few decades, however, in developing robust and useful models for understanding both the earth's climate systems, as well as the ecological responses to climate.

This chapter provides an overview of the types of climate and ecological response models that are relevant to vulnerability assessments of species, habitats, or ecosystems. The purpose of reviewing these models is not to suggest that all vulnerability assessments will be involved in running these models: rather, it is to ensure that assessors are knowledgeable about the range of models available, and can be well-informed consumers, understanding the basis for and assumptions underlying widely used models. In particular, most vulnerability assessments will not involve running sophisticated and complex global climate change models, but will instead rely on existing scenarios and make use of available downscaled climate projections. Assessments more often will rely on application of ecological response models, although even those models may be supplanted or bolstered by existing studies in the scientific literature or by means other than modeling (e.g., expert elicitation).

Climate Models

Increasing emissions of CO_2, methane, and other heat-trapping greenhouse gases are perturbing average climate conditions at local to global scales in ways that cannot be predicted by the past. Instead, projections of future climate conditions rely on climate model simulations driven by assumptions about how population, energy use, and technology are likely to develop in the future. These assumptions are collectively known as *emission scenarios*, as they serve as the basis to estimate the emissions of greenhouse gases, particulates, and other pollutants that would result.

Lead authors: Katharine Hayhoe, Bruce Jones, and John Gross.

Emission scenarios are then used as inputs to global climate models in order to simulate the changes in temperature, precipitation, and other aspects of climate likely to result from that set of assumptions. Global climate models represent climate at a relatively coarse resolution and they do not resolve differences in climate variables at scales finer than several hundred kilometers. The "basic" global climate models are the General Circulation Models (GCM), which are mathematical models of a planetary atmosphere or ocean based on given equations for physics, fluid motion, and chemistry. At the most comprehensive end of the spectrum are the coupled Atmosphere–Ocean General Circulation Models (AOGCM), which address additional factors such as models for sea ice or evapotranspiration over land.

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Output from global climate model simulations can be used to calculate regional trends, but these are difficult to incorporate directly into planning efforts. For this reason, a range of downscaling techniques have been developed. Although downscaled climate projections often provide the spatial and temporal resolution needed to assess the impacts of climate change on a given region or system, it is important to understand the limitations of these data as well. Downscaled projections are uncertain for the same reasons as global projections: the range in plausible future scenarios; the sensitivity of the climate system to those emissions; our imperfect understanding of and ability to model the climate system; the natural variability of the climate system; and the degree to which the simulations are able to capture the relationship between local climate and large-scale drivers.

Due to the uncertainty inherent in future projections, multiple future scenarios should be considered in impact assessments. In an area where precipitation trends are highly uncertain, for example, a state might choose to consider two scenarios: one warmer and wetter, and one warmer and drier. Adaptation strategies that are robust to multiple likely climate change scenarios would be considered "no regrets" strategies. In some instances, expert opinion can be useful for assessing the likelihood of how future local climates will reflect regional projections or how habitats will change. Expert opinion should be accompanied by an estimate of certainty and description of the assumptions, evidence, or reasoning underlying the opinion.

Historical and Future Scenarios

Control Scenarios

Climate models are not rigidly controlled by boundary conditions, as are response models. Rather, they generate their own internal natural variability. Before they can be run in transient mode (i.e., generating information for real calendar years), climate model simulations begin with a long, time-independent control run. External forcing mechanisms (e.g., the strength of the sun and the concentrations of key atmospheric gases and aerosols) are set to preindustrial conditions and the model is run for several hundred years in order to "spin up" to the equilibrium condition in which our planet exists.

This is an essential step as climate models are, at their most basic level, simply numerical approximations of the fundamental laws of physics that govern nature at the scale of the planet, including conservation of momentum, conservation of mass and energy, and the four laws of thermodynamics. Control runs are not intended to be used by anyone outside the modeling community; their purpose is to establish a baseline set of model conditions that can be used to initiate a transient simulation beginning in preindustrial times and moving forward in to the future.

Historical Scenarios

Once a preindustrial control run has been completed for any given climate model, a transient (time-dependent) simulation can be run, beginning in the year that was used to set conditions for the control run. This initial year varies from about 1850 to 1890, depending on the global modeling group. Historical scenarios run from the beginning year, in the 1800s, through 1999. Each month, external forcing mechanisms observed or measured for that month in the past are input to the models. These observed drivers can include changes in solar radiation, volcanic eruptions, human emissions of greenhouse gases and other radiatively active species, and secondary changes in ozone and water vapor.

Collectively, these historical total (human and natural) forcing scenarios are known as the "20th Century Climate in Coupled Models" or 20C3M scenarios in the IPCC AR4. These historical 20C3M scenarios are essential as they provide a baseline of observed climate against which future climate change can be quantified. Future climate projections should never be compared directly to historical observations in order to calculate the amount of change that may occur, as even the best models contain biases relative to observations. Rather, future projections must be compared to historical simulations, as biases are assumed to remain relatively constant over time. This change, or delta, provides the most reliable information on future change.

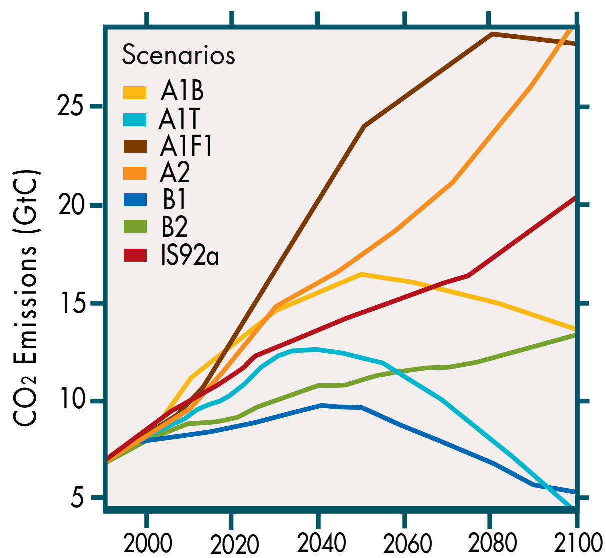

Figure 4.1. Projected future carbon emissions for the SRES emission scenarios. Emissions for the highest scenario (A1FI) correspond to the red dotted line at the top, while emissions for the lowest (B1) scenario are indicated by the solid green line (Nakicenovic et al. 2000).

Emissions Scenarios

To estimate potential climate changes through 2100, we need to ask:

- How will human societies and economies evolve over the coming decades?
- What technological advances are expected, and how will they affect emissions?
- Which energy sources will be used in the future to generate electricity, power transportation, and serve industry?

The answers to these questions will affect future emissions of greenhouse gases from human activities. And these emissions will in turn determine future climate change at both the global and the regional levels.

To address these questions, in 2000 the IPCC developed a set of future emissions scenarios known as SRES (Special Report on Emissions Scenarios) (Nakicenovic et al. 2000). These scenarios use a wide range of projections for future population, demographics, technology, and energy use to estimate the greenhouse gas emissions that would result from a variety of possible futures. In doing so, they cover a wide range of plausible futures that illustrate differences in the extent and severity of the global warming that result from alternative emissions choices (Figure 4.1).

For example, the SRES higher-emissions or fossil-intensive scenario (A1FI) represents a world with fossil fuel–intensive economic growth and a global population that peaks mid-century and then declines. New and more efficient technologies are introduced toward the end of the century. In this scenario, atmospheric CO_2 concentrations (the amount of CO_2 in the atmosphere as a result of emissions) reach 940 ppm by 2100—more than triple preindustrial levels.

The lower-emissions scenario (B1) also represents a world with high economic growth and a global population that peaks mid-century and then declines. However, this scenario includes a shift to less fossil fuel–intensive industries and the introduction of clean and resource-efficient technologies. Emissions of greenhouse gases peak around mid-century and then decline. Atmospheric CO_2 concentrations reach 550 ppm by 2100—about double preindustrial levels.

Concentration Pathways

New Representative Concentration Pathways (RCP) (Moss et al. 2010) are under development for the IPCC Fifth Assessment Report (AR5). In contrast to the SRES scenarios used in the AR4, the RCPs are expressed in terms of carbon dioxide equivalent (CO_2-eq) concentrations in the atmosphere, rather than direct emissions.

Although climate model simulations are not yet available for the RCPs, it is still possible to place SRES-based projections into the context of these new scenarios by converting the SRES emission scenarios to CO_2-eq concentrations. When we do that using the simple energy-balance climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change), we see that the highest RCP 8.5 corresponds closely to the higher SRES A1FI emissions scenario, with end-of-century CO_2-eq concentrations of 1465 ppm for RCP 8.5 as compared to 1360 ppm for A1FI (Figure 4.2) (Wigley 2008). In contrast, the lowest RCP 2.6 projects a future where emissions are reduced significantly below even the lowest of the SRES scenarios, with CO_2-eq concentrations rising to nearly 500 ppm then falling to 450 ppm by the end of the century. The mid-low RCP 4.5 corresponds most closely to SRES B1, with CO_2-eq concentrations of nearly 600 ppm by the end of the century as compared to 640 ppm for B1.

Figure 4.2 is an important comparison as it enables the climate model projections currently available (and indeed, all that will be available through 2012) to be placed in the context of the next generation of climate scenarios. It also reveals that the substantial difference between the SRES A1FI and B1 scenarios, although conservative in comparison to the RCPs in its estimate of the lower end of the range of future emissions, is still sufficient to illustrate the potential range of changes that could be expected, and how these depend on energy and related emission choices made over coming decades.

Uncertainties in Future Scenarios

It is important to note that, as broadly separated as they are, neither the SRES nor the RCP scenarios cover the entire range of possible futures. While the recent economic decline slowed CO_2 emissions growth rates in comparison to previous years, actual emissions remain near the top of the range of IPCC scenarios for the period 2000 to 2010 (Manning et al. 2010).

On the other hand, significant reductions in emissions, on the order of 80 percent below 1990 levels or more, could stabilize CO_2 levels below the lowest SRES emission

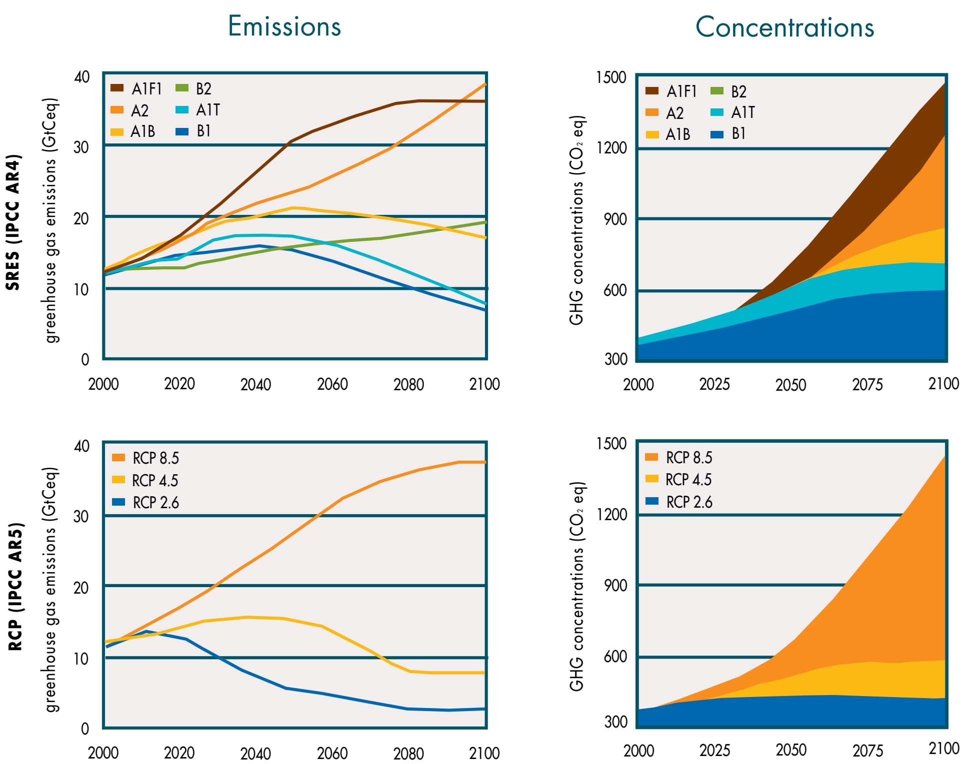

Figure 4.2. Projected future CO2-equivalent emissions and concentrations for the SRES emission scenarios (IPCC AR4) and Representative Concentration Pathways (IPCC AR5).

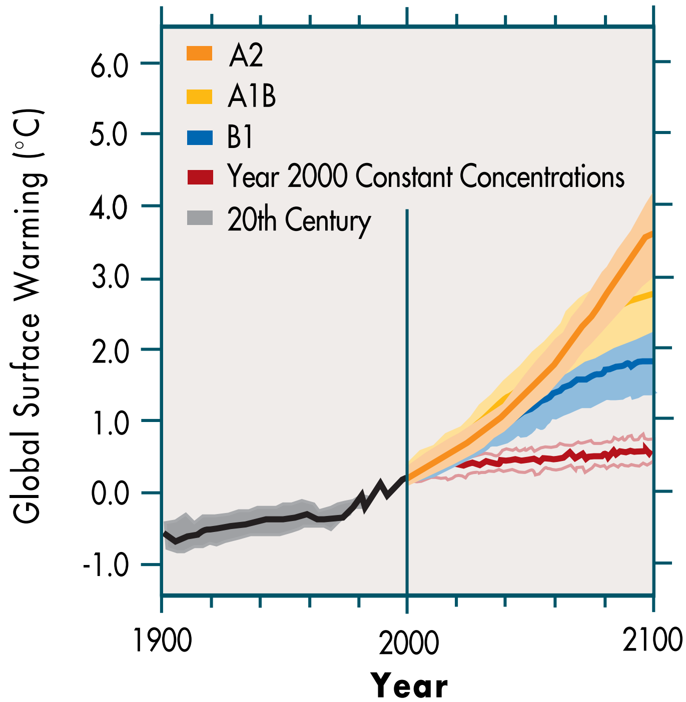

Figure 4.3. Projected future global temperature change for the SRES emission scenarios (degrees Celsius). The range for each individual emission scenario indicates model uncertainty in simulating the response of the earth system to human emissions of greenhouse gases (IPCC 2007b).

scenario (e.g., Meinshausen et al. 2006). Such policy options were not considered in the SRES scenarios, although the new RCPs (Moss et al. 2008, 2010) currently under development for the IPCC Fifth Assessment Report at least partially address this issue.

Global Climate Models

Description

Emissions or concentration scenarios are used as input to global climate models, which vary in complexity. The most complex are the AOGCMs. These are large, three-dimensional coupled models that incorporate the latest understanding of the physical processes at work in the atmosphere, oceans, and earth's surface. As output, AOGCMs produce geographic grid-based projections of precipitation, temperature, pressure, cloud cover, humidity, and a host of other climate variables at daily, monthly, and annual scales.

Because of the complexity of these models, they are generally designed and run by large research teams at supercomputing centers. Models are constantly being enhanced as scientific understanding of climate improves and as computational power increases. Over time, the number of global climate models has grown. By 2008, 16 international climate modeling teams had submitted historical and future simulations from 25 different climate models to the IPCC's AR4. All future simulations by these models agree that both global and regional temperatures will increase over the coming century in response to increasing emissions of greenhouse gases from human activities (Figure 4.3).

Model Selection

Some models are more successful than others at reproducing observed climate and trends over the past century in particular geographic regions. Inter-model comparisons (e.g., Kunkel et al. 2006; Wang et al. 2007; Stoner et al. 2009) generally find that climate models tend to fall into three broad categories: "good" models that are able to simulate important climate features, from Arctic weather systems to natural variability such as El Niño, across the globe; "fair" models that perform well in some regions and at some tests, but poorly in others; and "poor" models, usually those in relatively early stages of development, that consistently fail to reproduce fundamental aspects of the earth's climate system.

For the purposes of global climate model selection for impact analyses, however, the most relevant point is that multi-model comparisons have shown that, for a given emissions scenario, the average of multiple models generally provides a more robust picture of future conditions than any one model (Tebaldi and Knutti 2007). Moreover, evaluating which set of models may be "best" at simulating future trends over any given region and for a certain variable is a long and involved process, generally requiring a fundamental understanding of climate dynamics that have contributed to climate variability and long-term trends over the region of interest. (Although simple biases or differences between models and observations have been used in the past to judge which models are "better" than others, this practice is highly discouraged as the information derived from such a calculation bears little relevance to actual model performance in simulating climate change and may mislead more than it may guide.) So in evaluating the potential impacts of climate change on any given region, it is always best to use the average of multiple global climate models rather than to rely on one or two. As it may not be possible to use all global climate model simulations, some general criteria for model selection are the following:

- Consider only well-established models, whose strengths and weaknesses are already extensively described and evaluated in the peer-reviewed scientific literature. The models should have participated in the Coupled Model Intercomparison Project (CMIP; http://cmip-pcmdi.llnl.gov/) or otherwise been evaluated and shown to adequately reproduce key features of the atmosphere and ocean system. Key features include seasonal circulation patterns, atmosphere–ocean heat fluxes, El Niño, and other teleconnection patterns affecting climate in the region (Covey et al. 2003; AchutaRao and Sperber 2002; Chapman and Walsh 2007; DeGaetano et al. 2008; Vrac et al. 2006).

- The models chosen should encompass the greater part of the range of uncertainty in climate sensitivity simulated by global climate models. Because many of the processes at work in the earth–atmosphere system are not yet fully understood, these are represented somewhat differently in different global climate models. A range in projected temperature change and other climate variables arise from the different climate sensitivity of the models.

- From a purely practical perspective, the projections required for the impact analysis must be available from that model, preferably for multiple future scenarios in order to encompass the uncertainty in predicting future drivers of change.

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Box 4.1. How Much Sea-Level Rise Should We Plan For?

Asking how much sea-level rise to assume in coastal vulnerability assessments is a common question, but not necessarily straightforward to answer. As with modeling the climate system itself, projecting how much global sea levels will rise due to global warming is complex, and there are many sea-level rise scenarios in the literature. In general, global sea-level rise figures refer to changes in eustatic sea level, referring to changes in the volume of seawater. For planning purposes, it is important to recognize that a number of other factors affect the amount of relative sea-level change experienced in a given area. Local land subsidence, for example, will mean that the rate of relative sea-level rise in that area will be higher than the eustatic rate. Nevertheless, projections for eustatic sea level are an important baseline for assessing coastal vulnerability.

Modeling eustatic sea level requires integrating factors such as thermal expansion of the oceans as well as rates of change of land-based ice, including glaciers and continental ice sheets, all of which are subject to uncertainties. Some of the most widely used scenarios are from the IPCC, whose most recent estimates range from an additional 7 to 23 inch rise in global average sea level over 1990 levels by the 2090s (IPCC 2007b). There is compelling new evidence, however, that because these figures ignore recent dynamic changes in Greenland and Antarctica ice flow, they underestimate the rate of sea-level rise that we are likely to experience during this century (Overpeck and Weiss 2009; Pfeffer et al. 2008). Taking at least some of this accelerated melting into account, Vermeer and Rahmstorf (2009) suggest that a feasible range might be 30 to 75 inches for the period 1990-2100. Complicating matters, the magnitude of sea-level rise will not be globally uniform because of ocean circulation patterns and the earth's rotation, gravitational differences, local and regional geological differences, and other factors (Bamber et al. 2009; Mitrovika et al. 2009; Church et al. 2004; Yin et al. 2009).

Ultimately, choosing which scenarios upon which to base vulnerability assessments and associated climate change adaptation strategies will depend on how much risk we are willing to accept. When relatively little is at stake in the way of infrastructure investment or public inconvenience, we could choose to design for a conservative or low-end sea-level rise scenario. Where more is at stake, such as the decimation of habitats critical to a region's ecological and economic well-being, we might design for a mid-range or aggressive sea-level rise scenario. The bottom line, however, is that we may never know with certainty how much or how fast sea level will rise. Accordingly, using a range of scenarios in your assessment might be the optimal approach.

- Finally, note that within any climate model, uncertainties will vary for different simulated phenomena. For example, large-scale surface temperature is generally trusted more than precipitation, which requires many physical processes to be simulated correctly at the same time and place.

Downscaling of Global Model Simulations

The geographic grid cells that form the basis of AOGCMs typically range in size from about 160 to 800 kilometers per side. In general, this type of resolution

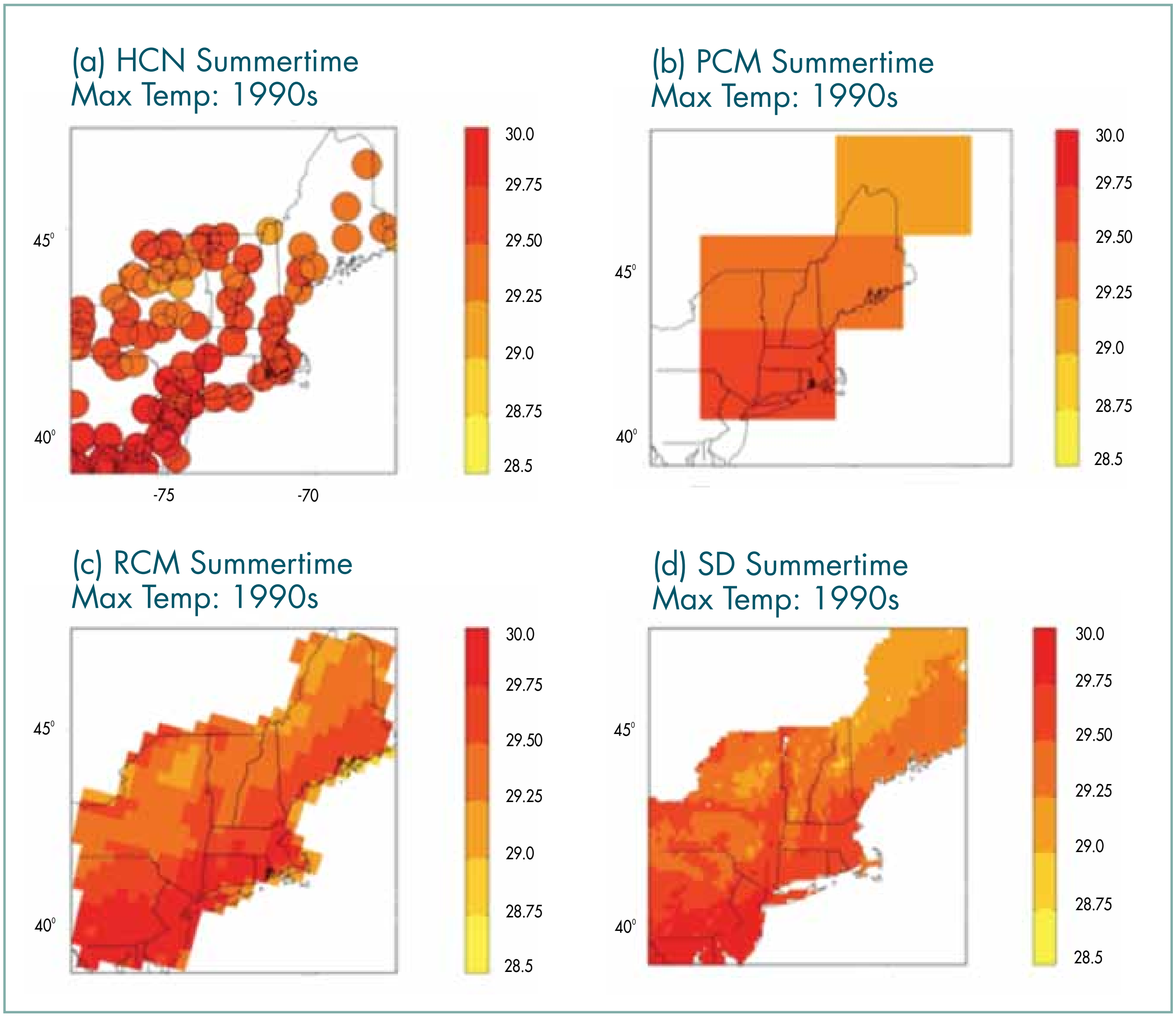
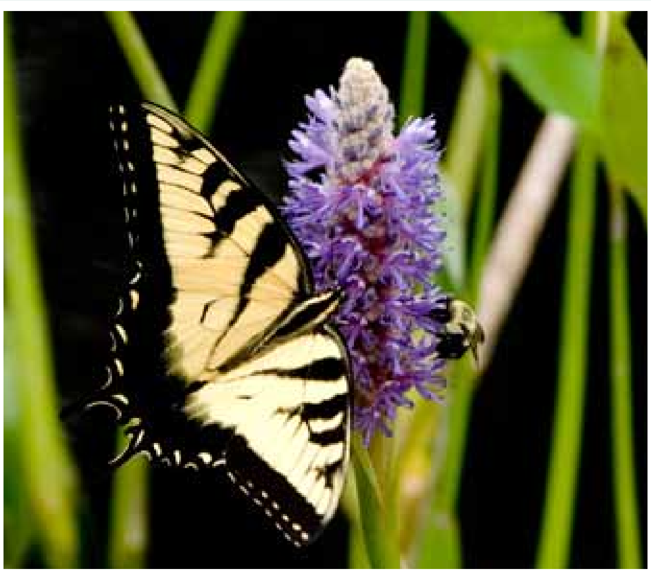


Figure 4.4. Average summer maximum temperature in the U.S. Northeast for the 1990s, based on (a) observations from weather stations in the Historical Climatology Network, (b) the global climate model PCM, (c) regional climate model simulations, and (d) statistically downscaled simulations. From Hayhoe et al. 2008.

is too coarse to capture the fine-scale changes experienced at the regional scale. For this reason, a number of downscaling techniques have been developed to transform global climate model output into higher-resolution projections capable of resolving the impacts of climate change on local conditions.

Dynamical Downscaling

Dynamical downscaling, or regional climate modeling, uses a high-resolution climate model centered over a relatively small region and driven by global climate model output fields at its boundaries. Model grid cells range from 10 to 50 kilometers, and contain substantially different physics than the global models in order to resolve the physical processes that occur at spatial scales below those of the global models. Regional climate models are able to simulate the dynamic changes in climate likely to occur as global climate changes; however, regional climate model simulations are expensive to run and few global climate models save the high-resolution temporal fields (at 3 or 6 hours) required to drive the regional models. Hence, regional model simulations tend to be limited to specific timeslices from future decades, rather than a continuous time period, and tend to be driven by several global models rather than the full suite of IPCC global climate models. The most comprehensive set of regional model simulations has been generated by the North American Regional Climate Change Assessment Program (NARCCAP), which uses four regional model–global model pairs to simulate conditions for 2041 to 2070 compared to 1971 to 2000.



Ron Schreiber

Statistical Downscaling

Statistical downscaling relies on historical instrumental data for calibration at the local scale. A statistical relationship is first established between AOGCM output for a past "training period," and observed climate variables of interest (here, daily maximum and minimum temperature and precipitation). This relationship is averaged over at least two decades to remove year-to-year fluctuations. The historical relationship between AOGCM output and monthly or daily climate variables at the regional scale is then tested using a second historical "evaluation period" to ensure the relationship is valid. If so, then the relationship is finally used to downscale future AOGCM simulations to that same scale.

Unlike regional climate modeling, statistical downscaling assumes that the relationships between large- and small-scale processes remain fixed over time. This assumption may not always be justified, particularly for precipitation. However, analysis of 37 stations in the state of Illinois suggests that this relationship only breaks down for the most extreme precipitation events above the 99th percentile of the distribution (Vrac et al. 2006). Analyses for the Northeast (Hayhoe et al. 2008) further indicate that, in areas of variable topography such as mountains and coastlines, statistical methods trained to match historical spatial patterns may perform better than regional climate models that are limited by their convection schemes (see Figure 4.4). In addition, statistical downscaling has a substantial time and cost advantage; hundreds of years of model simulations can be downscaled using the same computing resources required to run only a few years of regional-model downscaling. Three of the case studies in Chapter VII use statistical downscaling for climate change data. Case Studies 1, 3, and 6 rely on a tool called the ClimateWizard (www.climatewizard.org), which was developed by The Nature Conservancy, University of Washington, and University of Southern Mississippi to enable technical and nontechnical users to access historical and projected climate change information for a given area based on downscaled data from a range of climate models, emissions scenarios, and time periods. In Case Study 7, researchers will be conducting their own statistical downscaling projections for at least six future climate projections.

Ecological Response Models

Ecological response models are a critical part of the overall vulnerability assessment process. They provide a way to assess the sensitivity and potential adaptability or resilience of wildlife species, habitats, and ecosystems to climate change (Wormworth and Mallon 2007). They also are fundamental to understanding the kinds of climate variables that are needed to conduct vulnerability assessments. As such, information from response models enhances the iterative dialog between biologists/ecologists and climatologists such that downscaled climate change variables address the most appropriate scales (temporal and spatial) and scope (types of variables that relate to sensitivity and/or resilience) needed to conduct the vulnerability assessment. This dialog is critical in identifying the spatial extent of the downscaled climate information that will then be used to assess exposure of species, habitats, and ecosystems. Moreover, response models help identify indicators and potential thresholds or tipping points that can be used in vulnerability assessments (Bradley and Smith 2004; Groffman et al. 2006).

The decision on which model or combinations of models to use depends on the species, habitats, and ecosystems of concern, the types of questions being asked, and the particular end-users' needs. The local geographic and biophysical characteristics of habitats and ecosystems require the use of response models that are well suited to the specific environmental settings (Primack et al. 2009). Moreover, the type of questions and needs associated with the vulnerability assessment affect the scale and scope of the assessment. The objective of some vulnerability assessments is to target species or geographic areas where species, habitats, and/or ecosystems are potentially most vulnerable to declines in conditions due to climate change (Bradley and Smith 2004). These types of vulnerability assessments are usually conducted at large basin or regional scales, and the results are used to target species and geographic areas where further attention (data gathering, modeling, etc.) is needed. Other vulnerability assessments rely on more complex models involving specific species or habitats in specific geographies, as well as a range of species traits and processes (Martin 2007).

An important part of model selection and/or development process is to clearly identify the endpoints of interest. Endpoints are definable and measurable aspects of the environment upon which environmental assessments are made. Lack of clear endpoints often reduces the relevance and utility of the assessment results (Boyd 2007). In some cases, species' vulnerabilities are assessed because they are the endpoint (e.g., a species listed through the ESA) or because they affect ecosystem functions (e.g., an invasive species as it affects fire disturbance regimes) (Hunter 2007).

Types of Response Models

This section briefly describes different types of response models and how they are generally used. Different approaches are often used in combination (Martinez-Meyer 2005), but for clarity we provide basic descriptions of each.

Conceptual Models

Conceptual models are qualitative descriptions and diagrams of key attributes and processes related to specific species, habitats, or ecosystems of concern (see Schlesinger et al. 1990 for an example related to desertification). They also illustrate or describe important linkages to stressors, such aspects of climate and land use, and how changes in stressors affect important attributes (e.g., soil texture) and functions (nutrient uptake, water flux, etc.). These linkages to stressors provide the basic information needed to assess vulnerability (e.g., sensitivity), and help inform the spatial extent of the stressor needed to analyze exposure. Nearly all types of other response models are built from well-conceived conceptual models as they help identify key variables in models needed to assess sensitivity and exposure. For a review of conceptual model development see Heemskerk et al. (2003). Various types of conceptual modeling tools and software can be found at http://www.fileheap.com/software/conceptual_data_model.html.

General Characterization Models

Characterization models usually represent broad groups (e.g., amphibians, riparian species) or generalized traits to identify how groups of species might respond to climate and/or habitat change. These models can be fairly simple. For example, they can involve groupings of species based on their preference for certain habitats. Or, they can involve species grouped by physiological, functional, and/or other biological traits, and their potential sensitivity (response) to specific aspects of climate change (Lavorel et al. 1997). In most cases, spatial distribution of sensitivity is estimated by applying the classes of vulnerability (characterization part) to species distribution maps (Lavorel et al. 1997). Another characterization approach involves meta-analyses whereby existing studies are pooled together to estimate common responses of species (Parmesan and Yohe 2003; Allen et al. 2010). These can be especially effective at validating responses over large areas. The NatureServe Climate Change Vulnerability Index is an example of an easy-to-use characterization tool to assess vulnerability (http://www.natureserve.org/prodServices/climatechange/ClimateChange.jsp) (see Case Study 1).

Expert Opinion Models

These models are constructed from the opinions of experts on a particular species, habitat, or ecosystem. They are often used when existing data preclude or are insufficient to develop a quantitative model. A series of workshops and/or surveys are often used to gather data from experts that are then used in model development. In some cases results from expert input are combined with other data (e.g., from existing publications). Statistical approaches (e.g., Bayesian statistics) are often used to combine these data from different sources to produce estimates of potential responses and uncertainty (Berliner et al. 2000; Prato 2009). Expert opinion is often used in assembling conceptual models (see previous discussion). There are many software modules that can be downloaded to assist in development of expert opinion models. Some examples include the Bayesian Analysis Toolkit (http://www.mppmu.mpg.de/bat/), Treeage Pro software (http://www.treeage.com/products/index.html), and the Delphi Decision Aid site (http://armstrong.wharton.upenn.edu/delphi2/).

Habitat and Occupancy Models

Habitat and occupancy models are perhaps the most common models used to address potential vulnerability of species to climate and land-use change. Some habitat models, such as those that have been developed by the U.S. Geological Survey GAP model habitat suitability over large geographic areas based on the development of habitat criteria (developed mostly from expert opinion and published literature). These requirements (rules) are expressed as ranges in specific biophysical attributes (e.g., climate, soils, vegetation or land cover, elevation, etc.) that a species will occupy (e.g., "suitable" habitat). The requirements (range of biophysical conditions) are then applied to wall-to-wall biophysical data, such as through Geographic Information System (GIS) coverages or grids, to determine the spatial distribution of suitable habitat for individual species. In a few cases, species ranges and suitable habitat have been defined largely by climate variables (e.g., Climate Envelope models) (Harrison et al. 2006; Pearson and Dawson 2003). In these cases, species sensitivities and vulnerability can be directly assessed with climate data. In cases where suitability is defined by vegetation or land cover attributes (including distribution), models of habitat shifts associated with climate change scenarios are needed to conduct the assessment (Johnson et al. 2005).

One example of this type of model is the Sea Level Affecting Marshes Model (SLAMM), in which a flexible and complex decision tree incorporating geometric and qualitative relationships is used to represent transfers among coastal habitat classes under various scenarios of sea-level rise (Clough et al. 2010). Case Study 5 uses SLAMM (Version 5.0) in an assessment of coastal habitat vulnerability in the Chesapeake Bay region. Vegetation- and habitat-associated response to climate change seem to be the most prevalent type of response model used to evaluate potential effects of climate change on species.

Niche-based models are also used to estimate species distributions and habitat suitability, but they generally involve more quantitative approaches with estimates of the probability of occurrence of a species. Approaches such as Genetic Algorithm for Rule-set Production (GARP) (Stockwell and Peters 1999) and Maximum Entropy modeling (Maxent) (Phillips et al. 2006) are examples of niche-based models. Niche and occupancy models produce probabilities of occurrence using locations records of species (e.g., from museum records, systematic surveys, and other databases) and wall-to-wall biophysical data such as elevation, topography, temperature, precipitation, soils, and geology to name a few (Ballesteros-Barrera et al. 2007). As such, they define the "habitat niche" of the species. Other statistical models incorporate approaches like Regression Tree and Random Forests (O'Connor et al. 1996; Lunetta et al. 2004; Garzón et al. 2006). These also can be used to access habitat suitability for species, but have the advantage of being able to assess how the importance of biophysical attributes change among different geographies (O'Connor et al. 2006).

When climate change variables are important attributes of these models, direct responses to different climate change scenarios can be assessed statistically. When biophysical attributes such as vegetation and land cover are the most important variables, species responses to climate change are evaluated by applying models of vegetation and/or land cover responses to climate. Statistical functions generated from these models result from spatial variation and not the responses of species and habitats to climate change over time. That is, they use spatial variability to determine how species and habitats might respond to climate change. However, recently, phylogenetic and phylogeographic analyses have been used in combination with niche-based models to improve response models by adding a historical response component (Waltari et al. 2007). These analyses use molecular markers and tree-based statistical approaches to determine how species have responded (diversification, range contraction, etc.) to historical climate change.

Software used to develop niche and occupancy models can be downloaded for free from the Internet, including GARP (http://www.nhm.ku.edu/desktopgarp/), Maxent (http://www.cs.princeton.edu/~schapire/maxent/), Regression Trees and Random Forests (http://rattle.togaware.com/rattle-download.html), and Bioclim (http://software.informer.com/getfree-bioclim-download-software/). Additionally, many of the species models developed by the GAP program can also be downloaded, including biophysical data (http://www.nbii.gov/portal/server.pt/community/maps_and_data/1850/species_modeling/7000).

Vegetation/Habitat Response Models

Many of the approaches and models described for animal species above are also used to estimate potential response of plants to climate change (Lawler et al. 2006). However, because of greater depth of historical records for plants (e.g., pollen records), it is often possible to refine plant and vegetation response models using historical records (Cole 2010). Moreover, plant and vegetation distribution records are considerably more abundant than animal records and, therefore, are easier to model using statistical approaches (Van Mantgem et al. 2009). Vegetation and plant community models are critically important to assess animal species changes, especially when animal distributions and habitat suitability are defined by vegetation and plant community variables. Robinson et al. (2008) provide an extensive review of vegetation climate models, broadly grouped into statistical species distribution models, GAP models, landscape models, biogeochemical models, and dynamic global vegetation models.

Physiologically Based Models

Physiologically based response models incorporate sensitive aspects of individual species physiologies that influence foraging, nesting/reproduction, thermoregulation, and migration (Root 1988a and 1988b; Martin 2001; Reist et al. 2006; Bernardo et al. 2007; Hunter 2007). Broad-scale changes in species distributions have been tied closely to physiological constraints (Root et al. 2003). The aim is to relate the physiological traits and processes to climate change variables. These models can be used as part of general characterization models or as part of habitat models (Root et al. 2003; see earlier discussions). More complex models quantify interactions between key physiological variables and other variables, such as behavior, growth, and survival, and how important climate variables such as temperature affect interactions (Biro et al. 2007). However, complex models of these types are difficult to build over large areas because of the amount and type of data needed (e.g., data on movement patterns, behavior, growth, survival, etc.). Therefore, these models are most commonly built for specific species in specific geographies. We are unaware of any off-the-shelf software or tools that permit development of physiologically based climate response models.

Ecological Models

There are several ecological models that can be used to assess sensitivity and vulnerability of important ecological processes to climate change. Ecological response models evaluate how climate change variables affect fundamental ecological processes such as carbon and nitrogen fluxes, evapotranspiration, and plant nutrient cycling (Christensen et al. 2008; Tague et al. 2009). The CENTURY model is a general model of plant–soil nutrient cycling and it has been used to simulate carbon and nutrient dynamics for different types of ecosystems, including grasslands, agricultural lands, forests, and savannas (Ojima et al. 1996). DayCent-Chem, which was built off of the CENTURY model, predicts carbon and nitrogen dynamics within forests and leaching of different types of nitrogen cations from the forests to streams (Hartman et al. 2007). The MC1 model is a dynamic vegetation model that combines the CENTURY biogeochemical model with a biogeographical model, MAPSS (Mapped Atmospheric-Plant Soil System) (Bachelet et al. 2001). The Regional Hydro-Ecologic Simulation System (RHESSys) is a GIS–based hydro-ecological modeling framework, which simulates how water, carbon, and nutrients fluctuate through the environment on a watershed scale (Christensen et al. 2008). The PnET is a suite of three nested computer models, which provide a modular approach to simulating the carbon, water, and nitrogen dynamics of forest ecosystems (Aber et al. 1995). All of these have climate-related inputs that permit an analysis of the potential impacts of climate change on fundamental ecological and hydrological processes.

Some of these models can be downloaded from the Internet, including RHESsys (http://fiesta.bren.ucsb.edu/~rhessys/), PnET (http://www.pnet.sr.unh.edu/), and the CENTURY model (http://www.nrel.colostate.edu/projects/century5/).

Box 4.2. Ecological Thresholds

Ecological thresholds are important when considering response models because they represent situations where a small change in a driving variable, such as temperature or precipitation, leads to a disproportionately large response. When a system crosses such a threshold, the fundamental drivers and important processes can change abruptly, and these abrupt departures are often very difficult to include in models. In biological systems, climate-related threshold events include death of corals as a result of high water temperatures (Ward et al. 2007), widespread loss of piñon pines due to drought and high temperatures (Breshears et al. 2005), and the sudden eruption of spruce beetle in Alaskan forests when recent temperature increases permitted reproduction in a single season (Werner et al. 2006).

At the level of a single species, threshold events may result from a simple, direct effect of climate, such as exceeding a lethal temperature. At the ecosystem level, threshold events may be very broadly distributed, and they frequently involve positive feedbacks that amplify effects that otherwise may been a smaller perturbation to the system (U.S. CCSP 2009a). Wildfire behavior is a good example of a physical process with multiple thresholds (Peters et al. 2004). When small, wildfire spread is determined largely by local fuel attributes. As fire extent and intensity increase, several thresholds are crossed and the processes that drive fire behavior are almost completely different. Very large wildfires generate their own surface winds that can drive a fire across areas with small fuel loads and little fuel connectivity. Models with fundamentally different structures, scales, and processes are needed to accurately simulate wildfires across this range of scales (Peters et al. 2004).

Thresholds pose special problems for conducting climate change vulnerability and risk assessments. We know little about the location, even approximately, of most ecological thresholds, while the consequences of crossing a threshold can be profound. A commonsense approach to thresholds is to focus on an opposing attribute—the resilience of an ecological system. Resilience is the ability of a system to retain characteristic processes and structures when subjected to change or disturbance. As mentioned previously, many recommendations for responding to climate change focus on increasing the resilience of systems (U.S. CCSP 2009a; Heller and Zavaleta 2009), and these actions will help avoid catastrophic thresholds.

Limitations of Response Models

All models are simplifications of the real world and, as such, have limitations in their use and applications. Most response models used in vulnerability assessments are simple models involving shifts in species ranges based on direct interactions with climate change (e.g., temperature tolerance), or based on shifts in habitats associated with climate change. These approaches are used because data on species attributes (e.g., demography, habitat preferences, etc.) and species and habitat distributions are available. However, these models tend to ignore other factors and species traits that can affect vulnerability to climate change. These include:

- Changes in interactions between species, including competitive interactions and disease (Peterson et al. 2002; Murray et al. 2006).

- Nonlinear, complex responses (e.g., thresholds or tipping points) associated with indirect interactions (Burkett et al. 2005) (see Box 4.2).

- Interactions between climate change and other important drivers or stressors such as land-use and land-cover change (Root and Schneider 2002).

- Horizontal flow processes such as species migration (immigration/emigration) that can determine a species' ability to move across an area, either in direct response to climate change or as an indirect response to habitat shifts (McRae et al. 2008).

Another issue regarding response models is transferability to different geographies and scales. General relationships established using broad-scale response models may not hold up when assessing vulnerability of a species at a local scale (Frederiksen et al. 2004; Torti and Dunn 2005). Moreover, it may be difficult to transfer response models developed in one biophysical setting to another because of differences in local responses to climate variables (Primack et al. 2009).

Species selection may also affect the outcome of vulnerability assessments. Species with limited distributions have greater uncertainty in their response to climate change than species with broader ranges (Schwartz et al. 2006). Therefore, decisions on which species to include in a vulnerability assessment can affect the outcome and accuracy of the assessment.

Potential responses of species to climate change also may be affected by landscape context. Landscape context has been shown to be an important factor in species survivorship and response to stressors such as land use (Ricketts 2001; Baum et al. 2004). Most species response models lack factors associated with landscape context and pattern. One exception is the PATCH model (Schumaker et al. 2004), which incorporates aspects of landscape pattern and species traits in assessing vulnerability. This model can be downloaded from the Internet (http://www.epa.gov/wed/pages/news/03June/schumaker.htm).

Availability of Response Models

We highlighted a variety of models that can be downloaded from the Internet. Some of these models are relatively simple to use, while others require extensive data sets and adjustments to the models for individual applications. However, even simple models should be used carefully, with close examination of the caveats involved on any particular modeling approach. There is a need for a Web portal that provides links to the range of existing response models, and for enhanced simulation frameworks that facilitate linking (e.g., climate models to ecological response models). The Terrestrial Observation and Prediction System is an example of a sophisticated simulation framework that links historical climate data, remotely sensed data, climate projections, and response models (Nemani et al. 2009).

V. Addressing Uncertainty in Vulnerability Assessments

This chapter addresses issues and approaches for dealing with uncertainty specifically within the context of conducting climate change vulnerability assessments (i.e., uncertainties related to identifying and modeling the sensitivities, levels of exposure, and adaptive capacity of the assessment targets). The following chapter (Chapter VI) discusses how to develop adaptation management and planning activities in light of those uncertainties.

Dealing with uncertainty is nothing new in natural resource management.

To begin, we define *uncertainty* as it applies in both of these contexts. According to the IPCC (2007a), uncertainty is:

"An expression of the degree to which a value (e.g., the future state of the climate system) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain projections of human behavior. Uncertainty can therefore be represented by quantitative measures (e.g., a range of values calculated by various models) and/or by qualitative statements (e.g., reflecting the judgment of a team of experts)."

Quantification of uncertainty can allow for inclusion into a risk assessment or analysis. Risk assessment involves estimating both the probability of an event occurring, and the severity of the impacts or consequences of that event. Analyses of risk, therefore, provide an opportunity to address quantifiable uncertainties through probabilistic calculations. Not all uncertainties can be addressed in a risk assessment, as there are unknowns that in many cases cannot be quantified. While risk assessment may allow for the inclusion of some types of uncertainty, it is also important to communicate those uncertainties that cannot be handled through exact quantification.

Managers have always made decisions even though there are uncertainties that cannot be quantified, much less reduced or eliminated. Dealing with uncertainty is nothing new in natural resource management. Being transparent about the general magnitude of uncertainty and understanding the range of possibilities given the uncertainty allows managers to articulate the reasoning for making a specific decision. With regard to climate change, managers may be seeking "bet hedging" strategies that make sense under a number of plausible future scenarios or that are generally robust to uncertainty.

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With respect to vulnerability assessments, the goal should be to use the best available information on the uncertainties involved in estimating vulnerability, while recognizing that it may be necessary to reassess vulnerability and the associated uncertainties in an iterative fashion as new information becomes available. The assessment of uncertainty should identify both the best estimate of how vulnerable a system is to climate change but also the potential range of vulnerability given uncertainties.

The Language of Uncertainty

Before diving into specific methods for assessing uncertainty, it is important to acknowledge the need for "a language of uncertainty." The vulnerability assessment will synthesize scientific information from field studies, experimental studies, and modeling experiments, as well as the scientific knowledge of the experts pulling the information together. Users of the vulnerability assessment will want to know what the authors conclude about the assessment results based on the variety of different sources of information. How much confidence do the authors have in the results of the vulnerability assessment? There is a need to be consistent in describing the uncertainty so that the degree of uncertainty can be clearly communicated across vulnerability assessments (U.S. CCSP 2009c). We present several methods that can be used to describe the certainty of the assessment.

Uncertainty in the Scientific Literature

Methods to quantify uncertainty or confidence in assessments and analyses have been the subject of much study (e.g., uncertainty can arise in a variety of ways in an analysis or an assessment). Quantitative analyses of species vulnerability to climate change use mathematics or statistics to describe the relationship between climate and the species of interest. In these quantitative analyses, uncertainty can arise in the structure of the mathematics used to describe the phenomena as well as the field data used to parameterize the equations. For example, different vegetation models may describe quantitatively the growth of vegetation using different mathematical expressions, which can mean slight differences in the results under climate change. Uncertainty is also found in what is not known about the phenomena. For example, how elevated CO_2 will influence plant growth is not known precisely, and the vegetation models differ in their expression of this process.

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When the assessment is based on quantitative and qualitative analyses and a synthesis of the scientific literature by experts, then uncertainty is found in the lack of available information specific to the question of interest in addition to the uncertainty in the quantitative studies. The breadth and nature of the authors' background and experience also contributes uncertainty. For example, assessing the climate impacts on a particular bird species may be limited by what is known today about relationships between the bird's biology and climate metrics such as temperature and precipitation. However, there may also be more complex interactions with climate, such as soil moisture affecting the habitat the birds use.

Many techniques are available to quantify and communicate uncertainty in mathematical, computer, and statistical models, many of which are summarized in the U.S. Climate Change Science Program's recent publication *Best Practice Approaches for Characterizing, Communicating, and Incorporating Scientific Uncertainty in Climate Decision Making* (U.S. CCSP 2009c). Risk analysis methods, for example, can be used to assess uncertainty when the range of all possible events is known, and objective probabilities can be assigned to these events. The challenge in assessing climate change impacts is in quantifying the range of all possible events. In reviews of the attempts to quantify uncertainty in the IPCC reports, reviewers note that the process was limited by the amount of work done in the primary literature on quantifying uncertainty in the field or modeling studies. Fewer techniques are available to structure the uncertainty in assessments where information from a variety of sources is synthesized to assess the vulnerability of species or communities or ecosystems to climate change. It should also be noted that this discussion focuses only on the assessment of vulnerability. These results must be cast against the broader background on which the decision is made—and there will be uncertainty in those other factors influencing the management of the species, habitat, or ecosystem.

IPCC Approach to Uncertainty

The IPCC represents the longest focused attempt to describe uncertainty in the context of climate change and has been evolutionary in the development of the methodology used (Risbey and Kandlikar 2007). The 2007 IPCC reports were explicit about the language they used in describing uncertainty and levels of confidence in climate change. Yet, even though a common set of guidance was given to the authors, the uncertainty language in the IPCC

Quantitatively Calibrated Levels of Confidence

Terminology	Degree of Confidence in Being Correct
Very high confidence	At least 9 out of 10 chance of being correct
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than 1 out of 10 chance

reports reflected the disciplinary nature of the subjects—for the physical sciences, the uncertainty language can build on the quantitative analyses in the sciences; for the socio-economic analyses, a more qualitative approach was taken given the nature of the primary literature being less quantitative.

“Where uncertainty is assessed more quantitatively using expert judgment of the correctness of underlying data, models or analyses, then the following scale of confidence levels is used to express the assessed chance of a finding being correct” (IPCC 2007a):

“Where uncertainty in specific outcomes is assessed using expert judgment and statistical analysis of a body of evidence (e.g. observations or model results), then the following likelihood ranges are used to express the assessed probability of occurrence” (IPCC 2007a):

“Where uncertainty is assessed qualitatively, it is characterized by providing a relative sense of the amount and quality of evidence (that is, information from theory, observations or models indicating whether a belief or proposition is true or valid) and the degree of agreement (that is, the level of concurrence in the literature on a particular finding). This approach is used by Working Group III through a series of self-explanatory terms such as: high agreement, much evidence; high agreement, medium evidence; medium agreement, medium evidence; etc.” (IPCC 2007d).

Some uncertainties can be quantified using statistics and modeling approaches, while others may require more qualitative assessment.

A key observation about the language of uncertainty in the IPCC reports is that it has evolved as scientists learn how to further refine their science and the uncertainty related to their analyses (Risbey and Kandlikar 2007). One criticism of the analysis literature is the absence of a thorough assessment of the uncertainty. In some cases, exploring the uncertainty in quantitative analyses can be expensive in terms of time and effort and hence are not done as extensively as someone applying that analysis might prefer. Further, the lack of a consistent approach to describing uncertainty in the IPCC reports has been seen as inevitable given the very different nature of the science and the role of human decisions in the potential responses to climate change.

Likelihood Scale

Terminology	Likelihood of the Occurrence/Outcome
Virtually certain	>99 percent probability of occurrence
Very likely	>90 percent probability
Likely	>66 percent probability
About as likely as not	33 to 66 percent probability
Unlikely	<33 percent probability
Very unlikely	<10 percent probability
Exceptionally unlikely	<1 percent probability

Assessing and Understanding Uncertainty

Identifying Sources of Uncertainty

Uncertainty in climate change vulnerability assessments can be rooted in a number of stages in the process, including: limited/unreliable data; unidentified or unknown interactions with non-climate stressors; unidentified or unknown interactions among different elements of climate change; unidentified or unknown interspecific interactions; unidentified or unknown thresholds; ambiguously defined concepts or terminology; scientific disagreements about what is known; or uncertain projections of human behavior. Some of these uncertainties can be quantified using statistics and modeling approaches, while others may require more qualitative assessment. A combination of these different methods can be used to bound the uncertainty and understand the range of possibility for vulnerability to climate change (Refsgaard et al. 2007).

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The following are a few examples of methods available to address uncertainty in climate change vulnerability assessments:

- **Monte Carlo Simulation.** One common quantitative approach for measuring uncertainty is Monte Carlo analysis, as exemplified in the Nevada case study in Chapter VII (Case Study 1). Put simply, a Monte Carlo simulation is a computer-based statistical technique that uses random sampling to convert uncertainties in the input variables of a model (e.g., incomplete knowledge of the climate sensitivity of a particular species) into probability distributions over output variables (Park 2008; Refsgaard et al. 2007; New and Hulme 2000; U.S. EPA 1997).

- **Expert Elicitation.** The vulnerability assessment for Massachusetts fish and wildlife habitats (Case Study 4) addressed uncertainty via "expert elicitation," which is a formal, systematic process to determine subjective judgments about uncertainties from relevant experts (Refsgaard et al. 2007). Expert elicitations are often warranted in cases where there are many sources of uncertainty and where critical information may be unavailable. The results of expert elicitation are often characterized quantitatively as probabilities that represent their levels of confidence. However, it is also important to include documentation of the evidence and criteria used by the experts to support their decisions.

- **Scenario Analysis.** A relatively straightforward way to address uncertainties inherent in projecting the future is to base assessments on multiple scenarios (Walker et al. 2003). Scenario uncertainty implies that there is a range of possible outcomes, but the mechanisms leading to these outcomes are not well understood and it is, therefore, not possible to formulate the probability of any one particular outcome occurring. For example, if downscaled climate models are unable to determine whether future conditions in a particular area will be warmer and wetter or warmer and drier, assessing the vulnerability of species or systems under both possible scenarios may be warranted. Similarly, given the currently wide range of possible scenarios for eustatic sea-level rise and the numerous factors that can affect relative sea level at a local or regional level, projecting future impacts and vulnerability based on a number of scenarios and assumptions may offer the most flexibility for determining possible management strategies (see Case Study 5).

Combining Multiple Sources of Uncertainty

Understanding the degree of uncertainty in each of the components that make up a vulnerability assessment is useful in understanding the overall vulnerability of a system to climate change. However, one of the major goals of doing a vulnerability assessment should be to combine the different components of the assessment in a way that provides an understanding of the range of vulnerability given the uncertainties in each of the components. Being able to combine these multiple sources of uncertainty is really the glue that brings vulnerability assessments together into a synthetic product that can be used for decision-making and adaptation planning.

Combining the various sources of uncertainty is important because the uncertainties may interact to magnify or reduce the overall uncertainty. For example, there may be a species in the arid southwestern United States that is moisture limited, and global climate models range from projecting small increases to fairly large decreases in precipitation, with temperatures increasing 2.5 to 4.5 degrees Celsius by the 2080s. Although there is a degree of uncertainty in the different components, combining the temperature and precipitation information shows that the increase in temperature will offset any projected increase in precipitation resulting in a moderate to large decrease in water availability, and thus a consistent increase in that species' vulnerability. On the other hand, if a different species in this same area has a springtime temperature threshold that cues it to flower at a certain time, which is known within a range of approximately 4 degrees Celsius, the vulnerability of the species may range from very little and unlikely to fairly great and likely.

The key to combining multiple sources of uncertainty is to identify interactions between the different components, such as how temperature and precipitation interact to affect soil moisture and river flows. This can be done qualitatively through conceptual models, diagrams, and narratives, or more quantitatively through scientific models and computational algorithms. The method used for combining uncertainty should be chosen based on the methods used to assess uncertainty of the components (e.g., qualitative vs. quantitative), the degree of understanding about the interactions between the components and the resources available for combining the data (e.g., technological capacity and budget).

VI. Using Vulnerability Assessment Results

Vulnerability Assessment Outputs

Conducting a vulnerability assessment is not an endpoint. Vulnerability assessments are an intermediate step, and results provide information used to develop adaptation strategies and inform management planning. The specific uses of results from vulnerability assessments are determined by factors such as the selection of conservation targets, management scale, tolerance for risk, and management approaches. Two common outputs from vulnerability assessments are a ranking of the relative vulnerability of target species or habitats, and an assessment of the specific factors that pose threats to species or habitats.

Relative vulnerability rankings may be displayed in tables or spatially through maps. These rankings can range from expected complete loss of the target, to a ranking of greatly increased abundance or distribution. In this way, conducting a vulnerability assessment helps to identify expected winners and losers under altered climate conditions. The vulnerability assessment case studies provided in Chapter VII offer examples of a wide range of outputs from vulnerability assessments. These assessments were conducted for locations throughout the United States, at various spatial scales, and for targets ranging from species to broadly defined habitat types.

Vulnerability assessments provide information to develop adaptation strategies and inform management planning.

Vulnerability assessments should also provide a confidence value associated with their relative vulnerability ranking as an output. This facilitates a transparent consideration of uncertainty in subsequent conservation and management decision-making. However, one must be careful not to allow uncertainty to preclude consideration of climate impacts on species and habitats. As discussed previously, uncertainty is inherent in all projections, whether or not climate is one of the factors considered in making the projections. In fact, simply because climate change is having and will continue to have major impacts on species and habitats, a greater degree of certainty is inherent in assessments accounting for climate change than those that do not recognize the influence of climate change on species and habitats. Although the magnitude of climate change's impacts on species and habitats may be uncertain, it is important to understand that climate change vulnerability assessments can, at

Lead authors: Doug Inkley, Molly Cross, Jennie Hoffman, and John O'Leary.

a minimum, reveal information about the direction of species and habitat changes in response to climate change (e.g., whether populations or habitat area are likely to increase or decrease).

Another important output is the identification of the specific factors contributing to a species' or habitat's vulnerability. When assessing vulnerability, non-climate factors contributing to vulnerability (e.g., habitat fragmentation; the extent of watershed covered by impervious surfaces; impacts from invasive plants and animals; pest and pathogen outbreaks; and impacts from water withdrawals and aquifer depletion) should be included. Identification of specific vulnerability factors, from both climate and non-climate sources, as well as their interactions, is key to developing potential adaptation strategies. Knowing the factors or combination of factors that make a species or habitat vulnerable allows managers to develop specific management or conservation strategies that can help reduce those vulnerabilities.

Informing Existing Planning Efforts

Most state, federal, and tribal natural resource agencies, as well as non-governmental organizations engaged in natural resource protection, are guided by well-established planning processes. A useful aspect of vulnerability assessments is that they can help inform the management process regardless of the administrative structure, function, and operating procedures of different management agencies. Carefully choosing the targets of the vulnerability assessment and methodology of assessment will make it easier to integrate the results of the climate change vulnerability assessment into the existing planning framework used by agencies.

Vulnerability assessments can be used to help inform many aspects of fish and wildlife conservation and management, including selecting which species or habitats should be the focus of conservation efforts, identifying priority areas for land acquisition, informing management decision-making, and directing monitoring efforts. Box 6.1 describes an example of how the Massachusetts Division of Fisheries and Wildlife is integrating habitat vulnerability assessment into its land protection prioritization process and management decision-making. Similarly, Case Study 6 describes a two-pronged assessment approach that builds on vulnerability assessment to identify potential management options.

Eric Engbretson/USFWS

Box 6.1. Informing Land Protection Priorities in Massachusetts

The Massachusetts Division of Fisheries and Wildlife recently completed a Habitat Vulnerability Assessment (HVA) to inform their planning processes (see Case Study 4 in Chapter VII). The HVA was performed by an expert panel that determined the relative vulnerability to climate change for 20 key habitat types, as well as a confidence score for each habitat evaluated and an identification of the various factors contributing to a habitat's vulnerability ranking and confidence score. These results have been added as another factor for consideration in agency management, acquisition, and research and monitoring programs (Manomet Center for Conservation Sciences and MDFW 2010c). Potential management responses being considered include the following:

1. Promote resistance and resilience. The ability of a system or species to resist adverse climate change impacts will depend largely on its intrinsic resistance to the stressors and its resilience—its ability to recover from stress. The resilience of many species and systems has already been compromised by anthropogenic stressors and they are now in a weakened state. While there are no guarantees that increasing the resilience of these resources will safeguard them under climate change, it is certain that their current lack of resilience will render them vulnerable. Four main solutions to promoting resistance and resilience have been proposed:

- Mitigating the effects of non-climate stressors
- Conserving existing biodiversity, ecological functions, and high-quality habitats
- Restoring degraded habitats
- Managing habitats for ecological function

2. Implement landscape-level planning. One of the main impacts of climate change will be to increase the likelihood and magnitude of shifts in the distributions of species, habitats, and ecosystems. A landscape-level planning focus will be necessary to accommodate this. Specifically, it will be important to take such a view to: 1) Identify and preserve movement corridors; 2) Improve habitat connectivity to facilitate movement of displaced organisms; and 3) Improve buffering to safeguard core, high-quality habitats.

3. Promote effective on-the-ground management of sites and habitats. Adaptation goals need to be translated into effective on-the-ground management actions that will strengthen the resistance and resilience of sites, habitats, and species under a changing climate. Specifically, site managers and biologists need to focus on two primary management goals—managing resistance and resilience, and managing change.

4. Promote and implement "climate-smart" regulation. Some of the conservation regulations that have served well in the past may not be as effective under climate change. For example, regulations that prohibit the management and manipulation of resources and habitats might not be optimal at a time when a changing climate is forcing responses in resources. In such cases it may be necessary to introduce a degree of management flexibility into these existing regulations.

Selecting Conservation Targets

Climate change vulnerability information can be integrated into processes aimed at identifying species or habitats most in need of conservation attention, such as efforts to identify and prioritize SGCN for State Wildlife Action Plans. In some cases, a consideration of climate change vulnerability will cause agencies to add species to their SGCN lists or alter the level of priority of an existing SGCN. The same may apply to habitats that agencies consider to be of high conservation need or priority.

While the relative vulnerability rankings an assessment generates may help managers understand which species are more and less vulnerable, it will not dictate whether to focus attention on the most vulnerable, the least vulnerable, or something inbetween. This emphasizes the fact that a vulnerability assessment is not an endpoint, but a source of information that can be incorporated into planning and decision-making. Furthermore, because vulnerability assessments should elucidate the specific factors that contribute to a species' or habitat's vulnerability, it can help managers identify options for reducing that vulnerability through management and conservation actions. In some cases there may be practical management options, but in other cases the factors leading to vulnerability may be very difficult or simply not feasible to address. This is an important consideration in selecting conservation targets and objectives.

Setting Land Protection Priorities

Among the most powerful strategies for the long-term conservation of biodiversity is establishment of networks of protected areas that represent the full range of a region's species and ecosystems, and include multiple, robust examples of each type. These principles of *representation, resiliency,* and *redundancy* are at the core of many comprehensive conservation planning and land protection efforts (Shaffer and Stein 2000; Margules and Pressey 2000; Scott et al. 2001). Climate change vulnerability assessments can help aid such planning efforts by augmenting knowledge of the current distribution and status of species and ecosystems with projections of the possible future conditions and locations. Combining the results of species assessments may reveal landscape areas likely to have relatively high or low species diversity or important habitat for species of management concern. In either case, the results can be used to identify priority areas for areas for protection based on the principles of representation, resiliency, and redundancy. Land protection strategies can therefore take into account not only existing values and conditions, but also the likely value of specific areas under a changing climate.

A vulnerability assessment is not an endpoint, but a source of information to incorporate into planning and decision-making.

Informing Management Decisions

Vulnerability assessments ideally incorporate uncertainty about climate change and about a system's response to it. Adaptation planning ideally evaluates management options across that range of uncertainty. As previously discussed, vulnerability assessments can help you to evaluate whether your existing goals, objectives, and targets are still appropriate in a changing climate, or to develop new goals, objectives, and targets (Millsap et al. 1990). Having identified management or conservation goals, objectives, and targets, the next step is to decide which actions will best achieve those aims.

Directing Monitoring Efforts

Multiple management objectives and multiple factors affecting species of management concern, combined with limited resources, necessitate that monitoring programs to assess the success/failure of management objectives be designed to yield useful information in a cost-effective manner. In some cases, monitoring may be of the status or health of the target species or habitats, which should help determine the effectiveness of various management strategies. In other cases, it may be important to monitor major factors affecting the status of species or habitats. Because the process of assessing vulnerability requires determination of the major factors affecting the status of habitats and species, one can return to the vulnerability assessment to inform decisions about the most appropriate factors to monitor. Monitoring of these factors should provide useful information about species or habitat status.

Furthermore, if some of these factors are directly being managed in order to provide appropriate conditions for priority species or habitats, the degree of success in creating these conditions will come to light through their monitoring.

The potential factors to monitor that have major effects on species or habitats will no doubt vary widely depending upon the species and habitat type, and even vary within the range of given species and habitats. It will be important to ensure that the factors being measured provide useful information. Where key thresholds are identified for species or habitats, monitoring of these thresholds is important, especially if these factors are themselves being addressed in management.

There will very likely be many instances wherein the major factors affecting a species are not known at the time of the vulnerability assessment, or there is a high degree of uncertainty associated with the results. In these situations, the vulnerability assessments should help reveal those species for which further research is necessary to identify key factors and increase confidence in the vulnerability assessment results (Williams et al. 2008; IPCC 2005). Assuming success of this research, vulnerability assessments could be conducted again for these species and habitats and appropriate factors used in monitoring management results. Until then, it will be difficult to know how to manage for a species and which factors to manipulate and monitor for management purposes.

Dealing with Uncertainty in Adaptation Planning

As highlighted in Chapter V, resource managers often must make conservation decisions under uncertainty, particularly where information about future conditions must be considered. Some management responses will be effective in meeting conservation goals under a range of potential climate futures, while others may need to be tailored to more specific conditions (Lawler et al. 2010). When future conditions are fairly certain, it makes sense to ask "Which actions will produce the single best outcome?" When there is significant uncertainty about future conditions, answering that question becomes increasingly difficult because the answer depends on which future comes to pass. In such situations it may make more sense to ask "Which actions will give me the best chance of some acceptable outcome?" This approach is called robust decision-making, and it is essentially a bet-hedging strategy. Rather than maximizing the chance of the single best outcome, it seeks to maximize the likelihood of an acceptable outcome. While this approach may initially seem at odds with the mandate to make decisions based on "the best available science," it is not. If the best available science is telling you that there are important uncertainties that will affect your management success, then taking a robust approach is in fact a decision based on the best available science. Two tools that can help resource managers make adaptation planning decisions under uncertainty are adaptive management and scenario planning.

Instead of striving for the single best outcome, it may make more sense to ask "which actions will give the best chance of some acceptable outcome."

Adaptive Management

The U.S. Department of the Interior defines adaptive management as "a systematic approach for improving resource management by learning from management outcomes," based on principles laid out by the National Research Council (Williams et al. 2007; NRC 2004). The overarching purpose of adaptive management is to enable natural resource managers and other relevant decision-makers to deal with uncertainty about future conditions by supporting the development of conservation projects based on existing information and then providing the flexibility to modify their management activities to improve their effectiveness as new information becomes available. It is a concept that has been around for many years, and it has often been identified as a priority in resource management plans. Salafsky et al. (2001) identify a series of steps for adaptive management in conservation:

- Start: Establish a clear and common purpose
- Step A: Design an explicit model of your system
- Step B: Develop a management plan that maximizes results and learning
- Step C: Develop a monitoring plan to test your assumptions

- Step D: Implement your management and monitoring plans
- Step E: Analyze data and communicate results
- Iterate: Use results to adapt and learn

Adaptive management may be particularly useful in cases where immediate action is required to address short-term and/or potentially catastrophic long-term consequences, such as the collapse of important ecosystem services, or where management actions are likely to have "no regrets" near-term benefits (Ojima and Corell 2009).

It is important to recognize, however, that effective adaptive management can be difficult for several reasons, including insufficient long-term monitoring resources, unclear or conflicting conservation and management goals, political and institutional resistance to changing management practices, and/or inability to control a particular outcome through management (Johnson 1999).

Scenario-Based Management Planning

Another framework for robust decision-making, or for decision-making under uncertainty in general, is scenario planning. Just as the use of multiple climate change scenarios can help address inherent uncertainty in assessing vulnerability, they also can provide a useful framework for informing possible adaptation options, particularly in cases where the levels of uncertainty about potential future conditions are especially high and uncontrollable (Peterson et al. 2003) (see Figure 6.1). The goal here is to identify and consider a broad range of options, appropriate responses to the array of future scenarios, and what management mechanisms you can put in place that will allow you maximum likelihood of success and flexibility given the array of possible future scenarios.

Scenarios, at their simplest, are descriptions of some plausible future. They are not predictions or forecasts, and

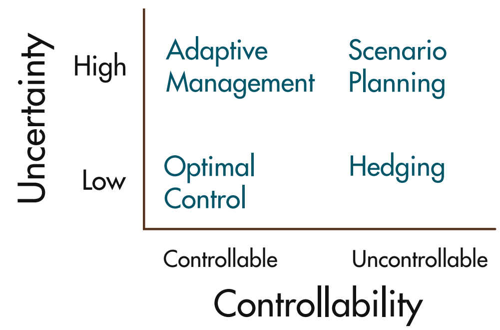

Figure 6.1. A framework for management under different levels of uncertainty (Peterson et al. 2003).

scenario planners make no assumptions about which scenario is most likely (if you knew which was most likely, you would not need scenario planning). Scenarios can be quantitative or qualitative, and they may include a complex web of interconnected problems or focus on a simple subset of the issues. Which is more appropriate depends on the goal of the scenario planning exercise and available information. Qualitative, exploratory scenarios may help to set the stage for the development of quantitative, targeted scenarios by stimulating creative thinking and deepening managers' and planners' understanding of their system. In a similar fashion, exploratory scenarios that include a range of complexity may help to identify those elements on which it is most important to focus.

Scenario planning exercises typically use around three to five different scenarios. Scenarios are created for the particular scenario planning exercise, and will ideally: (1) bracket the range of plausible futures, and (2) highlight those elements of uncertainty most important to management and planning. Having developed the scenarios, managers and planners then brainstorm possible management options and look at the performance of those options across all scenarios. Are there management approaches that are effective in all scenarios? Are there management options that are highly effective in one but disastrous in others? As you go through this exercise, you can highlight areas where uncertainty about climate change or the system's response to it is more or less important. For instance, if a particular management action is best regardless of future rainfall, decreasing uncertainty in rainfall projections would not be particularly useful. If, on the other hand, rainfall timing or intensity is the single biggest determinant of which management action is best, then you would want to focus on reducing uncertainty around those projections.

Scenario planning provides multiple benefits. It not only helps with making particular decisions in uncertain conditions, but increases the more general ability of planners and managers to cope with uncertainty. It also facilitates the design of monitoring programs that target key elements of uncertainty, be they uncertainty about climatic change, system responses to that change, or the effect of particular management actions.

Lindsay Baronoski

Not considering climate change in management is akin to traveling in unknown territory without a map—one is not likely to arrive at the desired destination.

Matt Greene

Looking Ahead

The development of vulnerability assessments has resulted from concern about the pervasive impacts of climate change across the landscape. With so many species and habitats likely to be affected, it is critical that managers know the likely status of species and habitats in a changing climate. Not considering climate change in management is akin to traveling in unknown territory without a map—one is not likely to arrive at the desired destination or result (Lawler et al. 2010).

An added benefit of conducting vulnerability assessments is that they are not specific to assessing vulnerability to just climate change. Properly executed, vulnerability assessments should account for the factors affecting species and habitats, regardless of what those factors are. This comprehensive nature of vulnerability assessments makes them all the more important as a tool for informing the development and implementation of management objectives.

Regional vulnerability assessments, such as that underway in the Pacific Northwest (Case Study 7), will provide information useful to different agencies across the areas. Regional collaboration across several states to conduct vulnerability assessments may be economically efficient in a time of distressed state wildlife agency budgets and may also foster multi-state relationships (AFWA 2009). Furthermore, in light of the landscape-scale impact of climate change, increased collaboration among states is likely to be beneficial as species and habitat ranges move across the landscape.

VII. Case Studies

A number of climate change vulnerability assessments for species and ecosystems have been completed or are currently underway across the country. The following seven case studies provide examples of some of the different assessment approaches described in this guide and demonstrate the considerable variability that is possible in terms of assessment scale and scope.

The first four studies are broader, "coarse filter" approaches, which can provide users with a useful tool to compare relative vulnerability across a range of targets and at varying degrees of detail. These approaches are based primarily on static attributes of species, habitats, and ecosystems, and they do not involve the direct use of dynamic simulation models (although Case Studies 1 and 3 incorporate use of a tool for downscaling relevant climate data). Refuges, state agencies, or protected areas that are well staffed may have the capacity to conduct these types of assessments primarily with existing staff.

The fifth case study, which highlights a habitat-based assessment and a subsequent assessment of associated species, involved the use of a habitat response model to project the impacts of sea-level rise on coastal wetland communities, based on existing scenarios for sea-level rise. Approaches such as this often require the use of expertise that may not normally be available at one site but that may be accessible through partnerships with other agencies, organizations, or individuals.

The sixth study applied an integrated climate change assessment and adaptation framework in the Four Corners region of the Southwest, building on the completion of a state-wide vulnerability assessment and two adaptation-oriented workshops for natural resource managers in New Mexico. The assessment entailed evaluation of the level of climate exposure (based on regionally downscaled data) in relation to existing conservation priorities identified in the four states' Wildlife Action Plans and ecoregional assessments. This enabled managers to prioritize vulnerable landscapes for adaptation action.

The final case study is the broadest and most ambitious assessment described in this guide. The assessment encompasses a very large spatial scale and a broad range of habitats and species. The study incorporates elements of other approaches, including detailed species-specific data, dynamic climate projections, and climate–space niche models to identify vulnerable species, biodiversity "hotspots" at risk, and habitats at risk to climate-induced changes. Table 7.1 provides a general summary of each of these case studies.

Table 7.1: Summary of Case Studies							
	1. Nature-Serve Nevada Species Assessment	**2. EPA Endangered Species Framework**	**3. Species Assessment for the Middle Rio Grande**	**4. State-level Habitat Assessment for Mass.**	**5. Coastal Habitats and Species**	**6. Integrated Framework for the Four Corners**	**7. Pacific Northwest Assessment**
Location and Extent	Nevada, statewide	National	New Mexico, regional	Massachusetts, statewide	Chesapeake Bay Region (two studies)	Southwest, Four Corners region	Pacific Northwest, regional
Status	In progress	Completed	Completed	Completed	Completed	Phase 1 Completed	In progress
Targets	263 priority animal species (invertebrates and vertebrates)	Six threatened and endangered vertebrate species	Terrestrial vertebrate species occupying riparian habitats	20 habitats	5.1: Coastal wetland habitats 5.2: Marsh bird species of concern	Species and habitats identified as conservation priorities	Species and habitats
Climate Change Models?	Yes, down-scaled climate data based on ClimateWizard	No (used published projections)	Yes, down-scaled climate data based on ClimateWizard, and published projections	No (used published projections)	No (used published projections)	Yes, down-scaled climate data based on ClimateWizard	Yes, down-scaled climate data based on multiple model simulations
Other Models?	General characterization	General characterization, expert opinion	General characterization, expert opinion	General characterization, expert opinion	Habitat and occupancy model (SLAMM)	General characterization, expert opinion	Climate niche, habitat, and hydrological models
Detail	Low	Moderate	Low	Moderate	Moderate	Low	High
Work/ Time	Low (application time per species = 30-45 minutes)	Moderate	Moderate	Moderate (1 year)	Low-Moderate 5.1=1 year 5.2=4 months	Moderate (2.5 years)	High (3-4 years)
Cost	$160,000	$60,000	$60,000	$70,000	5.1: $40,000 5.2: $25,000	$200,000	$800,000
Lead	B. Young	H. Galbraith	D. Finch	H. Galbraith	5.1: P. Glick 5.2: M. Wilson	C. Enquist	J. Lawler
Citations	Young et al. (in press)	U.S. EPA 2009	USDA Forest Service, Rocky Mountain Research Station 2010	Manomet Center for Conservation Sciences and MDFW 2010a, 2010b	5.1: Glick et al. 2008a, 2008b 5.2: Wilson and Watts 2009	Enquist and Gori 2008	Lawler et al. 2009, 2010

Case Study 1. NatureServe's Climate Change Vulnerability Index for Species in Nevada

This case study highlights how an accessible "vulnerability index" can be used to readily assess the impacts of climate change on species of concern at a state-wide scale. The state of Nevada is emerging as a leader in addressing how climate change alters the way states need to manage species and habitats to maintain biodiversity. In 2008, a coalition of Nevada state agencies and nonprofits initiated activities to revise their state Wildlife Action Plan to fully address the effects of climate change. These organizations are now well advanced in the research and review exercises that will form the basis of their revisions. This case study describes how one member of the coalition, the Nevada Natural Heritage Program, is contributing to this effort by using the Climate Change Vulnerability Index developed by NatureServe to conduct rapid assessments of the relative vulnerability of Conservation Priority Species.

Purpose

Although Nevada's original Wildlife Action Plan (2006) identified climate change as a stressor to key habitats and species, it did not go into detail about how climate warming could cause substantial ecosystem change or what management actions are necessary to stem the loss of wildlife.

Mike Peterson

By 2008, it was clear to the groups that had developed and were responsible for implementing the Plan that an amendment was necessary to adequately reflect the major changes needed to manage for biodiversity under conditions of rapid climate change. Updating the Plan to account for climate change would also position the state to receive federal funding that might come from climate change legislation. Additionally, funding was available through the Division of State Land's Question One Conservation Bond Program. Thus, the partners, including the Nevada Department of Wildlife, The Nature Conservancy, Nevada Natural Heritage Program, Lahontan Audubon Society, and Great Basin Bird Observatory, successfully applied for funding to develop this amendment.

Conservation Objective

The objective of the project is to broaden the applicability of Nevada's Wildlife Action Plan to understand the health of the state's wildlife, including vulnerability to

Lead authors: Bruce Young, Jennifer Newmark, and Kristin Szabo.

climate change, and to prescribe actions to conserve wildlife and key habitats before they become more rare and costly to protect. The Plan develops objectives and strategies for the conservation of 27 key habitats found in the state.

Assessment Targets

Nevada Natural Heritage is responsible for assessing the vulnerability of all 263 Conservation Priority species that were identified in the original Wildlife Action Plan. The species include 1 mussel, 74 snail, 40 fish, 7 amphibian, 20 reptile, 72 bird, and 49 mammal species. Once this assessment is completed, the outcome will contribute to habitat vulnerability models run by a partner organization. Nevada Natural Heritage hopes to eventually extend the vulnerability assessment to many more species, including plants and abundantly distributed species.

Scale and Scope

The Nevada assessment is restricted to a state-wide analysis. Developing future regional assessments that examine how species may expand into and retreat from states would be helpful to provide a more comprehensive picture of the complex changes in population size and location taking place. Currently, though, existing funding mechanisms favor state-based approaches. The time scale for the species vulnerability assessments is mid-century. Mid-century represents a time frame that is before the major climate models and emissions scenarios begin to have widely divergent predictions, resulting in less uncertainty than for longer time horizons.

In terms of cost and time, once the distribution of natural history information on a species is researched and compiled—NatureServe has already done this for many species (available at NatureServe Explorer, http://www.natureserve.org/explorer)—it can take as little as 30–45 minutes to rank a species. The cost of this assessment will be approximately $160,000.

Assessment Approach

The Nevada partners have divided the tasks according to each organization's strengths:

- The **Department of Wildlife** provides oversight and management of the project in coordination with the other partners. It organizes team meetings and helps solicit public comments on draft documents. The Department of Wildlife will also be responsible for interacting with the U.S. Fish and Wildlife Service to obtain formal approval for revisions to the Wildlife Action Plan.

- As stated above, the **Nevada Natural Heritage Program** is responsible for assessing the vulnerability of the individual Conservation Priority species to climate change.

- **The Nature Conservancy** will use a modeling approach to understand the vulnerability of Nevada habitats to climate change.

- The **Lahontan Audubon Society** will help facilitate workshops, work with the public, perform outreach activities, and help edit document drafts as they are written.

- The **Great Basin Bird Observatory** will use climate envelope models to estimate how bird distributions may shift as a result of climate change. Like the species assessments undertaken by Nevada Natural Heritage, the results of these models will form input into The Nature Conservancy habitat models.

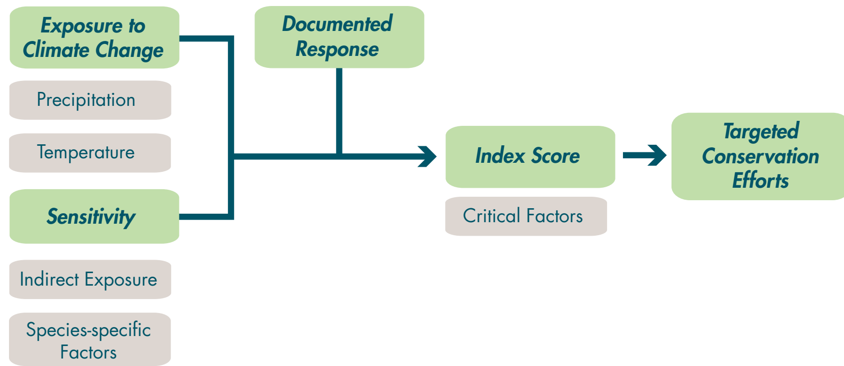

Figure C1.1. Framework for NatureServe's Climate Change Vulnerability Index.

Nevada Natural Heritage had a limited amount of funding and a short time frame for completing its task of reviewing the vulnerability of a large number of species. The program elected to use the Climate Change Vulnerability Index as a rapid and cost-efficient means of completing this task.

The Index separates a species' vulnerability into two main components: exposure to climate change within its range and inherent sensitivity to climate change (Williams et al. 2008) (see Figure C1.1). Data for these two components take the form of downscaled climate predictions across the range of the species within the assessment area (in this case, the state of Nevada) and scoring of the species against 17 factors related to its anticipated climate change sensitivity, such as dispersal ability and habitat specificity. Additional factors addressing exposure and adaptive capacity, such as natural or anthropogenic barriers to dispersal, as well as observed responses to climate change (if available) are also included. These factors are all documented in the scientific literature to be correlates or predictors of vulnerability to climate change. The outcome is one of six possible Index categories: three Vulnerable (Extremely, Highly, and Moderately), two Not Vulnerable (Presumed Stable, Increase Likely), and one Insufficient Evidence. The Index complements standard conservation status assessments such as the NatureServe G- and S-rank system that contributed to species' designation as Conservation Priorities in the original Wildlife Action Plan. More information about the Index as well as the Index itself can be found at http://www.natureserve.org/climatechange.

Biologists from Nevada Natural Heritage used distribution and natural history information from their databases together with climate predictions downloaded from the ClimateWizard to complete assessments for all 263 Conservation Priority species. Next, they convened a panel of independent biologists familiar with Nevada wildlife to review their work and confirm or adjust how the factors were scored for each species. This process is currently ongoing and will result in final assessments that feed into habitat vulnerability models that will form another section of the revised Wildlife Action Plan.

Assessment Results

Like most of the world, Nevada will experience significant warming. Mid-century climate predictions suggest warming of 2.6 to 3.2 degrees Celsius and slight decreases or increases in precipitation in different parts of the state (Maurer et al. 2007). Results for a preliminary assessment of 216 vertebrates and mollusks listed as Conservation Priority species in the Nevada Wildlife Action Plan revealed that the Index sorted taxa into widely differing levels of vulnerability to climate change (Figure C1.2). Mollusks and fish were the most highly vulnerable groups, whereas some mammals and fish may increase their abundance or expand their ranges in Nevada as the climate warms. Demonstrated adaptation to a limited range of precipitation regimes, migration to or through a few restricted and potentially vulnerable locations or lack of regular distribution shifts in response to environmental conditions, and dependence on specific vulnerable aquatic/wetland habitats were the factors that most commonly contributed to vulnerability to climate change. Surprisingly, anticipated land-use changes designed to reduce greenhouse gas emissions as a means to mitigate climate change (such as solar, wind, and geothermal projects) are another factor contributing to vulnerability for some species due to associated habitat loss and fragmentation. Good dispersal ability, broad physical habitat requirements, migration to broad geographical areas or a tendency to shift distribution in response to environmental conditions, and demonstrated adaptation to a broad range of temperatures were the factors that most commonly decreased vulnerability. One noteworthy outcome is that the Index flagged a number of currently common species (i.e., NatureServe global conservation status rank G4 or G5) such as the American pika, bighorn sheep, and sagebrush vole as vulnerable to climate change. Thus, conservation status is not a reliable proxy for vulnerability to climate change.

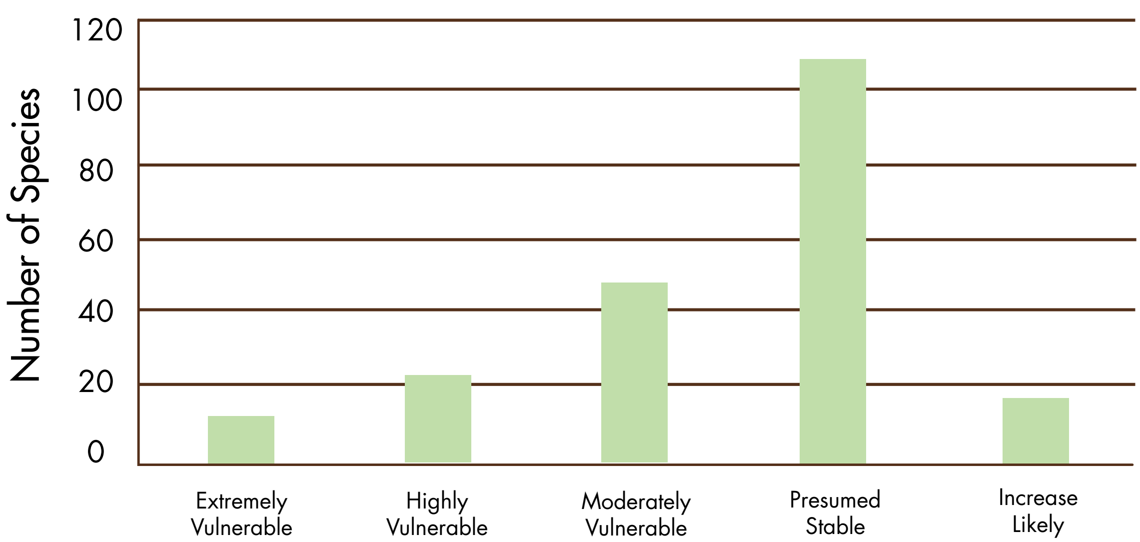

Figure C1.2. Vulnerability of Nevada Conservation Priority species as calculated by the Climate Change Vulnerability Index.

Uncertainties

This assessment addressed uncertainty in two ways. One source of uncertainty concerns the differing projections by climate models of mid-century temperature and precipitation regimes in Nevada. The Nevada Natural Heritage Program addressed this uncertainty by using an average of an ensemble of 16 global circulation models as the exposure data for the Climate Change Vulnerability Index. The results therefore are not tied to any single climate model.

A second source of uncertainty relates to how a particular species is scored against the Index sensitivity factors. Incomplete knowledge about a species' natural history and how it affects vulnerability for a particular factor can add uncertainty to the overall vulnerability score. The Index allows users to select more than one vulnerability value for each factor to reflect this uncertainty. The Index calculates an overall vulnerability score using an average of the values assigned for each factor, but also runs a Monte Carlo simulation to explore the probability that the overall score could change depending on what the "true" value might be for each factor scored with multiple values. The Index calculates a measure of confidence in species information (very high, high, moderate, or low) depending on the percentage of Monte Carlo runs that yield the same overall vulnerability score as calculated with the averaged data. For the Nevada species, the Monte Carlo simulations revealed that confidence in the Index score was very high or high for 61 percent, moderate for 27 percent, and low for 12 percent of the species (Young et al., in press).

Outcomes and Next Steps

As review of the assessments of the full set of Conservation Priority species is completed, The Nature Conservancy is assessing the vulnerability of key habitats to climate change. Subsequently, the partners will examine the Index results for each species, including the factors that most frequently led to species being categorized as vulnerable, the habitat model results, and the bird models produced by the Great Basin Bird Observatory to determine the management strategies necessary to create resilient wildlife populations and mitigate potential impacts to climate change. After receiving comments from the public, the partners will finalize the text of the climate change amendment to the Plan and submit it to the U.S. Fish and Wildlife Service for formal approval.

An amended Wildlife Action Plan will not accomplish its objective unless its recommendations are put into practice. The partners responsible for preparing the climate change amendment also make up the implementation team for the Plan. As part of their work on the team, they will work to incorporate the recommendations from the Plan into ongoing private, state, and federal management activities. These actions will take many forms depending on the purview of each agency. The Nevada Natural Heritage Program will use the results of the vulnerability assessment to target particularly vulnerable species for monitoring. Comprehensive information on the locations and biological conditions of vulnerable species will contribute to proactive management decisions that could result in decreased conflicts between wildlife and development in the future. For example, monitoring data for a species that has limited dispersal ability or is encountering barriers to dispersal could provide an early indication of when translocations of populations should be considered.

In conjunction with implementation activities, the partners are participating with the Heinz Center and the Wildlife Habitat Policy Research Program to use performance measures to monitor the effectiveness of management actions. For priority conservation goals, they have begun to develop logic models that pictorially describe pathways by which factors can affect a conservation goal. The models point to specific indicators that can be measured to monitor progress toward each conservation goal. This approach allows the partners to gauge their success and alter their strategies when needed, before wasting resources on ineffective actions.

Challenges and Lessons Learned

One challenge in developing the Index was deriving and calibrating criteria for diverse plants and animals. Research in the past decade has led to a substantial increase in understanding about the factors that correlate with climate change vulnerability, but analyses are typically available only for selected taxonomic groups. Assembling an interdisciplinary team to develop, test, and refine the Index proved necessary to address how the myriad natural history attributes of North American plants and animals confer increased or decreased vulnerability to climate change.

Nevada's approach of having a general biologist perform preliminary assessments and then inviting specialists to review the results in a workshop setting proved to be successful. The specialists provided a broader interpretation of the criteria, and their individual expertise with particular species went beyond information found in the published literature. The general biologist provided leadership for the process and ensured that the criteria were applied consistently across taxa. Also, an advantage to carrying out the assessments within the Nevada Natural Heritage Program was the easy access to spatial information about the locations of populations of Conservation Priority species for calculating exposure.

Case Study 2. U.S. Environmental Protection Agency's Threatened and Endangered Species Vulnerability Framework

Purpose

This case study provides an overview of a framework developed to assess the relative vulnerabilities of threatened and endangered animal species to climate change and existing stressors.

Lead authors: Hector Galbraith and Jeff Price.

Conservation Objective

Organisms listed as Threatened or Endangered (T&E) under the Endangered Species Act suffer a significant risk of extinction due to the adverse effects of current natural or anthropogenic stressors. Climate change, either acting alone or by exacerbating the effects of these existing stressors, may constitute an important new threat for many of these species (Peters 1992; Schneider and Root 2002). If future conservation priorities, strategies, tactics, and resource allocations are to reflect these changing circumstances, there is a need to develop new conservation tools. In particular, tools are needed that integrate the likely effects of both current and climate change stressors to identify the T&E species that may face the greatest increased risk of extinction or major population reductions, and the specific climatic, physiological, and/or ecological factors that contribute to these increased risks.

Assessment Targets

For this study, the T&E vulnerability framework was tested on six T&E species: bald eagle (now removed from the T&E list), golden-cheeked warbler, salt marsh harvest mouse, Mount Graham red squirrel, desert tortoise, and the Lahontan cutthroat trout. These species were selected because they are very different in their ecologies, demographics, status and distribution, population trends, and susceptibilities to different stressors and, because of these differences, provide an adequate test of the framework.

Steve Maslowski/USFWS

Scale and Scope

This framework can be applied at a range of spatial and temporal scales, depending on the habitat range of the focus species as well as the climate change scenarios used.

Assessment Approach

Framework Structure

The framework for evaluating risks to a T&E species due to climate change and other stressors comprises four connected modules and a narrative (Figure C2.1). Module 1 categorizes the comparative vulnerabilities of T&E species to existing stressors (i.e., not including climate change). This "baseline" vulnerability is subsequently combined with the categorization in Module 2 (evaluating vulnerability to climate change) into an estimate of overall future vulnerability in Module 3. Module 4 combines certainty scores from Modules 1 and 2 into an evaluation of the overall degree of certainty that we can assign to the framework predictions. The narrative that accompanies each species' evaluation details the rationales and justifications for the assigned scores in Modules 1 and 2.

The Narrative. Most categorizations in Modules 1 through 4 will be based largely on the results of literature reviews for each species being evaluated and on expert judgment. The narrative module of the framework reports the relevant results of those reviews and opinions, and it includes the justifications for the individual categorization scores in the modules. Thus, the primary aim of the narratives is to make the thought process and assumptions that result in the scores in Modules 1 through 4 transparent.

The narratives have three additional important aims:

1. To identify main sources of uncertainty and those areas where additional data might reduce uncertainty

2. To identify and describe the roles of the main stressors (climate and non-climate) in the estimate of vulnerability of the study species

3. To qualitatively describe potential population responses of the study species to the addition of climate change to the already existing stressors, and any resulting change in extinction risk

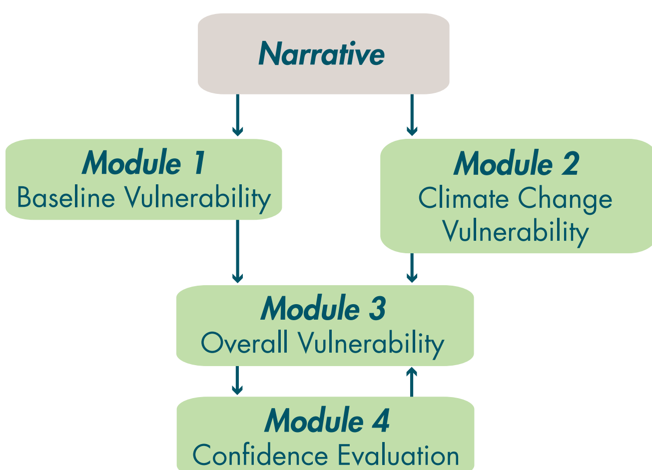

Figure C2.1. Framework for T&E Species Vulnerability Assessment.

Narratives for the species evaluated in this case study are available in the full (U.S. EPA 2009) publication.

Module 1—Evaluating Baseline Vulnerability. The probable baseline (i.e., current) vulnerability of the study species to extinction or major population reduction is categorized by scoring those elements of its ecology, demographics, and conservation status that influence the likelihood of its survival or extinction (irrespective of the potential effects of future climate change). There are 11 variables included in this module: (1) current population size, (2) population trend in the last 50 years, (3) current population trend, (4) range trend in last 50 years, (5) current range trend, (6) current (non-climate) stressors, (7) likely current stressor future trends, (8) individual replacement time, (9) future vulnerability to stochastic events, (10) future vulnerability to policy/management changes, and (11) future vulnerability to natural stressors. Each of these variables is assigned a numerical score (e.g., 1 for current population size of <100 vs. 6 for current population size of >50,000), reflecting their ordinal rankings. These individual scores are then combined in Module 1 into one of four baseline vulnerability rankings: critically vulnerable (Vb1) for those with a score of less than 18; highly vulnerable (Vb2) for a score of 18–25; less vulnerable (Vb3) for a score of 26–33; and least vulnerable (Vb4) for a score greater than 33.

Module 2—Evaluating Vulnerability to Climate Change. In this module, the likely vulnerability of a species to future climate change is assessed and categorized by scoring those elements of its physiology, life history, and ecology that will likely be important determinants of its responses. This is based on determining ordinal rankings for 10 Module 2 variables: (1) physiological vulnerability to temperature, (2) physiological vulnerability to precipitation change, (3) vulnerability to climate change–induced extreme weather events, (4) dispersive capability, (5) degree of habitat specialization, (6) likely extent of habitat loss due to climate change, (7) abilities of habitats to shift at same rate as species, (8) habitat availability within new range of species, (9) dependence on temporal interrelationships, and (10) dependence on other species. Again, each of these variables is assigned a numerical score (e.g., 1 for high sensitivity to a temperature increase vs. 4 for a species likely to benefit from temperature increase). The numerical scores for the 10 variables are then combined into an overall evaluation of the species' potential vulnerability to climate change: critically vulnerable (Vc1); highly vulnerable (Vc2); less vulnerable (Vc3); and least vulnerable (Vc4), likely to benefit from climate change.

Module 3—Evaluating Overall Vulnerability. In this module, the "best estimate" scores from Modules 1 and 2 are combined into a matrix to produce an overall best estimate evaluation and score of the species' vulnerability to climate change and important existing stressors (Table C2.1).

Module 4—Certainty Evaluation. The approximate level of certainty with which each "best estimate" score in Modules 1, 2, and 3 is categorized separately in the modules. These are codified as high (approximate probability of 70 percent or more), medium (approximate probability between 30 and 70 percent), or low (less than approximately 30 percent). These qualitative scores correspond to numeric scores of 3, 2, and 1, respectively. In Module 4, the best estimate certainty scores assigned to each of the variables in Modules 1 and 3 are combined into an index of the certainty associated with the overall vulnerability score in Module 3. The total minimum score (Modules 1 and 2 combined) is 20, while the maximum is 60. The numeric range between the two is arbitrarily and approximately equally divided into three categories: High, Medium, and Low certainties and a final certainty evaluation applied to each species.

Table C2.1. Module 3 - Overall Vulnerability Best Estimate Scoring Matrix

	Baseline (Module 1) Vulnerability Scores			
Climate change (Module 2) Vulnerability scores	Vb1	Vb2	Vb3	Vb4
Vc1	Vo1	Vo1	Vo2	Vo3
Vc2	Vo1	Vo1	Vo2	Vo3
Vc3	Vo1	Vo2	Vo3	Vo4
Vc4	Vo1	Vo2	Vo3	Vo4
Vc5	Vo2	Vo3	Vo4	Vo4

Important Framework Attributes

Process Transparency. The intended end result of the framework is to produce evaluations of the relative vulnerabilities of T&E species to climate change and other stressors. However, it is important that the process and reasoning through which the evaluation was arrived at be well documented and transparent. This will be essential in modifying species evaluations if new data are gathered that cast doubt on previous assessments. Ensuring process transparency and documenting important assumptions is as important a component of the framework as producing predictive scores.

Framework Precision and Accuracy. The results of a predictive framework will be speculative. Thus, in the absence of a posteriori knowledge, this framework provides approximations of species' ranked vulnerabilities. It is not intended that its results be considered completely accurate or precise estimations of a species' absolute vulnerability—the results should be regarded as indications of the comparative vulnerabilities of T&E species.

Treatment of Certainty/Uncertainty. See below.

Sources of Information and Expert Opinion. Some of the scores determined in this framework may be based on quantitative and empirical data (e.g., abundance estimates based on actual census data) published in peer-reviewed scientific or "gray" literature. However, for many less well-studied species, it is likely that many of the framework scores will be based not on actual empirical data, but will comprise rankings based on expert opinion.

Some species may benefit from climate change. Not all species may be adversely affected by climate change; it is possible some may benefit from new climatic regimes (for example, due to their habitats being expanded, or to their competitors or predators being adversely affected). It is essential that an effective framework reflect this reality.

Table C2.2. Summary of Species Evaluation Results

Species	Module 1 Baseline Scores	Module 2 Climate Change Scores	Module 3 Best Estimate Scores	Module 3 Alternate Scores	Module 4 Certainty Score
Golden-cheeked warbler	Vb2 (highly vulnerable	Vc1 (critically vulnerable)	Vo1 (critically vulnerable)	Vo2 (highly)	High
Bald eagle	Vb3 (less vulnerable)	Vc3 (less vulnerable)	Vo3 (less vulnerable)	Vo2, Vo4 (highly, least)	High
Salt marsh harvest mouse	Vb2 (highly vulnerable	Vc2 (highly vulnerable)	Vo1 (critically vulnerable)	Vo1, Vo2 (critically, highly)	Medium
Mount Graham red squirrel	Vb2 (highly vulnerable)	Vc2 (highly vulnerable)	Vo1 (critically vulnerable)	Vo1, Vo2 (critically, highly)	High
Desert tortoise	Vb3 (less vulnerable)	Vc2 (highly vulnerable	Vo2 (highly vulnerable)	Vo1, Vo3 (critically, less)	Medium
Lahontan cutthroat trout	Vb2 (highly vulnerable)	Vc2 (highly vulnerable)	Vo1 (critically vulnerable)	Vo1, Vo2 (critically, highly)	Medium

Assessment Results

The results of running the evaluative framework on the six test T&E species is shown in Table C2.2. The golden-cheeked warbler, salt marsh harvest mouse, Mount Graham red squirrel, and Lahontan cutthroat trout were categorized as "critically vulnerable." The desert tortoise was ranked "highly vulnerable," and the bald eagle (no longer listed as threatened or endangered, except for the Southwest population) was scored "less vulnerable." Species that are most vulnerable tend to be: restricted in their distributions, small in population size, undergoing population reductions, habitat specialists, and found in habitats that are likely to be most adversely affected by future climate change. Conversely, species like the bald eagle, which are widely distributed, are flexible in their habitat preferences and are considered to be stable or increasing, scored least vulnerable. Thus, the predictions of the model are consistent with what might be expected based on the ecologies and demographics of the test species.

Uncertainties

Uncertainty is inevitable when attempting to anticipate the effects of future stressors on organisms. Such uncertainty may have many sources, including the specifics or variability of likely future climates, the physiological sensitivity of the species, uncertainty about its demographics, population dynamics, or habitat ecology, or about the likely responses of habitats, or critical habitat components, to climate change. Any prediction regarding future vulnerability would be of limited practical value without an evaluation of the certainty/uncertainty associated with it. In this framework the degree of certainty is assessed in two ways. First, when scoring each module variable, "best estimate" and alternate (possible but less likely) scores are assigned by those applying the framework, based on the information gleaned in the literature. These are intended to capture the range of responses that may occur, rather than focusing on a single "point estimate" of responses. Second, each individual variable score is assigned a ranking certainty evaluation (i.e., high, medium, or low level of certainty). This three-point ranking is based on the five-category scale developed for the IPCC Third Assessment Report (Moss and Schneider 2000) (see Chapter V). These rankings are then combined into an assessment of the degree of certainty that should be associated with the final assessment of the species' overall vulnerability. For the species tested, the greatest uncertainties are associated with our relatively poor knowledge about the potential for direct, physiological effects on animal species; relationships between changes in temperature and precipitation regimes and the physiologies and behaviors of animals are apparently poorly understood.

Outcomes and Next Steps

This framework was developed for the U.S. Environmental Protection Agency's Office of Research and Development. The full report is currently awaiting publication and general release. For information on when this will occur or for a copy of the full report, readers should contact Susan Herrod-Julius at: Julius.susan@epa.gov.

Case Study 3. Species Vulnerability Assessment for the Middle Rio Grande, New Mexico

Summary

This case study describes a method for scoring terrestrial species that have potential to be vulnerable to climate change. The assessment tool seeks to synthesize complex information related to projected climate changes into a predictive tool for species conservation. The tool was designed to aid managers in prioritizing species management actions in response to climate change projections. We describe an application of the scoring tool to terrestrial species in a specific geographical region, the Middle Rio Grande of New Mexico, and provide a synopsis of the results of this regional assessment.

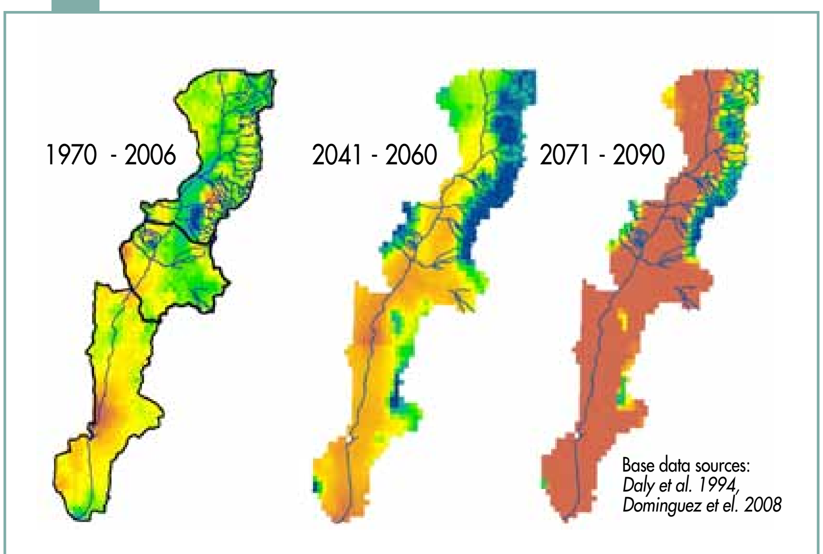

Figure C3.1. Current and future moisture stress in Upper and Middle Rio Grande. 1970—2006 = trend in moisture deficit. Preliminary future forecast: 2041–2060 = departure (difference) in deficit relative to 1951–2006 baseline; 2071–2090 = departure in deficit relative to 1951–2006 baseline (Bosque Working Group 2008).

Background

Land managers need adaptation and mitigation strategies to manage species within the context of ecosystem responses to a changing climate and varying responses of individual species. The U.S. Forest Service Rocky Mountain Research Station (RMRS) in Albuquerque is creating scientifically based decision-support tools for managers to anticipate climate-related changes and respond strategically to managing those effects. Vulnerability of species and populations to changes induced by global warming will be assessed using a scoring system being designed by RMRS. This system assigns scores from synthesized information related to the probability of climate-related population declines due to a number of factors, including: natural disturbances (e.g., flooding, wildfire); breeding requirements (e.g., link with seasonal food resources, breeding ponds); nonbreeding requirements (e.g., habitat changes, stopover sites); dispersal potential (e.g., connectivity of habitats, mobility); and exacerbating factors (e.g., rarity, proximity to human populations). Scores for an individual species are then combined to create an overall prediction of vulnerability to climate change.

Lead authors: Deborah M. Finch, Megan M. Friggens, and Karen E. Bagne.

The Bosque or riparian forest along the Middle Rio Grande has high value for wildlife but because of competing land and water uses is also vulnerable to degradation. Global climate predictions include higher temperatures in the Southwest, more variable rainfall, and more drought periods, which are conditions that will exacerbate the present issues (Christensen et al. 2007). Moisture stress along the Upper and Middle Rio Grande is projected to increase dramatically through this century (Figure C3.1). In addition, human populations in the region are expected to grow considerably, putting more pressure on natural systems competing for resources. Management actions can often be taken to mitigate impacts, but is most effective when scientifically based and anticipatory rather than reactionary. Land managers for the Middle Rio Grande Bosque would benefit from knowledge related to projected effects of climate change on species in their area. Depending on actions and magnitude of climate change effects, this strategy will help conserve biodiversity.

Purpose

This case study documents a new method for assessing the relative risk to persistence of individual species under projected changes in temperature, precipitation, and related climate phenomena (Bagne and Finch 2008). The RMRS assessment consists of a scoring system focused on simple predictive criteria for terrestrial vertebrate species and was specifically designed to be applied by managers. Relative vulnerability is assessed through the use of scores generated for individual species. The assessment is a flexible system that allows the user to incorporate data and information from a variety of sources. In addition, new information can be incorporated into the scoring process as climate modeling becomes more sophisticated and predictions more precise. Identification of the most vulnerable species, those with the highest scores, is one step toward implementing an effective management program.

In this case study, we summarize results from a final report (USDA Forest Service RMRS 2010) delivered April 2010 to our sponsors, U.S. Fish and Wildlife Service Region 2 (Bosque Improvement Initiative) and the U.S. Forest Service, Washington Office. The final report describes an application of the tool to species in a specific geographical region known as the Middle Rio Grande.

Conservation Objective

Global climate change has the potential to affect habitats and species worldwide within a relatively short period of time and, in fact, appears to already be altering ecosystems (reviewed by McCarty 2001; Peñuelas and Filella 2001; Root et al. 2003). In addition to current conservation challenges such as habitat loss, toxins, and exploitation that have long been part of species management programs, current climate change is relatively new and its impact is expected to grow. Already a number of species have been identified as at risk to changes in climate in New Mexico. With increasing droughts projected, populations of those species sensitive to drought conditions such as white-tailed ptarmigan, southwestern willow flycatcher, and Goat Peak pika are likely to decline (Enquist and Gori 2008). Particular habitat types, such as alpine tundra, are expected to decline along with the species dependent on them (Walther et al. 2005).

Assessment Targets

This assessment focused on the terrestrial vertebrate species occupying riparian habitats (known locally as "the Bosque," a Spanish word meaning "forest") along the Middle Rio Grande in New Mexico. This area is bounded by Elephant Butte Reservoir to the south and Cochiti Dam to the north. We created a future climate scenario for the Middle Rio Grande Bosque as well as upland areas surrounding the Bosque. Vertebrate species for the region were initially identified using the *Field Guide to the Plants and Animals of the Middle Rio Grande Bosque* (Cartron et al. 2008). Archival Middle Rio Grande data on birds, amphibians, reptiles, and bats (from D. M. Finch, RMRS) were also used to identify species for scoring. We removed species that were not resident within the Middle Rio Grande Bosque for at least part of the year, as well as those species that occur primarily in upland habitats. Rare species were included only if they were known to breed within the Bosque. Species that used the riparian corridor solely for migration, or otherwise had an intermittent or transient presence within the Bosque, were not included in the assessment list.

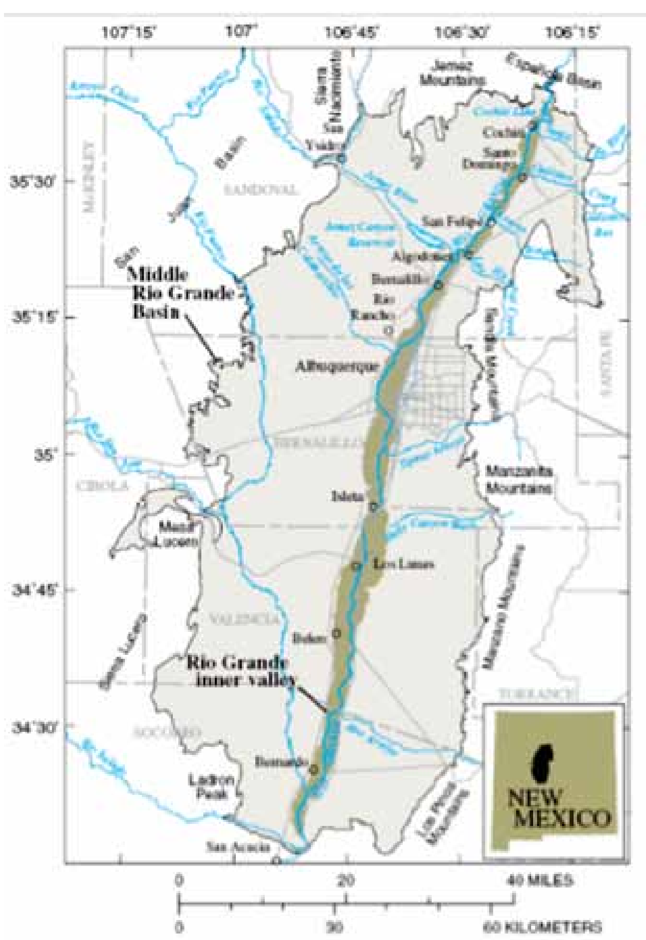

Figure C3.2. Major physiographic and hydrologic features of the Middle Rio Grande Basin.

Scale and Scope

Vulnerability of species and populations to changes induced by global warming was assessed using a scoring system similar to that developed for identifying avian populations at risk by Partners in Flight (Panjabi et al. 2005). A detailed account of the scoring for each species resulted. Scores are adjustable as new information arises. The basic process was as follows:

- Compile information on vertebrate species of the Middle Rio Grande Bosque
- Compile information on projected climate change effects for the Middle Rio Grande Basin
- In consultation with experts, create scores for individual species for each variable
- Create composite scores and prioritize species by vulnerability

The assessment for this case study evaluated the full array of terrestrial vertebrate species inhabiting riparian woodlands along the Middle Rio Grande in New Mexico. The geographical boundaries of the Middle Rio Grande are demarcated as the stretch of the river from Cochiti Dam (at its northernmost edge) downstream 160 miles to San Marcial and Elephant Butte Reservoir, and the Bosque portion of it extends south to San Acacia (Figure C3.2). The Middle Rio Grande Valley includes four New Mexico counties (Sandoval, Bernalillo, Valencia, and Socorro) and six Indian pueblos (Cochiti, Santo Domingo, San Felipe, Santa Ana, Sandia, and Isleta).

Assessment Approach

The system assigns scores from synthesized information related to probability of population declines as related to anticipated changes that directly or indirectly result from climate change. Possible scoring variables are: exposure to natural disturbance (e.g., flooding, wildfire); breeding requirements (e.g., link with seasonal food resources, temperature range, breeding ponds); nonbreeding requirements (e.g., habitat changes, stopover sites); dispersal potential (e.g., geographic barriers, mobility); and exacerbating factors (e.g., specialist species, physiological limitations, competition with invasive species). Scores in each category are assigned to individual species on an ordinal scale from lowest to highest risk. For example, when looking at natural disturbance a species may have a high score if it negatively responds to wildfires, which are predicted to increase. A species may have a low score if it responds positively to disturbances that are expected to increase or if its habitat is not threatened by these sources of disturbance.

The assessment comprises a series of questions that focus around variables or traits believed to reflect the potential impacts of climate change on the ability of individual species to survive and reproduce. Each question is accompanied by a series of potential responses that, in turn, are associated with a simple score of 1 (vulnerable), 0 (neutral or unknown), or −1 (resilience). Variables related to climate change effects on species were identified from four broad categories or factors: habitat, physiology, phenology, and biotic interactions.

In addition, we considered whether traits exhibited three primary functions of good scoring variables for assessment designs (Beissinger et al. 2000): (1) repeatability, (2) relation to quantitative values, and (3) independence from other scoring variables. Our adherence to these criteria, however, was limited because quantitative data currently available for species' response to climate change are rare and inherently imprecise for future projections. A separate score for uncertainly that reflects the quantity and quality of data used to score a species is also included.

Two types of scores are provided for different purposes: categorical scores and overall scores. Overall scores can be used to rank species and identify the most vulnerable or resilient species. Alternatively, overall scores can also be used to categorize species into broad vulnerability levels. Because not all species attributes translate to equal risk from climate change, composite scores allow for prioritization of species vulnerabilities for complex information. Categorical scores can be used to identify specific areas or traits related to vulnerability.

Scores for individual criteria can identify vulnerable and resilient characteristics that could aid in single-species management decisions. Identified areas of vulnerability or resilience and their relative influence can be used to target the most effective management actions (i.e., creation of corridors, land acquisition, captive breeding). In addition, scores can be adjusted and categories added as effects of climate change manifest or threats are identified by new research. Prioritization of species for management will have to additionally consider issues such as current vulnerability, economic feasibility, and regulations. Managers can also incorporate their own knowledge and local issues into considering species prioritization.

Middle Rio Grande Bosque Climate and Habitat Projections

We gathered information on projections for climate and related phenomena as well as disturbances and vegetation types to use for our assessment of the Middle Rio Grande species. To maintain relevance to management planning, we used projections for a period 20 to 50 years in the future. We used ClimateWizard to estimate changes in precipitation and temperatures for the region. We used vegetation projections created by Rehnfeldt et al. (2006) to estimate changes in area and distribution of major vegetation types (Brown et al. 1998). We also outlined specific predictions regarding changes to the riparian and upland habitat of the region using additional information from primary literature sources. Finally, we considered the effect of extreme weather conditions and disturbances, which although more difficult to accurately project, may be more critical to wildlife populations than average changes.

Results

The southwestern United States is expected to experience relatively large temperature increases and specific predictions for the region include an increase in the severity and duration of drought periods, more heat waves, greater variation in precipitation, increased wildfires and insect outbreaks, and increased evapotranspiration and salinization (Easterling 2000; Field et al. 2007; Garfin and Lenart 2007). Perhaps of greatest consequence will be the impact of these changes on southwestern water resources. Specifically, the Southwest is expected to experience a change in seasonal flood regimes, reduced snowpack, and an overall reduction in river and stream flows (Seager et al. 2007).

We predict there will be less open water, shorter duration for ephemeral ponds, and a decline in wetland habitats in the Middle Rio Grande Bosque. These changes will lead to a general loss of riparian vegetation and a narrowing of the riparian corridor. In addition, invasive tamarisk species are likely to increase to the detriment of native cottonwood species. Specific vegetation projections for 2030 showed decreases in Great Basin conifer woodlands (from 10 percent to 1 percent), semi-desert grasslands (38 percent to 25 percent), and a complete loss of Plains grasslands (estimated to comprise 52 percent of the current habitat). Chihuahuan desert scrub was predicted to increase from 0 percent to 74 percent.

Amphibians. Of the nine species of amphibians assessed, five species are found to be vulnerable to climate change. The most vulnerable species was the western chorus frog; three species had

Rick Lewis

neutral scores; and only one, the American bullfrog, appears to be somewhat resilient to climate change effects. Species with water-dependant larval or adult life stages were most vulnerable to future climate projections. The three species of spadefoot toads and the Great Plains toad tended toward lower scores because we predicted that the scrub and grassland habitats used by these species would increase in the Middle Rio Grande region.

Reptiles. Nineteen of 29 reptiles are vulnerable to climate change in the Middle Rio Grande Valley. Five species had high vulnerability scores. The Great Plains skink was the most vulnerable species, while the common kingsnake was the least vulnerable. In general, species that have a specific reliance on riparian habitat show some level of vulnerability to the future expected changes.

Birds. Of the 40 species of birds assessed, 25 species (51 percent) had scores reflecting an overall vulnerability to climate change. The southwestern willow flycatcher was ranked as the most vulnerable and the bank swallow was the least vulnerable. Fourteen species had neutral scores and five species may benefit from future warming trends. The southwestern willow flycatcher (federally listed as endangered), the western yellow-billed cuckoo (a candidate for federal listing), and the common yellowthroat depend on riparian habitat and were among the most vulnerable to potential population declines under future climate projections. The primary habitat of these species is expected to decline, they are sensitive to heat, and they rely on climate-driven cues and/or resource pulses, which are likely to change under future scenarios. The three most resilient species, spotted towhee, house finch, and brown-headed cowbird, are habitat generalists with a good capacity to respond to resource variation.

Most of the bird species we assessed that forage aerially on insects obtained positive overall scores, reflecting vulnerability (cliff swallow, barn swallow, ash-throated flycatcher, northern rough-winged swallow, and bank swallow). An exception to this trend was the eastern bluebird. The three species of woodpeckers had positive scores. Of the four species of raptors, three had

Bruce Stein

positive overall scores; western screech owl was the most vulnerable, followed by Cooper's hawk and great horned owl. By contrast, the score for American kestrel was negative.

Mammals. Thirty-six mammals were assessed for their potential vulnerability to climate change in the study region. The New Mexico meadow jumping mouse appears most vulnerable, while the desert shrew was the least vulnerable to future expected changes. Sixteen percent of the mammal species were vulnerable to climate change effects, 44 percent appear to be only slightly impacted, and 5 percent may benefit from future projected changes. In general, species that appear most at risk given future climate change predictions are animals with a high reliance on riparian areas (the New Mexico meadow jumping mouse and beaver), require dense vegetation or specific vegetation features (the woodrat), or are at risk of mismatch between critical resources and breeding (the hoary bat and black bear). Species not expected to be overly influenced by future climate changes tended to be opportunistic breeders (jackrabbit, desert shrew), with a wide diversity of habitat associations including habitats that are expected to increase in the future.

Uncertainties

All species assessments are prone to errors relating to uncertainties regarding species biology. We found considerable variation in the data available for each species under review. To account for this, we include an uncertainty score. For each of the categories, Habitat, Physiology, Phenology, and Biotic Interaction, we score a species based on the quality and quantity of data that was available for completing the assessment question. These scores are then added at the end of the assessment for an overall uncertainty score. This score is useful not only for estimating the potential for errors in our assumptions regarding species vulnerability but clearly identifies areas that are in need of further monitoring or research efforts.

Assessments of species vulnerability to climate change also have sources of uncertainty specific to the aim of predictions based on future climate scenarios. First, uncertainties exist regarding climate projections produced by climate models. To reduce the impact of individual error attributed to variations in a single model, we used temperature ranges and precipitation estimates that were produced in ensemble models, which average values from several individual models. Vegetation projections and other sources of data regarding future climate conditions are also prone to errors related to methodological procedures. We used most of these tools to gain a perspective on the trends of change rather than define definitive future scenarios. For vegetation projections, we relied less on subtle changes (slight loss or shift in certain habitat types), than on projections of severe change (total loss of habitat). We also considered predicted loss of vegetation type to be a robust result, whereas estimates of habitat shifts or invasion are more tenuous given the greater unpredictability of potential plant invasion and establishment and the time lag under which these transitions will occur.

Finally, there is uncertainty regarding the realized response of species to climate change. We have attempted to consider a comprehensive suite of traits that allow us to gauge species capacity to tolerate greater variation in resources, higher temperatures, and habitat changes. We have also attempted to account for species interactions within the framework of our tool. Though these efforts have improved the applicability of our tool, it is likely that there remain unpredictable consequences of climate change for species.

Outcomes and Next Steps

We will take these results and identify management (adaptation) strategies and actions for terrestrial species in the Middle Rio Grande Basin. We have also expanded the application of the vulnerability assessment scoring tool to other locations in the American Southwest, including scoring of endangered species on the Coronado National Forest, southeastern Arizona, and on the military bases Fort Huachuca and Barry Goldwater Range. Manuscripts that describe the scoring tool in detail and a Rocky Mountain Research Station General Technical Report that provides the full results of the Middle Rio Grande vulnerability assessment are in review. We are also beginning the process of developing a Web-based version of the tool that will be added to an appropriate Website such as the U.S. Forest Service Climate Change Resource Center Website (http://www.fs.fed.us/ccrc/).

Case Study 4. Vulnerability of Massachusetts Fish and Wildlife Habitats to Climate Change

Purpose and Conservation Objective

This case study describes the use of expert elicitation to assess the vulnerability of habitats at a state-wide scale. Funded by a grant from the Wildlife Conservation Society, Manomet Center for Conservation Sciences began working in early 2008 with the Massachusetts Division of Fisheries and Wildlife and other partners, including The Nature Conservancy, to make the state's existing Wildlife Action Plan "climate-smart." We are presenting the results of

J&K Hollingsworth/USFWS

Lead authors: Hector Galbraith and John O'Leary.

Table C4.1. Habitat Types Evaluated
Forested habitats
Spruce-fir forest
Northern hardwood forest
Southern/central hardwood forest
Pitch pine-scrub oak forest
Freshwater aquatic habitats
Cold water Rivers and Streams
Large cold water lakes
Smaller cold water lakes and ponds
Warm water ponds, lakes and rivers
Cold water kettle ponds
Connecticut and Merrimack mainstems
Freshwater wetland habitats
Emergent marsh
Shrub swamp
Spruce-fir boreal swamp
Atlantic white cedar swamp
Riparian forest
Hardwood swamp
Vernal pools
Coastal habitats
Intertidal mud/sandflats
Saltmarsh
Brackish marsh

this project in a series of reports. This first report provides background on the project by describing how biodiversity conservation is currently carried out by the Massachusetts Division of Fisheries and Wildlife, the history, objectives, and methods of the Wildlife Action Plan, and how the climate in Massachusetts has been changing and how it is expected to change over the remainder of this century. In subsequent reports, we address habitat and species vulnerabilities, likely ecological shifts under climate change, and potential management/conservation options.

It is important to note that, when we began this study, our assumption was that climate change was a new and separate issue apart from all of the current stressors that affect the resources we are responsible for and that we had already identified in the Wildlife Action Plan. Once we realized that climate change impacts were not a separate issue but would interact with existing stressors and could be thought of as an exacerbating factor to current stressors, it made it easier to understand how the assessment process could be used to look at the combined impacts from current stressors under climate change conditions. Also, one of the most important lessons learned from this study is that staff buy-in is critical for the assessment as well as the implementation phase.

Scale and Scope

This assessment focused on state-specific species and habitats under the scenarios of a doubling and tripling of CO_2 concentrations in the atmosphere. In terms of time and cost, the project took about 12 months to complete and cost approximately $70,000, including travel and in-kind costs.

Assessment Targets

Twenty Massachusetts habitats were selected for evaluation (Table C4.1). These cover most of the habitats listed in the Wildlife Action Plan, although they differ from the Action Plan habitats in two respects. First, some habitats listed in the Plan are unlikely to be vulnerable to climate change (caves and mines, rocky ridgelines and talus slopes, rocky coastlines) and were not considered in our analyses. Second, some important habitat types are subsumed within the overall habitat categories listed in the Action Plan. For example, there are many types of upland forest in Massachusetts, each of which may differ in their responses to climate change. For this reason we divided the Action Plan upland forest category into several distinctly different habitat types (e.g., spruce–fir forest, northern hardwoods, central hardwoods, etc.) and evaluated each separately (for example, see the evaluation for northern hardwoods forest at the end of this case study). These habitat subdivisions were based on information contained in Swain and Kearsley (2000).

Assessment Approach

The primary questions addressed in this phase of our adaptation work are:

- How do the Wildlife Action Plan fish and wildlife habitats rank in terms of their likely comparative vulnerabilities to climate change?

- How will the representation of these habitats in Massachusetts be altered by a changing climate?

- What degree of confidence can be assigned to the above predictions?

- Which vertebrate Species in Greatest Need of Conservation are likely to be most vulnerable to climate change?

To answer these questions we formed an expert panel of Massachusetts Division of Fisheries and Wildlife, Nature Conservancy, and Manomet Center ecologists and wildlife biologists. The panel included much of the professional expertise in Massachusetts on the status, distribution, conservation, and threats to fish, wildlife, and their habitats.

The main purpose of this expert panel was to provide answers to the vulnerability questions raised above.

The entire expert panel met twice at the beginning of the evaluative process and were provided with the following materials:

- A PowerPoint presentation on how the climate is projected to change in Massachusetts over the present century. This presentation was based on the most recent and detailed climate modeling studies that had been performed in the Northeast, particularly those of Hayhoe et al. (2006), and was intended to be a “primer” for non–climate change scientists on the details of likely future climate change (e.g., temperature, type, amount and timing of precipitation, extreme events, etc.).

- A list of the important habitat variables that should be considered when evaluating climate change impacts, based on existing literature on the intrinsic and extrinsic factors that determine the likely vulnerabilities of species and habitats (e.g., Parmesan and Galbraith 2004; Parmesan and Yohe 2003; Root et al. 2003; Schneider and Root 2002).

- An appraisal of how, in general, climate change is likely to affect habitats and biomes. This was based on previous work on the relationships between habitat distribution and extent and climate change and how habitats around the world are currently responding to climate change (e.g., Parmesan and Galbraith 2004; Parmesan and Yohe 2003; Root et al. 2003; Schneider and Root 2002; IPCC 2007c).

Paul F. Wagner

- A habitat vulnerability scoring system developed in collaboration with Division of Fisheries and Wildlife staff. This provides a framework for evaluating the comparative vulnerabilities of Massachusetts habitats. It is based on prior work evaluating the vulnerabilities of species to climate change and extends across the spectrum of expected responses, from habitats that may be at risk of being entirely eliminated from the state (scoring 7), to habitats likely to be relatively unaffected by climate change (scoring 4), to habitats that may extend their distributions greatly within the state in response to climate change (scoring 1).

- A three-point scoring system for assessing the levels of confidence that can be ascribed to vulnerability scores. This confidence scoring system was modified from one developed for the IPCC process (Moss and Schneider 2000).

After the meetings of the entire expert panel, three habitat subgroups were formed (freshwater aquatic habitats, forested habitats, freshwater wetlands). For each habitat type, a preliminary or straw-man vulnerability analysis was prepared in advance of the subgroup meetings and deliberations. This background information was not intended as a definitive analysis but only to generate and guide thought and discussion among the expert-panel members.

Based on above materials and their expert judgment, participants in each of the subgroups were asked in face-to-face discussions to evaluate the comparative vulnerabilities of the habitats for which they have expertise under the two emissions scenarios, asked to score them on the vulnerability scale, identify likely future ecological trajectories, assign confidence scores, and identify other non-climate stressors that could interact with and exacerbate the effects of climate change. Immediately after this subgroup meeting, the straw-men analyses were revised to reflect the subgroup discussions. These modified analyses were then circulated to the subgroups for further comment and finalization. At the conclusion of the subgroup process, the finalized habitat analyses were compiled into a unified report and circulated round the entire expert panel so that all could have an opportunity for comment, irrespective of habitat type. These comments were incorporated into this finalized analysis.

Assessment Results

This section summarizes the assessments described above by presenting the vulnerability scores, the levels of confidence associated with them, likely ecosystem trajectories under climate change, and potential adaptation options.

The vulnerability scores and confidence evaluations for the 20 habitat types are presented in Figure C4.1 and Table C4.2. For nine of the 20 habitat types the vulnerability scores for a tripling of CO_2 exceed that for the doubling, although by relatively small increments. This reflects the more extreme climate changes expected under the former. However, for 10 of the habitats the two emissions scenarios resulted in identical vulnerability scores and for one (shrub swamp) the tripling scenario resulted in a lower vulnerability score. These data indicate that a doubling of CO_2 is sufficient to trigger major effects on the habitats and that extending the exposure to a tripling has relatively small additional impacts.

Drawing from the habitat impacts, assessment participants were able to identify some of the associated Species in Greatest Need of Conservation (SGNC) that are likely to be most at risk under the various scenarios for CO_2 concentration (Tables C4.3 and C4.4).

Uncertainties

This assessment relied on expert elicitation to quantify levels of uncertainty. The confidence scores for the habitats in Table C4.2 range from High (n = 15), to Medium (n = 18), to Low (n = 6). Having developed and used these scores we are confident that: (1) a score of High indicates that the habitat is more likely than not to conform to the allocated vulnerability score. Thus, spruce–fir forest scores High vulnerability

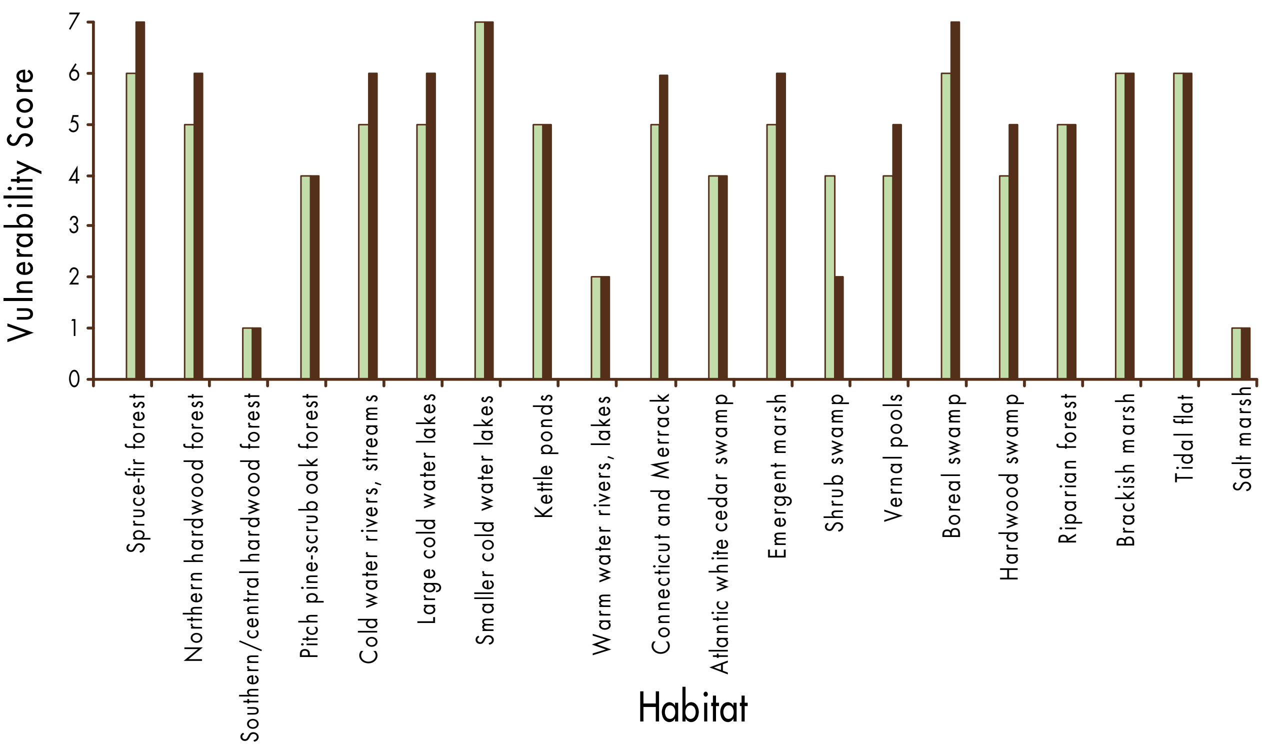

Figure C4.1. Habitat vulnerability to climate change. The lefthand bar in each pair represents a doubling of CO_2, while the righthand bar is a tripling.

Table C4.2. Vulnerability and Confidence Scores (in parentheses)		
Habitat	**Lower Emissions Scenario**	**Higher Emissions Scenario**
Forested Habitats		
Spruce-fir forest	6 (High)	7 (High)
Northern hardwood forest	5 (Medium)	6 (Medium)
Central/southern hardwood forest	1 (Medium)	1 (Medium)
Pitch pine-scrub oak forest	4 (Medium)	4 (Medium)
Freshwater aquatic habitats		
Cold water Rivers and Streams	5 (High)	6 (High)
Large cold water lakes	5 (Medium)	6 (Medium)
Smaller cold water lakes and ponds	7 (High)	7 (High)
Cold water kettle ponds	5 (Low)	5 (Low)
Warm water ponds, lakes and rivers	2 (Medium)	2 (Medium)
Connecticut and Merrimack main-stems	5 (Medium)	6 (Medium)
Wetland Habitats		
Emergent marsh	5 (High)	6 (High)
Shrub swamp	4/5 (Medium)	2 (Medium)
Spruce-fir boreal swamp	6 (High)	7 (High)
Atlantic white cedar swamp	4 (Medium)	5 (Medium)
Riparian forest	5 (Low)	5 (Low)
Hardwood swamp	4 (Medium)	5 (Medium)
Vernal pools	4 (Low)	5 (Low)
Coastal Habitats		
Intertidal mud/sandflats	6 (High)	6 (High)
Saltmarsh	1 (High)	1 (High)
Brackish marsh	6 (High)	6 (High)

(6 or 7) and High confidence. To us, this indicates that it is very unlikely that the "actual" vulnerability score for this habitat would deviate from 6 or 7; and (2) a habitat that has a confidence score of Medium is less certain. However, we consider it unlikely that the "actual" vulnerability of such a habitat would deviate much from the allocated score. For example, we consider it possible that a habitat that scores 4 on the vulnerability score and had a Medium uncertainty score could in fact have an actual vulnerability score of 3 or 5, but not 2 or 6. We are much less certain about habitats that have Low confidence scores and these should be read as implying considerable uncertainty in our scorings.

Outcomes and Next Steps

This assessment shows that different ecological systems are more or less vulnerable to climate change and, consequently, that we can expect to see major changes in their distributions across the Massachusetts landscape. What forms will these changes take? Until relatively recently our dominant model of change was for habitats or biomes to slowly replace each other as their optimum climatic conditions shifted. Thus, we might expect to see the highly vulnerable spruce–fir forests at upper elevations being replaced by northern hardwood forest as it moved upslope to track its optimum climatic conditions. This model of entire communities shifting has been an important step in our evaluations of what may occur to habitats under climate change (e.g., VEMAP 1995). However, it is simplistic and may not represent what may actually occur.

Different organisms have different intrinsic rates of response to climate change. For example, a northeastern warbler such as the American redstart can potentially shift its breeding range northward by several hundred kilometers in only a few days. However, the majority of the plants that make up the breeding habitat of this species are far less able to respond as rapidly—a similar shift could take decades or centuries. Rather than entire ecosystems or communities shifting their distributions across the landscape, we are much more likely to see them dissociating and separating, depending on their intrinsic response rates, and reconfiguring, into potentially novel combinations, upslope or further north. This dissociation and

Table C4.3. Habitats and associated vertebrate SGNC most at risk from a doubling of atmospheric CO_2 concentration.

Spruce-fir Forest	Spruce-fir Boreal Swamp	Smaller Cold Water Ponds	Brackish Marsh	Intertidal Mud and Sand Flat
Sharp-shinned hawk	Blue-spotted salamander	Northern leopard frog	Diamondback terrapin	Peregrine falcon
Blackpoll warbler	Sharp-shinned hawk	American eel	American bittern	Piping plover
White-throated sparrow	American woodcock	White sucker	Least bittern	Ruddy turnstone
Moose	Moose	Green heron	Northern harrier	Sanderling
Bobcat		Water shrew	King rail	Red knot
			Common tern	Snowy egret
			Short-eared owl	American oystercatcher
			American black duck	Short-billed dowitcher
			Snowy egret	Whimbrel
			Black-crowned night-heron	
			Sora	
			Saltmarsh sharp-tailed sparrow	
			Seaside sparrow	
			Eastern meadowlark	

Table C4.4. Habitats and additional vertebrate SGNC most at risk from a tripling of atmospheric CO_2 concentration.

Northern Hardwood Forest	Coldwater Rivers and Stream	Large Coldwater Lakes	Mainstem Rivers	Emergent Marsh
Jefferson salamander	Spring salamander	White sucker	American shad	Northern leopard frog
Blue-spotted salamander	Longnose sucker	Common loon	Shortnose sturgeon	Spotted turtle
Bog turtle	Slimy sculpin	Bald eagle	Atlantic sturgeon	Bog turtle
Ruffed grouse	Blacknose dace		Alewife	Blanding's turtle
Broad-winged hawk	Brook trout		American shad	Pied-billed grebe
Canada warbler	Burbot		American eel	American bittern
Rock shrew	Atlantic salmon		Atlantic salmon	Least bittern
Indiana Myotis	Louisiana waterthrush		Fallfish	King rail
Eastern small-footed bat			Green heron	Sora
Southern bog lemming			Bald eagle	Black-crowned night-heron
				Green heron
				Snowy egret
				Common moorhen
				Sedge wren
				Willow flycatcher
				Moose

reconfiguring is the current dominant model of how ecological communities may be affected by climate change.

How will this be expressed in Massachusetts fish and wildlife habitats? It is unlikely that over the next century we will see the northern hardwood forest community, with all its associated plant and animal species, simply move uphill to occupy a vacuum left by a retreating spruce–fir forest and all its associated plant and animal species. What is perhaps more likely is that in the shorter term (the next few decades) we will begin to see the elimination of the most climatically vulnerable components of the spruce–fir forest, while the forest may retain much of its overall structure and composition. At the same time that this is happening, the spruce–fir forest may be increasingly colonized by lower-elevation species that are able to tolerate cooler temperatures and move upslope quickly. Thus, the northern hardwood forest will permeate the spruce–fir. This permeation zone will spread uphill as the climate continues to warm and as lower-elevation plants spread uphill and cold-adapted species die out.

The process of uphill permeation by northern hardwood forest species and uphill retreat by spruce–fir forest species will result in the shorter term (the next 50 to 100 years) in a spectrum of forest types replacing the original spruce–fir. In lowest elevation areas where the spruce–fir forest originally occurred, it will likely be replaced by a community resembling higher-elevation northern hardwoods. At somewhat higher elevations, the new forest type will likely comprise a mixture of the two community types. At the highest elevation types of spruce and fir trees may persist, but it is likely that the understory will now comprise many lower-elevation species. Given enough time (perhaps by the end of this century) the spruce–fir forest may be gone. This does not necessarily mean that it has been entirely replaced by the northern hardwood community: some species that are today characteristic of spruce–fir forests may persist, while others that are characteristic of northern hardwoods may not be able to move far enough uphill. Thus, while we do anticipate community movement, it is less deterministic than some of our early models might predict and resembles a long-term community reshuffle, rather than complete replacement.

The description above implies a long, slow process of reshuffling of species. However, it is possible that the transitions could happen much more quickly if stochastic events intrude. For example, the warming temperatures could greatly benefit some of the invertebrate pests that afflict northeastern forests. This is already happening with mountain pine beetle in the West (Carroll et al. 2003) and the northward spread of hemlock wooly adelgid in the East (NECIA 2006). More frequent or increased-intensity attacks by such pests could result in a greater incidence of tree die-off, much more standing dead timber, and larger and more intense fires. If severe enough, these circumstances could "flip" the affected system, causing a much more rapid transition to the new habitat type.

The considerations described above apply to all climate-induced transitions that we may see in Massachusetts habitats over the next century. What this means for conservationists, planners, or land managers is that while we can identify the major elements of large-scale change, we must be wary of relying entirely on deterministic models (e.g., northern hardwood forest and all its associated species will oust spruce–fir forests from higher elevations), think more probabilistically, and be prepared for unforeseen surprises.

Example:
Northern Hardwoods Forest Vulnerability Evaluation
NTWHCS category: Appalachian northern hardwood forest
State ranking: S5
Vulnerability score: 5 and 6 (lower- and higher-emissions scenarios, respectively)
Confidence evaluation: High
Rationale

With the distributional range of this habitat extending from Quebec in the north, to high-elevation areas of Virginia and West Virginia, Massachusetts is close to the center of this community type's geographical distribution. In Massachusetts, where it is the predominant hardwood forest, it is generally restricted to an altitudinal range of about 1,000 to 3,000 feet, being more adapted to colder temperatures and shorter growing seasons than southern/central hardwood forest (but less so than spruce–fir forest). Mature northern hardwood forest tends to be dominated by sugar maple, yellow birch, and American beech, mixed with white pine, and eastern hemlock at lower elevations, with red spruce and balsam fir becoming important at the highest elevations where it grades into spruce–fir forest (Swain and Kearsley 2000). Black cherry, white ash, red maple, white birch, and gray birch often dominate early-successional northern hardwood forest following disturbance.

Within the broad matrix of northern hardwood forest a number of variants occur, depending on local conditions. These include rich mesic forests (dominated by sugar maple, basswood, and a unique assemblage of herbaceous plants), hemlock groves (on cool north-facing slopes or in ravines), and transition forests (which include oaks, hickories, and other species more typical of southern/central hardwood forest). Northern hardwood forest is not a fire-adapted community and human fire suppression over the past three centuries may have extended the range of this habitat in New England at the expense of oak forest, which is fire tolerant (J. Scanlon, pers. comm.). This forest type is vulnerable to attack by insects, including gypsy moth and hemlock wooly adelgid, and beech scale disease. Disturbance from blowdown, logging, or fire can lead to the (at least temporary) dominance of white pine over other species. In areas closer to human habitation or powerline cuts, nonnative plant species, including Japanese barberry, Japanese knotweed, etc., can form dense growths.

Being mainly a higher-elevation and northern community, it may be expected that this habitat will contract its range in Massachusetts as the climate warms. This contraction may be latitudinal and elevational. At the highest elevations it is likely to replace spruce–fir forest. At lower elevations it is likely that at least some of the species considered characteristic of northern hardwoods and that are most temperature sensitive (e.g., sugar maple, hemlock) will be replaced by elements of the southern/central hardwood forest (e.g., white oak, hickories, etc.). Thus, what is currently northern hardwood forest over much of low- and middle-elevation Massachusetts could transition to a southern/central hardwood community. Based on an elevation lapse rate of 1.8 degrees Fahrenheit for every 330 feet (http://www.spc.noaa.gov/exper/soundings/help/lapse.html), even the low-emissions scenario could contract the lower edge of this community upward by at least 1,000 feet. If this were the case, then its range would be restricted to higher elevations (>2,000 feet) in the Berkshires. Under the high-emissions scenario this upward movement potential could be close to 2,000 feet. This would mean that this habitat type might occur only at the highest elevations, where it has replaced spruce–fir. Based on this, a vulnerability score of 5 has been assigned under the low-emissions scenario and a score of 6 under the high-emissions scenario, with a confidence evaluation of Medium.

The confidence score is only Medium because uncertainties exist regarding how this community type might be affected by climate-related and non-related factors. Northern hardwood forest is vulnerable to fire. In contrast, southern/central hardwood forests are more fire tolerant. If a consequence of increasing temperatures, droughts, and soil drying is more frequent or hotter fires, this could accelerate the transformation of areas currently dominated by the former habitat type to areas dominated by the latter.

Other stressors that could be exacerbated by change and inflict adverse impacts on northern hardwoods include insect pests (wooly adelgids are already eliminating large tracts of hemlocks in Massachusetts, and emerald ash borer and Asian longhorned beetle are spreading rapidly north toward and into the state).

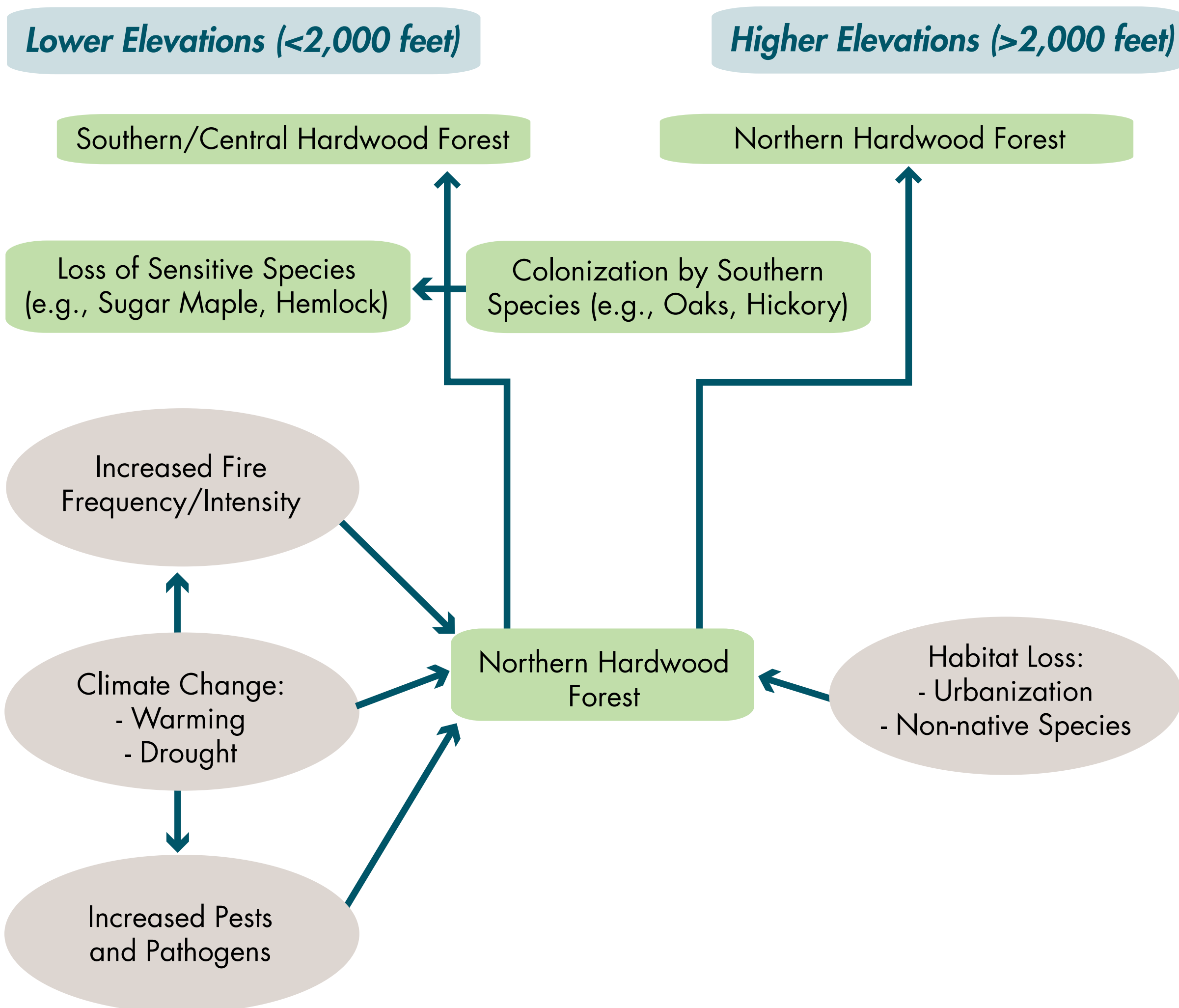

Figure C4.2. Conceptual model of how climate change and other stressors might affect Northern Hardwood Forest in Massachusetts.

If, as seems likely, warming temperatures facilitate overwinter survival of these pests and allow them to spread further north or upwards in elevation in Massachusetts, the northern hardwood forest could be adversely affected. Under the higher-emissions scenario, an increased frequency and severity of fire, and greater intensities and frequencies of insect/pathogen attack, could potentially eliminate this habitat type from the state. Moreover, this community type is currently under stress from human rural development and from colonization by nonnative plant species, as the state's population and peoples' housing expectations continue to grow. These factors could be major influences on the future status of this habitat. A conceptual model of how climate and non-climate stressors might affect northern hardwoods in Massachusetts is shown in Figure C4.2. Thus, while we conservatively score the vulnerability of this habitat type as 5 and 6 under the lower- and higher-emissions scenarios, it is possible that this might underestimate its vulnerability.

Case Study 5. Vulnerability to Sea-Level Rise in the Chesapeake Bay

This case provides an example of climate change vulnerability assessments for both habitats and species in the Chesapeake Bay region. Specifically, it highlights two studies, one building off the other, to identify how sea-level rise is likely to affect coastal wetland habitats and associated marsh bird species in the region.

National Wildlife Federation Coastal Habitat Study

In 2007, the National Wildlife Federation, working with Warren Pinnacle Consulting, Inc., initiated a study to identify the potential impacts of sea-level rise on coastal wetland habitats in the Chesapeake Bay region, including Delaware Bay and the ocean beaches of southern New Jersey, Delaware, Maryland, and Virginia.

Purpose

Local, state, and federal agencies, non-governmental organizations, and other stakeholders have already begun to develop climate change adaptation strategies for the region to help fish, wildlife, and people cope with the expected changes to their habitats and communities, including sea-level rise, as well as build in the flexibility to deal with unforeseen impacts. The purpose of this assessment is to provide decision-makers involved in this process with information about the vulnerability of the Chesapeake Bay region's coastal habitats to sea-level rise.

Conservation Objective

This assessment is intended to enhance and support efforts to address the impacts of climate change as part of the ongoing regional strategy to restore and protect the ecological integrity of the Chesapeake Bay and surrounding coastal areas.

Assessment Targets

The study focused specifically on coastal wetland habitats based on categories established for the U.S. Fish and Wildlife Service's National Wetlands Inventory. Habitat types include: swamp, tidal swamp, inland fresh marsh, tidal fresh marsh, transitional marsh, irregularly flooded (brackish) marsh, saltmarsh, estuarine beach, tidal flat, and ocean beach.

Scale and Scope

This was a regionally focused study, covering coastal habitats from Delaware Bay to the north, the Chesapeake Bay, and the ocean beaches from southeastern New Jersey down to the Virginia–North Carolina border. In terms of temporal scale, the study looked at a range of sea-level rise scenarios from the 2001 IPCC assessment, ranging from 0.31 meters to 0.69 meters in eustatic sea-level rise by 2100 (building over 25-year time steps from year 2000 levels). The study also modeled a rise of up to 2 meters by 2100 to accommodate for recent studies that suggest a

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significantly greater sea-level rise is possible during this century (Vermeer and Rahmstorf 2009; Overpeck and Weiss 2010; Rahmstorf et al. 2007). This study cost approximately $40,000 and took just under 1 year to complete.

Assessment Approach

The assessment was conducted by applying Version 5.0 of the SLAMM model, which was designed to simulate the dominant processes involved in wetland conversions and shoreline modifications among a multitude of different habitat types under various scenarios of sea-level rise. There are a number of modeling tools available to assess the impacts of sea-level rise, ranging from simple "bathtub" models that show general inundation of coastal lands based on relative land elevation (e.g., DGESL 2003) to more detailed models that can simulate dynamic ecological processes at multiple spatial scales (e.g., Barataria-Terrebonne Estuarine Landscape Spatial Simulation Model, or BTELSS) (McLeod et al. 2010; Reyes et al. 2000). The SLAMM model was first developed two decades ago and has been applied in a number of studies. (Craft et al. 2009; Galbraith et al. 2002; Lee et al. 1992; Park et al. 1989). It provides an accessible, middle-of-the-road tool that allows for fairly detailed, scientifically sound regional assessments within the constraints of relatively limited data availability, budgets, and time.

Data inputs for SLAMM are generally readily available in most areas of the United States. For example, habitat composition data are based on the National Wetlands Inventory; coastal elevation data are available through the U.S. Geological Survey's National Elevation Dataset, which in many places has been significantly improved through high-vertical-resolution Light Detection and Ranging (LiDAR) data; historic sea-level trends and the salt boundary (the elevation below which lands are periodically inundated by salt water) are calculated using National Oceanic and Atmospheric Administration tidal gauge data; and factors contributing to relative sea-level change can be determined through the scientific literature, expert opinion, and other sources.

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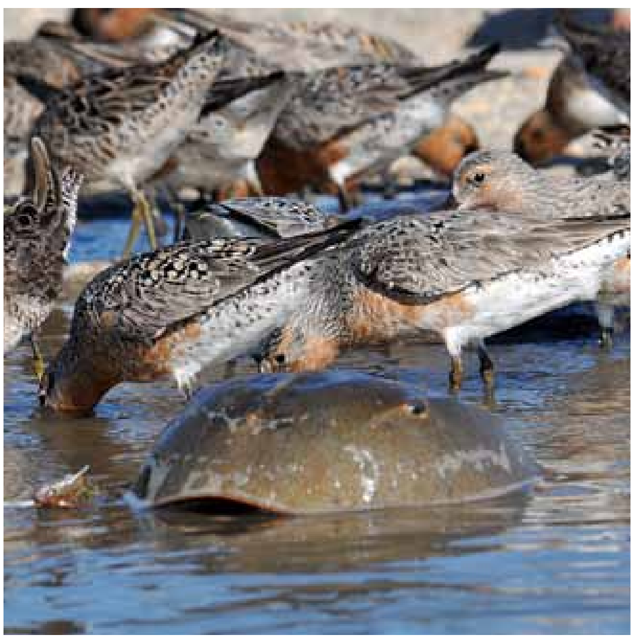
The SLAMM model addresses the relative sensitivity of habitat types to sea-level rise based on known ecological traits such as the tolerance for salinity of associated plant species. Elements of exposure to sea-level rise are based on land elevation as well as the scenarios of sea-level rise modeled. Adaptive capacity is addressed in terms of both intrinsic and extrinsic factors. One of the most important features of SLAMM is its ability to capture important localized differences in relative sea level. As mentioned previously in this guide, estimates of global sea-level rise due to climate change are based on what is called eustatic sea-level rise, which refers to the changes in ocean volume due to thermal expansion and the melting of glaciers and ice sheets. At the localized level, the amount of relative sea-level rise can vary due to factors (both natural and human-influenced) that determine changes in vertical land elevation, such as land



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subsidence, sedimentation, and marsh primary production. In the Chesapeake Bay, for example, many areas have been naturally subsiding (declining in elevation), which increases the amount of relative sea-level rise affecting the region, making those areas more vulnerable. In contrast, some coastal habitats such as marshes and beaches may at least to some extent be able to accommodate moderate changes in sea level by increasing in elevation due to the buildup of sediments. Rates of change among these variables can be included in the model. In addition, SLAMM can incorporate areas where habitats may not be able to move inland as sea level rises due to the existence of coastal armoring such as seawalls and dikes (factors that reduce the adaptive capacity of these habitats). Finally, the model output can be displayed as percentage changes in habitat area as well as shown on maps, both of which are useful for decision-makers.

Assessment Results

Model results vary considerably across the region, but overall the most significant changes to coastal wetlands and other habitats occur in the eastern and southern regions of the Chesapeake Bay, most of Delaware Bay, and along the coastal barrier islands and beaches. For example, under the scenario of a 0.69-meter sea-level rise, which is the IPCC's (2001a) A1B Max scenario for the year 2100, coastal marshes would be inundated with salt water, converting 83 percent of brackish marsh to saltmarsh or open water (see Table C5.1). Overall, the area of tidal marshes (including tidal freshwater marsh, irregularly flooded marsh, transitional saltmarsh, and saltmarsh) declines by 36 percent under this scenario. Ocean and estuarine beaches

	Pct of Init. Cond Map	Init. Cond. (ha)	A1B-Mean Yr. 2100 (ha)	A1B-Mean Pct. Change	A1B-Max Pct. Change	1 Meter Pct. Change
Global SLR by 2100 (m)			**0.387**	**0.387**	**0.694**	**1**
Dry Land	59.0%	4,152,259	4,019,563	-3%	-4%	-5%
Developed	4.2%	292,323	292,323	-0%	-0%	-0%
Swamp	6.9%	482,570	533,811	11%	8%	7%
Cypress Swamp	0.1%	4,535	4,551	0%	0%	0%
Inland Fresh Marsh	0.5%	32,635	33,202	2%	-1%	-3%
Tidal Fresh Marsh	0.2%	14,441	14,102	-2%	-16%	-36%
Trans. Marsh	0.1%	10,511	26,209	149%	229%	275%
Irregularly Flooded Marsh	2.7%	193,289	113,146	-41%	-83%	-88%
Saltmarsh	0.4%	27,438	100,516	266%	183%	100%
Estuarine Beach	0.5%	32,065	9,982	-69%	-58%	-53%
Tidal Flat	0.4%	27,278	7,962	-71%	9%	15%
Ocean Beach	0.0%	2,051	771	-62%	-69%	-91%
Inland Open Water	0.8%	55,190	54,325	-2%	-2%	-3%
Estuarine Open Water	19.8%	1,393,904	1,532,910	10%	19%	24%
Open Ocean	3.1%	216,847	227,220	5%	5%	6%
Inland Shore	0.0%	3,059	1,967	-36%	-38%	-44%
Tidal Swamp	0.7%	51,300	27,787	-46%	-57%	-68%
Rocky Intertidal	0.0%	5	1	-90%	-95%	-98%
Riverine Tidal	0.7%	46,614	37,969	-19%	-22%	-25%
Tidal Creek	0.0%	11	11	0%	0%	0%
Sum of Categories (ha)		**7,038,326**	**7,038,326**			

Table C5.1. Percentage changes in habitat area for entire study site (Glick et al. 2008a).

also fare poorly, declining by 69 percent and 58 percent, respectively. In addition, more than half of the region's important tidal swamp is at risk, declining by 57 percent by 2100. Many coastal plant and animal species have adapted to a certain level of salinity, tidal influence, and habitat composition, so these shifts will make habitats more favorable for some species and less so for others.

Figure C5.1 shows map-based model results for the Blackwater National Wildlife Refuge, Maryland, and surrounding areas under the 0.69-meter scenario (IPCC A1B Max) (just one of multiple scenarios run). Significant changes in the composition and extent of coastal habitats occur at this site, including a loss of 39 percent of dry land, 92 percent of inland freshwater marsh, and 94 percent of irregularly flooded (brackish) marsh, much of which converts to open water. One of the reasons this area is so vulnerable is because, in addition to facing eustatic sea-level rise, land subsidence is greater than for many other parts of the Chesapeake Bay due to groundwater withdrawal for agriculture (U.S. FWS 2005). In addition, marshes in much of the Eastern Shore appear to have relatively lower rates of natural accretion (Kearney et al. 1998). It is important to note that high-quality LiDAR data were used for this study site.

Uncertainties

It is important for decision-makers to recognize that, as with all predictive models, SLAMM has its limitations and is subject to uncertainty. One element of uncertainty is associated with projections for future sea-level rise. The SLAMM model itself does not project changes in eustatic sea level—it relies instead on sea-level rise scenarios developed by others, such as the IPCC. As discussed above, there is currently

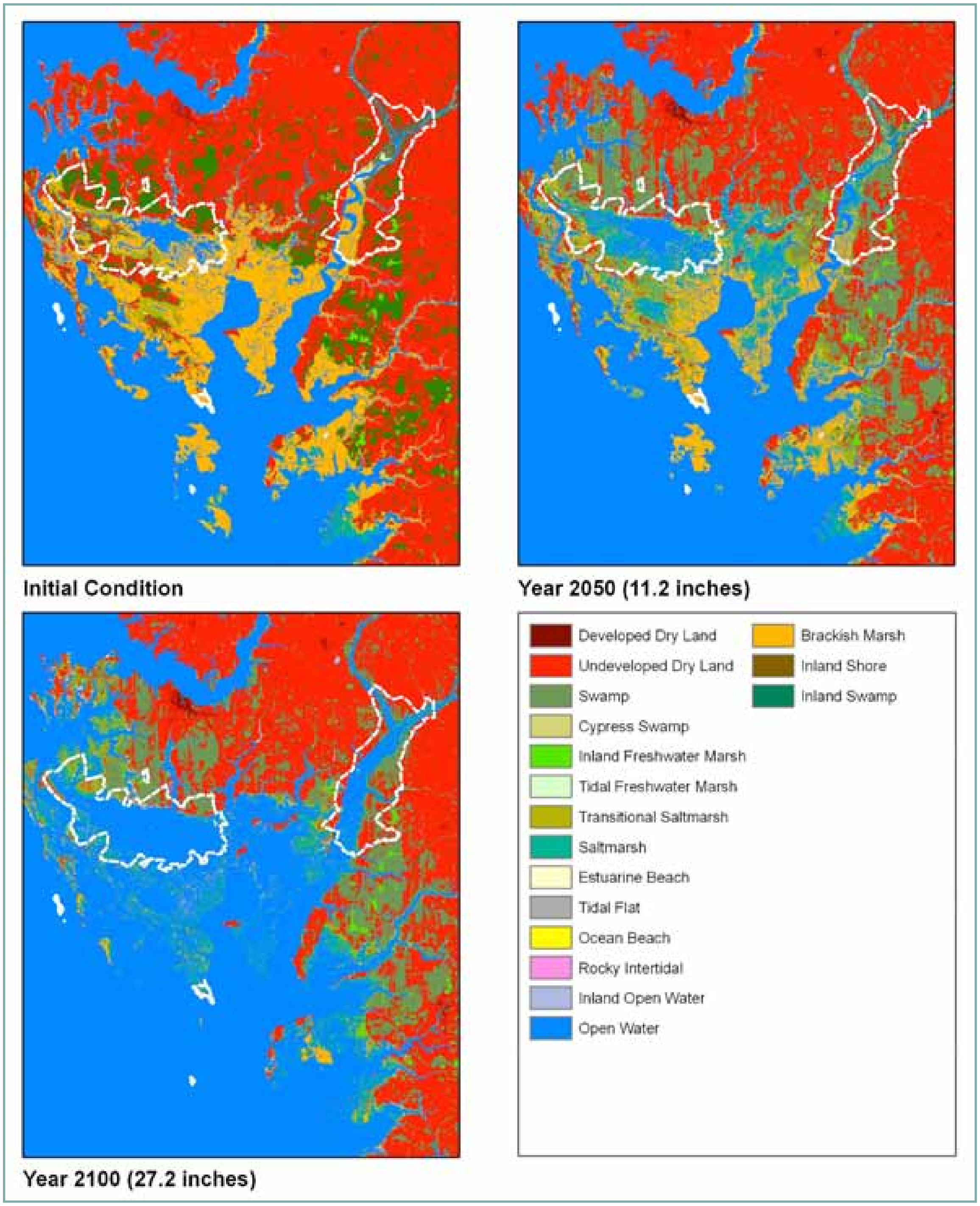

Figure C5.1. Sea level rise and marsh conversion projections for Blackwater National Wildlife Refuge, Maryland (Glick et al. 2008a).

a wide range of possible scenarios for sea-level rise, depending on the assumptions and factors used. Rather than choosing any one scenario, we applied multiple scenarios in our analysis to inform potential management responses.

Apart from any uncertainties in the sea-level rise projections themselves, confidence in SLAMM projections depends in large part on the quality of the data inputs. For example, areas where LiDAR elevation data are unavailable have a wider "zone of uncertainty" with respect to the delineation of vulnerable lands at or below a specific elevation, a factor that we address qualitatively in the results for this particular study. In addition, given that it is a relatively simple model, SLAMM does not capture some of the more complex systematic changes that could occur over time, which may include dynamic changes in marsh accretion or localized geomorphology. For example, the SLAMM model used for this assessment (Version 5.0) includes a simplifying assumption that rates of accretion (and subsidence) will remain linear into the future. This assumption, in particular, has been a source of criticism of the SLAMM model (e.g., Cahoon and Guntenspergen 2010; Kirwan and Guntenspergen 2009). It is important to note that newer versions of SLAMM (e.g., Version 6.0), incorporate dynamic feedbacks for marsh accretion based on elevation, distance to river or tidal channels, and salinity (Clough et al. 2010).

However, the use of the simplifying assumption for rates of relative sea-level changes in this or similar studies does not mean that its results are not useful. As with any vulnerability assessment, what is important is that the major model assumptions and areas of uncertainty are made transparent when communicating the study results. Users can then use their own judgment about their relevance for informing decisions regarding coastal restoration and management actions. Ultimately, the response strategies will vary for different areas, and more detailed, site-specific studies may be warranted to supplement these findings by identifying factors that have not been effectively captured by the model or remain uncertain.

Outcomes and Next Steps

The results of this analysis were published as two documents, including a detailed technical report (Glick et al. 2008a) and a summary (Glick et al. 2008b). In addition, the National Wildlife Federation has made all data and model results available to interested parties, including local, state, and federal agencies, academic institutions, and non-governmental organizations, to support additional analyses.

Center for Conservation Biology Marsh Bird Study

Purpose

Based on the results of the National Wildlife Federation's sea-level rise study described above, scientists at the Center for Conservation Biology at the College of William and Mary and Virginia Commonwealth University have conducted assessment of the potential impacts of sea-level rise on the population size of saltmarsh breeding birds within the Chesapeake Bay (Wilson and Watts 2009). The Chesapeake Bay region supports 30 percent of the total saltmarsh cover along the Atlantic Coast and is an important breeding area for several marsh bird species of concern. Based on assessments by the National Wildlife Federation, the U.S. Climate Change Science Program (U.S. CCSP 2009b), and others, it is clear that the saltmarsh ecosystem of the region is highly vulnerable to the impacts of sea-level rise.

Conservation Objective

The objective of this assessment was to examine the potential impact of sea-level rise on the capacity of the Chesapeake Bay region to support saltmarsh bird populations during the breeding season. Because marsh bird abundance and distribution are influenced by the physical characteristics of marshes such as salinity, vegetation, patch size, and elevation, the impact of sea-level rise on the population size of each species is more complex than simply calculating net changes in marsh area alone. Given that SLAMM is able to identify changes in the composition of coastal wetland habitats, as well as their extent, the National Wildlife Federation study provides an excellent platform for this assessment.

Assessment Targets

This assessment focused on several marsh birds of concern, including the willet, black rail, saltmarsh sparrow, clapper rail, Virginia rail, marsh wren, and seaside sparrow. Each of these species has specific habitat requirements based on the composition of coastal marsh types. The willet, black rail, and saltmarsh sparrow, for example, rely exclusively on high marsh, which is only inundated during extreme high-tide events and dominated by plants such as saltmeadow hay, saltgrass, and often interspersed with shrubs such as marsh elder or saltbush. Clapper rails, Virginia rails, marsh wrens, and seaside sparrows, on the other hand, use both low and high marsh but reach their highest densities in the low marsh, which is inundated with each tidal cycle and dominated by smooth cordgrass and black needlerush.

Scale and Scope

The GIS-based study used the National Wildlife Federation study's habitat change projections for several of the sea-level rise scenarios, including 0.39 meters by 2100, 1 meter by 2100, and 2 meters by 2100 (Glick et al. 2008a). For their purposes, some of the habitat types were aggregated into high saltmarsh, low saltmarsh, and transitional saltmarsh to correspond with the marsh types preferred by various marsh bird species. This study cost approximately $25,000 and took about 4 months to complete.

Assessment Approach

For the purposes of this study, each GIS raster cell from the National Wildlife Federation SLAMM analysis was assigned a value for the dominant habitat cover category. We then converted the rasters for emergent tidal marshes that were coded as high salt marsh, low salt marsh, and transitional salt marsh into vector-formatted polygons using ArcMap 9.1 (Environmental Systems Research Institute 2005) and grouped any like-valued cells ≤30 meters from each other into a single marsh patch. This grouping allowed neighboring cells to share the identity of a larger marsh complex while cells >30 meters away from an aggregation would be grouped into a different marsh complex. We placed the resulting aggregations into one of five marsh area classes: (1) <1 hectare, (2) 1–5 hectares, (3) 5–10 hectares, (4) 10–50 hectares, and (5) >50 hectares.

Bird population sizes for each map iteration were identified by extrapolating known values of bird density (birds/ha), based on research conducted within the Chesapeake Bay. Available habitat was delimited for each species by its (1) geographic distribution over the study area, (2) habitat associations, and (3) patch-level incidence rates for each area class. These associations were then incorporated into an equation that calculated changes in species' populations associated with projected changes in marsh habitat area due to sea-level rise.

To address potential uncertainty, confidence intervals were calculated for each population estimate by substituting the upper and lower 95 percent confidence interval values of each bird density for patch area class values in their modeling equation. As these factors change over time due to sea-level rise, so do the population sizes and distribution of associated marsh bird species.

Assessment Results

The total area of saltmarsh was reduced between initial conditions and the year 2100 for all sea-level rise scenarios. These changes were dominated by reductions of high marsh. Sea-level rise was also responsible for a shift in the rank order of abundance between low marsh and high marsh. In turn, model results suggest that the current rates of sea-level rise will reduce the size of breeding populations of widespread species 35 to 40 percent between the years 2000 and 2100. These reductions likely represent conservative estimates since global rates of sea-level rise are predicted to accelerate. Population reductions of 69 to 80 percent are possible if sea levels increase by 1 meter or greater.

The differential impacts of sea-level rise on high versus low marsh are projected to result in dramatic changes in the bird community on a regional scale. Marsh birds such as the black rail and saltmarsh sparrow that rely exclusively on high marsh habitat will be at very high risk of extirpation from the region. Habitat area for these species is projected to decline to about 50 percent of current area under the 0.39-meter scenario. Habitat for both the black rail and saltmarsh sparrow was reduced 89 percent from the 1-meter scenario and 99 percent from the 2-meter scenario for each species, respectively.
In addition, populations of clapper rails, Virginia rails, willets, seaside sparrows, and marsh wrens were projected to decline by about 40 percent in the 0.39-meter scenario, about 80 percent in the 1-meter scenario, and about 75 percent in the 2-meter scenario.

Uncertainties

(Addressed above.)

Outcomes and Next Steps

The results of this study illustrate the need to address specific management actions that reduce the adverse impacts of sea-level rise on marsh birds. Because significant loss of marsh area is likely, particularly under the higher projections for eustatic sea-level rise, there will be an increasing need to protect remaining marsh patches to compensate for these losses.

Case Study 6. An Integrated Climate Change Assessment Framework in the Four Corners Region

Summary

This case study describes the use of a regional-scale vulnerability assessment framework that includes identification of potential management responses. In the western United States, temperatures have exceeded global averages by 70 percent relative to the 20th century (Saunders et al. 2008). The region faces a 90 percent chance of continued declining snowpack, earlier peak flows in rivers and streams, and higher rates of evaporation from reservoirs, leading to increased competition for already over-allocated water resources (IPCC 2007b). Warming trends are projected to continue, with climate in the semiarid Southwest resembling "Dust Bowl" conditions by mid-century (Seagar et al. 2007). Ecological consequences of these effects are already being observed and documented in the region, including recent widespread forest dieback and population changes in native species (Inouye et al. 2000; Breshears et al. 2005). Natural resource professionals need to better understand the regional impacts of climate change so that they can take informed adaptive action in managing the landscapes that provide ecosystem services to human communities and habitat for a diversity of species. To address the need for information and guidance on responding to the potential consequences of climate change, The Nature Conservancy initiated the Southwest Climate Change Initiative (SWCCI), a collaborative effort between The Nature Conservancy and partners (state, federal, non-governmental organizations, universities) in the Four Corners states. More information about this study can be found at: http://nmconservation.org/projects/new_mexico_climate_change/.

B. Klein

Purpose and Conservation Objective

In 2006, the New Mexico Chapter of The Nature Conservancy first launched its own climate change ecology and adaptation program. Building on the completion of a state-wide climate change assessment and two adaptation-oriented workshops for natural resource managers in New Mexico (Enquist and Gori 2008; Enquist et al. 2008), The Nature Conservancy then launched the SWCCI. The Initiative specifically seeks to further develop and apply an integrated assessment approach that examines regional climate impacts, prioritizes adaptation actions based on potential vulnerability, and identifies specific climate adaptation strategies in

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priority landscapes in the region using an adaptation planning framework. The conservation objective of the project is to provide a straightforward approach for integrating climate change into existing conservation and management planning and decision-making processes. Ultimately, with continued refinement and development of this suite of nested-scale approaches, the project seeks to cultivate dialogue and collaboration between conservation practitioners, managers, and policy-makers from multiple jurisdictions, so that they can work toward reducing the vulnerability and increasing the resilience of current and future conservation priorities to ongoing climate change.

Scale and Scope

The assessment covers an area that comprises four states of the southwestern United States: Arizona, Colorado, New Mexico, and Utah. The New Mexico state-level climate and vulnerability analyses took 2.5 years to complete, with an approximate cost of $75,000, including significant in-kind contributions from external partners. The expanded SWCCI project conducted the baseline regional assessment in 1 year; the adaptation planning workshops in each of the four states were implemented over the course of 1.5 years (Phase 1). Together, the first phase of the SWCCI project cost approximately $200,000.

Assessment Approach and Targets

Regional Assessment

The SWCCI integrated framework begins with a spatially explicit rapid regional assessment of climate exposure using the ClimateWizard analysis tool. Specific climate metrics include departures and trends in temperature, precipitation, and moisture stress (i.e., evaporative demand). We mapped and analyzed these metrics

Michael D. Peterson

across the four states both retrospectively and prospectively. For historical analyses, ClimateWizard uses publicly available PRISM climate data set at a cell resolution of 4 square kilometers (Daly 1994). We used an ensemble of 16 IPCC AR4 global circulation models statistically downscaled to 12 kilometers for the future analyses (Maurer et al. 2007). Annual and seasonal trends were evaluated for the time periods analyzed (1950 to 2006, 1970 to 2006, 2020 to 2039, and 2069 to 2099). Statistical summaries were generated for each climate metric and time period for the region and for each state, ecoregion, and watershed. To identify potential vulnerability, we next evaluated climate change exposure in relation to existing conservation priorities, or targets (e.g., geographies, habitats, and sensitive species), identified in the four states' Wildlife Action Plans and ecoregional assessments. We used species occurrence data provided by NatureServe for our species-focused analyses, NatureServe vegetation analysis data for habitats, and spatial data of The Nature Conservancy's network of conservation areas for priority geographies.

Landscape Adaptation Planning

The second part of the SWCCI integrated framework aims to identify a suite of place-based adaptation strategies for potentially vulnerable species, ecosystems, or natural processes in priority landscapes. We specifically use an approach recently developed by a Wildlife Conservation Society–National Center for Ecological Analysis & Synthesis working group comprising managers and scientists from academia, non-governmental organizations, and federal agencies. This framework allows local scientific experts and managers to work in a transparent, participatory process to identify climate change threats and impacts and translate this information into a portfolio of strategies that are applicable to the landscape of interest. The proposed strategies can then be evaluated in the social, political, regulatory, and economic contexts that motivate and constrain management goals and policies. Subsequent iterations allow the incorporation of newly available information.

As the **first step** in this process, participants select a target and related management goals. In the **second step,** we define a plausible *climate change scenario* (e.g., warmer–drier with increased climate extremes) to apply to the target and goal. The **third step** involves building a *conceptual ecological model* and assessing known and potential climate change impacts. As part of this model, we consider other social, political, economic, and ecological constraints on the system, how they are interconnected, and how they will likely be affected by the selected climate change scenario. In the **fourth step,** we identify management *intervention points* for the target, or the components of the system that management can affect. We then identify management actions, or adaptation strategies, that can be taken at those points to address climate change impacts. The **fifth step** consists of *evaluating the identified adaptation strategies* based on their effectiveness (e.g., ability to affect target), robustness to variations in the climate change scenario and/or management objective, and the ability to monitor success. We also address the issue of uncertainty associated with a strategy, asking if the effect on the target will be "win-win" (where there could be multiple benefits), "no regrets" (less risky approach), or "proactive/anticipatory" (most risky).

Results

Regional Assessment

Temperature increased across the Southwest from 1951 to 2006, rising an average of 0.5 degrees Celsius (about 1 degree Fahrenheit) every 30 years. The temperature increase was consistent across scales, rising significantly across 70 to 100 percent of the watersheds, habitats, ecoregions, and states that we evaluated. Precipitation also increased across the region in the historic period, increasing by about 10 percent every 30 years. However,

Maja Smith

this trend was less consistent across scales, rising in only 36 to 75 percent of the units we evaluated. Several areas were actually drier, but none of these were significant. Climate change models predict that temperature will continue to rise in future, between 1 to 3 degrees Celsius by 2020 to 2039 and 3 to 5 degrees Celsius by 2080 to 2099. The temperature rise pattern is fairly consistent across scales. Predicted changes in precipitation are less consistent across time and space, ranging from −6 percent to +6 percent in 2020 to 2039 and −13 percent to +11 percent in 2080 to 2099.

Our preliminary analyses suggest that many sensitive-species-rich watersheds are among those that have been (1951 to 2006) and will continue to be exposed to extreme temperature changes. In particular we found that the Lower Colorado-Lake Mead (Arizona) and Upper Colorado-Dirty Devil (Utah) watersheds may be the most vulnerable places in the Southwest given these criteria and large percentage of freshwater and endemic species. Conversely, there are sensitive-species-rich watersheds that have experienced less exposure during the past 55 years. These places may be the ones that may have more resilience to predicted future temperature changes—at least in the shorter term. These include the Upper Pecos (New Mexico) and Upper Arkansas (Colorado) watersheds.

Landscape Adaptation Planning

Using the results of the regional assessment in a convened meeting of stakeholders, we identified case study landscapes in each of the Four Corners states for implementation of the collaborative Wildlife Conservation Society (WCS) and National Center for Ecological Analysis and Synthesis (NCEAS) adaptation planning process. We subsequently have engaged representatives from local agencies and non-governmental organizations to plan and implement the process in medium-sized workshops in each landscape for local resource managers. The goal of the workshops is to translate available climate change science, so that managers can overcome uncertainty paralysis and begin to identify strategies for helping species and ecosystems adapt to climate change. Specific objectives of the workshops are to (1) provide background information on climate change and its effects in the focal landscapes and (2) identify opportunities for learning, collaboration, and application of the adaptation planning process for natural resource management in the focal landscapes. As of December 2009, we have held two workshops in the Jemez Mountains of New Mexico and the Gunnison Basin of Colorado. Additional workshops are being planned for the Four Forest Restoration Initiative focal area in the vicinity of Flagstaff, Arizona (April 2010), and for the Bear River Basin of Utah (May 2010).

Maja Smith

Uncertainties

Assessment Climate Data

At a spatial resolution of 4 square kilometers, the PRISM model estimates monthly temperature and precipitation using a combination of climate station data, a digital elevation model, and expert-based knowledge of complex climatic processes, such as rain shadows and temperature inversions. As a statistically interpolated raster data set, there are inherent uncertainties associated with data that are further away from points (or data cells) with actual station data. These "inbetween" areas should be interpreted with some caution, particularly those values associated with a single data cell. Problems with station data can also exist, as some of these may have shorter periods of record or may have been physically moved during the course of data collection. Furthermore, geographical areas with complex topography may be particularly subject to data anomalies (e.g., the mountainous area of Colorado). Uncertainty associated with downscaled future climate models was also addressed.

Assessment Targets

We viewed conservation priorities as "surrogates of sensitivity" because we presumed all units of native biodiversity, especially drought-sensitive species, are likely to be sensitive on some level to rapid and abrupt climate change, despite adaptive ability (e.g., Sala et al. 2000). This may be especially true for species, ecosystems, or places that have formalized conservation status, given that they were identified at least in part because of specific attributes (e.g., rarity, endemism, etc.) that may render them susceptible to human-induced threats. In a subsequent phase of the project, using results of the first phase as a guide, we will investigate specific climate-related sensitivities related to species of concern and habitat types. Although our approaches *do not specifically measure* a conservation priority's adaptive capacity, we generated hypotheses of which conservation priorities are most and least vulnerable to ongoing climate change were developed. These will be used to further develop and refine future analyses.

Outcomes and Next Steps

We are currently in the process of writing up the results of our regional assessment in a report format written for natural resource professionals from across the Southwest. Our target distribution date is June 1, 2010. Our target completion date is June 2010, when we will post it to the project's Website (see above). We also are in the process of writing a project team charter to identify specific next steps for refining and further developing our assessment methods and related funding opportunities.

Jemez Mountains Climate Change Adaptation Workshop

This was the first in a series of four workshops to be organized by the SWCCI, held on April 21 to 22, 2009, in Los Alamos, New Mexico. More than 50 representatives of state and federal agencies, tribal governments, and non-governmental organizations participated. Over the course of 2 days, managers, scientists, and conservation practitioners worked together to identify adaptation strategies under two climate change scenarios—one moderate and one more extreme—for two ecological process–based conservation features, fire and in-stream flows. Participants found that many of the conservation strategies already being planned or implemented in the Jemez Mountains can be used to prepare for climate change. But, even under the more conservative of the two climate change scenarios we explored, the scale, sequencing, priority, and cost of these strategies will likely need to be adjusted if management objectives are to be met. Examples of priority strategies identified by the overall group included: system-wide management planning for fire and climate change; improvement of riparian ecosystem health by fencing out elk and cattle or by reducing the landscape's elk herd; landscape-scale ecological fire management; widening the prescribed fire window (i.e., expanding the suite of weather conditions under which prescribed burning can be implemented); and applying forest thinning prescriptions to promote snowpack retention and maximum precipitation infiltration. Participants also listed numerous actions that could be taken to carry out these strategies, and they identified both barriers to and opportunities for implementation.

Gunnison Basin Climate Change Adaptation Workshop

This was the second workshop organized by the SWCCI, held on December 2 to 3, 2009, in Gunnison, Colorado. Fifty-seven representatives of 20 state and federal agencies, local governments, academic institutions, and non-governmental organizations participated. Using two climate change scenarios, managers identified strategies using the adaptation framework for three "conservation features." Similar to the Jemez Mountains workshop, many strategies resemble existing ones. Examples of priority strategic actions that emerged from the workshop for the three conservation features include:

- **Gunnison sage-grouse:**

  - Retain water in most vulnerable sage-grouse habitats via restoration of seeps and springs and implementing more efficient agricultural practices

  - Improve and restore nesting and wintering sage-grouse habitats

- **Gunnison headwaters:**

  - Manage upland vegetation for groundwater recharge and base flow maintenance

  - Construct and/or restore wetland complexes

- **Alpine wetlands:**

  - Build snow fences to augment water inputs

  - Increase buffer zones around alpine wetlands

Participants of both workshops recognized that more work is needed to develop strategies to reduce the impacts predicted under extreme climate change scenarios. The ecological changes that could occur under these scenarios require more intensive and extensive management intervention or perhaps even wholesale changes in management goals. Participants expressed an interest in continuing to work together to refine our understanding of climate change, impacts to species, ecosystems, and ecological processes, and to refine the identified strategies. Participants also acknowledged that effective communication among local stakeholders and policy-makers is critical to building trust and to engaging people in the development of realistic management objectives as we face the possibility of undesired future conditions.

Overall workshop planners were pleased with the outcomes of the two workshops, noting that the planning framework gives managers the opportunity to document logic and assumptions, justify specific options in what is a relatively transparent process. Additionally, participants identified future information and research needs. Perhaps most importantly, the workshops provided a forum to promote landscape-level collaboration and continued dialogue via the formation of informal climate change learning networks.

A final, synthetic report of the four workshops describing emergent and divergent strategies, recommendations for moving the process forward, and lessons learned is targeted for completion by the autumn of 2010. Pending additional funding, we hope to conduct follow-up workshops focused on implementation, testing, and monitoring of identified management strategies using an adaptive management framework.

Case Study 7. Pacific Northwest Climate Change Vulnerability Assessment

Summary

This case study describes the early stages of a broad, regional-scale vulnerability assessment for species and habitats that is applying a range of assessment approaches. This collaborative project is creating a digital database of climate change sensitivities of species and systems in the Pacific Northwest and will identify which are inherently most sensitive to climate change. Species and systems sensitivities are based on physiology, habitat requirements, life history, dispersal ability, population growth rates, location, ecological climate effects, and disturbance regime effects. Sensitivity is being identified by experts, scientific literature, and pertinent data sets. This database will provide natural resource managers with critical information that can be combined with the management tools already in their toolbox to address climate change and better prepare for the future.

Background—Climate Change in the Pacific Northwest

Pacific Northwest temperatures have increased by about 0.8 degrees Celsius and models project warming of 2.0 degrees Celsius by the 2040s and 3.3 degrees Celsius by the 2080s (Mote and Salathé 2009). Precipitation is also projected to change, with general increases projected for the Pacific Northwest, and with a more intense seasonal precipitation cycle—autumns and winters may, in fact, become wetter and summers may become drier. Regional climate models indicate that overall extreme precipitation in western Washington will increase and the snowpack in the Cascades will decrease (Mote and Salathé 2009).

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Purpose of the Vulnerability Assessment

The Pacific Northwest Vulnerability Assessment was developed in response to the considerable challenge that climate change poses to natural resource managers. Leading this voluntary approach, the University of Washington is partnering with key collaborators, such as scientists, natural resource managers, and conservation planners in the Pacific Northwest region to conduct a climate–ecological vulnerability assessment.

Lead authors: Michael Case and Josh Lawler.

David J. Mills

Conservation Objective

The assessment will provide managers and planners with information about which species and systems will be most vulnerable to climate change and in what ways they will be vulnerable. This information can be used to prioritize management actions, design adaptation strategies, and apportion scarce resources.

Assessment Targets

The assessment targets both species and ecological systems (habitats). One of the goals of this project is to develop a digital database of inherent climate change sensitivities for species and systems of concern throughout the Pacific Northwest and to provide resource managers and decision-makers with important information about how species and systems will likely respond to climate change. The project database and related modeling assessments will also allow researchers to address important scientific questions regarding the potential impacts of climate change on natural resources.

Scale and Scope

The assessment covers an area that extends beyond the borders of Washington, Oregon, and Idaho (see Figure C7.1). Current project funding to populate and analyze the database will continue until 2011. However, access and use of the database will continue into the future and will eventually cover a broader spatial scale.

The resource needs for this type of assessment are significant (the project will likely require a total of $800,000 and 3 to 4 years to complete), but it is being conducted at a regional scale, considers both selected species and broad habitat categories, and combines the resources of state and federal agencies, academic institutions, and non-governmental organizations.

Assessment Approach

This project is a collaboration among researchers, managers, and planners at the University of Washington, U.S. Geological Survey, The Nature Conservancy, the National Park Service, the U.S. Forest

Service, the Washington Department of Fish and Wildlife, the University of Idaho, the National Wildlife Federation, the Oregon Department of Fish and Wildlife, and Idaho Fish and Game.

The Pacific Northwest Climate Change Vulnerability Assessment includes two distinct components; the first is a database that will highlight and detail the sensitivity to climate change of species and habitats in the study region. For this project, sensitivity is defined as a measure of the inherent susceptibility to climate change. Some species and systems are inherently more susceptible to climate change than others. The estimated sensitivity of individual species is currently assessed on the following characteristics: ability of the species to disperse and whether dispersal barriers exist; dependency on disturbance regimes such as fire or flood regimes; physiology and ecology (i.e., sensitivity to temperature, precipitation, salinity, pH, CO_2); dependency on and persistence of climatically sensitive habitats (such as alpine areas, shallow wetlands, and perennial streams); whether the species is a generalist or specialist, and whether its existence is tied to other species. The sensitivity of ecosystems and communities will be based on hydrological sensitivities, component species sensitivities, proximity to the coast, and the effects of disturbance regimes. The database will be used in conjunction with a sensitivity index to produce a ranking of more than 400 species and systems with respect to their sensitivity to climatic change.

The second component of the assessment involves modeling the potential effects of climate change on species and habitats of the Pacific Northwest. The initial step of this part of the project is to statistically downscale climate change projections to produce projected changes in climate at approximately 1-square-kilometer resolution for at least six different future climate projections. This relatively high-resolution data will provide information

Figure C7.1. Study area.

that is more applicable to regional planning and natural resource management. We will then use these downscaled climate projections in conjunction with soils data as inputs to a dynamic global vegetation model to project potential changes in the vegetation of the region. Vegetation types will be defined by their relative composition of different basic plant functional types such as broad-leafed deciduous trees and grasses. These vegetation data will then be used to model the current and potential future ranges for 12 bird and mammal species in the

Richard Dalby

Pacific Northwest. Specifically, we will use a hierarchical modeling approach to project future species distributions. First, we will use continental-scale models (e.g., Lawler et al. 2009) to predict future species distributions at a 50-square-kilometer resolution across the study region. These predictions will provide estimates of the future range boundaries of the each species. Then, within the projected future ranges, we will project future distributions at a 1-square-kilometer resolution using regional distribution models that take both changes in climate and changes in vegetation (habitat) into account.

Relevant uncertainties related to the data and analyses are highlighted throughout the project and database. For example, when entering species and system characteristics into the database experts are asked to assign uncertainties along with their answers and these uncertainties are reported in the database output. Additionally, the project assigns levels of uncertainty to the simulated climatic and bioclimatic changes and the simulated vegetation changes.

Assessment Results

While still in the early stages of populating the database, preliminary analysis has examined the overall sensitivity (calculated by the database index) of more than 20 species present on the Olympic Peninsula (see Figure C7.2). The results of this analysis highlight the potential vulnerability of species that rely on sensitive habitats and have stronger physiological sensitivities to climate change (Halofsky et al., in press). Species that occupy vulnerable habitats, such as the Olympic torrent salamander (headwater streams), Cascades frog and Van Dyke's salamander (aquatic habitats), Dogstar skipper butterfly (meadows), Makah copper butterfly (wetlands), and the Olympic marmot, mountain goat, Clark's nutcracker, and gray-crowned rosy finch (high-elevation habitats), were generally ranked as highly sensitive to climate change. Similarly, specialist species in terms of habitat and diet, such as Clark's nutcracker, northern spotted owl, gray-crowned rosy finch, Van Dyke's salamander, American marten, and northern flying squirrel, were ranked as moderately to highly sensitive to climate change. More generalist species, such as the barred owl, black bear, Roosevelt elk, snowshoe hare, and mountain beaver, were not ranked as highly for sensitivity to climate change.

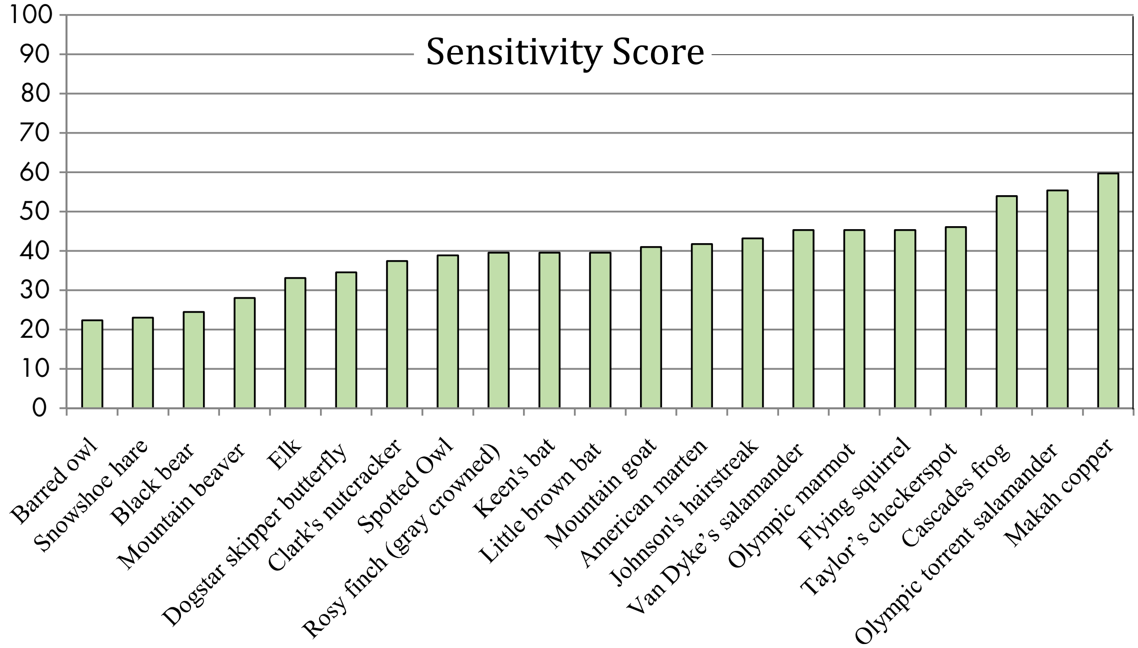

Figure C7.2. Climate change sensitivity scores for selected species on the Olympic Peninsula.

Uncertainties

There are many different types of uncertainty associated with forecasts of future climate changes (Giorgi 2005) and the impacts that these changes will have on species and ecosystems. These uncertainties are often not explicitly described in climate change studies, making it difficult for conservation planners to determine how much they should rely on particular results. In response, we are in the process of identifying and describing the uncertainties associated with the different results produced by our analyses. Examples of uncertainties include:

- Uncertainties associated with model simulations of particular variables (e.g., there tends to be more certainty in AOGCM temperature simulations than in AOGCM precipitation simulations)

- Temporal variations in uncertainties (e.g., the uncertainty in AOGCM future climate simulations tends to increase the farther out in time the predictions are from the present)

- Uncertainties created by variability among AOGCM simulations (e.g., one AOGCM may simulate dry winter conditions for a region while another AOGCM simulates wetter winter conditions for the same region)

- Uncertainties inherent in the vegetation and species distribution models

To compensate for the high uncertainty associated with future climate projections, this project will produce six maps (one for each of the six climate change simulations) of projected future ranges for each of the modeled species. By overlaying the projected distributions, we will be able to highlight model agreement and disagreement for each species and to identify areas where species ranges are simulated to change the most.

Outcomes and Next Steps

Both the database and modeling components of this study make an important contribution to understanding the impacts of future climate change on the species and habitats of the Pacific Northwest. The database assesses the sensitivity of the Pacific Northwest's conservation targets to climatic changes. The analyses of the projected climate change and simulated vegetation change provide an indication of the potential magnitude and spatial character of future climate change (i.e., exposure). The modeled changes in species distributions reveal how climate change may affect the future distributions of key species in the region.

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The preliminary results presented above illustrate how this sensitivity assessment process can be useful in identifying species and groups of species that will likely be most sensitive to climate change. As demonstrated at the Olympic Peninsula expert meeting where some of the data were collected, this process can lead to useful discussions about how individual and groups of species may be affected by climate change. While the results of this initial analysis are still under development, project leads are in the process of incorporating recommendations and concerns. For example, in addition to the default index equation, database users will also be able to weight specific characteristics and thus influence their individualized output.

Ultimately, this study will integrate these results and produce an assessment of the climate change vulnerability of species and systems in the Pacific Northwest. Using these data, we will describe and assign a level of uncertainty to the projected changes and, as in the other parts of the study, we will work with conservation scientists to produce documentation, analyses, and visual displays of data that will be useful in developing management and planning responses to climate change impacts. This project is committed to providing relevant and useful information and thus will continue to evolve to meet the needs of managers and decision-makers in the region.

Glossary

Adaptive capacity. The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences (IPCC 2001b).

Adaptive management. A systematic approach for improving resource management by learning from management outcomes. In principle, its purpose is to enable natural resource managers and other relevant decision-makers deal with uncertainty about future conditions by supporting the development of conservation projects based on information available and then providing the flexibility to modify their management activities to improve their effectiveness as new information becomes available (Williams et al. 2007).

Carbon dioxide equivalent (CO_2-eq). The concentration of carbon dioxide that would cause the same amount of radiative forcing as a given mixture of carbon dioxide and other greenhouse gases. In the IPCC reports, CO_2-eq includes the six greenhouse gases specified in the Kyoto Protocol (IPCC 2007b).

Climate. "Average weather" patterns or trends for a particular region over a period of many years. (NCAR 2004).

Climate change. Climate change refers to a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use (IPCC 2007b).

Climate change adaptation. Climate change adaptation for natural systems is a management strategy that involves identifying, preparing for, and responding to expected climate changes in order to promote ecological resilience, maintain ecological function, and provide the necessary elements to support biodiversity and sustainable ecosystem services (Glick et al. 2009).

Climate model. A numerical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties (IPCC 2007a). The climate system can be represented by models of varying complexity.

Confidence. A level of "confidence" can be used to characterize uncertainty that is based on expert judgment as to the correctness of a model, an analysis, or a statement. Standard terminology by the IPCC puts "very high confidence" at "at least 9 out of 10 chance of being correct, and "very low confidence" at "less than 1 out of 10 chance" (IPCC 2005).

Downscaling. A method that derives local- to regional-scale (10 to 100 kilometers) information from larger-scale models or data analyses. In statistical downscaling, a statistical relationship is derived between observed local climate variables and predictors at the scale of global climate model output. Dynamical downscaling, or regional climate modeling, explicitly simulates the process-based physical dynamics of the regional climate system using a high-resolution, limited-area climate model (IPCC 2007b).

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Ecological thresholds. An ecological threshold is the point at which there is an abrupt change in an ecosystem quality, property, or phenomenon, or where small changes in an environmental driver produce large responses in the ecosystem (Groffman et al. 2006).

Exposure. The nature and degree to which a system is exposed to significant climate variations (IPCC 2001b).

Forcing mechanisms. Anything that changes the energy balance of the earth's system, leading to a net change in the earth's average temperature. Examples include regular variations in the earth's orbit, changes in ocean circulation, volcanic eruptions, and changes in the composition of the earth's atmosphere (IPCC 2007a).

Global climate model. Global climate models are large, three-dimensional coupled models that incorporate the latest understanding of the physical processes at work in the atmosphere, oceans, and earth's surface. They range from lower-level General Circulation Models (GCMs) to coupled Atmosphere–Ocean General Circulation Models (AOGCMs) (IPCC 2007b).

Greenhouse gas. Greenhouse gases are the gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the earth's surface, the atmosphere itself, and by clouds. The primary greenhouse gases include water vapor (H2O), carbon dioxide (CO_2), nitrous oxide (N2O), methane (CH4), ozone (O3), although the Kyoto Protocol also addresses several entirely human-made greenhouse gases, including sulfur hexafluoride (SF6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs) (IPCC 2007a).

Phenology. Recurring plant and animal life cycle events, such as flowering, leafing, or migration.

Refugia. Physical environments that are less affected by climate change than other areas (e.g., due to local currents, geographic location, etc.) and are thus a “refuge” from climate change for organisms (U.S. CCSP 2008b).

Resilience. The amount of change or disturbance that can be absorbed by a system [e.g., an organism, population, community, or ecosystem] before the system is redefined by a different set of processes and structures (i.e., the ecosystem recovers from the change or disturbance without a major phase shift) (U.S. CCSP 2008b).

Resistance. The ability of an organism, population, community, or ecosystem to withstand a change or disturbance without significant loss of structure or function. From a management perspective, resistance includes both (1) the concept of taking advantage of/boosting the inherent (biological) degree to which species are able to resist change and (2) manipulation of the physical environment to counteract/resist physical/biological change (U.S. CCSP 2008b).

Risk assessment. A risk assessment is the process of identifying the magnitude or consequences of an adverse event or impact occurring as well as the probability that it will occur (Jones 2001).

Sensitivity. Sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli (U.S. CCSP 2008b).

Uncertainty. An expression of the degree to which a value (e.g., the future state of the climate system) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain projections of human behavior. Uncertainty can therefore be represented by quantitative measures, for example, a range of values calculated by various models, or by qualitative statements, for example, reflecting the judgment of a team of experts (see Moss and Schneider 2000; Manning et al. 2010; IPCC 2007b).

Vulnerability. The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. It is a function of the sensitivity of a particular system to climate changes, its exposure to those changes, and its capacity to adapt to those changes (IPCC 2007a).

Vulnerability assessment. A key tool for carrying out adaptation planning, and informing the development and implementation of climate-smart resource management practices.

Weather. Weather is the mix of events that happen each day in our atmosphere, including temperature, rainfall, and humidity.

Acronyms

20C2M	20th Century Climate Coupled Model
AFWA	Association of Fish and Wildlife Agencies
AOGCM	Atmosphere-Ocean General Circulation Model
AR4	Fourth Assessment Report of the IPCC
AR5	Fifth Assessment Report of the IPCC
BTELSS	Barataria-Terrabonne Estuarine Landscape Spatial Simulation Model
CCSP	U.S. Climate Change Science Program
CMIP	Coupled Model Intercomparison Project
CO_2	Carbon Dioxide
DGESL	Department of Geosciences Environmental Studies Laboratory
DGVM	Dynamic Global Vegetation Model
EPA	U.S. Environmental Protection Agency
ESA	Endangered Species Act
ET	Evapotranspiration
FWS	U.S. Fish and Wildlife Service
GAP	Gap Analysis Program
GARP	Genetic Algorithm for Rule-set Production
GCM	General Circulation Model
HVA	Habitat Vulnerability Assessment
IPCC	Intergovernmental Panel on Climate Change
ISAB	Independent Scientific Advisory Board
IUCN	International Union for Conservation of Nature
LiDAR	Light Detection and Ranging
MAGICC	Model for the Assessment of Greenhouse-gas Induced Climate Change
MAPSS	Mapped Atmospheric-Plant Soil System
MDFW	Massachusetts Division of Fisheries and Wildlife
NARCCAP	North American Regional Climate Change Assessment Program
NECIA	Northeast Climate Impacts Assessment
NRC	National Research Council
PDSI	Palmer Drought Severity Index
ppm	Parts Per Million
RCP	Representative Concentration Pathway
RHESSys	The Regional Hydro-Ecologic Simulation System
RMRS	Rocky Mountain Research Station
SGCN	Species of Greatest Conservation Need
SGNC	Species of Greatest Need for Conservation
SLAMM	Sea Level Affecting Marshes Model
SRES	Special Report on Emissions Scenarios
SWCCI	Southwest Climate Change Initiative
T&E	Threatened and Endangered
TNC	The Nature Conservancy
USDA	U.S. Department of Agriculture
USGCRP	U.S. Global Change Research Program
UV	Ultraviolet
VEMAP	The Vegetation/Ecosystem Modeling and Analysis Project
VIC	Variable Infiltration Capacity

Climate Change Vulnerability Assessment Resources

Publications

Vulnerability Assessment Frameworks and Guidance

Intergovernmental Panel on Climate Change (IPCC). 2005. *Guidance Notes for Lead Authors of the IPCC Fourth Assessment Report on Addressing Uncertainties.* Intergovernmental Panel on Climate Change, Geneva. http://www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf.

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Web-Based Tools

Bioclimatic metrics: WorldClim, http://www.worldclim.org/.

Climate Adaptation Knowledge Environment (CAKE): http://www.cakex.org/

ClimateWizard: http://www.climatewizard.org.

Compendium of conceptual ecological response models: http://www.fileheap.com/software/conceptual_data_model.html.

Drought indices and hydrologic models: http://drought.unl.edu/whatis/indices.htm; Variable Infiltration Capacity model, http://www.hydro.washington.edu/Lettenmaier/Models/VIC/.

Ecological models: The Regional Hydro-Ecologic Simulation System (RHESsys), http://fiesta.bren.ucsb.edu/~rhessys/setup/downloads/downloads.html; PnET, http://www.pnet.sr.unh.edu/download.html; the CENTURY model, http://nrel.colostate.edu/projects/century5/.

Expert opinion ecological response models: Bayesian Analysis Toolkit, http://www.mppmu.mpg.de/bat/; Treeage Pro, http://www.treeage.com/products/index.html; Delphi Decision Aid, http://armstrong.wharton.upenn.edu/delphi2/.

GAP Program models: http://www.nbii.gov/portal/server.pt/community/maps_and_data/1850/species_modeling/7000.

Landscape model: PATCH, http://www.epa.gov/wed/pages/news/03June/schumaker.htm.

NatureServe Climate Change Vulnerability Index: http://www.natureserve.org/prodServices/climatechange/ClimateChange.jsp.

Niche and occupancy ecological response models: GARP, http://www.nhm.ku.edu/desktopgarp; Maxent, http://www.cs.princeton.edu/~schapire/maxent/; Regression Trees and Random Forests, http://rattle.togaware.com/rattle-download.html; Bioclim, http://software.informer.com/getfree-bioclim-download-software/.

NOAA Coastal Climate Adaptation: http://collaborate.csc.noaa.gov/climateadaptation/default.aspx

USDA Forest Service Climate Change Resource Center: http://www.fs.fed.us/ccrc/.

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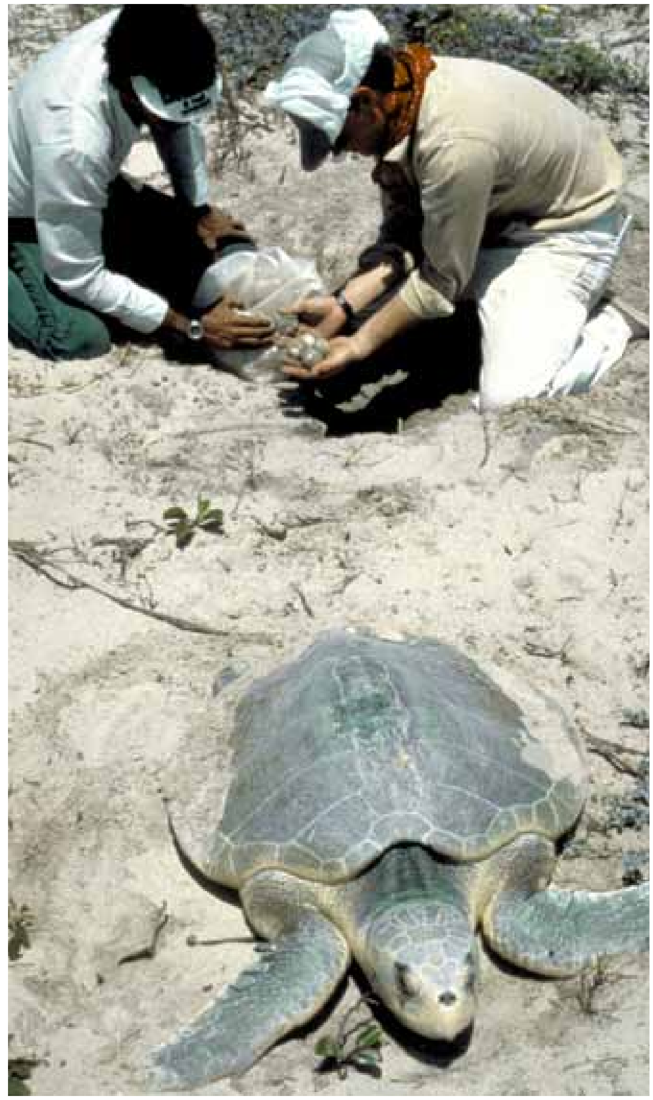

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