

# Forest Conservation and Management in the Anthropocene: Adaptation of Science, Policy, and Practices



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## **Abstract**

Climate change is but one aspect of the Anthropocene, a new epoch in which the effects of human activities have become the predominant force in the global biosphere. More than just an overlay on the traditional concerns of sustainable natural resource management, the uncertainties associated with these effects are creating a “no-analog future” in which much of the existing science relating to the functioning and response of forest ecosystems—which serves as the fundamental basis for current forest management practices and policies—must be reconsidered. In these collected papers, leading scientists, resource managers and policy specialists explore the implications of climate change and other manifestations of the Anthropocene on the management of wildlife habitat, biodiversity, water, and other resources, with particular attention to the effects of wildfire. Recommendations include the need for a supporting institutional, legal, and policy framework that is not just different but more dynamic, to facilitate resource management adaptation and preparedness in a period of accelerating environmental change.

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*Cover image: Smoke from the Deep Harbor Fire levels off at sunset on the Wenatchee National Forest, courtesy Eli Lehmann. Above: Scars from a wildfire in the Bob Marshall Wilderness, courtesy Terra Fondriest.*

# Forest Conservation and Management in the Anthropocene:

Adaptation of Science, Policy, and Practices

**Edited by:**

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## FOREWORD

The future of America's forests is more uncertain now than at any time since science-based sustainable forest management was established in this country more than a century ago. The Conservation Movement of the late 19<sup>th</sup> and early 20<sup>th</sup> century saw the creation of federally protected public forests, establishment of the basic laws and policies that guide the sustainable management of state, private, and tribal forests, and development of an unrivaled capacity for forest research and science. Our knowledge of forests has never been better, yet an area of forest larger than that of several states stands dead or dying, with millions more acres imperiled not by foreign invasive species, but by native insects and pathogens with which these forests have co-existed for millennia. United States wildland firefighting technology and capabilities are widely acknowledged as the best in the world. Yet millions of acres of public and private forests go up in smoke each year, and natural resource agencies warn that fire losses may soon be double what they are today.

What is going on here? What has changed? Since the days of the Conservation Movement and Gifford Pinchot's urgent call to action to protect America's forests, our population has grown from 76 million people to 325 million. Human habitation and development continues to erode the nation's forest land at an alarming rate. It presses hard up against the boundaries of public lands, and insinuates itself deep into forests in ways that make wildfires more likely, and more costly and deadly when they occur. Here, as in the rest of the world, climate has become more unpredictable, more extreme, and more damaging; and the gathering momentum ensures that this trend will continue for decades to come. The physical infrastructure built to support today's population has itself become a barrier to migration, seed dissemination, and other strategies that species have relied upon to adapt to changing climate in earlier ages.

The Pinchot Institute recently brought together some of the nation's most accomplished scientists and conservation leaders to consider the future of America's forests in the "Anthropocene"—the newest geologic epoch, in which Man is acknowledged as the dominant force influencing the Earth's natural systems. Many of these experts came at the question from the perspective of their particular discipline—biodiversity conservation, water resource protection, or conservation of wildlife and fish habitat. A few focused on the forests themselves, without which none of these individual resources could be sustained, and offered up a number of valuable, creative approaches to integrating the management of public and private forests across regional-scale landscapes.

Somewhat surprising was the way wildfire policy and management emerged as the keystone to it all. Experts identified many useful steps to be taken to conserve biodiversity, water, and other resources in the changing world of the Anthropocene. But the current and projected effects of wildfire are so pervasive and its influences so profound that a strategy aimed at protecting any of these important public resources must begin with a more deliberate and more successful strategy for managing wildfire.

Massive wildfires and dying forests are often thought of only in the context of federal forests in the West. But the environmental changes of the Anthropocene will affect resources on other lands as well, in every corner of the country. Wildfires and forest mortality from insects and disease will become much larger factors in the predominantly private forests of the South. Iconic American tree species such as the sugar maple, ash, and hemlock are poised to go the way of the

chestnut and elm. As Hurricanes Sandy and Irene demonstrated recently, protecting the forested headwaters of rivers and reservoirs will become even more important to buffering the effects of extreme storms, and protecting water supplies for New York, Philadelphia, Boston, Atlanta and hundreds of other cities and communities in the East.

Since the days of Gifford Pinchot and Theodore Roosevelt, we have developed a thorough understanding of the nation's forests, built upon the solid foundation of decades of science and practice. But scientists and conservation leaders themselves are sounding a warning that what lies ahead is a 'no-analog future' in which neither current science nor past experience can be relied upon to adequately inform decision making, or prepare for secondary and indirect effects that are so unprecedented and so unexpected that no one could have predicted them.

So even in the current budget-constrained environment, meaningful additional public and private investment will be needed to support new science, and to accelerate the application of what we already know—to restore ecosystems and channel wildfire on federal forests, and to strengthen the financial underpinning for sustaining private forest lands. This will be a task not just on 'all lands' but for all hands—natural resource agencies, legislative policymakers, forestland investors, conservation leaders, and everyone across the country who recognizes the important difference that forests make in our lives and those of future generations.

V. Alaric Sample

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*Pinchot Institute for Conservation*

*January 24, 2014*

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## EXECUTIVE SUMMARY

America's forests are undergoing changes unlike any seen before in human history. With each passing year, new precedents are being set for the extent and impacts of wildfires. Record areas of forests stand dead or dying, not just from exotic insects and diseases, but from species that have been native to these forests for eons. Subtler but potentially more profound changes are taking place each day as native plant and animal species quietly disappear from their historic home ranges.

In the midst of this time of unprecedented change and new uncertainties, the stewards of America's forests, both public and private, must decide how they will act differently if they are to sustain the forests themselves and the array of economic, environmental, and societal values and services forests provide—water, wildlife, biodiversity, wood, renewable energy, carbon sequestration. Side by side with some of the best climate and resource scientists, forest resource managers are striving to understand, prepare for, and adapt to the effects of climate change. As they do their best to anticipate a 'no analog future' in which the lessons of the past can offer little guidance, they must assess the risks associated with several alternative courses of action, and then manage those risks through intensified monitoring and continuous readjustments aimed at preserving as many options as possible for future resource managers. In short, these options are to:

- Resist the effects of climate change, taking advantage of niches here and there where survival may be possible.
- Make systems more resilient to the impacts of new patterns of disturbance, with strategies to survive the periodic and perhaps intensifying shocks and still have the ability to recover afterwards.
- Accept that the magnitude of the changes are too large and the momentum too great for either of these approaches to work, and that the only practical strategy is to realign one's future expectations, continuously monitor the changes taking place on the ground, and modify management actions accordingly in order to sustain key values or ecosystem services.

The papers in this volume summarize the results of current research on the effects of climate change on a variety of resource management activities—biodiversity conservation, wildlife habitat management, water resource protection, forest carbon management, sustainable wood production, and reducing the risks and impacts of wildfires. They also reflect the efforts of natural resource managers on both public and private lands to better understand, prepare for, and adapt to the accelerating effects of climate change and other aspects of the "Anthropocene" epoch. Three overarching conclusions emerge.

A better integrated approach is needed to understanding, preparing for, and adapting to the effects of climate change on natural resources. Scientists and natural resource specialists in wildlife habitat management, biodiversity conservation, water resource protection, and other disciplines are all working to develop effective climate change adaptation strategies, but there is still a strong tendency to focus within rather than across disciplines. Land and resource management requires an integrated approach of course, but there is an added concern that strategies developed independently to optimize one set of objectives, e.g., carbon management, may dictate

management activities that run counter to strategies oriented to other objectives, such as biodiversity conservation.

Wildfire management and policy is central to adaptation strategies across all resources. There is much more to climate change adaptation than managing the increasingly damaging effects of wildfires, but how these risks are managed will have a profound influence on biodiversity, wildlife, water, carbon and virtually every other aspect of any climate change adaptation strategy. The development and effective implementation of policies to limit the ecological, economic, and social impacts of wildfires are not the only consideration, but they are an essential consideration.

A more dynamic policy framework is needed as a basis for natural resource management that can adapt to climate change. To the extent that the existing institutional, legal, and policy framework for natural resource management is based on science, it must continue to evolve just as science itself evolves. The most important lesson is not that the existing policy framework should be replaced by a new one, but that policies themselves must be dynamic enough to accommodate rapidly changing environmental conditions. Statutes and regulations that provide a broad enabling framework will be more effective than prescriptive laws and rules that reflect theories and approaches that are highly changeable, and that will continue to evolve with new scientific knowledge.

The Anthropocene, this new epoch in which *Homo sapiens* has become the predominant force in the global biosphere, is about more than just a changing climate. The climate has always been in a state of flux, and certain past episodes have been as drastic as what the world is witnessing today. Species and communities have in most instances found ways to adapt and survive, through migration, mutation, or other coping mechanisms. One thing that is different this time is the pace of the change. The challenges of forest management adaptation to climate change are great, but the opportunities may be even greater. Throughout the papers, several key recommendations emerged to enhance forest conservation. These vary from budgetary needs to administrative and management options, often integrating the domains of water, fiber, biodiversity, carbon, fire, and communities under the unifying theme of forests.

## **RECOMMENDATIONS**

### *1. Strengthen the institutional framework for long-term investment in forest restoration and sustainable management*

It is essential that Congress and the Administration increase federal investments to reduce fire risk in a manner that makes forests more resilient and resistant to fire and other stressors. This should be based on a broadly supported long-term strategy so that, with respect to the annual process by which federal budgets and appropriations are determined, steady progress can be made toward overarching goals for resource protection and long-term sustainability.

Strengthen results-based cooperation on forest restoration through initiatives such as the Collaborative Forest Landscape Restoration (CFLR) Program. The active involvement of local communities and stakeholders plays an essential role in the management of public lands, but the challenges of forest restoration will require an unprecedented level of cooperation among federal

land managers, stakeholders, and organizations that provide the local economic infrastructure for carrying out resource protection and restoration activities in the field.

Maintain capacity for multi-resource management and protection through increased administrative and budgetary efficiencies. Given the scope of the wildfire management challenge on federal lands, it is likely that other resource programs will continue to be underfunded relative to actual needs for resource protection and stewardship. The U.S. Forest Service is currently experimenting with Integrated Resource Restoration (IRR), a budgetary tool that attempts to increase efficiency by blending funding sources for a variety of forest, watershed, and wildlife habitat programs. The IRR is being employed in three regions on a pilot basis (Northern, Southwest, and Intermountain). Congressional and Administration support will continue to be essential for this pilot to be successful, and for the U.S. Forest Service and outside parties to closely monitor the results in terms of improved agency capacity, program accomplishments, and budgetary accountability.

*2. Create and fund a new federal fire suppression funding mechanism to free up resources for proactive management referenced above*

Policy action is needed to guarantee adequate resources for wildland fire first responders, and to do so in a way that allows needed investments in the up-front risk reduction programs discussed above. Even with a robust, proactive approach to land management, federal fire preparedness and suppression resources will still need to be maintained at an effective level to protect life, property, and natural resources. But emergency preparedness and response resources must be provided through a mechanism that does not compromise the viability of the forest management activities that can actually serve to reduce risks to life and property and mitigate the demand for emergency response in the future. The current system of funding fire preparedness and suppression at the expense of hazardous fuels and other key programs threatens to undermine—and eventually overtake—the vital management and conservation purposes for which the USDA Forest Service and Department of the Interior bureaus were established.

*3. Accelerate implementation of cooperative stewardship authorities*

Stewardship contracts and agreements are among the most valuable tools the U.S. Forest Service and BLM have to carry out ecosystem restoration actions, including hazardous fuels treatments, on federal forests. Permanent authority for stewardship contracts and agreements was provided within the Agricultural Act of 2014 (Public Law 113-79; 2.7.14). The following specific steps are needed to achieve two main objectives: (1) expedite agency-level policy direction on stewardship contracting to resource managers in the field at both the U.S. Forest Service and BLM, and (2) immediately initiate the agency-level process for enhancing the implementation of stewardship contracting in the field.

Release updated guidance to agency field staff related to the permanent authorization of stewardship contracting and how the authorities can be used to accelerate the pace and scale of restoration of our federal lands. The Forest Service and BLM operate under different policy frameworks, but that should not prohibit interagency coordination. Agency and Department communications related to the Farm Bill should include consistent messaging and communications.

Develop a forum or communications process for interested stakeholders to remain current. Provide guidebooks to help with industry, tribal and citizen outreach on the use of stewardship contracts and agreements as a key tool for enhancing partnerships among stakeholders and expanding the on-the-ground work that the federal agencies can accomplish. Evaluate opportunities to use the recently expanded Good Neighbor authority to work with stewardship contracts and agreements (Public Law 113-79). Expedite the release of an updated Forest Service stewardship contracting handbook. Consider the recommendations from the FY 2012 Stewardship Contracting Programmatic Monitoring report ([http://www.pinchot.org/gp/Stewardship\\_Contracting](http://www.pinchot.org/gp/Stewardship_Contracting)), and the recommendations from the Stewardship Contracting Roundtable and regional partners.

*4. Increase capacity of communities to become fire adapted*

Programs such as State and Volunteer Fire Assistance and Forest Health Protection provide important resources to help states and local communities develop and sustain community wildfire protection capacity. These programs foster the development of fire-adapted communities. Policy makers should seek opportunities to allocate other federal resources in a way that rewards communities for proactive actions that collectively result in national benefit.

*5. Seek policy adjustments that foster innovation and improvement in National Environmental Policy Act (NEPA) implementation, thereby increasing the scale and quality of resulting projects and plans*

There is broad commitment to the principles of public engagement and environmental review embodied in NEPA. There may be opportunities to significantly increase the efficiency of these processes, while continuing this commitment, through targeted adjustments in policy and implementation. The U.S. Forest Service is currently testing and tracking a variety of innovative NEPA strategies that hold promise for broader application. Adaptive NEPA, for example, is a relatively new approach in which the official record of decision allows sufficient leeway for some variety of subsequent federal actions, thereby greatly streamlining the analysis, allowing for more efficient project implementation, and enabling land managers to more effectively incorporate emerging science.

*6. Increase shared commitment to and support for forest restoration by state and local governments*

Federal agencies alone cannot prevent the loss of homes, infrastructure and other values in the wildland-urban interface (WUI). Individuals and communities living in the WUI must meaningfully invest in preparing for and reducing their own risk from fire. Post-fire studies repeatedly show that using fire resistant building materials and reducing flammable fuels in and around the home ignition zone are the most effective ways to reduce the likelihood that a home will burn. Similarly, community investments in improved ingress and egress routes, clear evacuation strategies, strategic fuel breaks, and increased firefighting capacity can go a long way toward enabling the community to successfully weather a wildfire event.

*7. Enhance participation of additional sectors of society, such as water and power utilities, recreation and tourism, public health, and industrial users of clean water*

There are tremendous opportunities for diverse and sustainable sources of non-federal funding to provide an effective complement to federal land management resources, thereby facilitating an overall increase in landscape-scale forest restoration on federal lands. There are a number of efforts underway, including water funds, which produce revenue for upstream forest restoration that benefits downstream water users and water companies while enhancing the restoration and maintenance of federal forests. Other utility and industrial partnerships can be developed.

#### *8. Increase the safe and effective use of wildland fire*

The beneficial use of fire as a tool for resource management is another area where greater forest restoration efficiency and effectiveness could be achieved. By increasing the use of both controlled burns and naturally ignited wildland fires to accomplish resource benefit, land managers can accomplish both ecological and community protection goals on a larger scale and at reduced cost.

#### *9. Increase research on economic, social, and ecological impacts of forest investment*

It is essential that the federal government and other sectors invest in monitoring, research, and accountability studies for fuels treatment, wildfire management strategies, and related efforts. This requires relatively small investments, when compared to the costs of fire suppression and fire damage, but it is essential if scientists are to really learn what works and what does not. Furthermore, new technologies, including remote sensing, LIDAR, and focused social science studies can offer creative new perspectives to increase efficiency of action.

There is a higher level of interest and public concern over the state of the world's forests than at any time in recent history. Moreover, forest science is becoming more relevant than ever to sustaining the economic values and environmental services that forest ecosystems provide and that society needs. These interdisciplinary approaches to forest conservation are required if we—scientists, managers, practitioners, policy-makers, and citizens—are to create the new knowledge and broader public understanding that will be essential to conserving and sustaining forest ecosystems in the Anthropocene.





# Introduction

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## **V. Alaric Sample**

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Throughout Earth's history, its climates have been changing, and biotic systems have mutated, migrated, and otherwise adapted as tectonic shifts have reconfigured the continents and polar ice caps have ebbed and flowed across the latitudes through glacial cycles. In our own era, there is growing evidence that changes in climate that in the past have taken place over the course of millennia are now taking place in a matter of decades. These accelerated changes in climate are challenging the ability of both human civilization and the natural systems on which it depends, to adapt quickly enough to keep pace. Through efforts like the Intergovernmental Panel on Climate Change and the United Nations Framework Convention on Climate Change, leading scientists around the world have focused their energies on understanding the nature and implications of these changes, and the world's governments are striving to develop the institutions and resources to enable timely and effective actions to mitigate and adapt to changes that are anticipated or already under way.

The people and organizations charged with the conservation and sustainable management of the world's forests and their associated renewable natural resources are at the forefront of efforts to understand and address these challenges. As stated in recent report by a group of federal natural resource management agencies and nonprofit organizations, "Rapid climate change is the defining conservation issue of our generation... 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" (Glick and others 2011).

Conserving biological diversity in the world's forests is a particular challenge as both plant and animal species are prompted to follow the climate-driven movement of the ecosystems and habitats in which they evolved (Hannah 2012; Hannah 2002; Lovejoy and Hannah 2005). Ecological communities disassemble as species capable of migrating do so, and those that are not remain behind. Those that can migrate now must traverse



landscapes that in earlier epochs were not filled with highways, cities, farms, and other manifestations of a rapidly expanding human population that is relatively new on the geologic time scale. Designated parks, refuges, reserves, and other traditional approaches to protecting habitat are still important (Caro and others 2011), but may be less effective when the species themselves are on the move (Kareiva and others 2011). This is prompting biologists, resource management professionals, and policymakers to consider new approaches to conservation planning (Anderson and Ferree 2010), and strategies focused on large landscapes—vast areas that stretch from Yellowstone National Park to the Yukon, or from the southern Appalachians to Labrador (Anderson and others 2011). These immense landscapes encompass cities, towns, and agricultural working lands, as well as a mosaic of public and private forests that are all managed for different purposes and objectives. For these landscape-scale conservation strategies to be environmentally, economically and socially sustainable—and politically possible—new governance models must be developed to facilitate an unprecedented level of communication, coordination, cooperation, and collaboration (McLachland and others 2007; Marris 2011; Kareiva and others 2012).

Much more than wildlife habitat conservation is at stake. For thousands of communities across the nation, forests are key to maintaining adequate supplies of clean water to meet municipal, agricultural, and industrial needs. Forests in the headwaters and riparian areas of the nation's rivers and streams are low-cost, high-return guarantors of water quality, water supply, and favorable timing of seasonal flows. All of these are critical considerations in the western US and parts of the South where higher temperatures, prolonged droughts, and shifts in precipitation patterns are already causing economic and social disruptions (Milly 2008). Other regions in the eastern United States anticipate a continuing increase in precipitation in the form of extreme storm events, accentuating the essential role that intact forests serve in storm water control and flood mitigation.

The low-cost and largely self-maintaining “green infrastructure” that forests provide is vulnerable to both direct and indirect effects of climate change. The direct effects of drought, elevated temperatures, and changing precipitation patterns can be seen in reduced tree growth, lower survival rates in tree seedlings and young growth, and reforestation failures in the wake of natural disturbances. The loss of certain more climate-sensitive tree species within a forest can change the overall species composition or mix, eliminating food sources and habitat for native wildlife species.

Forests that are already under a high degree of environmental stress from these direct effects of climate change are more vulnerable to its indirect effects. Forests in many parts of the world are experiencing extraordinary and often unprecedented levels of mortality from insects and disease. Incidents involving even endemic or native pests and pathogens, which would normally kill only a small fraction of the trees in a forest, are in some regions causing near 100-percent mortality over areas of thousands of square miles (Allen and others 2002). The resulting large volume of dead and dying trees invites wildfires that themselves are unprecedented in size and severity (Brown and others 2004). Following events such as these, the harsher climate makes reforestation and ecological restoration that much more difficult and prone to failure, often leading to increased soil erosion, stream sedimentation, impacts on terrestrial and aquatic habitat, and damages to water supplies, storm water control, and flood mitigation.

These climate change effects are largely outside the experience and expertise of today's forest managers, on both public and private lands. The magnitude of these changes and the speed with which they are taking place are essentially unprecedented in the lifetimes of resource management professionals currently in the field. Even the knowledge base for forest management practices that has been built up over the past two centuries is itself based on forest science developed almost entirely within a period of relative climate stability. Successfully meeting the challenges of forest conservation and sustainable management in an era of accelerating climate change will require certain forest science, policies, and practices that do not yet exist, and will have to be developed.

Vulnerability assessments that encompass terrestrial and aquatic habitat, biodiversity, vegetation management, hydrology, and forest road systems are essential to understanding the potential effects of climate change on forest ecosystems as a whole, and the implications for the range of environmental, economic, and social values and services that forests provide.

This new science cannot be developed in isolation. In order for this new knowledge to be readily useful and to make a difference on the ground where it counts, it must be developed in the context of actual resource management planning and decision making (USDA 2008; USDA 2010). Budgets and human resources will never be unlimited for managers of either public or private forest lands. Resource managers need decision support tools that allow them to integrate vulnerability assessments with action strategies to establish reasoned priorities and make the best-informed decisions possible (Peterson and others 2011; Halofsky and others 2011). Resource managers must be able to utilize these tools to determine what they need to do differently in the future, and what existing practices will continue to be the best approach as part of an overall strategy for mitigating and adapting to climate change.

## **ADDRESSING INSTITUTIONAL AND POLICY CONSTRAINTS TO IMPLEMENTING ADAPTATION STRATEGIES**

The objectives of the national policy conference were to (1) summarize recent advances in the scientific understanding of the projected effects of climate change on forest ecosystems and their responses to natural disturbance and human interventions, (2) describe strategies for adapting current resource management practices to sustain these evolving ecosystems and the array of social, economic, and environmental services they provide, and (3) identify opportunities to evolve the existing institutional and policy framework to support timely and effective implementation of adaptation strategies for both public and private forest lands.

The forest sector technical report for the most recent National Climate Assessment (Vose and others 2012) describes current circumstances as follows:

Significant progress has been made in developing scientific principles and tools for adapting to climate change through science-management partnerships focused on education, assessment of vulnerability of natural resources, and development of adaptation strategies and tactics. In addition, climate change has motivated increased use of bioenergy and carbon (C) sequestration policy options as mitigation strategies, emphasizing the effects of climate change-human interactions on forests, as well as the role of forests in mitigating climate change. Forest growth and afforestation in the United States currently account for a net gain in C storage and offset

approximately 13 percent of the Nation's fossil fuel CO<sub>2</sub> production. Climate change mitigation through forest carbon management focuses on (1) land use change to increase forest area (afforestation) and avoid deforestation, (2) carbon management in existing forests [protecting large carbon stocks; increasing fuels treatments; increasing forest growth], and (3) use of wood as biomass energy, in place of fossil fuel or in wood products for carbon storage and in place of other building materials. Although climate change is an important issue for management and policy, the interaction of changes in biophysical environments (e.g., climate, disturbance, and invasive species) and human responses to those changes (management and policy) will ultimately determine outcomes for ecosystem services and people.

Although uncertainty exists about the magnitude and timing of climate-change effects on forest ecosystems, sufficient scientific information is available to begin taking action now [emphasis added]. Building on practices compatible with adapting to climate change provides a good starting point for land managers who may want to begin the adaptation process. Establishing a foundation for managing forest ecosystems in the context of climate change as soon as possible will ensure that a broad range of options will be available for managing forest resources sustainably (Paquette and Messier 2010; Victor 2005; Sedjo and Botkin 1997).

The conference examined existing constraints to timely and effective implementation of adaptation strategies, and steps that can be taken in the near term to accelerate the evolution of policies and institutional frameworks to address these constraints. These include:

**Education and awareness.** There is a lack of public awareness of how climate change affects natural resources influences the level and nature of adaptation by public institutions. The lack of experience and understanding of climate science by resource managers can lead to low confidence in taking management action in response to climate threats (GAO 2007); similar limitations through the chain of supervision and decision making constrain appropriate efforts (GAO 2009).

**Monitoring and adaptive management.** Adaptive management has been understood as a core component of ecosystem management for more than two decades, but climate change is necessitating and even more central role for real-time monitoring, reporting, and incremental adjustments in land and resource management plans and activities (Peterson and others 2011; Swanston and Janowiak 2013). The effectiveness of adaptive management on public lands as well as private has been limited by the weak institutional framework for monitoring, by inadequate funding and by lack of analyst capacity.

**Policy and planning.** Public agencies and private organizations alike are constrained by hierarchies of laws, regulations, and policy direction developed before the effects of climate change were recognized or well understood; they are based on the assumption of stable and predictable climate, and thus provide limited authority for resource managers to accommodate the dynamics of climate change. Forest management organizations of all kinds confront operational challenges in working at spatial and temporal scales compatible with climate change adaptation.

**Budget and fiscal barriers.** Significant additional funding will be needed for: education and training; development of science-management partnerships; vulnerability assessments; and development of adaptation strategies. Collaboration across organizational as well as geographic

boundaries, leveraging of institutional capacities, and other innovative solutions will be needed to address the budget challenge.

The characteristics that define the Anthropocene—the Age of Man—are about more than just the changing climate. It is about more than 7 billion people occupying virtually every biome on the planet, and human infrastructure that influences both our ability to mitigate climate change, and to adapt to it (Zalasiewicz and others 2010). We know that climate change is already affecting forests around the world, and strongly influencing their ability to provide the environmental, economic, and societal values and services on which society depends. These effects are already evident today in extraordinarily destructive wildfires and floods, unprecedented epidemics of insects and pathogens, and other manifestations of forest ecosystems already under high levels of environmental stress. Based on the combined results of numerous climate models, it is expected that these climate changes will strengthen and accelerate over the next several decades and perhaps centuries.

Significant progress has been made in developing the science and management approaches needed to understand, prepare for, and ultimately to adapt to these changes. There is much more we need to learn, but we know enough now to begin taking decisive actions on the ground to implement adaptation strategies on both public and private forest lands. The bottlenecks we are now encountering are not based so much on the limitations of our science as on limitations in the policies and the existing institutional framework within which forestry is practiced.

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# Section I:

Monitoring and Projecting Effects of Changing Climatic Regimes and Other Large-scale, Long-term Influences on Forest Ecosystems and Sustainable Management of Forests

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# Climate Change in the Age of Humans

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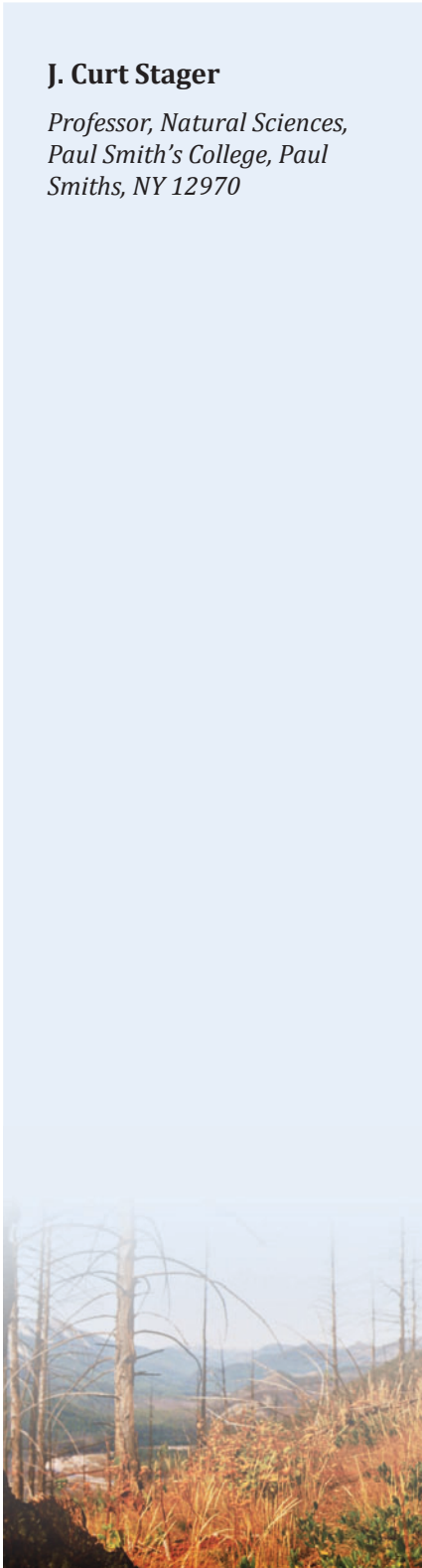
***Abstract:** The Anthropocene epoch presents a mix of old and new challenges for the world's forests. Climatic instability has typified most of the Cenozoic Era but today's situation is unique due to the presence of billions of humans on the planet. The potential rate and magnitude of future warming driven by continued fossil fuel combustion could be unprecedented during the last 56 million years, and the recovery of atmospheric carbon dioxide concentrations to pre-industrial conditions is likely to last tens of thousands of years. Paleocological records suggest that responses of forests to human-driven climate change may be complicated by differential mobility and resilience among species as well as by the variable distribution of soil, moisture, and light regimes along latitudinal gradients. The future will be difficult to model and predict precisely, not only due to the inherent complexity of the climate system but also because of uncertainty regarding the dispersal and adaptation of forest species as well as the possible development of new technologies, cultural changes, and the raising of artificial barriers to adaptive migration. Nevertheless, the Anthropocene epoch is a useful concept for re-envisioning modern humankind as a powerful force of nature that will influence the distribution and composition of ecosystems for many millennia to come.*

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## INTRODUCTION

Human-driven climate change is only one of many challenges that forests must face during the 21st century and beyond. Even without adding more heat-trapping carbon dioxide to the atmosphere than all of the planet's volcanoes combined (Gerlach 2013), the presence of billions of human beings on Earth represents a major source of environmental change. In what is being called the Anthropocene epoch, the Age of Humans, we have become so numerous, our technologies so powerful, and our societies so interconnected that we have become a force of nature on a geological scale.

The Anthropocene term apparently arose spontaneously among many members of the scientific community, including ecologist Eugene Stoermer and chemist Paul Crutzen (Crutzen and Stoermer 2000; Stager 2011), who recognized the scope of human influences in the modern world. There is no consensus yet on when it began. Most definitions date it to the Industrial Revolution, but



human impacts on what were previously thought to be “untouched” landscapes have long affected forests through mega-herbivore extinctions, land clearance, fires, and cultivation (Willis and others 2004; Willis and Birks 2006; Lorenzen and others 2011). Although its authorship and timing are difficult to pin down, the Anthropocene concept nevertheless provides a useful context for ecosystem management.

With approximately one quarter of the planet’s carbon dioxide reservoir now attributable to our fossil fuel emissions, our behavior has become an integral part of global ecology. Our artificial nitrogen fixation now matches or exceeds natural production of available nitrogen worldwide, we change the appearances of continents through land use practices, rising sea levels, and shrinking ice masses, we disperse some species widely while driving others to extinction, and we direct evolution through changes in gene flow, selective breeding, and genetic engineering. The human presence affects the very survival of forests as well as their distribution, reproduction, and community structure, and it will make the ecological consequences of future climatic changes unique in the history of the planet.

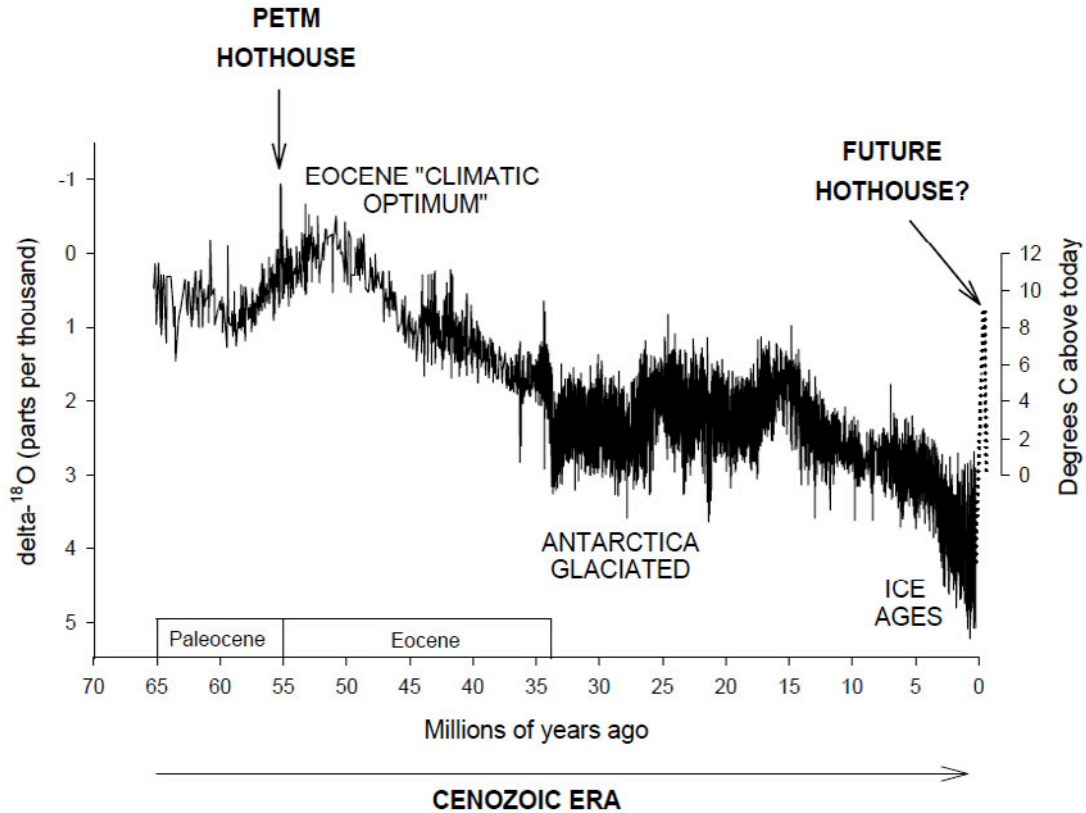
Theoretical modeling provides possible examples of what may lie ahead in terms of climate, but proxy records of geologic history can also help to show which scenarios are most realistic and provide examples of biotic responses to climatic shifts in the past.

## **CLIMATES OF THE PAST**

Today’s anthropogenic climatic effects are superimposed on a background of variability that includes both cyclic and irregular fluctuations on multiple spatial and temporal scales. Long, high-resolution records from ice cores, tree rings, cave formations, and aquatic sediments show that abrupt and extreme climate events are not limited to human causes, and that many of today’s tree taxa have experienced such changes before.

The last 50 million years of the Cenozoic Era was dominated by cooling from the high-CO<sub>2</sub>, hothouse of the Eocene “climatic optimum” (Figure 1). The reasons for this are still unclear, but tectonism, weathering of the continents, and sequestration of carbon in marine sediments are likely contributors to the cooling trend (Garzione 2008). Temperatures fell low enough for an Antarctic ice cap to form between 45 and 34 million years ago, and during the last 3 million years temperatures have dropped far enough to trigger several dozen ice ages.

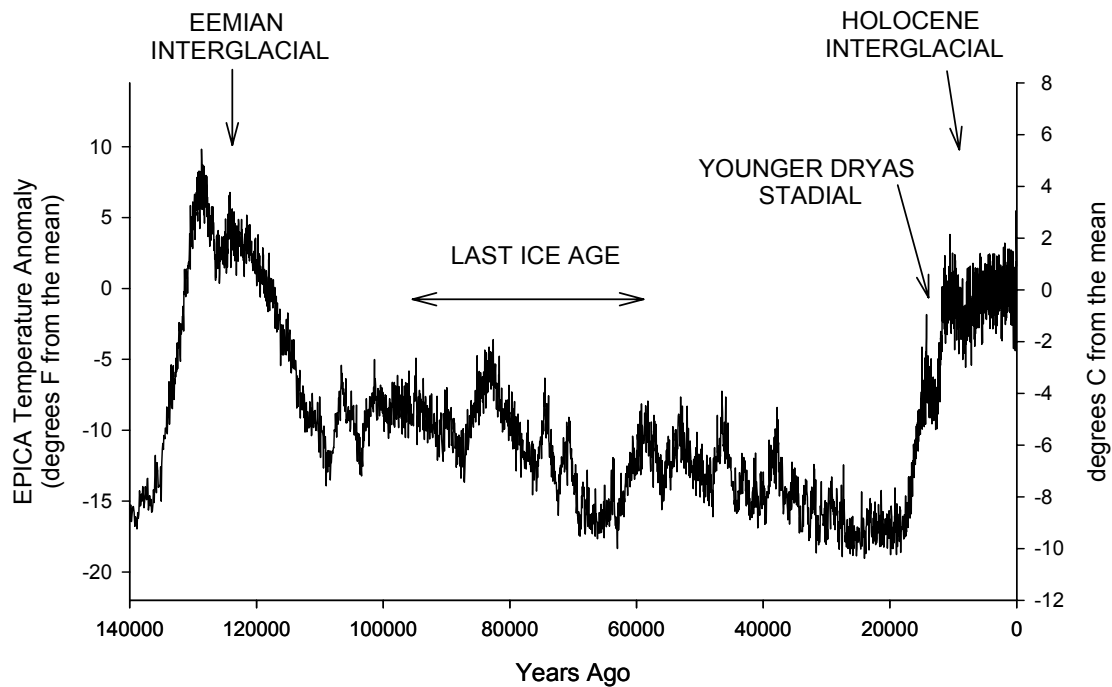
The overall cooling pattern of the Cenozoic was also punctuated by abrupt warming events. One of the most commonly cited examples was the PETM (Paleocene-Eocene Thermal Maximum) that occurred 56 million years ago and lasted roughly 200,000 years (Figure 1; Dickens 2011). Atmospheric CO<sub>2</sub> concentrations are thought to have reached or exceeded 3000 ppm following the release of 2000-5000 gigatons (Gtons; billions of metric tons) of carbon-rich gases into the atmosphere, possibly through volcanism in the Atlantic basin as well as other factors (Pearson and Palmer 2000; Dickens 2011). Global average temperatures rose by 5-10°C above their already-warm states within 20,000 years or less, plant species migrated poleward, and insect herbivory on foliage increased, possibly in response to higher temperatures (Wing and others 2005; Currano and others 2008). Deciduous redwood forests encircled the Arctic Ocean, *Nothofagus* beech forests covered Antarctica, and ice-free, richly vegetated continents and land bridges facilitated the rapid migration of species (Bowen and others 2002; Smith and others 2006; Williams and others 2008; Cantrill and Poole 2012).



**Figure 1.** Deep-sea oxygen isotopes and temperatures during the Cenozoic Era (after Zachos and others 2008).

Millennial-scale periodicities in the tilt, wobble, and orbital path of the Earth have been primary pacemakers of ice ages during the last 3 million years. Between cold glacial (longer) and stadial (shorter) periods, seasonal insolation cycles triggered warm interglacials and interstadials, as well. Sediment core evidence suggests that summers became wetter and 8°C or more warmer than today in Arctic Russia during insolation peaks between 3.5 and 2.5 million years ago that included repeated expansion of boreal forest over tundra (Brigham-Grette and others 2013).

The last such warm period, often referred to as the Eemian Interglacial, produced regional temperatures 1-3°C higher than today between 130,000 and 117,000 yr BP (years before present, relative to AD 1950). The Arctic Ocean was partially ice-free but most of the Greenland and Antarctic ice sheets remained intact despite occasional surges that lifted sea levels at least 7 meters higher than today (Blanchon and others 2009; Clark and Huybers 2009; Nørgaard-Pedersen and others 2009). Conifers invaded Siberian tundra north of Lake Baikal, large stands of spruce, pine, and birch developed in southern Greenland, and woodlands in the Adirondack mountains of upstate New York resembled those of today's Blue Ridge, with pollen records from Eemian-age lake deposits revealing the prevalence of oak, hickory, and black gum (Muller and others 1993; De Vernal and Hillaire-Marcel 2003; Granoszewski and others 2004). Rainfall intensified abruptly over 200 years or less in monsoonal Asia, and greener, moister conditions in tropical Africa and the Middle East helped Stone Age peoples to migrate through what are now the Sinai and Negev deserts (Schneider and others 1997; Chen and others 2003; Yuan and others 2004; Vaks and others 2007).



**Figure 2.** EPICA ice core record of Antarctic temperatures from the Eemian Interglacial to present (after EPICA Community Members 2004).

More rapid and short-lived disruptions also occurred during glacials (Figure 2), including Dansgaard-Oeschger cycles and Heinrich events associated with ice sheet surges and extreme climate fluctuations. Around 17,000 yr BP, massive ice-rafting and cooling in the North Atlantic basin contributed to a sudden, catastrophic collapse of the Afro-Asian monsoon system which desiccated Lakes Victoria, Tana, and Van, and produced genetic bottlenecks in human populations in India (“Heinrich Stadial 1;” Stager and others 2011). Around 13,000 yr BP, the Younger Dryas stadial represented an abrupt return to glacial-type conditions in much of the northern hemisphere that began within less than a decade in some locations and caused severe aridity in much of tropical Africa and southern Asia (Mayewski and others 1993; Stager and others 2002). The end of the Younger Dryas 11,700 years ago represented a rapid shift to the warmer conditions that have dominated the Holocene epoch to modern times.

During the last 11,700 years, the fluctuations preserved in ice core records were not as dramatic as they were during the preceding glacial period, leading to a common misperception that climates of the Holocene were stable before the Industrial Revolution. In fact, ecologically significant instability was still common, even at the poles (O’Brien and others 1995; Mayewski and others 2004). High summer insolation in the northern hemisphere during the early Holocene contributed to ice retreat on the Arctic Ocean and the expansion of lakes and forests throughout tropical Africa (DeMenocal and others 2000; Stager and others 2003; Kaufman and others 2004), the effects of El Niño-Southern Oscillation (ENSO) increased notably after about 5000 yr BP (Moy and others 2002), and other rapid climate changes also occurred throughout the Holocene (Mayewski and others 2004).

Within the last millennium, regional warming during the Medieval Climate Anomaly (ca. 1000-700 yr BP) brought severe drought to much of North America and East Africa and more widespread

cooling occurred during the Little Ice Age (ca. 600-200 yr BP) triggering alpine glacial advances in Europe (Mayewski and others 2004; Maasch and others 2005; Verschuren and others 2009). During the last century, non-human sources of variability including ENSO, the North Atlantic Oscillation, shifting westerly wind tracks, and the eleven-year solar cycle have repeatedly disturbed temperature and precipitation regimes over wide areas of the planet (IPCC 2007; Stager and others 2007, 2012).

In sum, high-resolution paleoclimate records reveal far more natural variability than was once assumed from earlier work that failed to sample geological archives in sufficient detail. The rapidity of recent climatic changes is not, as has sometimes been suggested, by itself sufficient evidence to identify humans as the cause.

The ancestors of today's forests experienced numerous climatic shifts in the past, so change alone is not a unique threat in and of itself. However, these records also offer stern warnings about what may lie ahead as a result of human activities in the Anthropocene. The idea of an ice-free Earth, acidified oceans, and massive, rapid climatic disruptions due to greenhouse gas buildups are not merely fantasies among doom-and-gloom radicals; we now know that such things really can happen because they have happened before, even without major human impacts. And although a facile interpretation of geological history might lead one to conclude that climate change is not a threat because it is "natural and ongoing," a more careful reading of paleoecological records shows that extreme climatic shifts of the past would be most unwelcome in today's world with more than 7 billion human beings in the picture.

## **CLIMATES OF THE FUTURE: THE LONG TERM**

What does the future hold? Climates will continue to change as they always have, but the effects of human presence will redefine the baselines upon which natural variability plays out. We are essentially loading the world's weather dice through a hotter, more vigorously circulating atmosphere. The limitations of models along with uncertainties regarding human behavior and technology forbid precise portrayals of what lies ahead, but the general direction and nature of global-scale changes are clear. The more greenhouse gases that we release, the higher global mean temperatures will become and the farther inland oceans will advance. Paleoclimate records also show that, in general, large-scale warming has tended to increase the water content and extent of monsoon systems, to shift mid-latitude storm tracks poleward, and to reduce the extent of ice sheets, glaciers, and sea ice.

Surprises can also emerge from such a complex system, however. For example, although much of tropical Africa became more arid during northern hemisphere coolings and tends to experience more intense rainfall in years just prior to solar maxima, an as-yet unexplained reversal of the cool-dry, warm-wet relationship produced dramatic lake level rises in East Africa during a prolonged solar minimum of the cool Little Ice Age, thereby weakening confidence in our understanding of how tropical climates operate (Stager and others 2005, 2007; Verschuren and others 2009). It has also been proposed that retreat of Arctic sea ice during recent years has contributed to rapid, erratic, and extreme swings in regional climates of the northern hemisphere (Francis and Vavrus 2012). We will not be able to model our way into complete preparedness for everything that the climate system may do in the future, but reasonable generalizations can nonetheless be made from long-term perspectives on the nature and causes of climate change.

One source of insights into future carbon dioxide dynamics is the work of scientists such as David Archer, whose pioneering research at the University of Chicago has been corroborated by other investigators as well (Archer 2005; Archer and Brovkin 2008; Eby and others 2008; Schmittner and others 2008). The astoundingly long-term views of the future that these studies provide show that we are setting in motion a much larger and longer-lasting array of disruptions than the relatively short-term global temperature rise that currently occupies our attention (Stager 2011).

At the heart of these findings is a simple question: “where does carbon dioxide go when it leaves our smokestacks and tailpipes?” Roughly three quarters of it will dissolve directly into the oceans during the next several centuries to millennia, leaving slow weathering of carbonate and silicate minerals to wash the airborne remainder into the sea over tens of thousands of years (Figure 3). When fossil fuel emissions inevitably level off and decline, whether by design or by depletion, marine uptake will cause atmospheric CO<sub>2</sub> concentrations to level off and then to drop nearly as steeply as they rose until the oceans can absorb no more and mineral reactions more slowly consume the leftovers. During the relatively brief turnaround phase of “climate whiplash,” many of the selection pressures that operated in the context of rising temperatures may swing into reverse during the cooling that follows (Stager 2011).

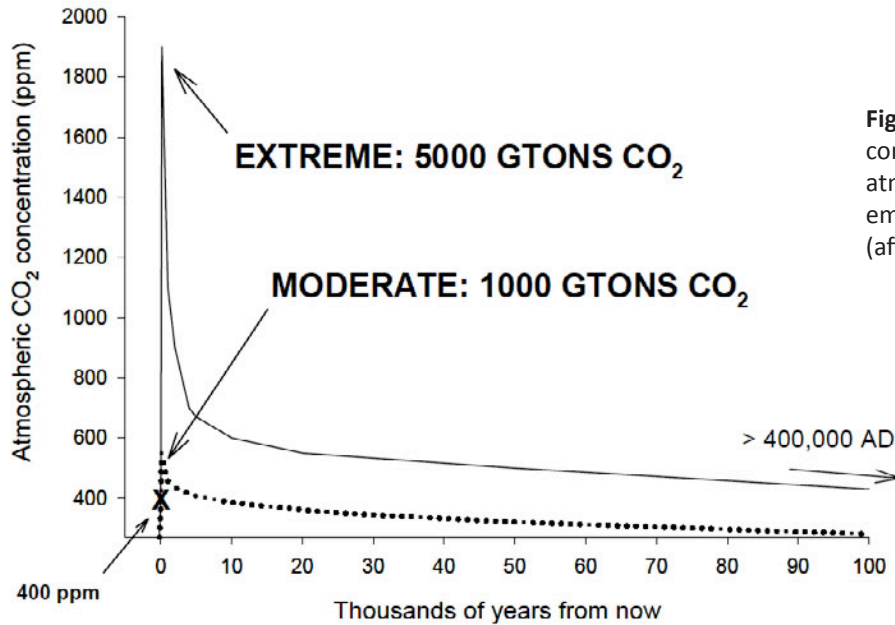
The form and timing of the peak, whiplash, and the long tail of the cooling-recovery curve will largely depend upon how much carbon dioxide we release during the next century or so. In a relatively moderate emissions scenario such as B1 (IPCC 2007) in which non-fossil energy sources quickly replace coal, oil, and gas, approximately 1000 gigatons (Gtons) of carbon will have been emitted since the Industrial Revolution. If instead we burn all remaining fossil fuel reserves in a scenario more like A2 (IPCC 2007), then a total discharge of closer to 5000 Gtons is more likely. This would lead to a higher, later, and more protracted peak and a much longer recovery (Figure 3).

In one moderate scenario in which emissions decline after AD 2050, atmospheric concentrations of CO<sub>2</sub> reach 550–600 ppm by AD 2200 (Figure 3; Stager 2011). At thermal maximum around AD 2200–2300, global average temperatures are 2–4°C higher than today. After a whiplash stage lasting several centuries, CO<sub>2</sub> concentrations decrease steeply for several millennia due to marine uptake, and then fall within the range of pre-industrial conditions after tens of millennia, possibly as long as 100,000 years. Even in this relatively mild case, the thermal effects of the excess carbon dioxide in the atmosphere are likely to prevent the next ice age, which orbital cycles could otherwise trigger around AD 50,000 (Berger and Loutre 2002; Archer and Ganopolski 2005).

In a more extreme scenario, CO<sub>2</sub> concentrations peak close to 2000 ppm around AD 2300 and take at least 400,000 years to recover (Figures 3,4; Stager 2011). The whiplash stage lasts for several thousand years, producing a seemingly stable plateau of PETM-style warmth 5–9°C warmer than today that could persist long enough for ecosystems and cultures to co-evolve with before the long recovery period destabilizes them again.

In both scenarios, the staggered responses of temperature and sea level to changing CO<sub>2</sub> concentrations further complicate environmental settings for future forests as well as for human beings. In Figure 4, for example, global mean temperature continues to climb for several centuries after the CO<sub>2</sub> peak, and sea levels continue to rise for thousands of years after the thermal peak because the temperatures are still high enough to melt continental ice masses.



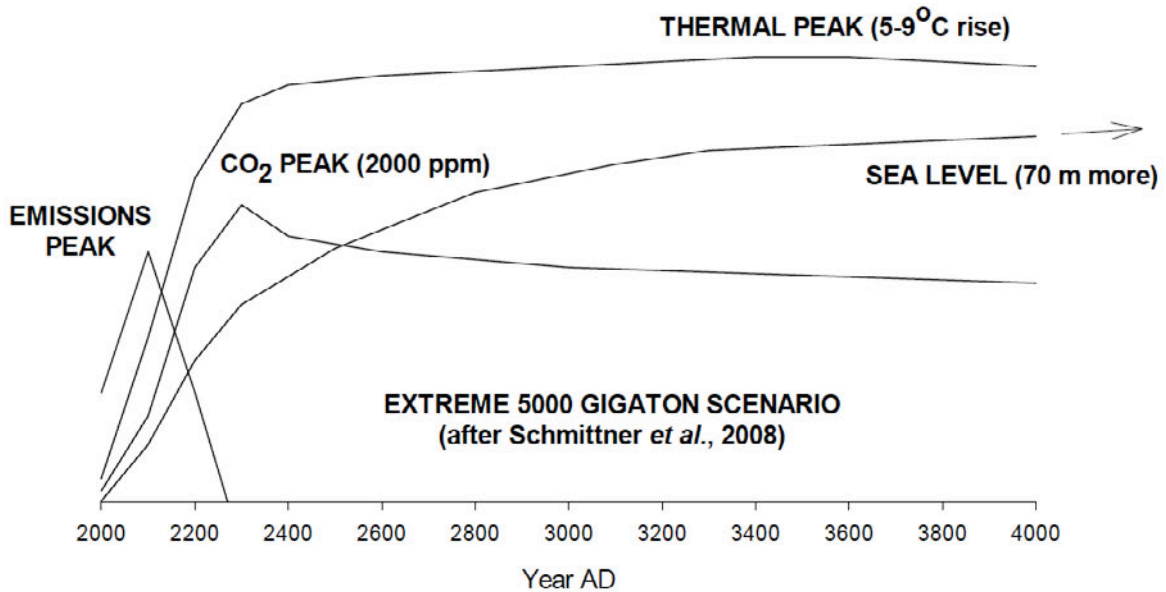


**Figure 3.** Carbon dioxide concentrations in the atmosphere under two emissions scenarios (after Archer 2005).

What does the geological record reveal about possible consequences of such scenarios for future forests? The more moderate case has much in common with the Eemian Interglacial. Although it was not caused by greenhouse gas buildups, it did produce conditions warmer than today in many locations, particularly during summers in the northern hemisphere. Even though it lasted for about 13,000 years, it failed to de-ice the planet entirely, and polar bears and other arctic biota survived it. Extensive poleward migrations of forests and animals resulted, and rapid changes in sea level followed sporadic destabilizations of ice sheets, eventually submerging much of Florida.

The more extreme case has much in common with the PETM, which did result from a greenhouse gas release comparable to our own. Fossil carbon is depleted in the stable isotope,  $^{13}\text{C}$ , and a dramatic global decline in  $\delta^{13}\text{C}$  in PETM sediments due to enormous geological inputs of fossil carbon into the air and oceans is a diagnostic marker for that event. A similar global dilution of  $^{13}\text{C}$  content of the world and its inhabitants is currently under way as a result of our own fossil carbon emissions, and its isotopic signal is being preserved in the geologic record as an anthropogenic sequel to the PETM. Warming during the PETM increased the intensity of rainfall, weathering, and runoff over most of the planet, and it left no refuge for cold habitats.

Conditions similar to those of the PETM are likely to develop again in a “burn-it-all” emissions scenario, but several factors will differ in an Anthropocene reprise of former hothouse states. A modern return to the  $\text{CO}_2$  concentrations and temperatures of 56 million years ago would involve increasing those parameters from a much lower thermal baseline that currently allows extensive cold-dependent ecosystems to exist at high latitudes and altitudes. The overall pace of the changes associated with such a return to an ice-free world, were they to occur over a span of several centuries, would outstrip those of the PETM and similar greenhouse warmings of the earlier Cenozoic which occurred when the atmosphere and oceans were already warmer than now (Figure 1).



**Figure 4.** Sequential environmental changes expected in an extreme 5000 Gton carbon emission scenario (after Schmittner and others 2008).

The responses of forests so far back in time may not be directly comparable to those of the Anthropocene, but more recent sediment records suggest that many of today’s plant species may be quite resilient to climatic fluctuations if they are free to migrate in response. Pollen and other data from Arctic Russia show that when summer temperatures there were 8°C or more higher than today 3.5-2.5 million years ago, forests in the region changed their geographical distributions and abundances but still consisted of larch, pine, birch, alder, spruce, and other taxa that have also persisted through multiple glacial and interglacial periods to the present day (Brigham-Grette and others 2013). Human presence, however, could seriously restrict such adaptive movements during the Anthropocene.

We cannot know exactly what new technologies will eventually arise or how future societies will respond to the climatic settings that we bequeath to them. Perhaps an ice-free Arctic will come to seem both natural and preferable to the frozen state that we now consider to be normal, and what we would call “recovery” might be experienced as a global cooling disaster thousands of years from now. Even so, potentially important insights arise from such long-term perspectives:

- (1) Human influences on the planet have become more powerful than many of us yet realize.
- (2) Rapidity of climatic change can be more ecologically stressful than the magnitude or direction of change. The last century’s warming (ca. 0.7°C) proceeded at least twice as quickly as the onset of the Eemian Interglacial, and in an extreme emissions scenario global mean temperature could rise by 2-5°C per century between now and AD 2300 (Figure 4), significantly faster than the onset of the PETM.
- (3) Although extreme climatic instability has occurred before, the restriction of free migration and other human impacts now make such instability more challenging for species and ecosystems of the Anthropocene.

## CLIMATES OF THE FUTURE: THE 21ST CENTURY

Although the upward direction of global average temperature change is easy to anticipate, variable responses within different components of the climate system will make accurate prediction of regional and local-scale conditions difficult. Long-term, global-scale climates are easier to simulate and predict than the more here-and-now, down-to-earth scales of change that many forest managers and urban planners deal with. The inherent limitations of global climate models can be magnified when they are downscaled to focus on relatively short time scales and specific regions, and demand for detailed projections on the regional and local scales sometimes leads people to ask more of climate models than they can reliably produce (Hulme and others 2009; Hefferman 2010; Schiermeier 2010; Trenberth 2010). The limitations of global climate models are often magnified when they are downscaled to focus on relatively short time scales and specific regions, and linking these in turn to models of hydrology or biological processes can amplify errors further (Schiermeier 2010; Trenberth 2010; Beier and others 2012).

A recent comparison of 16 commonly cited models that were downscaled to the Lake Champlain watershed of Vermont and New York illustrates some of the problems that may be faced in such studies (Stager and Thill 2010). All of the models anticipated significant warming by AD 2100, but they disagreed on the magnitudes and seasonality of the changes. The question of seasonality has serious implications for forest ecology because the distribution of temperatures through the year affects ecologically important factors such as snowpack, spring runoff, and net water balance in summer. Perhaps the most reliable projection regarding future temperature in this region may simply be that it will increase as greenhouse gas concentrations rise, which one could conclude even without the aid of models.

Precipitation patterns are also important to forests, but they are more difficult to simulate and to predict (Schiermeier 2010). Precipitation can vary tremendously over small geographical areas, making it difficult to obtain accurate observational records of regional precipitation alone, much less to develop accurate predictive models. Topography, humidity, wind direction and speed, albedo, and other factors further complicate regional-scale modeling of future precipitation. ENSO also strongly influences precipitation patterns around the world, but there is as yet no consensus regarding its likely behavior in the future, and similar uncertainty obscures the future of the North Atlantic Oscillation, Pacific Decadal Oscillation, and other sources of variability, as well (IPCC 2007). In the case of the Lake Champlain study, the 16 regional precipitation scenarios varied in magnitude, seasonality, and even in the direction of trends. Although it is common in such cases to note that the ensemble average of the models states thus and so, it is difficult to know in advance which models are the most accurate, and sticking with the majority may mean rejecting a more reliable minority.

Despite these limitations, observational data and paleoclimate records can document regional and local patterns that have accompanied global-scale changes of the last century, and which can help to inform speculations about future changes. Such data indicate that poleward retreat of the austral westerly wind belt in a warming future could reduce winter rainfall over southwestern Australia and the fynbos region of South Africa (Bjostoch and others 2009; Stager and others 2012). A warmer atmosphere is likely to be more energetic and turbulent and to carry more water vapor from the oceans and vegetation (IPCC 2007), and an associated widening of the tropical rain belt has already been observed (Seidel and Randel 2007). The effects of such processes are

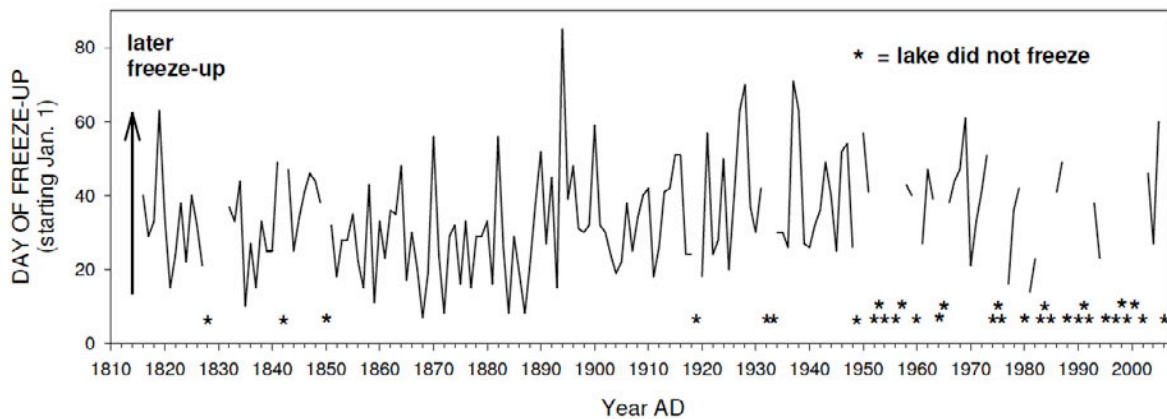
also apparent in historical records of decreasing ice cover on Lake Champlain and a recent rise in the intensity of extreme precipitation events which, in turn, supports model projections of similar trends in a warmer future (Figure 5; Stager and Thill 2010).

Even if climate models cannot tell us exactly what will happen in the future with complete certainty, they can still provide valuable examples of what realistically could happen. High-quality, multi-parameter simulations can reveal unexpected consequences from perturbations in complex systems that might otherwise be overlooked, and they provide ballpark ranges of variability that can sometimes be refined further through reference to historical records. The spectrum of precipitation variability suggested by diverse arrays of models may also provide helpful estimates of the possible magnitudes of such changes.

As noted in the case of the Champlain watershed, most downscaled models anticipate warmer and wetter conditions by AD 2100, but some suggest that aridity may prevail in some seasons as well (Stager and Thill 2010). Preliminary results from the analysis of fossil diatoms in lake sediment cores indicate that severe droughts occurred in the Champlain basin during the Medieval Climate Anomaly, which links warming to aridity as the minority of models do. However, extreme droughts also occurred during the subsequent cool Little Ice Age, and local observational records show higher lake levels and rising storm intensities have accompanied warming since the 1960s. From what at first appears to be confusion over the future of precipitation in this region, a useful insight emerges: we cannot expect precipitation patterns in the watershed to remain stable, nor can we expect them to be entirely predictable. This, in turn, highlights the need to build resilience into forest management plans.

#### FOREST MANAGEMENT IN THE ANTHROPOCENE

Forests have long experienced climatic instability in the past, but the most extreme, global-scale disruptions were uncommon in relation to the lifetimes of individual organisms. In addition, most of those events were not accompanied by very large increases in atmospheric carbon dioxide concentrations: Eemian CO<sub>2</sub> levels, for example, remained well below the 400 ppm that prevails at the time of this writing. Perhaps most importantly, none of the extreme climatic shifts of the past occurred while such a large array of additional anthropogenic factors were in operation.



**Figure 5.** Freeze-up dates for the main body of Lake Champlain. Asterisks indicate winters in which the lake did not completely freeze (after Stager and Thill 2010).

We are sailing into an uncertain future with no exact historical analogs to inform us and little more than educated guesswork to guide us, but it is clear that the rapid pace and global extent of Anthropocene warming will make it increasingly difficult to preserve biotic communities in their present form.

The ecological effects of long-term climatic change may be particularly abrupt on regional and local scales when physiological or physical thresholds are crossed. When winter temperatures are no longer cold enough to exclude an herbivorous insect or pathogen from a habitat, sudden changes in forest composition may result (Dale and others 2001), and the melting point of snow and ice is a fixed boundary across which today's seasonally cold ecosystems will be pulled as the world warms. Old-growth forests that were established in western North America under cool, moist conditions of the Little Ice Age may become increasingly vulnerable to sudden replacement by other taxa through future disturbance events (Willis and Birks 2006). In addition, latitudinal shifts and meanders in major wind belts can bring rapid, extreme climatic changes to sites that lie adjacent to or beneath them.

Paleoecological records show that vegetational communities did not always move as coherent units during climatic shifts of the past, and differential migration rates and climatic tolerances of different species will likely produce new combinations in a warming future (Pitelka and others 1997; Williams and Jackson 2007). As paleoecologist Tom Webb (1988) once said, "plant assemblages are to the biosphere what clouds, fronts, and storms are to the atmosphere... they are features that come and go." Current distributions of tree species do not necessarily reflect their true potential bioclimatic niches, which may further limit our ability to predict their responses to future changes, and the effects of climatic shifts on animal communities can indirectly influence forests as well. The recent lack of winter ice on Lake Superior, for example, may be helping to alter forest structure on Isle Royale because it more fully isolates the local wolf population from the mainland. The negative effects of inbreeding among the wolves, in turn, encourage resident moose populations to expand and more heavily browse the island's forests (Mlot 2013).

As warming pushes isotherms poleward in coming centuries, they may force taxa to enter regions in which their preferred soils, precipitation patterns, and/or light regimes are not available, and no-analog communities and novel environmental settings are likely to emerge in the future as they have in the geological past (Williams and Jackson 2007). If rising temperatures open the high Arctic to colonization by forests, for instance, plants that can tolerate the long darkness of circumpolar winters will be most likely to replace what is now tundra, potentially creating vegetational assemblages that have not existed since the early to mid-Cenozoic or, possibly, at any previous time in history (Sturm and others 2003).

Although human intervention may produce new or "unnatural" ecosystems in the future, paleoecological records show that novelty is not unusual in Earth history. Humans have been affecting forest composition for tens of thousands of years, and differential rates and modes of dispersal in the face of environmental instability have often led to new combinations of species. Some of the vegetational communities that we are familiar with today are surprisingly young; oak savannas of northeastern Iowa and grassy montane parklands of northwestern Wyoming originated roughly 3000 years ago, ponderosa pine forests of the Bighorn Basin arose 2000 years ago, and mixed northern hardwood/conifer forests of northeastern Michigan may be only a thousand years old (Jackson 2006 2012). In light of the ephemeral nature of many plant communities and the

huge extent of the modern human footprint, a long-term Anthropocene perspective suggests that managing ecosystems in ways that include difficult trade-offs, triage, or new combinations of species does not necessarily make them too unusual or unnatural to be desirable (Kareiva and others 2007).

Human behavior will probably have the largest but least predictable influences on the future of forests in the Anthropocene. The amount of heat-trapping carbon emissions that we eventually release will determine the trajectory of climatic change for tens of thousands of years to come. Our definitions of desirable and undesirable species and ecological processes are likely to change over time, with enormous consequences for the future of biodiversity. And in a world where the human presence can both aid and hinder the adaptive migration of species, our ability to help organisms to colonize new settings will become increasingly critical to their survival.

The unsteady nature of future climate will make the long-term stability of many forest communities an impossible goal, particularly for those that are confined within static and/or shrinking borders. Flexibility and resilience in the face of environmental and cultural change will become ever more important to the sound management of ecosystems in this new and unprecedented Age of Humans.

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# Evidence-based Planning for Forest Adaptation

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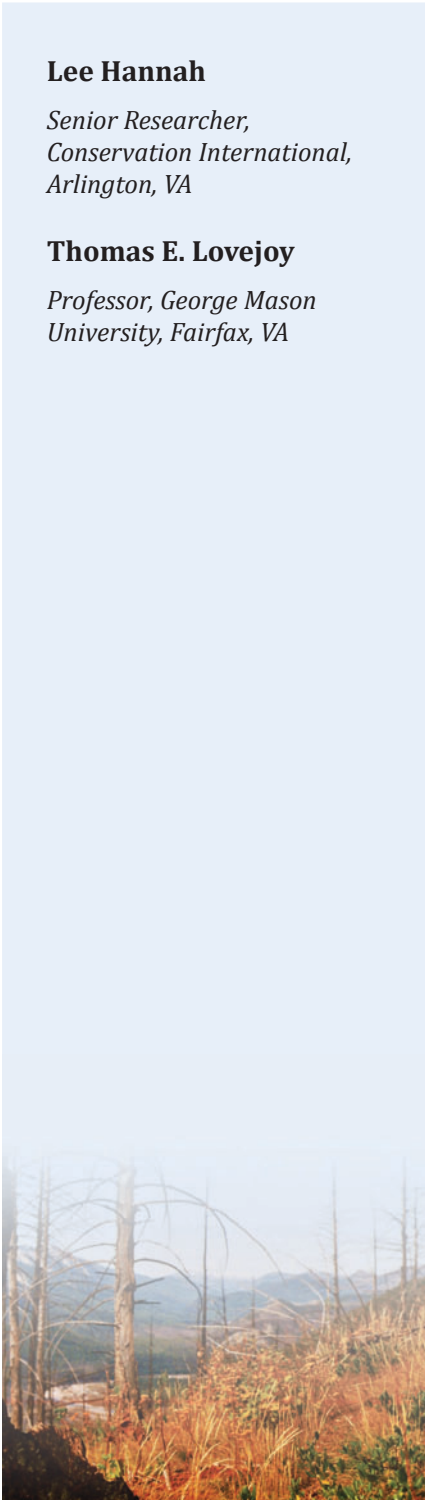
***Abstract:** Forest conservation under climate change requires conserving species both in their present ranges and where they may exist in the future as climate changes. Several debates in the literature are pioneering this relatively novel ground. For instance, conservation planning using species distribution models is advocated because it uses information on both exposure to climate change and species' sensitivities to climate change, while approaches focusing on land facets are advocated because there is uncertainty regarding both exposure and sensitivity. Other debates include assisted/managed migration versus natural dispersal as management paradigms and long-distance dispersal versus microrefugia as mechanisms of plant dispersal in the face of climate change. While these debates are invaluable to understand these new problems, in practical conservation planning they can become a barrier to effective action. Investing exclusively in one approach is a poor strategy in the face of uncertainty. A well-resourced conservation plan should draw information from multiple approaches (e.g., modeling, land facets and expert opinion). A formal portfolio theory can integrate results from multiple approaches and provide better long-term conservation results in the face of uncertainty in the Anthropocene.*

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## INTRODUCTION

Planning for forest conservation under climate change requires clear targets and stakeholder buy-in. Multiple lines of evidence are available to assist in climate change planning efforts, including paleoecology, modeling, geographic species distribution, and abiotic information such as soil type, slope and aspect.

All lines of evidence carry substantial uncertainty with respect to understanding future forest responses to climate change. Paleoecological responses to climate change are not perfectly analogous to future climate change—particularly the best known, the transition from the Last Glacial Maximum, which was warming from cool conditions as opposed to current climate warming which is occurring from already warm interglacial conditions (Bush 1996). Modeling carries uncertainties associated with both climate models and species' response models (Thuiller and others 2004).



Abiotic factors play key roles in mediating species' response to climate change, but cannot address species-specific climate sensitivities and therefore carry substantial uncertainties in understanding forest response to future climate change.

When addressing high uncertainty and multiple sources of uncertainty, drawing on multiple lines of evidence can be informative (Heller and Zavaleta 2009). However, many debates on climate change assessment fragment the field. Modelers argue with non-modelers about the level and sources of uncertainty (Pearson and Dawson 2003). Some conservation planners favor conserving the abiotic “stage” on which climate change response is played out (Anderson and Ferree 2010), while others favor targeting the “actors” in response—the species (Hannah and others 2007).

Adherence to one side or the other can limit information available for assessment. Here, we briefly summarize some of the debates and discuss how to formulate action while the debates continue. We argue that the most robust plans will be those that draw evidence from both sides of the debates.

## **CONSERVATION TARGETS**

Conservation targets for forest conservation planning can vary from biodiversity, to retention of ecosystem services to recreation. Selecting targets is largely a social process, and will determine the most relevant lines of evidence for conservation planning for climate change (Pressey and others 2007; Mawdsley and others 2009). Scientists play a critical role in the social process, helping to explain the importance of clear, defined targets and delineating the costs and rewards of different approaches to analyses.

Targets that are relevant under current climatic conditions may no longer be appropriate in a context of climate change. For instance, parks designated for the protection of high profile species may no longer harbor those species as climate change forces the species to move to suitable climate and habitat. This does not mean that current protection should be abandoned; it rather means that current targets have to be assessed in light of possible climate-driven changes. New targets may be needed to supplement or replace current conservation targets.

Unfortunately, in forest conservation planning, targets are sometimes not explicitly and transparently defined. This can contribute to varied expectations among stakeholder groups. For instance, scientists may assume biodiversity as a target, while the general public expects a target that has recreational benefit. This makes it difficult to efficiently access multiple lines of evidence and may foster or create false dichotomies in analytic approaches.

## **CONSERVING THE STAGE VERSUS CONSERVING THE ACTORS**

Two emerging schools of planning focus on ‘conserving the stage’ and ‘conserving the actors’. The theatrical analogy was initially posed for somewhat different reasons in “The ecological theater and the evolutionary play”, a collection of lectures by G. Evelyn Hutchinson (1965). The ‘stage’ is the biophysical template provided by the environment, while the ‘actors’ are species (Anderson and Ferree 2010).

One method for climate change planning is to conserve representative samples of the physical environment (soils, slope, aspect, and hydrology) that are relevant to species' distributions (see Anderson and others, this volume). By conserving the 'stage' (physical environment) and allowing climate change to unfold, the 'actors' (species) will be conserved (Anderson and Ferree 2010). A more direct approach simulates the movements of species in response to climate change, thereby conserving the 'actors' directly (Hannah and others 2005).

Since there is high uncertainty in climate and species distribution models, conserving the 'stage' provides a solid template on which species can respond on their own to climate change. This approach is less liable to systematic error because it is not biased by limitations in the understanding of species' sensitivities or accuracy of climate models.

Advocates for conserving the 'actors' assert that species' response to climate change is the product of exposure and sensitivity. Physical factors such as soils, slope and aspect are key elements in modulating climate change, but advocates of the 'actors' believe that species' niches must be considered to understand biological response and develop effective conservation plans.

The debate persists, in part, because of the challenges for distinguishing between the results of the two approaches. One test pitted the two approaches against one another in conserving species from the Last Glacial Maximum (LGM) to the present (Williams and others 2013). Using species and climate information from the LGM, this study reproduced conservation planning results obtained with current data. The abiotic 'stage' approach fared poorly, while the 'actors' approach showed positive correlation with plans made with current species' distributions. However, the data used in the 'stage' approach was very simple (latitude, longitude, elevation—no soils), so the test may put the 'stage' approach at an artificial disadvantage. It remains indisputable that climate models and species' distribution models (SDM) carry substantial uncertainties, so the attraction of the 'stage' approach is avoiding simulations and much uncertainty associated with modeling (while adding uncertainty associated with ignoring species sensitivities altogether).

## **MODELING VS. NON-MODELING APPROACHES**

In addition to the 'actors' versus 'stage' dichotomy is an ongoing debate between modeling and non-modeling approaches in understanding the biotic impacts of climate change (Pearson 2006). Species' Distribution Models (SDM) ignores a large body of transient effects and species interactions because there is an assumption that species' ranges are in equilibrium with climate. Experimental approaches show that competition and system interactions may result in strong changes in ecosystem response to climate change over time (Suttle and others 2007). Non-modeling evidence offers important insights unavailable through modeling. This does not mean modeling should be ignored, however, as models help us to understand past, current, and future trends which are a necessary part of research. Although models have limitations, they provide important (and perhaps otherwise unforeseen) cues. Models can help frame research agendas and provide preliminary answers while long-term research unfolds. In the physical sciences, modeling is well accepted in climate change analyses and policy-making. The fact that modeling is so much easier and quicker than long-term field experiments has resulted in the publication of far more modeling studies, perhaps out of balance to their value.

## **ASSISTED MIGRATION VS. NATURAL COLONIZATION**

Assisted migration, also known as managed translocation, is receiving increasing attention (Williams and Dumroese, this volume; McLachlan and others 2007; Hoegh-Guldberg and others 2008). As human-induced climate change may exceed rates of historical natural climate change, some species may not be able to keep pace with current changes in climate. To help these species survive, it may be necessary for us to move propagules or adults into suitable climates over time.

Plants have demonstrated long-distance range shifts over time in response to climate change (Clark and others 1998). Perhaps there are natural mechanisms, especially long-distance dispersal events, that are too rare to be commonly observed but which still occur frequently enough to allow rapid range shifts when the climate changes. If such mechanisms do exist, assisted migration may disrupt natural ecological processes, and conservation efforts by introducing un-natural range dynamics and competition.

## **ECOLOGICAL BENCHMARKS VS. NO-ANALOG COMMUNITIES**

Paleoecological data make it clear that species move individually in response to climate change—one species may move at different rates and in response to different climatic cues than another species. As a result, vegetation associations are ephemeral and will change over time. This creates a problem for conservation planning. If species associations are not fixed, then ‘vegetation type’ is not a viable benchmark for conservation (Williams and others 2001). At least two responses have been proposed to this dilemma.

Non-analog communities (communities which do not exist in current climate) are simply to be accepted as the norm. In the extreme, there is no such thing as a ‘natural’ community. Species combinations that don’t currently exist should be accepted, even in situations where the species is not currently native.

An alternative view is that ecological benchmarks (for instance, condition before human arrival) remain valid and management should pursue these benchmarks. Maintaining current communities artificially (e.g., through fire or fire suppression) is an acceptable management endpoint. In our view, this is practical when climate change is minimal and gradual, but can rapidly become impossible with the kinds of anthropogenic climate change that seem to lie ahead. This latter is recognized in the “Revisiting Leopold” report to the Secretary of the Interior (NPS 2012) because of the lag in understanding ongoing change.

## **LONG DISTANCE DISPERSAL VS. MICRO-HABITATS**

A mounting body of evidence suggests that tree populations may have expanded from microrefugia near ice sheets as climatic conditions became more favorable, rather than colonizing over long distances from southern macrorefugia (McGlone and Clark 2005). Other evidence suggests that long-distance dispersal of seeds is critical to the recolonization of plants over large distances after the LGM. If microrefugia were the major mechanism in post-LGM range expansions, then conserving micro-habitats and landscape connections is critical. If long-distance dispersal dominates the mode of range expansion, then connectivity is less critical and identifying and maintaining populations of long-distance dispersers is central.

## THE VALUE OF MULTIPLE LINES OF EVIDENCE

Scientific, political and social debates can be an asset or a barrier to developing effective forest conservation plans. They are an asset when considered collectively in the assessment process, but become a barrier when professional interests on one side of the debate exclude information offered by the other side. A well-resourced assessment should be able to draw on information from both sides. The debates persist because there is substantial uncertainty. In such situations, using multiple lines of evidence and investing in a portfolio of outcomes makes sense over investing in a single approach (Ando 2012).

Using multiple lines of evidence may seem contradictory to policy-makers and stakeholders. If models are uncertain, why do we use them? If we aren't sure that conserving the 'stage' provides useful surrogates for the movements under climate change, then why bother? Models and the 'stage' approach provide information, but when combined, are more robust than a single approach. Multiple lines of evidence don't provide a 'right' answer, rather they help provide solutions. For example, in an assessment in which the conservation target is biodiversity, modeling approaches that seek to 'conserve the actors' can be combined with approaches that 'conserve the stage'. The assessment would take not only areas of agreement, but also areas of disagreement, to create a portfolio of conservation areas robust to prevailing uncertainties. An assessment focused on ecosystem services might use abiotic stratification to maintain representation of land types or land facets, while using ecohydrological modeling to identify areas important to protect based on interactions of vegetation and the physical landscape.

Assessment resources can be allocated to developing multiple lines of evidence based on 1) what is possible (in the assessment timeframe), and 2) what contributes most to reducing uncertainty. For example, in an assessment of a temperate forest with 3 dominant species, there may be physiological data available that make it possible to develop a model of physiological response to climate change for the dominant tree species. Conversely, in an assessment of a tropical forest where data may be lacking, we can rely on a species distribution model (SDM) that requires only species occurrence data.

A recent species conservation study illustrates these points. Thorne and others (2013) examined the impacts of climate change on several possible forest conservation scenarios for mountain gorillas (*Gorilla beringeiberingei*) in east-central Africa. The conservation scenarios employed included restoring forest to connect mountain gorilla populations, annexing adjacent forest to existing parks, and retaining 'status quo' of existing parks only. The implications of climate change for these scenarios was explored through a series of modeling tools, including SDM, gorilla behavior models, and models of limiting plant resources. Different models offered strongly different views of the possible future. Some suggested that gorilla habitat might remain stable, while others simulated large losses of mountain gorilla forest habitat. The study left decisions about conservation action in the face of climate change to the conservation community, but clearly laid out the implications of different lines of evidence (models). It allowed decisions to be made based on a representation of possible model results, without endorsing any one individual model over another. The strength of the study was defining the decision space and populating it with plausible evidence, laying out assumptions and consequences without taking sides. Other analyses of forest conservation under climate change would benefit from similar approaches.

Allocation based on uncertainty reduction may be more complex. Precise calculation of uncertainty reduction may not be possible, yet it is clear that using both lines of evidence from one of the aforementioned dichotomies will be more robust in the face of uncertainty than investing in one side. For instance, an abiotic assessment using GIS layers would be a sound investment in conjunction with a moderately complex SDM effort over a highly complex SDM effort with no abiotic analysis.

The selection of clear conservation targets (e.g., biodiversity, ecosystem services) is critical in selecting relevant lines of evidence. Too often, conservation targets are implicit or undefined, leading to assessment methodology chosen by adaptation scientists based on their interests (e.g., biodiversity or ecosystem services) when stakeholders may place greater emphasis on other factors (e.g., open space and recreation). Scientists are not only stakeholders, but they are decision makers that serve to develop clear and explicit assessment targets.

## CONCLUSION

The impact of climate change on the biology of forests is clear and growing rapidly. Knowledge for forest management under these conditions understandably lags behind the need for action and decisions. At this early stage of understanding, different perspectives, such as “The ecological stage” (represented by the abiotic environment) vs. “The actors” (represented by species and individual organisms), can collectively contribute to pragmatic management and planning decisions.

Planners must also be aware that climate change doesn’t act in isolation. The human footprint on the planet is growing, and habitat loss to agricultural frontiers and other human uses will continue. Planning for climate change needs to be done in the context of ongoing habitat loss and other threats. When it does, there is great hope for robust forest conservation actions that will endure well into the future.

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# Adapting Forest Science, Practice, and Policy to Shifting Ground: From Steady-State Assumptions to Dynamic Change

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***Abstract:** What forestry needs in the Anthropogenic Era is what has been needed for the past 30 years. The proper methods, theory, and goals have been clear and are available; the failure has been, and continues to be, that our laws, policies, and actions are misdirected because we confuse a truly scientific base with nonscientific beliefs. The result is a confusion of folklore and science that is counterproductive, both for forests and for human needs and desires. Our love of forests gets confused with our attempts to understand them. In the practical world of incomplete knowledge, our management of forests needs to make use of what I call naturecraftsmanship, the art of science and practice, a sort of General Practitioner's approach to the use of medical research. We will not love forests less but like Thoreau, understanding the distinction, appreciate them more deeply. This paper explains what science, scientific concepts, measurements, and theory could be used, and discusses the deeper dilemma of our confusion of belief and knowledge.*

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## INTRODUCTION

My work in ecology began in forests, and forests continue to be a major emphasis. I have spent almost half a century trying to understand how forests work, and to use that understanding to solve forest-related environmental problems and to come to know the ways that forests are important to us, in addition to being sources of timber and other resources. I would like to share what I have learned, in the hope that it will improve the way we manage, use, and conserve forests in the 21st century. To understand forests as environments and how we are managing them and should manage and conserve them, we have to deal with three questions: Who owns and controls our forests? How do management and concepts have to change? And what has happened to public attitudes, interests, and appreciation of forests.



## **FOREST OWNERSHIP HAS CHANGED GREATLY IN THE 21<sup>ST</sup> CENTURY, WITH MAJOR EFFECTS ON CONSERVATION AND MANAGEMENT**

Until the 1980s, most U.S. private forests were owned by 15 major timber corporations, and forest research was expanding. Today, none of the major timber corporations own any significant forestland. They sold their forests, and now the major large private owners are real estate investment trusts (REITs) and timber investment management organizations (TIMOs). From the environmental side, the Nature Conservancy has grown to become one of the largest owners of private forestland in our nation. One cannot overestimate the importance of this change, but oddly, almost nobody knows about it, and almost nobody talks about it.

According to Peter Stein, writing in *Forest History Today*, “By 2004 only six of these fifteen were traditional forest product companies; of the remaining nine, seven were TIMOs and two were REITs. In 2010, only one of the top fifteen U.S. forestland owners was a traditional owner, while ten were TIMOs and four were REITs. In addition, since 1995, more than half of the nation’s 68 million acres of private industrial timberland has changed hands, most within the period from 2000 to 2005” (Stein 2011).

Before this change in ownership, forest corporations and environmentalists held many different opinions about how forest should be managed, but both were in it for the long term. Timber companies saw their profit from the sustained yield of their lands. But a primary goal of REITs and TIMOs is to make a profit by buying and selling land. There is less inherent incentive for sustainable forest management. Some REITs seem to be attempting to do a decent job of forest management, but those of us who hope for best management have to add a new level of watchfulness and action.

Forest research and its funding appear to have declined since the 1980s, when forestry was one of the central environmental issues. The traditional timber companies supported their own research, some of it substantial, like that of Weyerhaeuser Corporation. Research conducted by the fifteen previous major traditional timber companies is gone. In addition, a 2002 National Academy of Sciences (NAS) report noted that “the USDA [U.S. Department of Agriculture] Forest Service has experienced a 46 percent decrease in number of scientists in the last 15 years, from 985 in 1985 to 537 in 1999.” Since then the number of USFS [U.S. Forest Service] scientists has dropped even more, to 498 in 2008, the most recent estimate I have found (Committee on National Capacity in Forestry Research 2002). I note, however, that because research in forests is funded by DOE, NSF, USGS, NOAA, NASA and EPA in addition to the USFS, and is also funded by some private foundations, the apparent decline stated in the NAS cannot be completely substantiated. Still, the drop in in-house Forest Service research scientists is of concern in itself.

This NAS report warns “the waning Forest Service research base may be challenged as demands on forest resources increase. Enhancing the nation’s forestry-research capacity must deal with the tangible matters of substance—funding, facilities and equipment, and personnel—and with intangible matters of perception and values—priorities, organizations, structures, and leadership” (Committee on National Capacity in Forestry Research 2002).

Our current task, therefore, seems much more difficult and complex than it did 30 years ago. Even then, available data were generally inadequate for scientifically guided management. If the NAS report concerning U.S. Forest Service research scientist staff is representative of forest research in general, then it may also be true that today there is less information being collected and available. In addition, the data collected are often based on framings that are not helpful to today's practitioners.

## **SOME BASIC PRINCIPLES OF FOREST ECOLOGY**

To provide a context to discuss the future of forests, we have to accept that *nothing in the environment is constant; everything is always changing*. Ecosystems, species, and populations continuously vary with or without human influence. There is no balance of nature and there never has been (Botkin 2012; Botkin and others 1991). *Since the environment has always changed, all life has evolved with and adapted to environmental change*. Many species, perhaps most, require environmental change to persist (Heinselman 1973; Covington 2003; Noss and others 2006; Botkin 2012). Another consequence of the ever-changing character of nature is that *there is no single best state of nature*, not in terms of the persistence of species, of ecosystems, nor in terms of what is perceived as most useful and beneficial to people (Botkin 2012).

When people believed in a balance of nature, they also believed that there could be only one best state of nature: a (supposedly) constant state. In an ever-changing nature, it is possible in the abstract that there might be one best state, but in reality this is not the case. Our approach to conservation and management of forests must also include humility: *We can affect, but only partially control, Earth's environment*. As Buckminster Fuller put it, our problem is that we live on a planet that didn't come with an instruction manual. Globally, our environment is a set of very complex systems, none in a steady state, each affecting the others, and which we are only beginning to understand.

Furthermore, *people have altered the environment for at least 10,000 years, probably much longer* (Romer 2013). What people used to consider "virgin" nature—never touched by people—is turning out in surprisingly many cases to have been greatly affected by people. People have altered Earth's land surfaces for thousands of years (Ellis and others 2013). In Switzerland, pollen deposits dating ca 6,700 BCE indicate the presence of agricultural plants, and therefore human land clearing (Tinner and others 2007). And long before the rise of agriculture, people may have altered landscape through fire and played a role in the extinction of species. Miller and others (2005) point out that most of Australia's largest mammals became extinct 50,000 to 45,000 years ago, and speculate that the most likely mechanism would have been human-caused wildfires. So to speak of an Anthropocene Era means we have to speak about many thousands of years, in contrast to today's fashion, whereby in our typical temporally provincial way, we attribute major changes in the biosphere only to ourselves and our forebears since the industrial/scientific revolution. If we are going to speak accurately about an *Anthropocene Era*, then we have to allow that it began at least 10,000 years ago.

I would like to add that our conservation of forests must be approached from an understanding that *there are eight rationales for the conservation of nature: recreational, spiritual, inspirational, cultural, utilitarian, ecological, aesthetic, and moral* (Botkin 2001, 2012). Much modern environmentalism assumes there is only one approach and one solution to any environmental

problem, so conflicts among supporters of environmentalism come as a surprise. But different people may assign different priorities to the eight reasons we value the environment, resulting in conflicts even among those who believe they share the same large goals.

## **HOW CONSERVATION AND MANAGEMENT OF FOREST ECOSYSTEMS MUST CHANGE**

Given these principles of forest ecology, a variety of things have to change in our conservation and management of forest ecosystems. First of all, *we have to move away from attempts to keep all forests in a single state*. Because ecosystems have multiple states, and because forest ecosystem conditions often desired by people today are the result of past human alterations, forestry policies that attempt to exclude human actions on all forests must cease because they are necessarily doomed to fail and they sometimes do considerable harm. Although there is greater recognition by such environmental groups as the New Jersey Audubon Society, and often verbal recognition of these changes elsewhere, much policy is still based on “leave forests alone,” and public assertions continue to propose the same (Cecil 2013). Smokey the Bear continues to tell us that, “Only you can prevent forest fires.”

A study of birds in the Pine Barrens forests of New Jersey illustrates the importance of multiple states of ecosystems. There, the eastern kingbird was 22 times more common in early-successional, heavily managed forests (meaning timbered and managed for sustainable timber harvest) than in old growth. In contrast, the pine warbler was almost twice as common in the unmanaged and older forests than in the heavily managed forests (Williams 2013). If the world were only one or the other, some of the species would die out. In my own research on moose and their food supplies at Isle Royale National Park, it was clear that moose are creatures of young forests. They will not eat the spruce that is dominant in old-age boreal forests on the island, and they eat little of sugar maple, which dominates the old-growth deciduous forests of the island. Moose can reach up to 3 meters, which means that trees in dense and deeply shaded stands, typical of old growth, provide little food for them (Jordan and others 1971; Botkin and others 1973). These are two of many studies for many species that show the same kinds of patterns (Botkin 2012).

### ***Use Better Models and Connect Theory Better with Observations***

Ecology has long been theory-rich, but in the past most ecological theory was based on steady-state assumptions, heavily borrowed from simple equations of Newtonian physics. These models tended to be oversimplified and overly generalized, rarely tested against observations, and even when tested and disproved, they continued to be used (Botkin 1993). From the 1980s through the 1990s, it seemed that things improved, but strangely since then movement has been back to either overly simplified or overly complex models. Some recently developed models are intended to account for every variable, including many variables for which observations were not generally available, and so parameters could not be accurately estimated. Therefore, these models could neither be accurately calibrated nor validated. This has been especially true for models used heavily to forecast possible effects of global warming on biodiversity (Botkin and others 2007). These models violate Occam’s Razor, in a modern interpretation, meaning that an explanation should be no more complicated than necessary to account for all known observations. A detailed analysis goes beyond the scope of this paper but is reviewed in several of my other publications (Botkin 1993; Botkin 2012; Botkin 2012).

## ***Measure, Measure, Measure***

As long as we believed that nature was constant and that a single constant condition was best, we didn't have to know much about it; we could just let forests go, certain that left to themselves they would achieve this single best state. I note that mathematically there are actually three possible assumptions here: first, there is a set of states nature can be in, such that, once any state in that set is achieved, that state is self-perpetuating. This is not, however, the common belief. Another is that there is only one element in that set that can be self-perpetuating. Yet, a third is that regardless of where the forest is today, if humans practice hands-off, then the forest will move towards that happy golden state. The second two possibilities are the ones that are commonly assumed. However, once we accept the ever-changing character of all of nature, including forests, then we have to learn what the possible and characteristic states of a forest are. We must measure key factors and monitor them over time.

In my experience, key variables that are needed to understand how a forest ecosystem works and to solve a forest-related environmental problem have all too often not been measured, and if they were, the data were ignored. Here are some examples. In 1970, when James Janak, James Wallis, and I created the JABOWA computer model of forest growth, the first successful multispecies computer simulation in ecology, the general perception among my ecologist colleagues was that ecology was data-rich and theory-poor. But on the contrary, when we sought data to validate the model, we found that even the most obvious and straightforward data were rarely available (Botkin and others 1970; Botkin and others 1972).

In the 20<sup>th</sup> century, the U.S. Forest Service claimed that it maintained a series of permanent plots, 30x30 feet (just over 9x9 meters), where the species and diameter of every tree were recorded every ten years (Duncan 2004). I have searched for those data ever since and never found a single plot that was measured more than once using the same methods.

The best long-term monitoring I have found has been done in Australia, and in recent years, I have been working with Australian ecologists Michael Ngugi of the Queensland Herbarium, Toowong, Queensland, Australia and David Dooley, of the University of Queensland, Brisbane, Queensland, Australia, to use these data to further validate a JABOWA-derived model. When people talk about monitoring, typically the implication is that it has to have gone on for a very long time to be useful. But the data we have used from Australia cover 55 years (some as much as 70 years), a comparatively short time for forests. One of the benefits of this data is that methods were consistent, thorough, and extensive throughout the period. The monitoring was done in uneven-aged, mixed-species callitris forests on the 172,000 ha (425,000 acre) St. Mary's State Forest, Queensland, Australia, involving 143,200 trees from 26 species, sampled on 121 plots, each 0.4 ha (1 acre) (Ngugi and Botkin 2012; Ngugi and others 2013).

Although these are among the least known and most degraded forest communities in Australia, they are known habitat for threatened and rare fauna species. The model projections explained 93.9 percent (diameter at breast height (dbh)), 88.9 percent (basal area), 90.5 percent (stem density) and 88.6 percent (aboveground biomass) of the observed variation. To our knowledge, this is one of the most accurate validations of a forest dynamics simulation.

Moreover, as another example of the lack of forest data, in 1991 the state of Oregon passed a bill to fund an objective scientific study of the relative effects of forest practices on salmon, and I was asked to direct it. One would think that a state funding such a study believed that the information necessary to answer the question existed—for example, a map of the state’s forest; accurate history of logging by date, location, area cut, and methods; and annual counts of returning adult salmon. However, the state Department of Forestry told us they had no map of the state’s current or past forests. A year into the study, the state forester discovered one map, made in 1913, which had been stored in a men’s room and saved by a night watchman from being tossed out. We made a current one from Landsat satellite data. Counties, which did not record any information about area cut or methods, gave out logging permits, and these records were destroyed after five years. Of the 23 rivers we were required to study, salmon were counted on only two (Botkin and others 1995).

### ***Even When Data Exist, They Are Sometimes Ignored***

Since the 1970s there has been considerable interest in forest biomass and carbon storage. By the 1980s, I knew that the estimates in use had no statistical validity—they were not part of a single uniformed sampling program nor intended to be statistically representative of an entire biome or any large area. They were based on individual studies of forest stands of some particular interest to a scientist, and tended to be old-growth stands, which were considered the most natural and therefore the most interesting ecologically (Woods and others 1991).

I obtained funding to do the first statistically valid estimates of biomass and carbon storage from any large forested areas of Earth: the eastern deciduous forests and the boreal forests of North America (Botkin and Simpson 1990; Botkin, Simpson and others 1992; Botkin, Simpson and others 1993). Results were published in the early 1990s, but to my knowledge have never been used, even in current papers about biomass and carbon storage, and the methods have never been repeated. These statistically valid estimates give a lower range than those found in recent papers. For example, Houghton (2005) summarizes other studies and gives a range of 40.8 to 62.7 Mg/Ha (megagrams carbon per hectare) for boreal and temperate forests of Canada and the United States, while our study gives a mean of  $36 \pm 6$  Mg/Ha for temperate deciduous forests of North America and  $19 \pm 4$  Mg/Ha for North American boreal forests. Thus, our statistically valid estimate includes a value that is 47 percent of that Houghton reports for Canada, which I take to mean boreal forests, and 57 percent of that Houghton reports for the United States, which I take to mean the temperate deciduous forests (Houghton 2005).

My Australian colleagues report two other statistically valid studies, also ignored in the major summaries of carbon storage (Grierson and others 1992) and (Moroni and others 2010). Given the strong emphasis on international forest carbon-sequestering agreements and the funds that will be required, this kind of ignoring or ignorance of available data cannot continue. There is a basic irony here. The need to measure and to do scientific research becomes ever more obvious as the very forest research necessary declines. Adding to this irony is that we live in the information age, often drowning in data.

### ***Declining Interest in Forest Issues***

How could these two things happen—lack of monitoring and lack of interest in available data? Part of the answer is the decline in media attention and public interest in forests. Through the



1980s, forests were among the most talked about environmental problems. Most aspects of forest use were the subject of lively discussions, including the importance of old growth, the effects of forests on salmon habitat, the certification of forest practices as sustainable, whether timber corporations and the U.S. Forest Service were managing forests properly, the roles of stages in forest succession other than old growth (Sedjo and Botkin 1997). Certification of forest sustainability continues, but is little discussed broadly, especially regarding whether the methods in use are valid. I note that, in contrast, the certification of forest practices as sustainable remains a lively topic in management and economics.

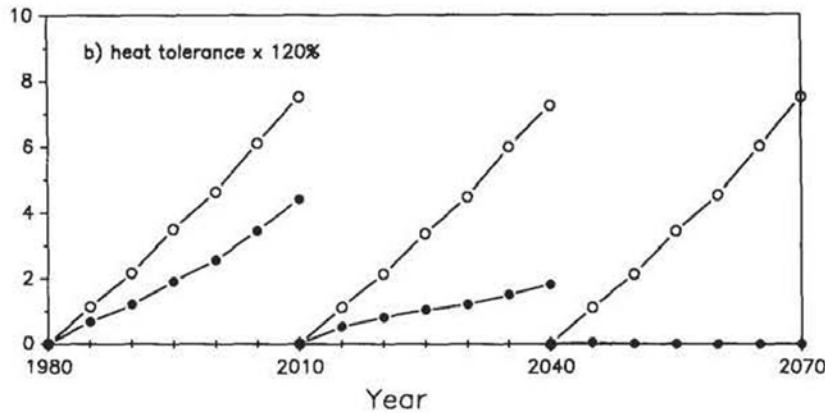
Today we hear about forests as possible carbon sinks and as players in climate change, and we become alarmed about forests when there are major wildfires. Much of public and media attention about forests is reduced to very simple statements, such as “Stop tropical rain forest deforestation.” One of our tasks is to renew public interest in and concern about forests, which in turn may help promote more government and private monitoring and research.

## NEW CONCEPTS OF ECOLOGICAL STABILITY

We must change how we characterize what is “normal,” “natural,” and “desirable” about forests, and about all ecosystems. Prof. Matthew Sobel, William E. Umstatter Professor of Industrial Economics at Case Western Reserve, and I addressed the problem of how to replace the concept of stability in ecology—the assumption that forests were steady-state systems—with analogous concepts that could be applied to dynamic systems (Botkin and Sobel 1975). In most environmental literature, the concept of stability is implicit and vague. Where defined explicitly, the concept was borrowed from, or equivalent to, the classical mechanics definition of a system that will tend to return to an equilibrium state, at rest, after being disturbed. We labeled this property “*static stability*.”

We proposed two replacements: *Persistence* within specified bounds, and *recurrence* of previous occupied states. (These definitions were not new in concept, but were used in the mathematics of stochastic processes.) To understand persistence, look at Figure 1, which shows forecasts of the growth of jack pine stands in southern Michigan in a specific, highly sandy soil, the only places where Kirtland’s warblers would nest (Botkin and others 1991).

A program to save the habitat of Kirtland’s warbler was set up in the state of Michigan with help from the Audubon Society and the U.S. Fish and Wildlife Service. The state set aside 12,140 ha (30,000 acres), in which stands were burned every 30 years. The question we asked was whether the jack pine could regrow in a forecasted global warming climate. The model was run in two scenarios: (1) under 20<sup>th</sup> century and, (2) forecasted global warming climates. The graph in Figure 1 shows the results for the control scenario, in which the 1950–1980 climate was treated as “normal.” Under this climate, the jack pine continues to regrow following fire, just as it had in the past. Each of the previous stages is therefore recurrent. In contrast, under the forecast global-warming climate, by 2010 a jack pine stand of 8 cm<sup>2</sup>/m<sup>2</sup> was no longer recurrent, and by today—2013—only the first three basal area levels were forecast to be recurrent. By 2040, the forecast is that jack pine would be completely nonrecurrent. We can therefore say that under global warming the jack pine forests are not recurrent, and therefore this is not what people hoped for with the intentional burning on forest stand, and would cause the local extinction of Kirtland’s warbler.



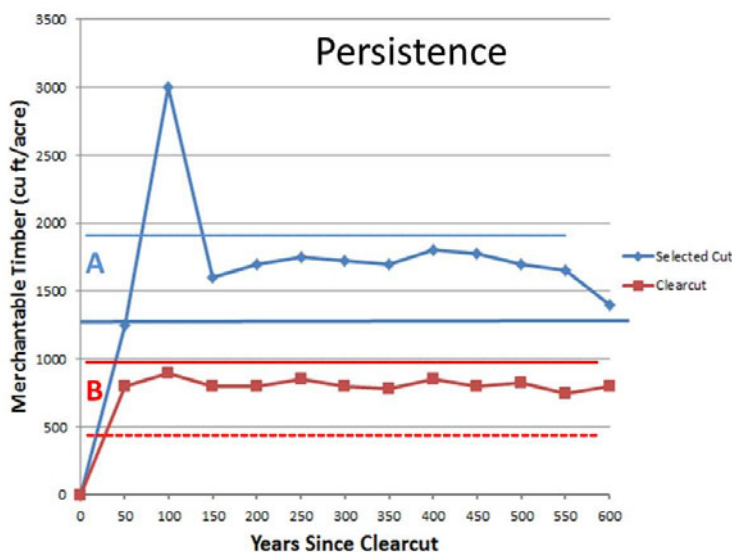
**Figure 1.** Persistence for simulated growth of two otherwise identical stands.

### Persistence Within Bounds

We also need to characterize how the variation in the states of a forest (the trajectory) compares between two different treatments. We call this *persistence*. To make this comparison for dynamic forest systems, we examine a trajectory—a time-series—of each treatment. Figure 2 illustrates persistence for simulated growth of two otherwise identical stands, each harvested every 50 years, one by clear-cutting, the other by a selective cut, which in this case is cutting all trees larger than 12.7cm diameter. The question being asked is: Over a long time, which treatment yields greater quantities of merchantable timber? Figure 2 shows the trajectories of each forest stand. It is clear that after an initial early succession rise, the selectively cut forest maintains a higher yield of merchantable timber than the clear-cut forest. There is no overlap between them. We say that the persistence of the clear-cut forest is completely different from that of the selectively cut forest.

### Naturecraftsmanship

The discussion so far raises the question: What do we do when adequate data and formal theory are lacking. In the past, the usual answer was to rely on gut feeling, heavily emotionally and ideologically influenced beliefs, disconnected from long-term observations of any kind, qualitative or



**Figure 2.** Forecasts of the growth of jack pine stands in southern Michigan.

quantitative. The correct, practical answer is what is known as “woodsmanship.” Speaking more generally, we can refer to this as “naturecraftsmanship.” I illustrate this with the work of Bob Williams, a certified forester practicing in the Pine Barrens of New Jersey, who received 2013 New Jersey Audubon’s Conservationist of the Year Award. In addition to improving the conservation of biodiversity in the unusual oak-pine forests of the southern New Jersey coastal plain, he has successfully planned timber harvests for commercial and government forests for more than twenty years, converting what had become little remembered and poorly cared-for forests into stands that provide valuable timber products and make profits for the landowners.

I spent a day with Bob visiting the forests, seeing stands of many stages and treatments, from ones that had never been logged for a century or more to ones that had been logged last year. At one stop he said he had thinned the forest we looked at. I asked him how he determined how much to remove. I was thinking as a scientist, in terms of carefully measuring the diameter and height of trees, or using other, faster methods to estimate biomass in a locale, or marking individual trees to be thinned out. Bob said he couldn’t afford to do these assessments, desirable though they were. Instead, he brought the logger who would cut the trees to an already thinned forest and told him, “I want that other forest to look like this.” Then he would train that logger, having him thin trees in a small area and telling him what he needed to change. After enough trials, he would let the logger continue on his own.

Bob listens to and makes use of scientific information. Two science professors were with us on the tour: Chris Williams, wildlife biologist, University of Delaware; and George Zimmermann, Chairman, Environmental Studies, Stockton College. Chris’s grad student had just completed the thesis I mentioned earlier, measuring bird use of forest areas of different ages, research that Bob integrated into his thinking.

In the practical world of incomplete knowledge, our management of forests needs to make use of naturecraftsmanship, the art of science and practice, a sort of General Practitioner’s approach to the use of medical research. I’ve worked with and met others who were experts on condors, salmon, and forests elsewhere in our country, who worked that same way. It’s what is missing today from the intense environmental debates that capture so much public attention, and which pit ideologies against quantitative science, sometimes leading to the misuse of scientific information, or at least dealing with it in an abstracted way. I contend that “woodsmanship” in its largest sense, perhaps “naturecraftsmanship,” is one of the key things lacking in environmentalism today, necessary for us to find ways to help conserve nature and save ourselves. naturecraftsmanship is somewhere between the two dominant approaches to environment these days: scientific research and ideological environmentalism.

To many, the ability to both harvest trees and improve the conservation of nature may seem an oxymoron, but Henry David Thoreau didn’t think so, as I explain in one of my ebooks, *No Man’s Garden: Thoreau and a New Vision for Civilization and Nature* (Botkin 2001, 2012). Logging per se did not interfere with Thoreau’s appreciation of the spiritual qualities of forested nature, as long as the cutting was not so large in area or so severe as to disallow any sense of contact with the forest, or seriously interfered with other land uses, especially when it was destructive to the point that the cutover land could not be used to build cities.

On his first trip to the Maine woods, he met two loggers and wrote, “I often wished since that I was with them,” calling their life “solitary and adventurous.” He continued this thought in *Walden*,

writing, “Fishermen, hunters, woodchoppers, and others, spending their lives in the fields and woods, in a peculiar sense a part of Nature themselves, are often in a more favorable mood for observing her than philosophers or poets, who approach her with expectation” (Thoreau [author], Moldenhauer [ed.]. 1973).

## **WILDERNESS IN THE TWENTY-FIRST CENTURY**

Since there is no longer any part of Earth that is untouched by our actions in some way, either directly or indirectly, there are no wildernesses in the sense of places completely unaffected by people. But there are three kinds of natural areas that we could maintain in the future: no-action wilderness, preagricultural wilderness, and conservation areas.

The first is an area untouched by direct human actions, no matter what happens. This kind of wilderness is necessary for observation as a baseline from which scientists can measure the effects of human actions elsewhere; it is an essential calibration of the dials we should set up to monitor the state of nature. Some may be important for biological diversity. Some may be pleasant for recreation, and some may become a nature never seen before.

The second kind, preagricultural wilderness is an area that has the appearance of landscape or seascape that most closely matches the ideal of wilderness as it has been thought about in recent decades. In North and South America, Australia, New Zealand, and other places in which the time of arrival of modern technological man is readily dated, the idea is to create natural areas that appear as they did when first viewed by European explorers. The first two we can regard as true wilderness and designate legally as protected wilderness areas (Botkin 2012).

Conservation areas, the third type of natural region, are set aside to conserve biological diversity, either for a specific species or for a kind of ecological community. Most require active intervention, as with the habitat of Kirtland’s warbler discussed earlier.

To these kinds of formally designated wilderness, we could add the kind of landscape that Thoreau sought, a place where he could experience *wildness*, a spiritual state existing between a person and nature, which he distinguished from *wilderness*, which was land or water unused at present by people and thus a state of nature. As I discuss in *No Man’s Garden: Thoreau and A New Vision for Civilization and Nature*, wildness meant so much to Thoreau that one day he wrote: “I caught a glimpse of a woodchuck stealing across my path, and felt a strange thrill of savage delight, and was strongly tempted to seize and devour him raw; not that I was hungry then, except for that wildness he represented” (Botkin 2012; Thoreau 1973). For Thoreau it was possible to find this wildness in places quite close to home and civilization, such as Walden. It is much like the idea behind Japanese gardens, meant for reflection and meditation.

## **SUMMARY**

To speak of an Anthropogenic Era, we have to mean an era beginning thousands of years ago, possibly 10,000 or more years ago, when people began to have major effects on the environment, at least in terms of lighting fires, clearing land, and altering the abundance of various animals, some driven to extinction. To deal with forests in our future, we must understand that most of the tools exist and have existed since the 1980s. It is merely a matter of applying them. The major obstacle

to this is the dominance of prescientific beliefs about nature, which continue to form the basis of many forestry laws, policies, actions, and attempts to conserve biological diversity. To get past these folktales, we have to change how we characterize what “stability” can mean for non-steady-state-system; how we characterize “normal,” “natural” and “desirable” in regard to forests, as well as about all ecosystems. We have to understand the functions of theory and models for non-steady-state systems. These models require appropriately detailed monitoring of key variables (not every variable). Where monitoring and theory are lacking, naturecraftsmanship—the art and practice of forestry by those familiar with both forests themselves and the best scientific research—is a practical alternative, and should replace the ideological, contrary to scientific, beliefs that still dominate.

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# Evolving Conservation Paradigms for the Anthropocene

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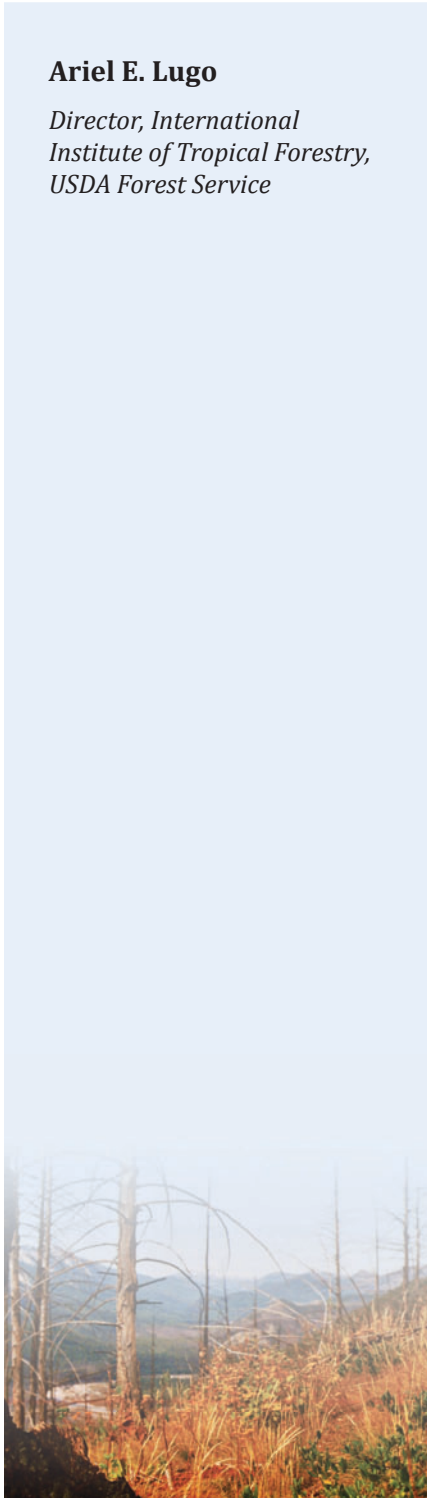
**Abstract:** *The Anthropocene will have fundamental effects on the species composition, function, and structure of the ecosystems of the world. Land management agencies such as the USDA Forest Service will need to adapt their policies and conservation activities to avoid engaging in continuous conflict with natural processes and unfamiliar biotic assemblages. Conservation paradigms need to evolve to face the Anthropocene without abandoning the wisdom and relevance of paradigms from previous eras of conservation activity. A new paradigm for conservation in the Anthropocene could be summarized as follows: Applying adaptive conservation to all human activities.*

*“Recognizing that species and ecosystems are naturally dynamic and are likely to become more so with anthropogenic impacts, maintaining the status quo should not be the conservation goal...” Moritz and Agudo (2013: 507).*

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## INTRODUCTION

With the onset of the Anthropocene (e.g., Crutzen 2002; Smith and Zeder 2013; Braje and Erlandson 2013), the conservation movement is in turmoil. On one hand there is an assertion of failure within the movement and a call for alternative approaches based on the new reality of the Anthropocene (Kareiva and others 2011). On the other hand, there is recognition of the increasing effects of human activity on Earth with serious concerns about yielding to the notion that humans are the major drivers of all biodiversity on the Planet (Caro and others 2011). Soulé (2013) suggests that a new conservation based on the Anthropocene and a humanitarian agenda would “hasten ecological collapse globally,” while Jacquet (2013) worries that the Anthropocene might be a phenomenon with psychological effects on people and the way that we perceive ourselves. These diverging stances express strong reasoning for particular world-views and paths forward. They also open the way for mixed approaches to conservation, integrating strategies that are often considered incompatible (e.g., Kueffer and Kaiser-Bunbury 2013).



This essay focuses on the role of the USDA Forest Service in adapting its conservation policies to the Anthropocene. I take a historical approach to show how the Agency has often adapted its conservation focus to the environmental realities of the moment, a strategy that has placed the Forest Service as a conservation leader in the United States. I then present the emerging new environmental conditions of the Anthropocene, which provide the impetus for the Agency to once again modify its conservation approach.

## **CENTERPIECES OF THE FOREST SERVICE CONSERVATION APPROACH**

Between the mid 19<sup>th</sup>-century and early 20<sup>th</sup> century, northeastern and southern United States experienced dramatic land cover changes involving the deforestation of lands and devastation of landscapes because no significant effort was given to replanting forests and restoring degraded lands (see Foster and Aber 2004 for a case study of New England). The conservation movement in the United States evolved in the 19<sup>th</sup> century in response to the poor conditions of lands and landscapes, the lack of conservation agencies, and the lack of knowledge about restoration activities (those interested in this subject are referred to chapter 2 in Benedict and McMahon (2006) for a chronological summary of involved people and events culminating with the current emphasis on green infrastructure).

Gifford Pinchot is considered a pioneer in forest conservation for developing a pragmatic approach to conservation through wise use of forestlands (Miller 2013; Forest History 2014). Pinchot collaborated with Raphael Zon who was responsible for developing scientific experimentation in support of conservation and for working to establish Experimental Stations and Forests within the USDA Forest Service. Zon was deemed the warrior of science in the USDA Forest Service (Young 2012) and through his collaboration with Pinchot helped develop a conservation philosophy that combined science with pragmatic field intervention by foresters. This conservation philosophy aimed at “the greater good for the greatest number in the long run” was effective and what the nation needed at that moment in history.

By the mid-20<sup>th</sup> century, the southwestern landscape of the country was also exhibiting signs of degradation associated with over-use and persistent human presence. Aldo Leopold, a graduate from Yale University’s Forestry School, was a USDA Forest Service employee stationed in the southwest. Leopold anticipated the need to preserve wilderness, promoted the restoration of degraded lands, and introduced the idea of a land ethic that would allow humans and natural systems to coexist in harmony (Meine 1988). This harmonious coexistence between humans and natural systems was Leopold’s definition of conservation. In his famous work *A Sand County Almanac* Leopold wrote: “To keep every cog and wheel is the first precaution of intelligent tinkering” (Leopold 1953: 145-146). Ideas of multiple uses of natural resources emerged from Leopold’s land ethic as well as approaches for rehabilitating those natural systems that had been mismanaged by the lack of sensibility to the limits of land use. Thanks to Leopold, prairies were restored, a wilderness system was established in the United States, scientific wildlife management was formalized (Leopold 1933), and the idea of a land ethic was established (Callicott and Freyfogle 1999). “Conservation of all the parts” became a motto of modern species conservation.

Today, professional land management and conservation agencies oversee protected areas that constitute about 27 percent of the country. These lands are managed using the holistic notion of ecosystem management, which emerged from USDA Forest Service research in collaboration



with university scientists (Johnson and others 1999). Should we then continue forward with our mission applying the conservation paradigms that we inherited from the last century, or is there a need for another leap or evolution in our relationship with natural systems? The answer to this question depends on how we perceive the world today and into the future. Is the world similar to what Pinchot and Leopold experienced or have things changed? And, will conditions change so drastically as to require a revision in the way we conduct conservation activities?

## **ENVIRONMENTAL TRENDS THAT REQUIRE OUR ATTENTION**

The changes in atmospheric temperature that have taken place on our Planet over the past century are twice as fast on land as on water and it is expected that the eventual 21<sup>st</sup> century temperatures will reach a 65 million year high (Diffenbaugh and Field 2013). The effects of these increasing temperatures are already becoming evident in a variety of ways. For example, in 2012, the USDA changed its 1990 Plant Hardiness Map used by gardeners and farmers as a guide to growing conditions in the country to reflect the measurable warmer conditions for plant growth in the United States (see: <http://planthardiness.ars.usda.gov/PHZMWeb/>). Also, mangrove trees, which are unable to survive hard frosts, are migrating north as a result of diminishing hard frost events in warm temperate coastal zones (Cavanaugh and others 2014). The expansion of insects and pathogens that are killing millions of trees in northeastern North America is also attributed in part to warmer temperatures at their northern limits (Dukes and others 2009; Lynch and others 2014).

More daunting for organisms however is the expected velocity of climate change over geographic space, which according to model simulations will be orders of magnitude faster than in the past. The velocity of climate change is defined as the distance per unit time that a species needs to move to keep its habitat temperature within the current local envelope. Diffenbaugh and Field (2013) estimate a velocity of climate change of several kilometers per year, which will strain the capacity of adjustment by organisms. When species are forced to move in response to changing environmental conditions, they will encounter other groups of species with whom they normally don't interact. This novel mixing of species is compounded by the introduction of species by human action, thus exacerbating the interactions. Human activities are transporting species across the world and, in the process, breaking the traditional biogeographical barriers that historically kept species in their native habitats (Lomolino 2004). The global flux of species and their subsequent mixing involves unprecedented magnitudes and has led to renewed interest in invasion biology (Davis 2009), which was originally anticipated by Elton (1958).

As discussed by Blois and others (2013) species interactions represent the mechanism by which the biota respond to environmental changes and lead to either resilient or decline patterns of response (Moritz and Agudo 2013). Biota on the move also leads to the reassembly of communities (Weiher and Keddy 1999) and to novel ecosystems (Hobbs and others 2013). In the Anthropocene, the reassembled communities will function in an environment dominated by the actions of people. Moreover, there are other anthropogenic environmental trends in progress today that affect social and ecological systems. The combined effects of, and synergy between, the trends now in progress as a result of anthropogenic activity further affect the ecosystems that support life on our Planet. In addition to those mentioned above, four other trends are in progress and affect the way we approach conservation today.

**Accelerated and altered biogeochemical cycles.** The cycles of chemical elements on Earth are known as the biogeochemical cycles and they influence all life's processes including the productivity of agriculture and natural ecosystems, and the availability of critical elements to plants, animals, and anthropogenic systems such as cities. These cycles used to be 100 percent under the control of natural forces. Today, humans have dramatically changed the speed, pathways, and components of the biogeochemical cycles of the Planet. Humans account for the following percentages of the global flux of carbon, nitrogen, phosphorus, sulphur, and water: 13, 108, 400, 113, and 16, respectively (Sterner and Elser 2002). Thus, the critical elements that sustain life on Earth are increasingly under anthropogenic control with unexpected consequences. Problems such as those of acid rain, water eutrophication, climate change, and ocean acidification are examples of unexpected consequences of the alteration of the biogeochemical cycles.

**Land Cover Change and Urbanization.** Just as in the time of Pinchot, the land cover of the United States is changing rapidly. Unlike the time of Pinchot however, the trend is not towards land degradation. Forest clearing for agriculture in the United States stabilized after the 1920s (Darr 1995). We now face the new trend of increasing urban cover at the expense of decreasing forest and agricultural cover (Drummond and Loveland 2010). The urbanization trend expands the urban-wildland interface and fragments forestlands at accelerating rates that exceed the population growth rate (see summary in DeCoster 2000). For example, in 1990 for each person added to the population, 0.22 acres of forests were converted to urban cover. In 2000 this rate of conversion increased to 0.50. About 85 percent of the population of the United States is now urban. We have made the transition from an agrarian to an urban country. Urbanization adds new habitats that pose novel challenges and opportunities to the survival of organisms and species. Moreover, the older and more diverse urban populations require environmental services and quality environments (air, water, green space) in the cities where they live.

**Reduction of global oil reserves (peak oil).** Fossil fuels power our civilization and enabled the onset of the Anthropocene (Crutzen 2002). This powerful energy source is finite and the rate of discovery of new oil fields has declined dramatically such that the rate of global oil extraction is reaching, or has reached, the point at which a continuous decline in the rate of extraction of oil will be the norm. The moment when the rate of oil extraction reaches a maximum is termed peak oil, and there is increasing agreement that the world has now reached that moment (see chapter 3 in Hall and Klitgaard 2012). Declining oil reserves have many social and economic implications (Hall and Klitgaard 2012) that are not part of this essay. However, for conservation activities the implications are clear. A lower level of fossil fuel availability reduces our capacity to sustain energy-intensive interventions in the landscape and forces a greater dependency on ecological processes and systems (Odum and Odum 2001).

**The development of the transdisciplines.** Dealing with the complexity of a changing world requires that all human knowledge be integrated in novel ways that transcend disciplines and traditional interdisciplinary work. Transdisciplines represent a new integral way of analyzing complex problems or situations (Wiek and Walter 2009). They cross discipline boundaries to solve complex problems and provide a framework for pragmatically sorting through many approaches while honoring their individual insights. This trend in knowledge synthesis responds to the complexities of the Anthropocene where both social and ecological systems interact under novel environmental conditions in ways that could not be imagined 100 years ago. Palmer (2012) calls this type of science actionable because of its potential to inform decisions, to improve the

design or implementation of public policies, or to influence strategies, planning and behaviors that affect the environment. This actionable transdisciplinary science is motivated to serve society and is as anticipatory as possible using all available knowledge.

The outlook developed above does not bode well for our traditional conservation approach. Historical ecosystems might be facing the “living dead” reality outlined for individual species by Janzen (1986) when he analyzed the future of tropical ecology in light of anthropogenic changes. He argued that many populations and individual species present today on landscapes are living dead because the conditions that led to their establishment and sustainability are no longer present, thus hindering their reproduction and regeneration. A significant number of our conservation activities, such as forest restoration, are based on the assumption of the natural balance of nature or the cyclic repetition of environmental conditions. If true, this assumption allows us to restore familiar historical systems and expect that they will self-sustain because historical conditions to which they are adapted will prevail over time. These conservation activities involve the use of native species for restoration purposes at the expense of introduced ones, because the native species are presumed to have “a home-court advantage” (Allendorf and Lundquist 2003). If our assumptions were to be wrong, so would be the conservation activities that we base on those assumptions.

Jackson (2012) reviewed the historical range of variation concept as currently used in conservation and resource management and concluded that the concept has value but must be modified to account for current and future conditions. He suggested that the question about the sustainability of ecosystems of interest under altered conditions must be addressed at the outset of any restoration or management intervention. How far can the system be pushed before it changes states? Jackson also added that the challenge of the Anthropocene requires engagement of both the social and ecological sciences in conservation. Without discarding concepts such as the idea of “naturalness”, it behooves the conservationist to acknowledge the elasticity of this and other traditional ideas that have served us well. What constitutes naturalness in the Anthropocene? Our failure to consider the consequences of the Anthropocene exposes us to the reality of living dead conservation products.

## **EFFECTS OF THE ANTHROPOCENE ON BIOTA**

Almost every aspect of the functioning of natural and anthropogenic systems is affected by the trends discussed above. We need to realize that at this moment, all biota of the world are in a continuous state of change and reaction to altered environmental conditions at local and global scales. There is abundant evidence of the changing environmental conditions and their effects on the biota, so much so that the volume of information can be overwhelming and difficult to interpret. One can either reach pessimistic or optimistic outlooks for the situation depending on one’s outlook about the relationship between humans and natural systems. Can we still make that relationship harmonious as viewed by Leopold? In other words, how do we conduct conservation in the midst of apparent chaotic changes?

I have argued that the brave new world of biodiversity conservation in the Anthropocene is one where conundrums, paradoxes, and surprises will prevail (Lugo 2012). A major reason for these surprises and paradoxes is the fact that the fundamental forces that drive the structure, functioning, and species composition of forests and other ecosystems are being dramatically

affected by human activity. Human activity changes the natural disturbance regime of ecosystems to new disturbance regimes that include both anthropogenic and natural disturbances acting in synergy. For example, a synergy occurs between increasing human activity on roadsides and wild lands and the opportunities for accidental fires, which can result in a new fire regime for affected ecosystems. Understanding disturbance regimes is important because they affect the successional pathways, the age of forests, and the level of their structural development (Johnson and Miyanishi 2007). They also affect species composition. In some instances, the resulting environmental conditions after a disturbance are novel such as on degraded lands, inside cities, or at the interface between urban and wild lands. We are surprised after disturbances, particularly anthropogenic ones, because introduced species can replace native ones. Native species lose their “home-court advantage” because the home court is no longer present, and the possibility of species invasions increases, leading to a paradox where local species are less competitive than introduced ones. Similarly, changes in land cover and urbanization lead to landscape fragmentation, which in turn affects landscape function and vulnerability to disturbances such as fire or species migration. Dealing with surprises and paradoxes is one of the great challenges of modern conservation.

Human activity and disturbances also set the biota in motion as shifts in environmental conditions induce species migrations. The movements are accelerated by introductions of species. As a result, species composition of affected ecosystems changes to novel combinations. Many of these emerging ecosystems are termed novel ecosystems because their particular species mixes are new to the landscapes where they occur (Hobbs and others 2006, 2013). Porter and Smith (2012) have already documented the predominance of novel forests throughout eastern United States. At least 138 introduced tree species are now naturalized in eastern forests.

The overall expression of life, termed biodiversity, changes in the Anthropocene because of the many changes in the biota and the habitats where they live. Humans enrich the biodiversity of forest stands, landscapes, countries, and regions by creating new habitats and novel plant and animal communities (Lugo and Brandeis 2005; Lugo and others 2012a, Lugo and others 2012b; Thomas 2013). Nevertheless, a major focus of the conservation discussion has been on the reduction of diversity by human activity through species extinctions, which obviously represents a serious threat to the conservation of all parts. However, the full range of human effects on biodiversity requires attention because even evolutionary processes are accelerated by human activity (Cox 2004). An accelerated evolution rate through hybridization is an adaptive natural response to novel anthropogenic environments (Thomas 2013).

The undergoing changes of the biota that result from the environmental shifts discussed earlier affect the rate or speed of ecosystem functioning, but not the fundamental functioning of ecosystems. For example, increased temperature will accelerate the respiration of organisms while changes in the quantities of carbon, nitrogen, and phosphorus will affect nutrient cycles and productivity of ecosystems. This means that rates of ecosystem processes either accelerate, decelerate, or maintain the same speed, but the processes themselves might not change. This is a fundamental point to consider when comparing novel and historical systems. When environmental conditions change, or an ecosystem is disturbed, it is normal to observe changes in rates of processes, species composition, and ecosystem structure. This is called ecological succession.

However, when ecological succession involves introduced species, some conservationists deem the process “unnatural” and thus open to anthropogenic intervention. The notion of “shoot first and ask questions later”, when dealing with introduced species has been suggested by several scientists as a way of maintaining historical species composition at all costs (e.g., Temple 1990; Coblenz 1991; Simberloff 2003). However, in the Anthropocene, before engaging in species eradication we need to understand the ecological processes in progress including the possibility that those species that we wish to eradicate might already be naturalized components of well-established novel communities. The eradication of naturalized species is subject to unexpected ecological risks that could affect the whole ecosystem (Zipkin and others 2009).

Another point to consider when evaluating novel ecosystems is that there is no reason to assume *a priori* that the functioning of these ecosystems, including their capacity to deliver ecological services, has been degraded or diminished relative to those of historical ecosystems. Studies of novel forests in Puerto Rico and Hawaii show that they maintain ecological functioning in spite of dramatic changes in species composition (Lugo and Helmer 2004; Mascaro and others 2012). The reason is that ecosystem functioning is more resilient than ecosystem structure or species composition. In fact, changes in species composition might be nature’s way of sustaining functional continuity in light of environmental change (Lugo 2013).

In short, in the Anthropocene we face a proliferation of new types of biotic communities as familiar historical systems decline. The new or novel ecosystems that replace historical ones are natural products of the forces of change that constitute the Anthropocene (Lugo 2013). All the environmental and biotic changes associated with the Anthropocene give urgency to understanding the limits of the sustainability of historical systems because the conditions that once nurture these systems are unlikely to return or remain unchanged. We are thus in a situation where change itself becomes the norm, and because humans are involved, the change is unpredictable. Moreover, peak oil means that the energy that powers our civilization and economy will be declining, thus limiting our capacity to invest in costly management schemes. Peak oil also raises issues about the feasibility of sustaining present conditions at a time when energy reserves are declining. We must make wise choices when dealing with the consequences of the Anthropocene lest we fail the test of Botkin’s conundrum.

## **BOTKIN’S CONUNDRUM**

As we face the effects of the Anthropocene on the biota, the natural impulse is to restore degraded lands to the historical conditions that we are familiar and comfortable with. This initial impulse works well under conditions that favor historical systems (e.g., Fulé 2008), but does not work well where historical conditions have changed dramatically to favor novel ecosystems. If novel ecosystems are involved, traditional restoration approaches will require reconsideration (Hobbs and others 2009). The notion of novel forests with unfamiliar species composition that include introduced species is not one that is easily accepted by a generation that was formed to conserve historical forests. Attempting to restore native fauna and flora regardless of environmental conditions have lead many government agencies to declare a war on introduced species and to restore lands to historical states. Unfortunately the extirpation of species from ecosystems is full of surprises, an example being in the Macquarie Islands where the extirpation of cats and rabbits resulted in changes in the vegetation that were very costly to reverse (Bergstrom and others 2009). It is very difficult to know what ecosystem state a restoration should aim at because

the number of historical states can be infinite (how far back should we go?) and we usually lack a blue print describing what we are trying to restore. In the Anthropocene we know that the conditions that favor historical forests might not return. Therefore, the key consideration for successful restorations is either knowing or anticipating the environmental conditions required to maintain desired species combinations. Can we assure such an environment for our favorite species combinations or are we at the mercy of environmental change? If so, how much are we willing to invest to reverse natural processes?

Ecologist Daniel Botkin said it best by articulating the conundrum that land managers face in the Anthropocene (Botkin 2001; see also Botkin 1990):

*“One can either preserve ‘a natural condition’, or one can preserve natural processes, but not both.”*

The natural processes of the Anthropocene will select for a biota adapted to prevailing anthropogenic conditions and those conditions inexorably favor the mixing of biotas and novelty in the resulting ecosystems. This does not mean that native species will cease to be important and prevalent, but it does mean that introduced species will also have an ecological role to play in prevailing ecosystems. We can ignore the Anthropocene and attempt to favor particular historical conditions not previously favored by the natural processes, but to do so will be costly in time, money, and resources, and will include the need for increased understanding of ecological processes. Botkin argues that we will not have the resources to both favor “natural” or historical conditions and natural processes because in the Anthropocene they move in opposite directions and to counteract natural processes is equivalent to fighting nature at a huge cost. Also, in the Anthropocene, anthropogenic biomes or anthromes will be as critical to the biota as wilderness, because human influence is increasing rather than decreasing in the world. As an example, by 2000, only one quarter of the terrestrial biosphere remained wild, the rest was under human influence (Ellis and others 2010). What kind of conservation paradigms do we then need and what kind of conservation agency is needed in the context of the Anthropocene?

## **A NEW PARADIGM FOR THE ANTHROPOCENE**

The pragmatic scientific conservation of Pinchot and Zon is still relevant today. However, scientific involvement in conservation must now include transdisciplines such as those of social ecology. Saving all the parts as suggested by Leopold is also relevant today. However, in the Anthropocene the parts will be mixed in ways he did not and we cannot anticipate. Instead of restoring ecosystems we will have to rehabilitate them in the context of new environmental conditions with an emphasis on functioning and ecosystem services rather than species composition. The species composition of novel ecosystems is a product of natural selection and efforts to modify it should be done cautiously and only when knowledge and resources are available to assure long-term success. Clearly a land ethic is imperative for any era of conservation as is the need to preserve wilderness. But are these measures sufficient? What is missing?

A new paradigm for conservation in the Anthropocene could be summarized as follows: *Applying adaptive conservation to all human activities*. This notion is different from traditional conservation in that conservation principles are relevant to all human activities, not just in protected areas, and that conservation must be adaptive and dynamic to keep pace with our changing

world. The Anthropocene requires that we adapt to novelty and the unpredictability of the environmental context under which we implement the mission of agencies such as the USDA Forest Service. Thus, a new paradigm of conservation must recognize that all species have a potential role to play when conditions turn uncertain. Moreover, species should not be judged by their geographic origin, but by their function in the communities they occupy (Davis and others 2011). In the Anthropocene, declining energy resources will again make us dependent on the natural productivity of the land (Odum and Odum 2001), which we must protect at all costs. Conserving all lands means urban lands as well as rural forestlands; it means public as well as private lands. Since human presence permeates the entire world, conservation principles must shadow all human activities if we are to prosper in the Anthropocene. How can we embrace this new conservation? How will the USDA Forest Service organize itself to lead by promoting conservation approaches for all human activities in the Anthropocene?

## **IMPLICATIONS FOR THE USDA FOREST SERVICE**

The Nation needs guidance in order to make sense of the uncertainty and complexity it faces in the Anthropocene in relation to its air, waters, forests, rangelands, fish, and wildlife. The USDA Forest Service is in a position to help make sense of this complexity and uncertainty because, among all federal environmental agencies, it is the only one with the mission and capacity that enables a holistic perspective on natural resources conservation. Also, only the USDA Forest Service has an active research and development program to support its conservation actions. Research and Development continues to be the eyes to the future and a source of innovation and anticipation for the USDA Forest Service as the Agency collectively faces the uncertainty of climate and environmental change.

The USDA Forest Service has the opportunity to lead the nation in embracing the new conservation paradigm by: acting as a steward of forests and ranges wherever they occur from montane wilderness to coastal cities; exerting its leadership through scientific management and collaboration; and refocusing its programs to address the challenges of the 21<sup>st</sup> century. This means expanding the ideas of Pinchot and Leopold to include the novelty and uncertainty that will predominate in the Anthropocene. It also means that the Agency needs to embrace the transdisciplines and implement a higher level of program integration than is evident today, when many programs function in isolation of other related programs.

Integrating programs across traditional agency silos will require revisiting the geographic distribution of USDA Forest Service units, determining which Agency functions could be centralized and which could not, and reducing the size of units so that they may function more effectively. All conservation activities should be conducted in an adaptive conservation mode (*sensu* Bormann and others 1999) to enable the capacity to adjust and adapt to uncertainty. The level and scale of conservation actions must be consistent with available resources (economic, human, and technical) and the ability to sustain management efforts for as long as they are needed. Boundary spanning between scientists, forest managers, and the public will be required to assure free flow of information across different technical specialties. The Agency as a whole needs to become more integrated, diverse, and inclusive while promoting safe and creative environments where innovation is expected and rewarded. Status quo is not an option in the changing world of the Anthropocene.

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# Terrestrial Protected Areas: Threats and Solutions

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**Abstract:** *We provide an overview of the principal threats to land based protected areas and then discuss measures by which protected areas can continue to be effective at conserving biodiversity this century.*

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## **INTRODUCTION**

A protected area (PA) is defined as “an area of land and/or sea especially dedicated to protection and maintenance of biological diversity, and of natural and associated cultural resources, and managed through legal or other effective means” (IUCN 1994). The IUCN divides PAs into six management categories ranging from strict nature reserves to those that allow sustainable use of natural resources (Table 1) (IUCN 1994). From a biological standpoint, the effectiveness of PAs as a conservation tool depends on its ability to incorporate biodiversity (e.g., Rodrigues and others 2004) and to buffer plant and animal populations against anthropogenic forces (e.g., Bruner and others 2001; Hayes 2006) and most appraisals generally suggest that PAs are successful in their goal of biodiversity conservation when compared to areas with no formal protection. Nonetheless, plant and animal populations inside PAs are not immune to anthropogenic forces. Here we review a selection of contemporary threats to terrestrial PAs in all IUCN categories and provide some ideas as to how PAs can cope with anthropogenic pressures in the future. Our purpose is not to provide an exhaustive list of threats to PAs (see Worboys et al 2005; Chape and others 2008) but instead to offer an up-to-date assessment of threats and how they can be addressed.

## **GLOBAL THREATS**

### ***Climate Change***

By the end of the 21st century, average global temperatures are expected to increase by 1.1 to 6.4°C (NRC 2010). Many species have already exhibited range shifts

**Table 1.** IUCN Protected Area Categories (IUCN 1994, adapted from Chape and others 2005), with percentages out of total PAs, including non-categorized PAs.

Category	Description	Percent by Number	Percent by Area
Category Ia	strict nature reserve: PA managed mainly for science	4.9	5.4
Category Ib	wilderness area: PA managed mainly for wilderness protection	1.2	3.3
Category II	national park: PA managed mainly for ecosystem protection and recreation	3.5	23.1
Category III	natural monument: PA managed mainly for conservation of specific natural features	17.3	1.4
Category IV	habitat/species management area: PA managed mainly for conservation through management intervention	24	15.5
Category V	protected landscape/seascape: PA managed mainly for landscape/seascape conservation and recreation	7.4	12.4
Category VI	managed resource PA: PA managed mainly for the sustainable use of natural ecosystems	3.7	22.1

in response to climate change (Root and others 2003), moving between 6.1 and 16.9 km per decade (Parmesan and Yohe 2003). Altitudinal shifts in species distributions have also been documented within PAs, with species showing average range shifts from 6.1 m (Parmesan and Yohe 2003) to 11 m (Chen and others 2011) up altitudinal gradients per decade. Increasing temperatures may also affect species interactions through changes in phenology or temporal mismatches, where one trophic level or taxonomic group shows more plasticity in timing of key events than others (e.g., Visser and others 1998).

Due to differences in response rates to climate change, species in PAs may lose or gain prey, predators, pollinators, or competitors leading to changes in interspecific interactions and formation of novel (non-analog) communities (Huntley 1991). However, our understanding remains largely theoretical at present, as there is a great degree of uncertainty regarding ecosystem and biotic responses to climate change.

**EXTERNAL THREATS**

***Isolation and Fragmentation***

Degradation of habitat between PAs results in loss of connectivity between PAs, whereas fragmentation of PAs reduces their effective size. Many parks and reserves were originally carved out of much larger wilderness areas, and as a result, the available habitat for animals and plants found within these areas extended well beyond their borders. However, in recent decades PAs have become increasingly isolated due to degradation of surrounding habitat. For example, nearly 70 percent of the lands surrounding PAs in tropical forests experienced habitat loss or degradation in the past 20 years (DeFries and others 2005). Fragmentation of PAs has arisen not only from direct habitat destruction and conversion to agriculture but also from construction of

roads and fences and hunting both inside and outside reserves (Newmark 2008). Fragmentation of habitat can lower genetic diversity of constituent populations, slow population growth rates, reduce trophic chain length of communities living in PAs, alter species interactions, and ultimately decrease biodiversity (Fahrig 2003, Rudnick and others 2012).

Effects of isolation and fragmentation on species are idiosyncratic and difficult to predict. Even within the carnivore guild, isolation can have dissimilar effects on different species. For example, isolation of PAs in the northern Rocky Mountain region of the USA had a greater impact on grizzly bears (*Ursus arctos*) than on wolves (*Canis lupus*) (Carroll and others 2004).

### **Human Population Pressure**

In many areas, human populations are growing quickly near reserve borders (Zommers and MacDonald 2012). Population growth near PA borders may be a result of migrants being “pushed” into areas near reserves due to lack of resources elsewhere, especially arable land for farming (“frontier engulfment”). Where agricultural expansion is a primary driver of population growth near PA borders, growth will likely continue so long as agriculture is the primary economic opportunity for local people. Alternatively, people may move to these areas because they are attracted to features of the PA, such as job opportunities in ecotourism, clean water, or the very resources that are being protected. Whatever the cause of population growth, increasing population pressure at reserve borders may exacerbate PA isolation and other threats to PAs.

### **PADDD**

Protected area downgrading, downsizing, and degazettement (PADDD) is a constant threat to PAs even as the global area covered by reserves continues to increase. Downgrading refers to a reduction in legal restrictions on human activities in PAs, downsizing to a reduction in reserve area, and degazettement to a loss of legal protection for an entire PA (Mascia and Pailler 2011). PADDD usually occurs for the extraction of resources for human needs. In the United States, demand for recreation in PAs may lead to increased public pressure and justification of PADDD. Some conservationists see PADDD as a positive conservation strategy because funds can be reallocated from poorly performing PAs, but there are many risks. If conservation embraces PADDD, it may be easier for PAs to be downgraded or degazetted for resource extraction without any corresponding conservation benefit.

## **INTERNAL THREATS**

### **Deforestation**

Protected areas are generally successful at reducing deforestation within their borders but deforestation remains a major concern in many regions and will likely pose an increasingly large threat to PAs. A meta-analysis of 49 locations from 22 countries showed that the majority of PAs had significantly lower levels of deforestation than non-PAs, but their effectiveness varied globally (Nagendra 2008). Deforestation in PAs occurs through extractive activities such as logging, fuelwood collection and charcoal production. Secondary and regenerating forests that have undergone extraction activities have consistently lower levels of biodiversity than primary forests (Gibson and others 2011). Proximate factors (such as agriculture, wood extraction) and

ultimate factors (such as economics and national policies) both drive deforestation in PAs; they are complex and often site or region specific (Geist and Lambin 2002).

### **Wildlife Exploitation**

Legal and illegal exploitation of wildlife occurs both outside and inside PAs and is a major driver of species declines globally. Wildlife offtake is driven by demand for medicine, luxury items (e.g., pets and fashion), trophy hunting, and food, resulting in a huge international trade (Smith and others 2009). Increased global wealth has driven an upsurge in wildlife exploitation for both medicine and luxury items. An estimated 80 percent of the world's people depend on traditional medicine (WWF 1993) most of which comes from plants (Engler and Parry-Jones 2007). Between 2000 and 2005, more than 6.7 million live birds, 7.9 million live reptiles and over 30 million reptile skins were traded globally (Engler and Parry-Jones 2007). Trophy hunting, another form of luxury-driven wildlife exploitation, is a valuable industry for many countries but it can have negative effects on wildlife populations in PAs when quotas are set unsustainably high (Lindsey and others 2007). Bushmeat consumption occurs on a vast scale. For example, the extraction of mammal bushmeat from the Congo Basin is a staggering 4.9 billion kg/year while 150 million kg are extracted from the Amazon (Fa and others 2002).

Each type of extraction can lead to negative consequences for species and ecosystems within PAs. Large-bodied animal species are particularly vulnerable because they have wide-ranging behavior, a low rate of reproduction, and are specifically targeted by hunters (Wilkie and others 2011). Removal of top predators negatively affects ecosystems by creating trophic cascades and reducing the length of the food chain (Estes and others 2011), while the removal of ecosystem engineers, such as elephants (*Loxodonta africana*), alters vegetation structure (Wilkie and others 2011). Many animal species are important seed dispersers or predators, and offtake can affect plant regeneration by decreasing seed dispersal, germination, and seed size of some plant species (Peres and Palacios 2007, Wright and others 2007, Galetti and others 2013).

### **Invasive Species**

Most PAs have at least one documented invasive species (90 percent of PAs surveyed; De Poorter 2007). As anthropogenic disturbance increases inside and outside PAs, the spread and establishment of invasive species within PAs will become an increasing threat. Increased predation is a common result of introduced animal species in PAs. For example, the introduced Burmese python (*Python bivittatus*) has led to a dramatic decline in frequency of observations of raccoons (*Procyon lotor*), and opossums (*Didelphis virginiana*), and a complete disappearance of once common rabbits (*Sylvilagus* spp.) in the Florida Everglades NP (Dorcas and others 2012). Conversely, introduced prey can also have negative impacts on their predators. In Kakadu NP in northern Australia, the poisonous invasive cane toad (*Bufo marinus*) colonized the entire reserve within two years, leading to the rapid decline of the quoll (*Dasyurus hallucatus*), a native carnivorous marsupial (Woinarski and others 2010).

Introduced parasites and disease can also have detrimental effects on native populations inside and outside PAs. Avian malaria and avian poxvirus were introduced to Hawaii in 1826, and it is believed that these diseases led to the extinction of at least 13 birds species (Sodhi and others 2011). Invasive species can also lead to the decline of native species in PAs through



competition (Gurevitch and Padilla 2004). In Yellowstone NP and surrounding areas, the invasive plant *Linaria vulgaris* has dramatically reduced the cover of native plants (Pauchard and others 2003). Competition has also been documented between animals in PAs, as seen in the decline of giant Galapagos tortoises (*Chelonoidis nigra*) due to the presence of non-native goats (*Capra hircus*) on Alcedo Volcano island in Galapagos NP (Márquez and others 2012).

The ability of PAs to buffer against invasive species is limited because waterways, roads, and in-park disturbances (natural and human) allow invasive plants to spread more easily (Foxcroft and others 2011). Recreation can also contribute to the spread of invasive plants within PAs (Pickering and others 2011), as can the expansion of invaders' potential ranges due to climate change (Hulme 2006). As global temperatures and human population increases, invasive species will become an increasingly large problem for PAs.

### **Livestock-Wildlife Conflict**

Livestock grazing has been implicated in environmental degradation, water shortages, and forage scarcity in and around PAs (Voeten and Prins 1999). And incursions of livestock into reserves are common. A study of 93 PAs by Bruner and colleagues (2001) found that over 40 percent of parks were ineffective at mitigating the impacts of grazing. Livestock negatively affects wildlife within PAs, with numerous studies documenting a negative relationship between livestock density and wildlife density.

Competition between wild herbivores and livestock is context-dependent. For example, wild ungulates and cattle compete for food during the dry season when resources are scarce but can enhance each other's diet quality during the wet season when resources are high (Odadi and others 2011). Livestock may even provide unexpected benefits to PAs by promoting seed dispersal (Brown and Archer 1989) and increasing plant diversity (Hickman and others 2004). In Guanacaste NP, native herbivorous seed dispersers are all extinct, but park officials have been able to use livestock to disperse seeds and restore native plant communities (Janzen 1982). Thus, the effects of livestock in PAs need not always be negative.

### **Fire**

Fire is a powerful ecological disturbance that shapes ecosystem structure and can maintain biodiversity. Fire activity can also dramatically alter habitat structure and affect nutrient and particle content of soil, water, and air. The threat of fire in PAs is a result of human-imposed deviations from natural fire regimes and can be divided into two situations. In the first, fire is uncommon in nature. But human influences have artificially elevated the frequency of fires. For example, in the Brazilian Amazon, fires occurred in at least 20 percent of reserves in most years, with more fires in dry years, near roads, and in forests with a high level of human impact (Adeney and others 2009). In the second situation fire is naturally common. For example, subtropical and temperate forests, grasslands, and shrublands are fire-adapted. Here the question of fire in PAs is an issue of maintaining regular fire in that ecosystem. Human activities including fire suppression and livestock grazing have reduced fire intervals in fire-adapted ecosystems worldwide over the past century leading to fuel buildup and woody species recruitment. Climate change and invasive species have increased susceptibility to fire in recent years, promoting severe fires in regions where fuel load has built up due to

suppression policies (Bowman and others 2011). Severe fires in National Forests and other PAs in the U.S. Northwest are a risk for endangered species, such as the northern spotted owl (*Strix occidentalis caurina*) (Spies and others 2006). Implementing fire-friendly policies can be difficult when people live near PA boundaries, and prioritizing fire in the landscape can be at odds with species-focused approaches such as the U.S. Endangered Species Act that may prohibit popular ecosystem management techniques like prescribed burning (Quinn-Davidson and Varner 2012).

### **Hydrology**

Decreasing water availability will have large impacts on PAs during this century. Alteration of hydrologic processes is often the result of anthropogenic demands for water, and with human populations expected to swell to over 9 billion by 2050, worldwide water demand will increase (UNEP 2010). Compounding the problem, water use over the last century has grown at twice the rate of population increase. Declines in water availability increase mortality of native plant and animal species and can have profound impacts on ecosystem services such as animal- or water-mediated seed dispersal (Konar and others 2013). Massive die-offs due to water shortages have been documented for a wide range of taxonomic groups in PAs, including migrating birds in Klamath NP (AP 2012) and mammals in South Africa's Kalahari Gemsbok NP (Knight 1995). In addition, many PAs act as dry-season water sources for wildlife (Western 1982).

Analysis of a century of hydrologic records from 31 North American rivers revealed flow declines for 67 percent; these rivers provide water for a large number of North American PAs (Rood and others 2005). The decrease in flow results from a combination of urbanization, irrigation, damming, and reduced snow pack due to climate change (Leppi and others 2012). Already, reductions in snow pack as a result of warming have led to decreases in seasonal water availability for PAs throughout the western USA (Hamlet and others 2005).

### **Mining**

Legal and illegal mining around PAs, as well as accidental mining spills, pollute water sources, destroy habitat, and threaten biodiversity. Indeed artisanal and small-scale mining (mineral extraction characterized by low levels of mechanization and high labor intensity) occurs in or around 96 of 147 PAs evaluated (Villegas and others 2012). Drainage and tailings from mining activities can contaminate watersheds with lethal levels of chemicals such as arsenic, mercury, and lead. In the Coto Donana, a protected estuarine marsh ecosystem in Spain, the accidental upstream release of 5 million cubic meters of acid waste from the processing of pyrite ore led to severe declines in fish, invertebrate, and bird species (Pain and others 1998).

### **Drilling**

Increased reliance on fossil fuels has sparked unprecedented levels of oil and gas exploration and extraction (Osti and others 2011). Demand for oil and gas is predicted to increase in coming decades (McDonald and others 2009) driving increased exploration in and around PAs. For example, in the federally owned section of the Arctic National Wildlife Refuge in Alaska, USA, there are approximately 7.69 billion barrels of recoverable oil, an amount roughly equal

to US oil consumption for 2007 (Kotchen and Burger 2012), and the possibility of opening this region for oil exploration has been intensely debated (Baldwin 2005, Snyder 2008). More than a quarter of the 911 UNESCO World Heritage sites worldwide are thought to be under threat from oil and gas extraction, with the Arabian Oryx Sanctuary in Oman being the first site in history to be delisted from the World Heritage list due to a significant reduction in size for oil and gas extraction (Osti and others 2011). In North America fossil fuel extraction activities disrupt migration patterns of caribou (*Rangifer tarandus*) and mule deer (*Odocoileus hemionus*; Hebblewhite 2011) and have led to significant population declines of the greater sage grouse (*Centrocercus urophasianus*; Naugle and others 2011). Many potential impacts of fossil fuel extraction on PAs have yet to be realized since oil and gas concessions within PAs have yet to be exploited. Opening these concessions will lead to increased CO<sub>2</sub> emissions, deforestation, habitat degradation, and biodiversity loss (Finer and others 2010).

### **Recreation**

Protected areas worldwide are used for recreational activities and there has been a substantial rise in non-consumptive wildlife recreation and nature-based tourism over the last four decades (Tisdell and Wilson 2012). Recreation in PAs can result in damage to the local environment and its wildlife. For example, on federally protected lands in the USA, recreation is the second largest danger to threatened and endangered species (Losos and others 1995). Creation of roads, trails and facilities leads to direct habitat destruction and to altered hydrologic processes, increased erosion and damage to tree roots (Pickering and Hill 2007). Trampling by hikers, bicycles, cross-country skiers, ORVs, and horses causes soil compaction and can result in decreased plant diversity and density (e.g., Torn and others 2009; Marzano and Dandy 2012). Trail proliferation in PAs degrades habitat beyond the anticipated boundaries of human impact (Farrell and Marion 2001).

Recreational activities can also negatively affect animals in PAs by causing direct mortality (e.g., collisions with ORVs), altering animal behavior (Buckley 2004), or introducing diseases (e.g., human-primate disease transmission; Wallis and Lee 1999). Even quiet, non-consumptive recreational activities that seem to have low impact can have detrimental effects on wildlife populations. For example, wildlife viewing reduces foraging efficiency in birds and causes higher nest predation or abandonment of young (Boyle and Samson 1985). On the other hand, revenue generated by tourism in PAs contributes to the conservation of wildlife (Buckley 2012, Steven and others 2013). Nature-based tourism can also be vital for the establishment and management of PAs. For example, tourism is the primary source of revenue for South African NPs and assists in funding the expansion of PAs and conservation projects (SANParks 2012).

### **Interactions**

Although we have discussed particular threats to PAs, these threats are connected through a web of interactions. Climate change will not only shift species distributions but will increase fire frequencies (Bowman and others 2009), provide opportunities for invasive species establishment (Hulme 2006), and cause more frequent droughts in some areas (Pittock and others 2008), thereby affecting park hydrology and necessitating greater use of PA resources by local people. In turn, deforestation can exacerbate climate change and make remaining forest edges

more susceptible to fire (Bowman and Murphy 2010). Population growth at PA borders will likely speed PA isolation via nearby agricultural land conversion (Zommers and MacDonald 2012) leading to livestock-wildlife conflict. Population pressure may also increase wildlife and timber extraction. Tourists visiting PAs for recreation may introduce or spread invasive species (Pickering and others 2011) and so on.

## **SOLUTIONS**

### ***More Protected Areas***

Although the number of PAs is increasing, many species and habitats remain unprotected. To take just a single example, the distribution of PAs in Africa overlaps poorly with distributions of endangered birds (Beresford and others 2011). To meet conservation needs of hitherto unprotected habitats and species, large NGOs and researchers have devised several plans as to where to focus conservation effort. These include Conservation International's 25 biodiversity hotspots (Myers and others 2000); the World Wide Fund for Nature (WWF) "Global 200" ecoregions (Olson and Dinerstein 2002); 24 wilderness areas (Mittermeier and others 2003); and the Wildlife Conservation Society (WCS) "Last of the Wild" initiative (Sanderson and others 2002). Other conservation organizations take a more species or taxon-specific approach. Bird Life International has spearheaded Important Bird Areas (IBAs) as a way to conserve habitat for threatened, migrating, or congregating birds. Several PAs have been created in the name of charismatic flagship species (Andelman and Fagan 2000). While some argue that the use of flagship species may detract from the protection of other species (Simberloff 1998), use of charismatic species can raise significantly higher revenue than less well known species (White and others 1997). The relative effectiveness of these and other conservation strategies remains largely untested.

### ***Enlargement***

Large PAs are better buffered from anthropogenic influences around their edges (e.g., fire), can sometimes fully encompass migratory routes, may provide sufficient area for population viability (especially for large predators), can serve to protect entire watersheds and ecosystem processes, are likely to fare better in the face of climate change, and are easier and less expensive to protect and maintain on a per hectare basis than smaller reserves (Peres 2005). Given the benefits of large reserves, enlargement of existing PAs is a credible solution to counter impending threats. Unfortunately, less than 0.05 percent of all PAs qualify as "very large PAs"—those reserves with an area of 25,000 km<sup>2</sup> or more—these account for only 26 percent of global PA coverage -while over 70 percent cover less than 10 km<sup>2</sup> in area (Cantú-Salazar and Gaston 2010).

Reserve size is frequently a political decision. For example, large PAs are often established along international boundaries as transboundary conservation areas. But in some cases PA designation can be influenced by species minimum area requirements (Woodroffe and Ginsberg 1998, Gurd and others 2001).

## ***Buffer Zones***

Buffer zones are areas around PAs designed to insulate them from the negative impacts of anthropogenic activities occurring immediately outside but also support low impact land-use wherein people can sustainably extract resources or even practice agriculture (UNESCO 1974, Noss 1983). From a biological standpoint, buffer zones increase the effective size of a PA and limit high-impact land and water use nearby, both of which are growing problems. For example, intermediate to large-sized buffers are predicted to decrease illegal extraction within the PA core (Robinson and others 2013) and can help prevent destruction of forest immediately bordering PAs that otherwise might form abrupt forest edges to PA borders (DeFries and others 2005). Furthermore, buffer zones can help protect wide-ranging carnivores that move outside reserves (Balme and others 2010).

Despite the recognized importance of buffer zones, only general guidelines exist for their development and management (Robinson and others 2013) and current understanding of the dynamics of anthropogenic pressures at park boundaries is still weak (Shafer 1999). Indeed, in certain areas, land-use is more intense in buffer zones around PAs than in areas further away for reasons that are unclear (Naughton-Treves and others 2005). Nevertheless, buffer zones remain an important protection strategy for achieving both conservation and socioeconomic goals: helping to protect biodiversity within PAs while providing access for local people to utilize resources at PA boundaries.

## ***Corridors***

Corridors between PAs are vital for wildlife population viability because such linkages allow species to disperse between PAs, maintain genetic variability within populations, rescue populations from local extinction, facilitate species' range shifts due to global climate change, and provide more area for species requiring large home ranges (Rudnick and others 2012). A review of empirical evidence notes that animals do use corridors and the ensuing connectivity can increase overall population viability (Beier and Noss 1998). Corridors can increase species movement between patches by 50 percent compared to patches unconnected by corridors, although corridor effectiveness of course differs among taxa, with linkages being more important for non-avian vertebrates and plants (Gilbert-Norton and others 2010).

Linking existing PAs may be an important tool for mitigating the threat of climate change (Heller and Zavaleta 2009). By allowing species to shift their distributions to climatically favorable areas, corridors increase the probability of long-term population viability (Krosby and others 2010). As a cautionary note, while corridors can be effective in connecting habitat patches and species that reside within them, they can potentially transmit disease, fire, and invasive species (Simberloff and others 1992). Nonetheless, corridors are being increasingly viewed as vital to the future success of PAs and numerous linkages between reserves are being planned and implemented globally (Jones and others 2009).

## ***Translocations***

As anthropogenic pressures continue to lead to local extinctions of populations within PAs, translocation of individuals may be necessary to maintain sufficiently large, viable metapopulations

of threatened and endangered species. Translocation, the purposeful movement of organisms by humans from one area to another, can be dichotomized into reintroduction and assisted colonization (Ricciardi and Simberloff 2009). Reintroduction involves the release of species into ranges where they historically occurred. For example, wolves were successfully reintroduced into Yellowstone NP in the mid-1990s and now have a viable population (Smith and others 2003).

Assisted colonization, the movement of species into areas not part of their historic range, is much discussed as a solution to helping species change latitudes in response to rapid climate change and to assist them crossing fragmented landscapes (Hoegh-Guldberg and others 2008). For example, *Torreya taxifolia*, a conifer endemic to Florida, has been planted throughout North Carolina in an attempt to save its dwindling populations (McLachlan and others 2007). Some have argued that relocated species have the potential to become invasive in their new habitats and may drive out native species or disrupt ecosystems (Ricciardi and Simberloff 2009). Others argue that this risk can be managed with nuanced evaluations of past species invasions (Sax and others 2009), and that inaction is an equally insidious threat (Schwartz and others 2009). If assisted colonization is adopted as a conservation strategy, PAs will be crucial in protecting newly established populations against further anthropogenic impacts.

## **Management**

Addressing many of the direct and indirect threats to PAs will depend on the effectiveness of PA planning and management (Knight and others 2013). For example, stopping illegal extraction requires law enforcement and negotiating with local communities; tackling invasive species requires prevention and removal techniques; and managing fire may require suppression or prescribed burning. The success of these activities depends on a clear management policy based on research and monitoring, effective communication, sufficient funding, and competent staff.

PAs are established for many reasons (Chape and others 2008), and any successful management framework should begin by clearly identifying those goals and establishing priorities that will allow the PA to succeed in the face of numerous direct and indirect threats. A reserve established to protect an endangered species may limit disturbance, whereas an ecosystem management approach may introduce natural disturbance as part of management activity. An extractive reserve must prioritize the resource in question while considering impacts of extraction on the ecosystem as a whole. A popular and effective framework for conservation in all PA types is adaptive management, which emphasizes ongoing adjustment of policy based on frequent monitoring of biodiversity. That said, considerable proactive and precautionary ecological and sociological management decisions will be needed to counteract the growing effects of climate change (Millar and others 2007, Heller and Zavaleta 2009).

Perhaps the most controversial issue in PA management is who should manage and how local communities should be involved in the process. Over the past few decades, community based conservation (CBC) schemes and integrated conservation and development projects (ICDPs) that involve the participation or compensation of local people (bottom-up management) became popular in response to sociopolitical injustices related to a century of strict protectionism (top-down management). Community involvement and compensation can further conservation goals by increasing local support for conservation and reducing activities such as wildlife and timber extraction from reserves. Enthusiasm for such approaches has waned, however, as some CBCs

and ICDPs have failed to produce win-win solutions to stem biodiversity decline and poverty that they promised (McShane and others 2011). Some conservationists are now advocating a return to the “fences and fines” approach, suggesting that it is the best way to protect biodiversity despite sometimes being politically unpopular (Adams and Hutton 2007).

Though community involvement has most often been identified with utilization and protectionism with preservation, the means and ends of management need not co-vary (Borgerhoff Mulder and Coppolillo 2005). In many cases, hybrid approaches that combine elements of community participation with preservationist goals may be best. For example, strict reserves may be managed or co-managed by communities, or have strong conservation education and outreach programs while tightly limiting resource extraction within the reserve.

## CONCLUSION

There is abundant evidence that PAs are effective at conserving species and landscapes globally. However, reserves are still vulnerable to many human activities that they aimed to prevent at the time of establishment, and they are now facing new threats which were formerly unanticipated. We began our review with climate change, a broad threat that is starting to affect PAs around the world. Next, we discussed threats that act on PAs at and beyond their borders, such as increasing isolation and human population growth. Then we examined threats acting inside reserves such as deforestation, wildlife exploitation, invasive species, grazing, fire, changing hydrology, mining, drilling and recreation. It is clear that many of these threats act synergistically. In the last part of the review we discussed ways that some of these threats can be ameliorated. Where possible, the creation of additional PAs can address many of these issues, but enlarging, buffering and connecting existing reserves will also be very important. Furthermore, nations need to invest in effective monitoring and management of their current PA network. While there is no single approach to addressing the current and future threats to PAs, conservation solutions are available and future challenges to terrestrial PAs can be overcome.

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## **Section II:**

Uncharted Territory: Assessing Vulnerability  
and Developing Options for Sustaining Key  
Values and Services From Forest Ecosystems  
Under Conditions of Elevated Uncertainty

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# Briefing: Climate and Wildfire in Western U.S. Forests

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**Abstract:** Wildfire in western U.S. federally managed forests has increased substantially in recent decades, with large (>1000 acre) fires in the decade through 2012 over five times as frequent (450 percent increase) and burned area over ten times as great (930 percent increase) as the 1970s and early 1980s. These changes are closely linked to increased temperatures and a greater frequency and intensity of drought. Projected additional future warming implies that wildfire activity may continue to increase in western forests. However, the interaction of changes in climate, fire and other disturbances, vegetation and land management may eventually transform some forest ecosystems and fire regimes, with changes in the spatial extent of forest and fire regime types. In particular, forests characterized by infrequent, high-severity stand replacing fire may be highly sensitive to warming. Increased wildfire combined with warming may transform these ecosystems such that fuel availability, rather than flammability, becomes the dominant constraint on fire activity. Climate will continue to warm for some time regardless of future greenhouse gas emissions, requiring adaptation to warmer temperatures. Changes in forest location, extent and type will result in substantial changes in ecosystem services.

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## **INTRODUCTION**

Climate change is generating higher temperatures and more frequent and intense drought (Cayan and others 2010; Peterson and others 2013). Globally, the last three decades (1980s, 1990s, and 2000s) have each in turn been the warmest in history (Arndt and others 2011). In the United States, 2012 was the warmest year on record (Blunden and Arndt 2013), and drought has become more widespread across the western United States since the 1970s (Peterson and others 2013). Climate projections suggest increased likelihood of heat waves in the western United States and droughts in the Southwest (Wuebbles and others 2013). Concomitantly, the fire season and area burned are expected to increase substantially by mid-century across the western United States due to expected climate change (Yue and others 2013).

Climate—primarily temperature and precipitation—influences the occurrence of large wildfires through its

effects on the availability and flammability of fuels. Climatic averages and variability over long (seasonal to decadal) time scales influence the type, amount, and structure of the live and dead vegetation that comprises the fuel available to burn in a given location (Stephenson 1998). Climatic averages and variability over short (seasonal to interannual) time scales determine the flammability of these fuels (Westerling and others 2003).

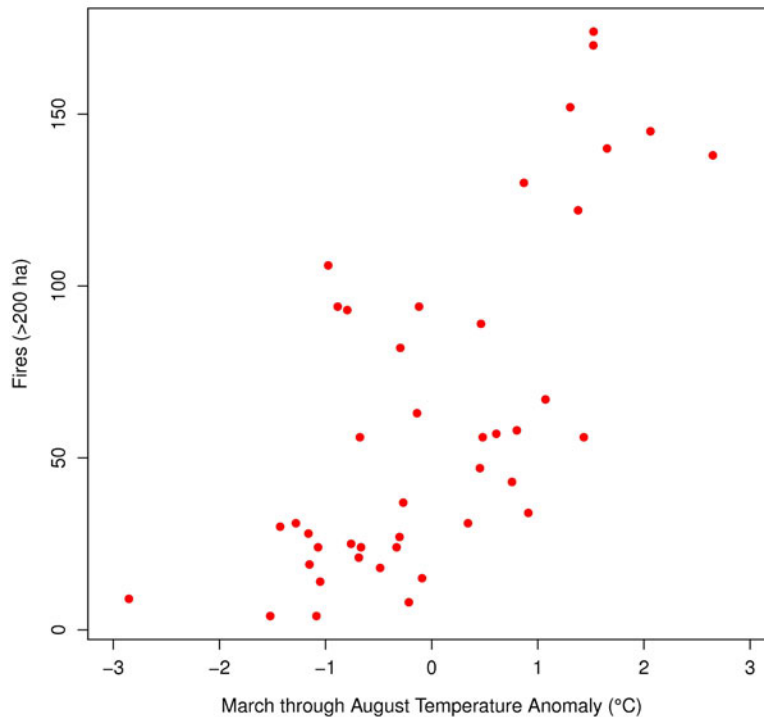
The relative importance of climatic influences on fuel availability versus flammability can vary greatly by ecosystem and wildfire regime type (Westerling and others 2003; Littell and others 2009; Krawchuck and Moritz 2011). Fuel availability effects are most important in arid, sparsely vegetated ecosystems, while flammability effects are most important in moist, densely vegetated ecosystems. Climate scenarios' changes in precipitation can have very different implications than changes in temperature in terms of the characteristics and spatial location of wildfire regime responses (namely, changes in fire frequency, average area burned, and fire severity).

While climate change models generally agree that temperatures will increase over time, changes in precipitation tend to be more uncertain, especially in arid midlatitude regions (Dai 2011; Moritz and others 2012; Gershunov and others 2013). Therefore, in ecosystems where wildfire risks have been strongly affected by variations in precipitation, there is less certainty about how these wildfire regimes may change. However, in ecosystems where wildfire risks have been sensitive to observed changes in temperature, climate change is likely to lead to substantial increases in wildfires. Also, as climate change alters the potential spatial distribution of vegetation types, ecosystems and their associated wildfire regimes will be transformed synergistically. In the following sections, we give an overview of climate-vegetation-wildfire interactions in western U.S. forests, and summarize recent scientific literature on the subject for several subregions.

While policies to mitigate climate change can help to limit changes in wildfire regimes, some level of additional warming is going to occur regardless, requiring adaptation. Despite ongoing progress in describing climate-wildfire relationships and their implications for western U.S. forest resources under a changing climate, significant challenges remain in incorporating this science into land management planning and policy for climate change adaptation and mitigation. Federal land management agencies have recently formulated extensive guidelines for this process, which we review in the concluding section below.

### ***Climate-Vegetation-Wildfire Interactions in the Western United States***

The type of vegetation (i.e., fuels) that can grow in a given place is governed by moisture availability, which is a function of both precipitation (via its effect on the supply of water) and temperature (via its effect on evaporative demand for water) (Stephenson 1998). As a result, the spatial distribution of vegetation types and their associated fire regimes is strongly correlated with long-term average precipitation and temperature (e.g., Westerling 2009). Climatic controls (temperature and precipitation) on vegetation type along with successional stage largely determine the biomass loading in a given location, as well as the sensitivity of vegetation in that location to interannual variability in the available moisture. These factors in turn shape the response of the wildfire regime in each location to interannual variability in the moisture available for the growth and wetting of fuels. Cooler, wetter areas (forests, woodlands) have greater biomass, and wildfires there tend to occur in dry years. Warmer, drier areas (grasslands, shrublands, pine savannas) tend to have less biomass and wildfires there tend to occur after one or more wet

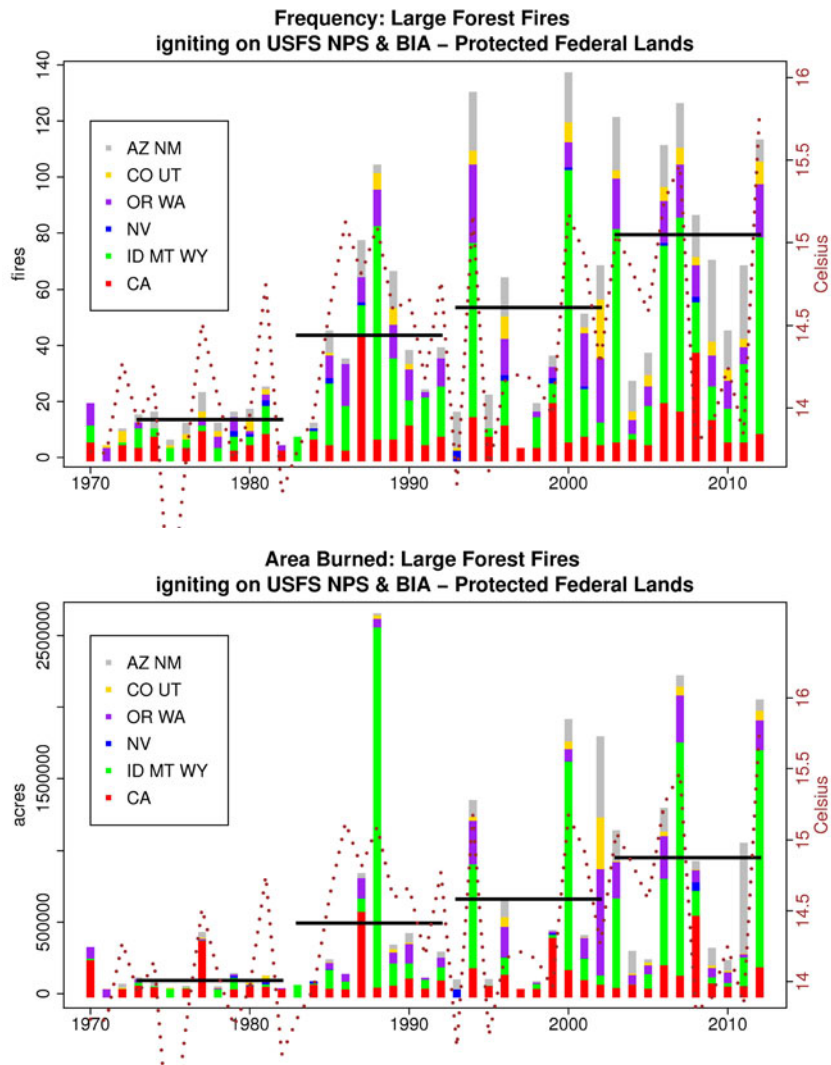


**Figure 1.** Scatter plot of annual number of large (> 200 ha) forest wildfires versus average spring and summer temperature for the western United States. Forest Service, Park Service, and Bureau of Indian Affairs management units reporting 1972-2004. Fires reported as igniting in forested areas only. Source: Westerling 2009.

seasons or years (Swetnam and Betancourt 1998; Westerling and others 2003; Crimmins and Comrie 2004).

Consequently, wildfire is much more sensitive to variability in temperature in some locations than in others. In the western United States, cool, wet, forested locations tend to be at higher elevations and latitudes where snow can play an important role in determining summer moisture availability (Sheffield and others 2004). Above-average spring and summer temperatures in these forests can have a dramatic impact on wildfire, with a highly nonlinear increase in the number of large wildfires above a certain temperature threshold (Figure 1). Westerling and others (2006) concluded that this increase is due to earlier spring snowmelt and a longer summer dry season in warm years. They found that years with early arrival of spring account for most of the forest wildfires in the western United States (56 percent of forest wildfires and 72 percent of area burned, as opposed to 11 percent of wildfires and 4 percent of area burned occurring in years with a late spring).

Fire severity tends to be highest, with large infrequent stand-replacing fires that burn in the forest canopy, in cooler, more moist forests at generally higher elevations and/or latitudes, such as the lodgepole pine forests in the northern and central Rocky mountains (Baker 2009). Prior to the era of extensive/intensive livestock grazing (post 1850s) and active fire suppression by government agencies (post 1900s), warmer, drier forests tended to have mixed or low severity, more frequent fire with more of the fire concentrated in surface fuels (grass, shrub, forest litter) and less tree mortality (Allen and others 2002). However, increased fuel loads due to historic fire suppression and land use changes, combined with more extreme climatic conditions, have resulted in high severity fire in some forests where it was rare prior to the 20th century (Miller and others 2009).



**Figure 2.** Frequency of (top panel) and area burned in (bottom panel) large (>1000 acre) forest fires. Fires are action fires for which suppression was attempted, reported by USFS, NPS and BIA as burning on federal lands in primarily forest vegetation. Fires are grouped by states (colored bar sections) with average regional spring and summer temperature overlayed (dashed line). Horizontal solid lines indicate averages for the last four decades. Large fires in the last decade are over 480% more frequent and burn 930% more area than fires in the first decade. Average annual area burned on these lands has increased by over 285,000 acres per decade for the last three decades, to just under 1 million acres per year at present.

The frequency of large (>1000 acre) forest fires and the area burned in those fires has continued to increase steadily over the last three decades as temperatures have risen throughout the region (Figure 2). Forests of the northern and central Rocky mountains where fire typically burned with high severity but was infrequent, have been the most sensitive to changes in temperature, accounting for the largest share of the increase in burnt forest area (Figure 2, Westerling and others 2006). As discussed below, projections of additional increases in future temperatures imply further increases in fire activity. However, warming and fire frequency may increase past critical thresholds, with some forests no longer able to sustain large high-severity fires. That is, fuel availability may become a limiting condition on fire in areas where climatic controls on fuel flammability were recently the dominant constraint on fire.

## REGIONAL SUMMARIES<sup>1</sup>

### *Regional Summary: Idaho, Montana, Wyoming Rockies*

Climate is generally semiarid with summer-dry conditions to the northwest, and summer-wet to the southeast (Bailey 1996), and generally moister and cooler conditions relative to regions at lower latitudes. Elevation ranges from 3000 to 7000 ft in the southern and central portions, and 3000 to over 9000 ft in the northern portion. Mixed evergreen-deciduous forests dominate montane and subalpine elevations in the north, with strong topographic controls on moisture fostering diverse forest vegetation zones to the south (Bailey 1996; Cleveland 2012). Forests with characteristically infrequent high-severity, stand-replacing fires account for the largest area (mixed spruce-fir, lodgepole pine), with significant forest area characterized by mixed- (e.g., Douglas-fir) and low- (e.g., ponderosa pine) severity fire regimes prior to the historical fire suppression era (Schoennagel and others 2004).

Notably, some northern Rockies ponderosa pine forests, usually associated with low-severity surface fire regimes in the literature, may have experienced occasional high-severity, stand-replacing fires during extended droughts of past millennia, as inferred from sedimentary charcoal studies (Pierce and others 2004). However, the patch sizes of these ancient high severity fires within ponderosa pine-dominant or mixed forests are unknown for almost all forests of these types, and it is possible that current large, high-severity patch sizes and subsequent geomorphic responses may be unique over the late Holocene, as similar sedimentary charcoal studies in Colorado pine and mixed-conifer forested watersheds suggest (Bigio and others 2010). In the only detailed, highly systematic study of tree age structures and fire scar evidence at stand to landscape scales in northern stands of ponderosa pine (i.e., in the Black Hills of South Dakota), Brown and others (2008) found that only about 3 percent of the landscape experienced high-severity fires during the three and one-half centuries prior to 1893, and overall, frequent, low-severity surface regimes dominated those landscapes.

In northern forests where infrequent, large high-severity fires occurred, these events likely were driven by extended drought associated with high pressure atmospheric blocking patterns (Romme and Despain 1989; Renkin and Despain 1992; Bessie and Johnson 1995; Nash and Johnson 1996; Baker 2009). Paleo studies support a strong influence of climate on fire-return interval (e.g., Whitlock and others 2003, 2008; Milspaugh and others 2004), with fuel controls playing a much lesser role (Higuera and others 2010).

Historically, burned area is concentrated in a relatively small number of very large fire events (Ballou and others 1992; Schoennagel and others 2004; Baker 2009). From 1972-1999, 66 percent of burned area in the ID - MT - WY Rockies occurred in only two years (1988 and 1994), and 96 percent of burned area in the Greater Yellowstone area occurred in one fire year (1988) (Westerling and others 2011a). This pattern is consistent with climatic controls on the flammability of plentiful fuels being the dominant constraint on the occurrence and spread of large wildfires (Littell and others 2009); namely, large areas burn in rare dry years.

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<sup>1</sup> Note that the scientific studies available to draw upon for each regional summary vary somewhat in focus. Consequently, the types of information incorporated into a survey like this vary more than would be the case for a summary of a research project that treats each region in a unified way.

The effect of changes in the timing of spring on wildfire has been particularly pronounced in the higher-latitude ( $> 42^\circ$  North), mid-elevation (1680-2590 m) forests of the Rocky Mountains, which account for 60 percent of the increase in forest wildfires in the western United States (Westerling and others 2006). Higher elevation forests in the same region had been buffered against these effects by available moisture, while lower elevations have a longer summer dry season on average and were consequently less sensitive to changes in the timing of spring.

The frequency and extent wildfire is projected to continue to increase in coming decades until fuel availability and continuity becomes limited and supplants climatic controls on flammability as the dominant constraint on the spread of large wildfires by mid-century in the Greater Yellowstone region (Westerling and others 2011a) and in the Rockies more generally (Westerling in preparation). Increased burned area of similar magnitude has been projected by the National Research Council (2011), applying models from Littell and others (2009) (see also Climate Central 2012).

### ***Regional Summary: Utah and Colorado***

Colorado and Utah also experience high geographic and interannual variability in temperature and precipitation due to elevation, topography, and latitude. In general, the region is characterized by summer-dry areas northwest of the Rocky Mountains under the influence of the subtropical high, and summer-wet areas southeast of Rocky Mountains and in southern portions of Colorado and Utah, due to monsoons from the Gulf of Mexico and Gulf of California (McWethy and others 2010).

A number of low-elevation forests (e.g., below 2100 m in the central Colorado Front Range; Sherriff and Veblen 2008) with grass or other fine-fuels in the understory record regional fires during dry summers when preceded by increased spring-summer moisture availability up to 4 years prior, that enhance fine-fuel accumulation and contribute to fire spread when subsequently cured (Donnegan and others 2001; Grissino-Mayer and others 2004; Brown and others 2008; Sherriff and Veblen 2008; Gartner and others 2012). Moister, higher-elevation forests lacking grass understories do not record this wet-dry signature in the fire record (Sibold and Veblen 2006; Brown and others 2008; Schoennagel and others 2011). Documentary records of area burned in ecoregions encompassing Colorado and Utah showed that moist antecedent conditions are associated with greater area burned (and were more important than warmer temperatures or drought conditions in the year of fire) in grasslands, shrublands and arid low-elevation woodlands with grass or shrub understories, but only fire-year conditions were significant in moister high-elevation and/or west-slope forests (Knapp 1995; Westerling and others 2003; Collins and others 2006; Littell and others 2009).

Littell and others (2009) found that area burned in the S. Rockies (1977-2003) was positively related to winter temperature, and negatively related to spring temperature, along with spring and summer precipitation and lagged drought; ( $r^2 = 0.77$ ; Littell and others 2009). Predictions for Utah and Nevada Mountains were linked to lagged spring temperature, but were much less robust ( $r^2 = 0.33$ ). The Southern Rockies only accounted for  $<1$  percent of recent increase in wildfire activity since 1985, in contrast to the Northern Rockies, which accounted for 60 percent, primarily related longer fire seasons and snowpack reduction (Westerling and others 2006).

Average annual summer and winter temperatures are expected to increase dramatically in Colorado and Utah by 2050, yet models show low agreement for precipitation (Fig. 5.1 in Ray and others 2010). However, Seager and others (2007) predict that the Southwest (125°W-95°W, 25°N-40°N, which includes most of Colorado and Utah) will become more arid during the next century as annual mean precipitation minus evaporation becomes more negative. Similarly, Gutzler and Robbins (2011) predict that higher evaporation rates due to positive temperature trends will exacerbate the severity and extent of drought in the semi-arid West.

Brown and others (2004) predict that reduced relative humidity will increase the number of days of high fire danger at least through the year 2089 compared to the base period, however, the Colorado Rockies and Front Range showed no change in predicted fire risk thresholds, suggesting little change in wildfire activity. This contrasts with a Spacklen and others (2009) study that predicts higher temperature will increase annual mean area burned by 54 percent by 2050s relative to the 1980-2004 period, with the entire Rocky Mountains showing large increases (78 percent) and high interannual variability.

The National Research Council (2011) predicts that burn area in parts of western North America may increase by 200 to 400 percent for each degree (°C) of global warming relative to 1950-2003, adapting methods developed by Littell and others (2009) to use temperature and precipitation as the predictor variables. Across Colorado and Utah, the southern Rocky Mountain Steppe Forest is predicted to experience the greatest increase in mean annual area burned (>600 percent), with the least in the Nevada-Utah Mountains (only 73 percent).

### ***Regional Summary: Arizona and New Mexico***

The Southwestern United States (Arizona and New Mexico) is generally a semi-arid region. Considerable topographic relief, however, results in a very diverse biotic landscape and consequent differences in vegetation and wildfire. These differences are often expressed along relatively short distances (10s of kilometers) and elevational gradients from desert basins to forested mountains. Natural fire regimes along these gradients vary from essentially no spreading wildfires in the pre-21st century historical record (e.g., lower Sonoran desert), to frequent, low-severity surface fires (e.g., mid-elevation ponderosa pine forests, with intervals between widespread fires ranging from 2 to 20 years), to low-frequency, high-severity, stand-replacing fires (high-elevation spruce-fir forests, with intervals between large crown fires ranging from 150 to 300+ years) (Swetnam and Baisan 1996, 2003; Margolis and others 2007, 2009).

Seasonal climate of the Southwest is characterized by bimodal precipitation, with winter-cool season and summer-warm season maxima, with a pronounced dry season during most years in late spring to early summer. The peak of fire activity tends to occur in this warm/dry season (May through June), with a maximum area burned in the driest weeks of June, and the maximum number of fire ignitions in July when monsoonal moisture and convective activity generates large numbers of lightning strikes (Crimmins 2006; Keeley and others 2009). Human-set fires are also important in Southwestern landscapes, both in the distant past (i.e., by Native Americans), and in the modern era. During some seasons and years human-set fires exceed areas burned by lightning set fires, especially during some recent years when extraordinarily large fires were set accidentally or purposely during spring-summer droughts. Paleo and modern records of fire and climate show the strong importance of both prior cool-season

and current spring-through-summer moisture indices to fire activity in this region (especially regionally synchronized fire events in the paleorecord and total area burned per fire season/year in the modern record; Swetnam and Betancourt 1998; Westerling and others 2002; McKenzie and others 2004; Crimmins and Comrie 2004; Crimmins 2006; Holden and others 2007; Littell and others 2009; Williams and others 2013).

Because comprehensive documentaries of wildfire only go back a few decades, paleo proxy records of past fire and climate activity have been developed to provide annual to millennial scale perspectives on fire, vegetation and inferred climate variability (Swetnam and Baisan 1996; Swetnam and Brown 2010; Falk and others 2011; International Multiproxy Paleofire Database; Anderson and others 2008; Frechette and others 2009; Bigio and others 2010).

These paleorecords demonstrate the follow specific findings:

- (1) Widespread surface fires were ubiquitous in ponderosa pine forests and mixed-conifer forests across the region before the advent of extensive livestock grazing in the late nineteenth century and active fire suppression by government agencies beginning about 1910. High-severity, stand-replacing crown fire occurred in some dense pinyon-juniper woodlands (Romme and others 2009), shrublands, and higher elevation spruce-fir forests (Margolis and others 2007; Margolis and Balmat 2009) in the pre-1900 period, but large, high-severity fires were rare in ponderosa pine forests. Although some evidence of high-severity fire in ponderosa pine and mixed-conifer forests has been found in charcoal sediments (e.g., Frechette and others 2009; Bigio and others 2010), and small patch size (<200 ha) high-severity fires have been reconstructed in a few tree-ring studies (Swetnam and others 2001; Iniquez and others 2009), we lack any clear evidence at this time that large patch size (>200 ha) high-severity fires occurred in ponderosa pine-dominant forests in the past were as extensive as those occurring today (Cooper 1960; Allen and others 2002).
- (2) Extreme droughts and regional fire activity are highly correlated over the past four centuries in the available tree-ring record. Lagging patterns are evident in lower elevation forests and woodlands, with wet conditions in prior 1 to 3 years, coupled with dry conditions during current year often leading to extensive regional fire years in the past (Swetnam and Betancourt 1998).
- (3) Decadal-scale variation in past fire activity is evident in parts of the Southwest, with occasional periods of 1 to 2 decades of either decreased or increased local to regional fire activity (Swetnam and Betancourt 1998; Grissino-Mayer and Swetnam 2000; Brown and Wu 2005; Margolis and Balmat 2010; Roos and Swetnam 2011). Many studies have shown some association between these annual-to-decadal-scale patterns and climatic variations (e.g., Swetnam and Betancourt 1990, 1998; Kitzberger and others 2007; Brown and Wu 2005).
- (4) There are relatively few long-term, sedimentary charcoal-based records of fire activity in the Southwest compared to other more mesic regions with more lakes and bogs. The available records do show, however, decadal-to-centennial-scale variations in fire and vegetation that are likely associated with climatic variations on those time scales (e.g., Anderson and others 2008). One striking finding in a comparison of tree-ring and charcoal-based fire histories is the unprecedented lack of fire in the most recent century (due to livestock grazing and fire suppression) in a record of more than 7,000 years (Allen and others 2008).



The longest modern records for the Southwest show a similar pattern to that observed in some other forests across the western United States during the 20<sup>th</sup>-21<sup>st</sup> centuries, namely, some large fires occurred during early decades of the 20<sup>th</sup> century, there were lower levels of fire activity during the mid-20<sup>th</sup> century (but with several large events, > 5000 ha during the 1950s drought), and after the late 1970s a rather sharp rise in numbers of large fires and area burned occurred (e.g., Rollins and others 2001; Holden and others 2007)

The post-2000 period includes several fires in forested landscapes that exceed in area any other wildfire in this two state region over at least the past 100 years (e.g., most notably, the 189,651 ha [468,640 acre] Rodeo-Chediski Fire in central Arizona in 2002, and the 217,741 ha [538,049 acre] Wallow Fire in east-central Arizona and west-central New Mexico in 2011 and the 63,000 ha [156,593 acre] Las Conchas Fire in New Mexico in 2011). Nearly simultaneously, over the past two decades large areas of forest and woodland have experienced extensive tree mortality due to a combination of direct drought-induced physiological stress and mortality, and attacks by phloem-feeding bark beetles (Allen and Breshears 1998; Breshears and others 2005). Williams and others (2010) summarize the mortality extent across the Southwest by these agents (drought, fire, bark beetles) and they estimate that nearly 20 percent of forested areas experienced high levels of tree mortality between 1984 and 2010.

Both the recent large fires and the extensive bark beetle outbreaks are unprecedented in the historical documentary record of the past century. There are older documentary records (e.g., newspaper accounts) from the late nineteenth century that refer to fires covering more than 400,000 ha (988,421 acre) (e.g., Bahre 1986). These reported large events, however, tended to be at lower elevations (i.e., in grasslands) as well as in some higher elevations. There are no known burn scars (“bald” mountain areas lacking trees because of past fires, or recovering forests) at the scales and extent (patch sizes) of recent high-severity burns (Cooper 1960; Allen and others 2002).

The importance of changed conditions (e.g., increase tree densities, dead fuel accumulations, understory species changes including invasive grasses) has commonly been identified as a major factor in unusual fire sizes and severity in recent decades in Southwestern ponderosa pine forests (e.g., Fule and others 1997; Allen and others 2002). It is interesting to note, however, that high forest densities in many Southwestern forests were already established by the middle of the 20<sup>th</sup> century. Cooper (1960), for example, noted in his comparisons of forest stands in central Arizona that about one-quarter of the stands had stem densities exceeding 12,000 trees/ha, and he described at length the increasing fire severity problems being observed at that time in these forests as a consequence of these changes. Harold Weaver described similar patterns of extensive pine thickets in Southwestern forests a decade earlier (1951). The extreme 1950s drought, which exceeds the current Southwest drought in total or maximum precipitation deficits in some parts of the Southwest, did result in a number of large fires (e.g., the Escudilla Fire and McKnight Fire of 1951, and the Dudley Lake Fire of 1956). But these fires were much smaller (<22,000 ha / 54,360 acre), and an order of magnitude smaller than some recent very large fires (e.g., 2002 Rodeo-Chediski and 2011 Wallow Fires). Moreover, the rates of spread observed on fires in recent years are truly extraordinary, and far outside the experience of modern wildland fire fighters. There were multiple days during both the Rodeo-Chediski Fire, Wallow Fire, and Las Conchas Fire (2011, in Jemez Mountains) when, for example, wind-driven, fast moving crown fires burned areas exceeding 16,000 ha in less than 24 hours, and in some cases, in less than 12 hours.

It is not possible at this time to precisely parse the relative importance of causes of these extraordinary recent fire behaviors and drought/bark beetle-induced forest mortality events among the various probable contributing variables (forest and fuel changes, invasive species, management and policy changes, and climate trends and variations). Interpreting from results of multiple types of analyses of broad-scale, best available data, however, it has been suggested that warming temperatures, in combination with extreme drought, are the likely key variables that are unusual in the context of the past century (Westerling and others 2006; Breshears and others 2005; Williams and others 2010, 2013). In a recent assessment of climate variables from the Southwest, Weiss and others (2009) confirm that the current drought has been “hotter” than previous major droughts of the twentieth century (e.g., the 1930s and 1950s droughts). Again, a telling line of evidence in support of this interpretation is the difference in “large fires” during the 1950s in central Arizona pine forests, which already had dense forest conditions in many places (Cooper 1960). No Southwestern forest fires exceeding about 22,000 ha (54,360 acre) occurred during that relatively “cooler” drought, as compared to the largest fire in Arizona state history—the Wallow Fire of 2011 (217,741 ha), which occurred in the exceptionally warm and dry June of 2011.

### ***Regional Summary: California***

About 13 percent of California’s forest area is composed of forest types with naturally high-severity (30 percent-80 percent crown-burned) fire regimes with mean fire return intervals (MFRI) of 15-100 yr (predominately cedar/hemlock/Douglas-fir, red fir), while nearly 70 percent is comprised of forest types that experienced frequent, low-severity prehistoric fire regimes (MFRI  $\leq$  10 yr, crown burned  $\leq$  5 percent; predominately mixed conifer, mixed California evergreen, redwood and ponderosa pine) (Stephens and others 2007). A policy of fire suppression and land use changes reduced the annual burned area in California forests from pre-settlement levels by more than 90 percent in the 20th century (Stephens and others 2007). Miller and others (2009) document trends toward increasing fire severity in the Sierra Nevada, and hypothesize that both fire suppression and increased precipitation over the 20th century increased fuel densities, contributing to increased fire severity. The frequency of large fires, total area burned, mean fire size and fire severity have all increased in northern California forests since the mid-1980s (Westerling and others 2006; Miller and others 2009) (Figure 1). Because a large portion of the interannual variability in northern California forest wildfire burned area is due to variability in ignitions from clustered lightning strikes, only a modest fraction of observed interannual variability in burned area can be explained by climate alone (Preisler and others 2011; Westerling and others 2011b).

Wildfire is predicted to increase substantially in northern California forests in the Sierra Nevada, Southern Cascades and Coast Ranges under some climate change scenarios. Westerling and Bryant (2008) project 100 percent-400 percent increases in the probability of large fire occurrence over much of the Sierra Nevada, Coast Ranges and Southern Cascades under a relatively warm, dry climate scenario (GFDL SRES A2). A study by the National Research Council (2011), applying regression methods from Littell and others (2009) for fire aggregated by ecosystem provinces similarly found increases exceeding 300 percent for a 1°C temperature increase. Westerling and others (2011b) find increases in burned area ranging from 100 percent to over 300 percent for much of northern California’s forests across a range of climate and growth and development scenarios using three climate models (NCAR PCM1, CNRM CM3, GFDL CM 3.1) for the SRES A2 emissions scenario. Spracklen and others (2009) find

increases in burned area on the order of 78 percent by midcentury for the GISS GCM under the SRES A1b emissions scenario, which is similar in magnitude to Westerling and others (2011b) for midcentury for northern California forests under GFDL SRES A2 scenarios. Conversely, increases in California forest wildfire frequency and burned area are more modest under a lower (SRES B1) emissions scenario, with end of century burned area roughly the same as midcentury (Westerling and Bryant 2009; Westerling and others 2011b; Yue and others 2013).

## **DISCUSSION: CLIMATE-WILDFIRE-VEGETATION INTERACTIONS**

The direct effects of anthropogenic climate change on wildfire are likely to vary considerably according to current vegetation types and whether fire activity is currently more limited by fuel availability or flammability. In the long run, climate change is likely to lead to changes in the spatial distribution of vegetation types, implying that transitions to different fire regimes will occur in locations with substantial changes in vegetation. At present, most long-term projections of changing wildfire activity have not successfully incorporated dynamic changes in vegetation types and fuels characteristics in response to climate and disturbance. This is an ongoing challenge for wildfire and climate science that is the subject of ongoing research. On the other hand, we can use existing fire-climate-vegetation interactions to understand the likely direction and magnitude of climate-driven changes in fire activity over the next few decades. Beyond that, we may be able to use these models and our understanding of current ecosystems to assess when changes in climate and disturbance regimes will begin to lead to qualitative changes in ecosystems. Given the lack of analogues to projected climate changes—especially the substantial changes in that latter half of the 21st Century that are projected to result from continued high emissions of greenhouse gases—precise modeling of future changes in vegetation and disturbances like wildfire becomes significantly more challenging for later in this century and beyond.

Climate change will result in higher temperatures and more frequent and intense drought (Cayan and others 2010), with the fire season and area burned expected to increase substantially by mid-century across the western United States (Yue and others 2013). In forests where wildfire is very sensitive to variations in temperature, the short-term result is likely to be an increase in the frequency of very active fire seasons and an increase in the number of large wildfires. There have been substantial increases documented in the frequency of large wildfires in forests of the Rocky Mountains of the western United States (Westerling and others 2006; Figure 2). These increases have been associated with warmer temperatures there in recent years. As climate continues to change later in this century, changes in vegetation types and amounts in these forests may lead to qualitative changes in fire-climate-vegetation interactions, as fuel availability may start to become a limiting factor in some places where forest wildfire regimes were historically limited by climatic controls on fuel flammability.

Conversely, higher temperatures and decreased precipitation could result in decreased wildfire activity in some dry, fuel-limited wildfire regimes, as the reduced moisture available to support the growth of fine fuels leads to less biomass and less continuous fuel coverage (Dettinger 2006). Any increases in precipitation might be counterbalanced to some extent by increased evaporative demand from higher temperatures.

The overall direction and spatial pattern of changes in precipitation under diverse climate change scenarios varies considerably across both future greenhouse gas emissions scenarios

and global climate models (Dettinger 2006). In ecosystems where climatic influences on fire risks are dominated by precipitation effects, this implies greater uncertainty about climate change impacts on wildfire in those locations (Westerling and Bryant 2007). Overall, however, greater warming will lead to more evaporation of moisture from soils and the live and dead vegetation that fuels forest wildfires. Given the substantial interannual variability in precipitation characteristic of western U.S. climate, it is likely that fire activity will at least increase in drought years in coming decades, across a broad range of future climate scenarios.

Climate scenarios (even those with rapid reductions in global greenhouse gas emissions) project increases in temperature substantially greater than those observed in recent decades (IPCC 2007), which have been associated with substantial increases in wildfire activity in western U.S. forests (Gillett and others 2004; Westerling and others 2006; Soja and others 2007; Williams and others 2013; Figures 1&2). Strategies for adapting to a warmer world will therefore need to consider the impacts of climate change on wildfire.

### ***Climate change implications for land management***

Changes in climate, nitrogen deposition, and disturbance regimes (fire, insects, floods, etc.) will likely lead to changes in ecosystem services in the coming decades, with losses in some areas and possibly improvements and expansion of services in others (Vose and others 2012; Turner and others 2013). Because of the speed of anticipated changes in climate, disturbance regimes and ecosystems, ecosystem changes in coming decades may be highly uncertain, with near-term changes dominated by transition effects. For example, parts of the Greater Yellowstone area may become unsuitable to sustain forest types that are currently dominant, but might be suitable for tree species that are currently not present (Westerling and others 2011a). Future ecosystem services will thus depend in part on the speed with which species ranges can shift on the landscape. Land management choices can both resist (e.g., fire suppression) and facilitate (e.g., assisted migration) changes in ecosystem and disturbance regime characteristics, and either or both types of approaches may be appropriate depending on management priorities for a given resource.

To address adaptation in management planning and policy, a number of guides relevant to the forest sector have been produced since 2007 (Table 1). One important component to help managers consider developing adaptation plans is providing examples. Miller and others (2011) provide examples for two generalized wilderness fire management objectives: Restore or maintain—restore fire to ecosystems that have been altered by fire suppression or other land use change, or maintain process of fire in ecosystems that have not been altered. Protect—protect ecosystems that are threatened by fires that are too frequent. Specific responses to climate change that might achieve restore or maintain objectives: revise fire and land management plans to reflect climate-mediated changes to fire regimes; modify fuel treatment specifications to ensure they will moderate fire behavior and effects under more extreme fire weather conditions. Specific responses to climate change for protect objectives would be: emphasize preparedness and revise preparedness plans to reflect longer fire seasons and higher fire danger; modify fuel treatment specifications to ensure they will moderate fire behavior and effects under more extreme fire weather conditions; revise fire use prescriptions to reflect higher fire danger and longer fire seasons.

**Table 1.** Climate change adaptation guide list from Millar and others (2012; Table 4.3)

Category	Emphasis	Reference
Adaptation Framework	General options for wildlands	Millar and others 2007
	Options for protected lands	Baron and others 2008, 2009
	Adaptation guidebooks	Peterson and others 2012; Snover and others 2007; Swanston and Janowiak 2012
Vulnerability Analysis	Climate change scenarios	Cayan and others 2008
	Scenario exercises	Weeks and others 2011
	Forest ecosystems	Aubry and others 2011; Littell and others 2010
	Watershed analysis	Furniss and others 2010
Genetic management	Seed transfer guidelines	McKenney and others 2009
	Risk assessment	Potter and Crane 2010
Assisted migration	Framework for translocation	McLachlan and others 2007; Riccardi and Simberloff 2008
Decisionmaking	Silvicultural practices	Janowiak and others 2011b
	Climate adaptation workbook	Janowiak and others 2011a
Priority setting	Climate project screening tool	Morelli and others 2011b

Land management agencies face significant challenges incorporating recent scientific findings on fire-climate interactions into land management practices. First, differences between a researcher’s “useful” result and the usability of that result by a manager must be bridged (Dilling and Lemos 2011). Human capacity is needed to translate research information into management planning and policy, and to understand the limits of scientific results in this context. Connecting environmental problems to policy is inherently difficult given complex biological, physical and social interactions, and the dependence on collaboration among scientists, policymakers and the public (Lemos and Morehouse 2005). Second, climate change projections include varying degrees of uncertainty depending upon factors such as emissions, input parameters, and the modeling system used. Climate model uncertainty can be quantified in a fairly straightforward manner, but uncertainty in outcomes of ecosystem response or management actions is much more difficult to quantify. Scenario planning is one means to address this uncertainty by considering alternative futures and impacts, identifying key vulnerabilities, and gauging adaptation and mitigation capacities (Weeks and others 2011; Cross and others 2012). A related challenge is that, while the cost of producing large numbers of scenarios has been greatly reduced by the spread of low-cost, high-performance computers and software, development of methods for

extracting and communicating useful information from large scenario data sets for policymaking and management applications has lagged. Third, adverse impacts of management activities on protected species and other protected resources must be avoided or mitigated as provided for under applicable laws.

The capacity for communities to adapt to changes in ecosystem services they rely on is determined in part by the extent of the changes they are exposed to, the extent to which existing infrastructure and systems for resource extraction can be adapted to changing conditions, and the diversity of their economies (Vose and others 2012). Notably, the majority of existing forest resources in the western United States is on federal lands managed by federal resource agencies. Characteristics of existing infrastructure for resource use and extraction on these lands are strongly influenced by policymaking at the national level, and the capacity for adapting forest resource management to changing conditions depends on federal priorities and a diverse national economy.

For communities in the wildland-urban interface exposed to risk of property destruction due to wildfire, the primary strategies for managing wildfire risks fall into three general categories: fire suppression, fire prevention, and development policies. Suppression involves actively extinguishing wildfires. Prevention measures seek to reduce the number, size and severity of large fires and their economic and ecological impacts, primarily through vegetation management (e.g., mechanical thinning, managed fires, cleared buffers) and ignition reduction (e.g., burn controls, park closures, warnings and educational campaigns). Development strategies include measures designed to reduce the impact of wildfires on structures, and of structures on the ability to manage wildfires safely and effectively. Measures include zoning ordinances to reduce the spread of development in fire-prone wild areas, and regulations to enhance the ability of structures to resist fire (e.g., fire proof materials, thermal barriers, cleared perimeters, fire-resistant landscaping; Caulkin and others 2014). A particularly challenging problem is the disconnect between state and local authority over land-use decisions affecting development in fire-prone areas versus federal responsibility for most of the fire suppression costs. Potential remedies include federal incentives to encourage greater state and local responsibility to use zoning ordinances, building codes, and wildfire insurance requirements to reduce risk in the wildland urban interfaces near federal lands (Gorte and others 2013).

Despite the considerable resources devoted to fire suppression, it is often ineffective under climatic conditions that foster the rapid spread of wildfires. Furthermore, the ecological consequences of this kind of intervention might turn out to have their own undesirable consequences. Reducing fire activity in the short run may increase risks in the long term by contributing to the build-up of fuels in otherwise fuel-limited wildfire regimes. This has already become a major problem in ponderosa pine forests in the Sierra Nevada and the southwestern United States due to fire suppression and land uses (such as grazing livestock) (Allen and others 2002). Conversely, if fires could be effectively suppressed, this might be a desirable course of action in some naturally dense forest ecosystems where very long return times between fires was previously the norm, if the result of climate change is that these forests would not regenerate post-fire and a substantial portion of the carbon stored in them would be released into the atmosphere.

Among prevention strategies, fuels management is likely to continue to be an important tool for building buffers around communities at risk from wildfire. It may also reduce the severity

of wildfires in locations where forests have accumulated biomass due to fire suppression and land use. However, thinning forests that are naturally densely vegetated constitutes an unnatural disturbance in itself, and may not always reduce wildfire risks. Development policies could make a substantial difference in the economic impact of wildfire in a warmer world by reducing the capital losses associated with catastrophic wildfires. By reducing the need to actively protect structures during a wildfire, these measures could also free up suppression resources that could be better employed protecting resources with cultural and natural conservation values, or restoring forests through the use of prescribed fire (Caulkin and others 2014). All of these measures (suppression, prevention, development) have been emphasized to varying degrees around the world. In places like the western United States, where there is a substantial and rapidly growing wildland-urban interface in fire prone areas (Gude and others 2008), development strategies hold out the greatest promise to reduce the economic impact of wildfires in a changed climate (Gorte and others 2013). However, they have only limited applicability to preserving ecosystem and resource values.

## **CONCLUSION**

The effects of climatic change on wildfire will depend on how past and present climates have combined with human actions to shape extant ecosystems. Climate controls the spatial distribution of vegetation, and the interaction of that vegetation and climate variability largely determines the availability and flammability of the live and dead vegetation that fuels wildfires. In moist forest ecosystems where snow plays an important role in the hydrologic cycle and fuel flammability is the limiting factor in determining fire risks, anthropogenic increases in temperature may lead to substantial increases in fire activity.

In dry ecosystems where fire risks are limited by fuel availability, warmer temperatures may not increase fire activity significantly. Warmer temperatures and greater evaporation in some places could actually reduce fire risks over time if the result is reduced growth of grasses and other surface vegetation that provide the continuous fuel cover necessary for large fires to spread. The effect of climate change on precipitation is also a major source of uncertainty for fuel-limited wildfire regimes. However, in some places these are the same ecosystems where fire suppression and land uses that reduce fire activity in the short run have led to increased fuel loads today as formerly open woodlands have become dense forests. For the immediate future, this increases the risk of large, difficult-to-control fires with ecologically severe impacts.

Thus, the combined long-term impact of diverse human activities has been to increase the risks of large wildfires in many places in ways that cannot be easily reversed. Even if prompt action is taken now to reduce future emissions of greenhouse gases, the legacy of increased atmospheric concentrations of these gases means that the risk of large fires will remain high and will continue to increase in many forests. Consequently, communities will need to adapt. The capacity for adaptation is strongly influenced by the size and diversity of the economy a community can draw upon.

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# Forest Ecosystem Reorganization Underway in the Southwestern USA— Does This Foreshadow Widespread Forest Changes in the Anthropocene?<sup>1</sup>

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***Abstract:** This paper addresses an important set of issues currently facing the forests of western North America—the intersection of 20th Century land use legacies and the emerging impacts of climate change on drought, forest stress, wildfire, and ecosystem change. The presented information comes from a variety of sources in the scientific literature, with a focus on the Southwest United States, particularly including observations from my home landscape of the Jemez Mountains in northern New Mexico. Historic fire suppression and two regionally wet climate periods fostered widespread buildups of forest densities and fuel loads since ca. 1900. With the recurrence of drought conditions coupled with warmer temperatures since the late 1990s, the overgrown forests in the Southwest have been subject to wildfires and tree mortality episodes of historically unprecedented extent and severity, along with emergent shifts in vegetation patterns. Currently observed trends are indicative of early-stage ecosystem reorganization in response to historic land management practices combined with recent novel climate stresses. This convergence of climate stress, human land use patterns and histories, and disturbance trends in the southwestern United States may foreshadow widespread forest ecosystem changes more broadly in North America, and globally.*

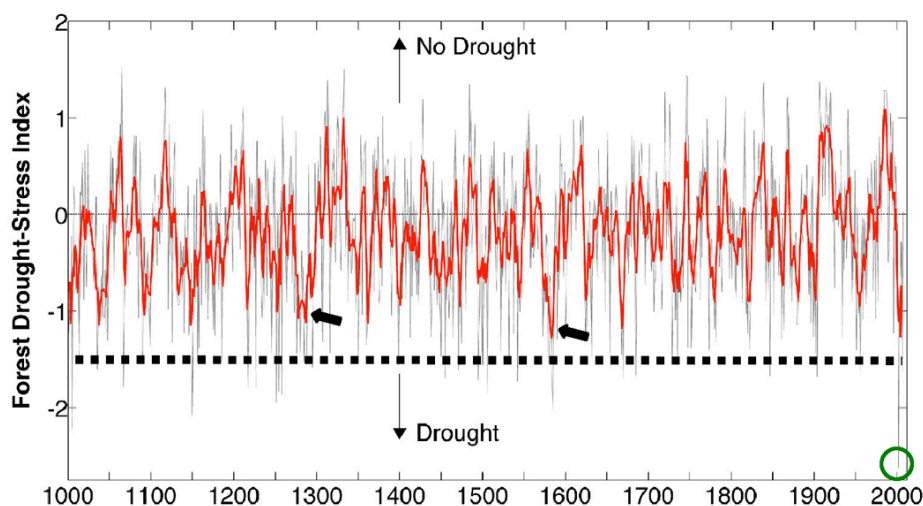
## INTRODUCTION

Extensive high-severity wildfires and drought-induced tree mortality have intensified over the last two decades in southwestern U.S. forests and woodlands, on a broad scale certainly unprecedented regionally since 1900. Abundant and diverse paleo-ecological and historical sources indicate substantial variability in Southwest fire regimes and forest vegetation patterns over the past

<sup>1</sup> This is a revised version of the paper originally appearing in RMRS-P-71 and titled: Forest ecosystem re-organization underway in the southwestern United States: A preview of widespread forest changes in the Anthropocene? The paper had not completed the USGS review process at the time of publication and this revised version has completed the review process.

10,000 years, providing longer-term context for recent fire and vegetation trends. In particular, over the past 150 years regional forest landscapes and fire regimes have responded sensitively, strongly, and in understandable ways to changes in human land management, as well as to interactions with climate variability and trends. Widespread, high-frequency surface fire activity ceased on most Southwest landscapes in the late 1800s due to changed land use patterns, grading into increasingly vigorous active fire suppression after 1910. Fire suppression allowed woody plant establishment to explode during several wet climate windows favorable for tree regeneration and growth, particularly ca. 1905-1922 and 1978-1995. By the early 1990s many Southwest forests likely had reached locally maximum potential levels of tree density, leaf area, biomass and carbon storage, and surface and ladder fire-fuel loads—unsustainable levels upon the inevitable recurrence of episodic drought. Decadal-scale drought returned to the region in the late 1990s, along with historically unprecedented warmth. This warm, global-change-type drought has affected the Southwest almost continuously since 2000 through the present (February 2014). The uniquely recent combination of anomalously overgrown forests and extreme global-change-type drought has fostered more extensive and severe forest disturbance processes, driving ongoing reorganization of Southwest forests into new ecosystem patterns.

The Southwest United States recently has been subject to large increases in severe wildfire activity and overall tree mortality in response to the combination of protracted drought and early 21st Century warmth. Research on physiological responses of diverse tree species to climate variables is providing important insights into the linked roles of drought and heat stress in driving Southwest forest productivity and health, physiological thresholds of tree mortality, and forest disturbance processes (Adams and others 2009; McDowell and others 2011). Williams and others (2013) recently derived a forest drought-stress index (FDSI) for the Southwest using a comprehensive tree-ring growth data set representing AD 1000-2007, driven by both warm-season temperature and cold-season precipitation (Figure 1). Substantial warming over the past 25 years is significantly amplifying regional forest drought stress, likely by increasing atmo-



**Figure 1.** Reconstructed Forest Drought Stress Index (FDSI) for the Southwest United States for the years C.E.1000-2007, updated from Williams et al. 2013. Annual values of FDSI in light grey, with a 10-year smooth in red. The megadroughts of the 1280s and 1580s are marked by arrows. The dashed line indicates the upper bound of the driest 50 percent of years of the 1580s megadrought, representing tree-killing levels of drought stress. Note that warm drought in 2002 (circled year) caused the worst year for regional forest growth in the tree-ring record since at least C.E. 1000.



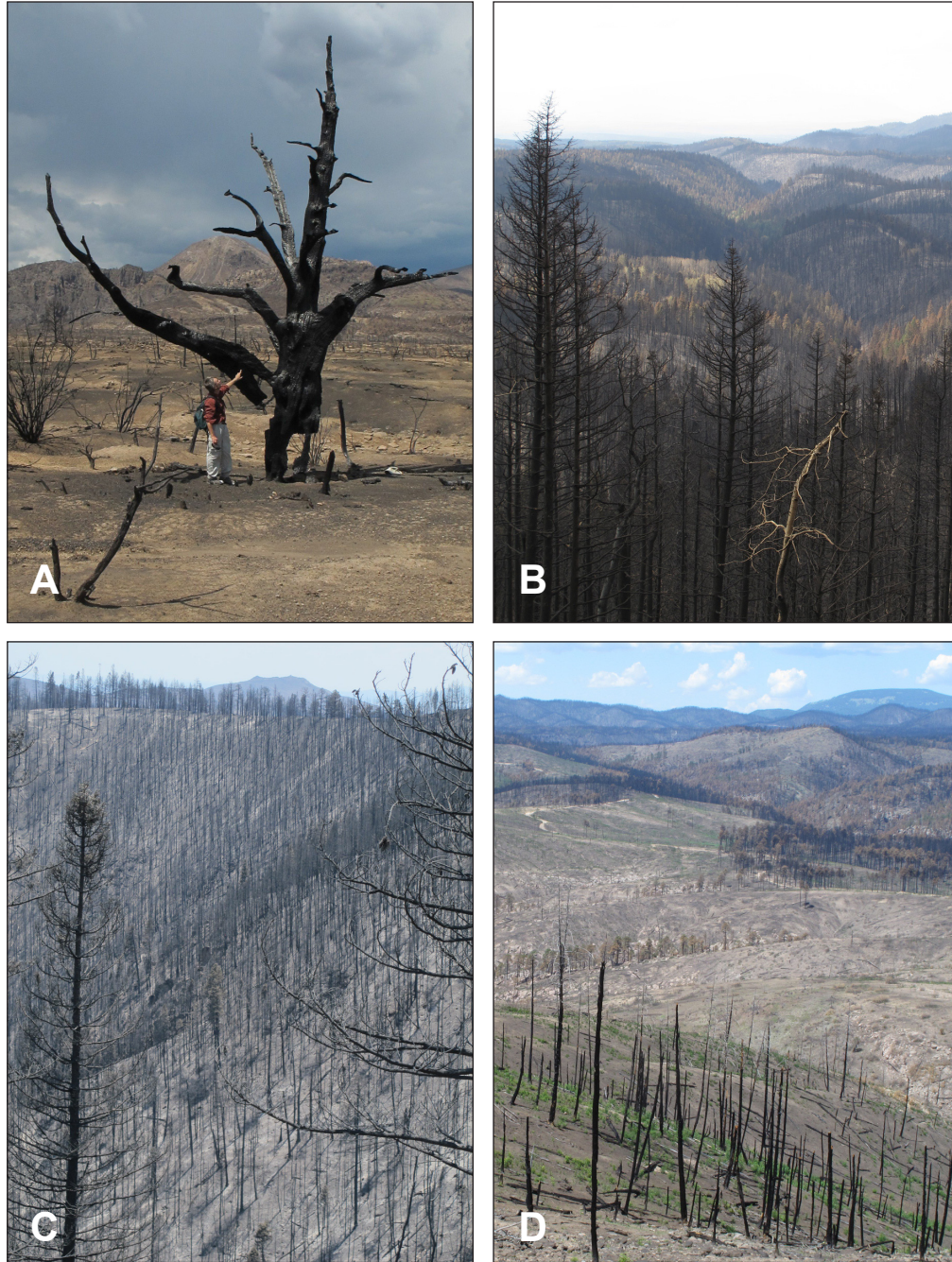
spheric vapor pressure deficits during the growing season months. Strong correspondence exists between FDSI and forest productivity, tree mortality, bark-beetle outbreaks, and wildfire in the Southwest, illustrating the powerful interactions among climate, land use history, and disturbance processes in this region. If regional temperatures increase as projected by climate models, the *mean* forest drought-stress by the 2050s will exceed that of the most severe droughts in the past 1,000 years (Williams and others 2013).

Multiple lines of evidence now indicate ongoing changes in forest structures and compositions in the Southwest, including documented changes in the elevational distributions and dominance of many plant species, pointing toward novel patterns emerging over the course of the 21st century. With the onset of global-change-type drought (Breshears and others 2005) since the late 1990s, overgrown forests in the Southwest have been subject to wildfires and tree mortality episodes of historically unprecedented extent and severity (Figures 2-4), in concert with increasing shifts in vegetation patterns (Figure 5). This paper describes the emergence of these disturbance drivers and some cascading ecological effects of various interactive landscape changes, along with adaptation strategies to enhance forest ecosystem resilience in the context of ongoing and projected climate trends.

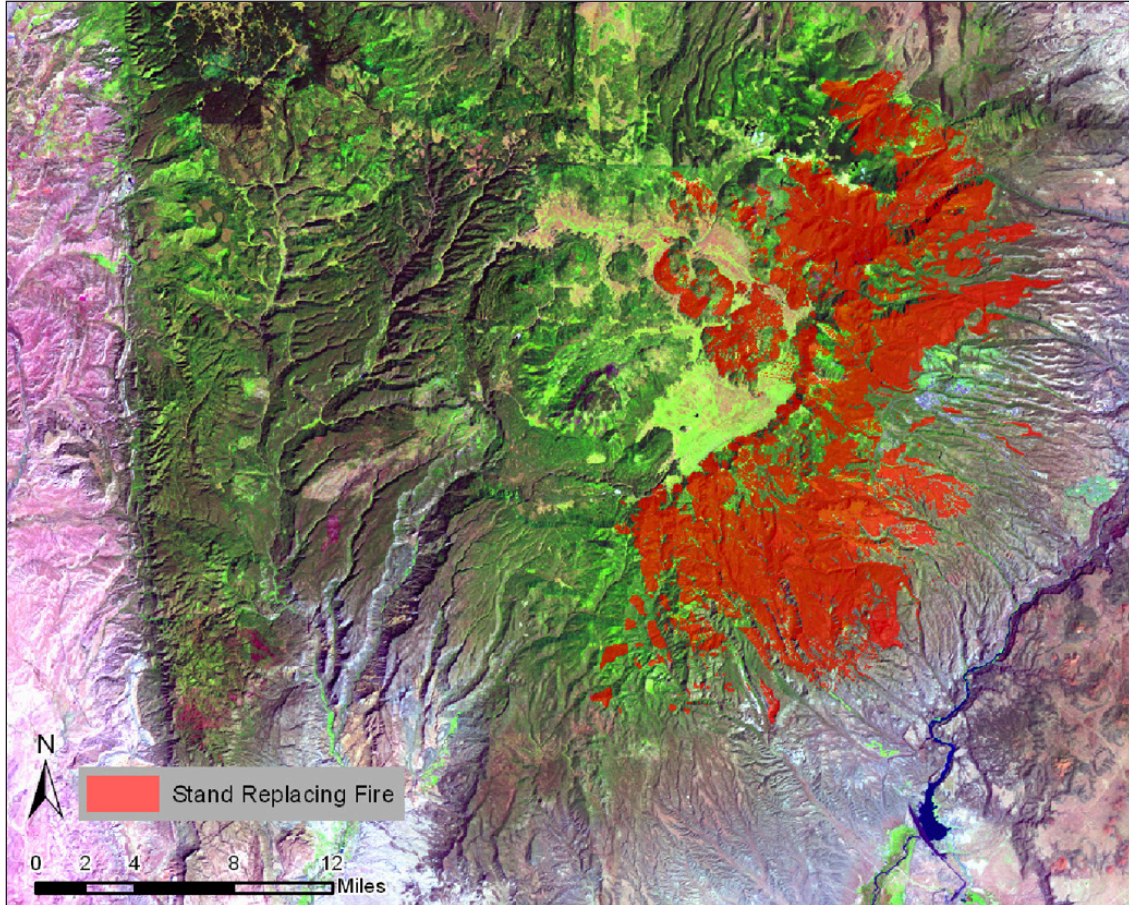
Forests globally exhibit great diversity in environmental drivers, histories, dominant ecological patterns and processes, biodiversity, etc.—which are expected to produce diverse responses (and levels of resilience) to projected global changes in climate and human uses this century. Even given this global diversity of forests and expected global change responses, the observed convergence of climate, human land use patterns and histories (including livestock grazing, forest management, fire suppression, human settlement/WUI, and ignitions), and disturbance trends in the southwestern United States may presage widespread forest ecosystem changes more broadly in North America, and globally.

## **LONG-TERM PERSPECTIVES ON CLIMATE, VEGETATION, AND FIRE IN THE SOUTHWEST**

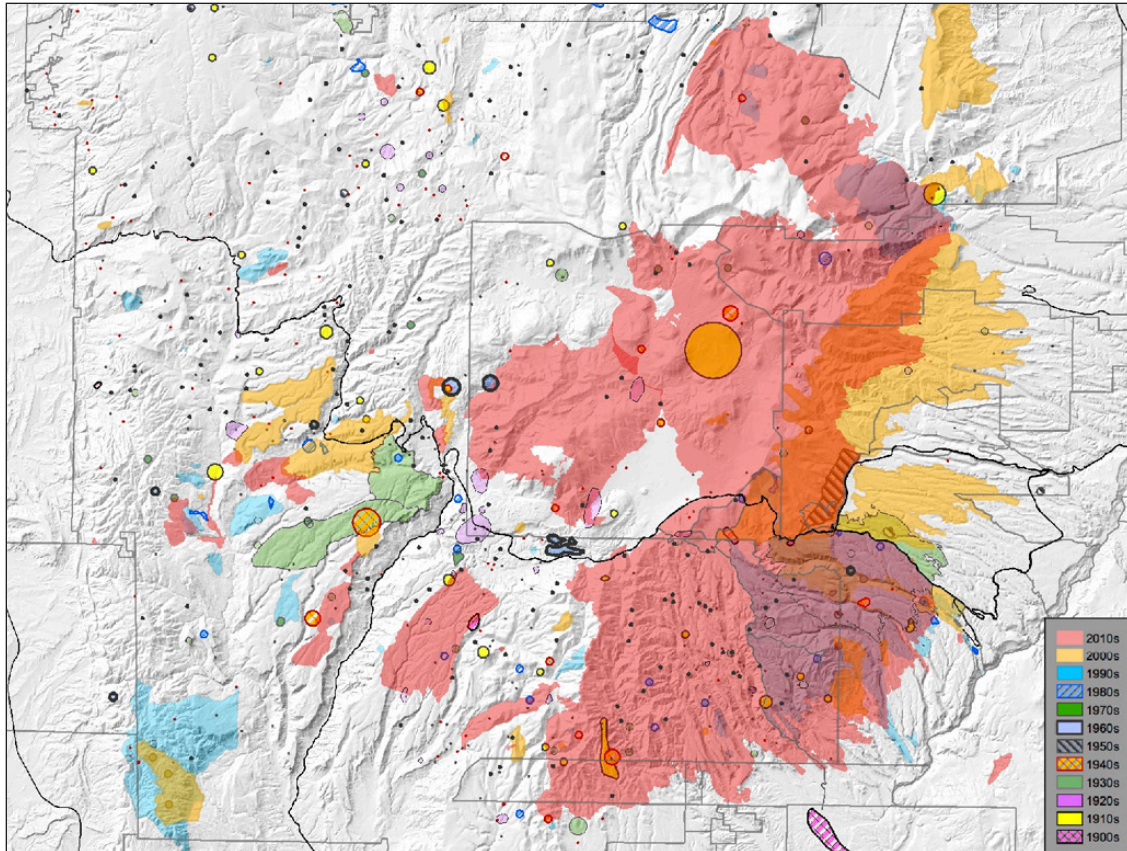
The Southwest United States has an abundance of diverse paleoecological records that make this one of the best places in the world to determine past patterns of climate, vegetation, and fire, providing context to evaluate recent trends in forest and landscape change. For example, in this region scientists have used information locked in the tree-rings of ancient wood to precisely reconstruct past patterns of precipitation, temperature, stream flow, drought stress, and tree growth and death going back as much as 2000 years (Swetnam and Betancourt 1998; Grissino-Mayer 2005; Salzer and Kipfmüller 2005; Swetnam and others 1999, 2011; Allen and others 2008; Brown and Wu 2005; Woodhouse and others 2010; Touchan and others 2010; Falk and others 2011; Margolis and others 2011; Fulé and others 2012; Roos and Swetnam 2012; Williams and others 2013; O'Connor and others 2014). Dendroclimatological data from the Southwest illustrate fluctuations in precipitation and associated forest drought stress at multiple time scales (Figure 1) that apparently are driven by atmospheric teleconnections with oscillations in ocean temperature patterns, particularly including the multi-year El Niño-Southern Oscillation (ENSO; Swetnam and Betancourt 1998) and the multi-decadal Pacific Decadal Oscillation (PDO) and Atlantic Multi-decadal Oscillation (AMO; McCabe and others 2008; Pederson and others 2013). Compared to other regions in the United States, the Southwest is characterized by relatively arid conditions and high levels of variability in precipitation at annual, decadal, multi-decadal, and centennial time scales (Swetnam and Betancourt 1998; Woodhouse and



**Figure 2.** High severity fire effects from first 14-hour run of the June 26, 2013, Las Conchas Fire—the various photos show fire effects across an elevational gradient of different vegetation types. From low to high elevation: 2-A, former piñon-juniper woodland “moonscaped” by surprisingly high-severity fire on Sanchez Mesa, likely from a 2 AM plume collapse, photo taken Aug. 2011; 2-B, severely burned mixed-conifer forest in upper Bland Canyon, photo taken July 2011; 2-C, severely burned mixed-conifer forest in upper Frijoles Canyon, photo taken July 2011; 2-D, view across formerly dense ponderosa pine forest (although snags in foreground are mostly Douglas-fir on a north-aspect slope) that burned with mixed-severity in Dome Fire of April 1996, with nearly no live conifer trees remaining after resultant shrub cover of oak and locust intensely re-burned in Las Conchas fire, photo taken August 2011. (Photos by C.D. Allen.)



**Figure 3.** Map of high and moderate fire severity (tree-killing) patches in the Jemez Mountains, New Mexico, only including fires with mapped severity data from 1977-2011—all but one fire occurred since 1996. The size of individual stand-replacing fire patches from recent fires now ranges up to >10,000 ha in this landscape. Map data primarily from various fire-specific Burned Area Emergency Rehabilitation (BAER) reports, on file at USGS Jemez Mountains Field Station.



**Figure 4.** Historic fire atlas summary map of the Jemez Mountains, showing perimeters of all recorded fires larger than 0.1 acres for the period 1909-2013, color coded by decade of occurrence. The source for pre-1960 fires is original hand-drawn fire atlas maps (with associated original annual fire suppression records in tabular form), curated by the Santa Fe National Forest; these fires were re-drawn on modern base maps and then digitized into a geographic information system (Snyderman and Allen 1997). Almost all post-1969 fires were mapped from various digital sources. Fires mapped as perfect circles represent occurrences with perimeter data lacking, but where a point location and a fire size-class were available. Note large extent of fires since 2000.



**Figure 5.** Retake photo pair of area reburned on 26 June 2011 by the Las Conchas Fire of mixed shrubs (Gambel oak and New Mexico locust) and ponderosa pine, in area previously burned by the 1996 Dome Fire. Photo 5-A, ghost logs, charred shrub stems, and ponderosa pine with “cooked” foliage, taken 3 July 2011. Photo 5-B, retake of Photo 5-A (note same charred snags in left foreground) on 3 October 2013, showing growth of oak and locust resprouts, with all ponderosa pine now needle-less and clearly dead. (Photos by C.D. Allen.)

others 2010). Such climate variability drives associated large changes in southwestern forest growth patterns. This is exemplified by the recent development of a regional forest-drought stress index extending back over 1,000 years (Figure 1), which strongly links warm growing-season temperatures to reduced growth of Southwest conifers (Williams and others 2013).

Other paleo-environmental evidence in the Southwest extends back tens (or even hundreds) of thousands of years in the form of plant pollen, other plant remains, and charcoal deposited in layers of sediment at the bottoms of lakes and bogs (e.g., Weng and Jackson 1999; Anderson and others 2008a; Fawcett and others 2011). These sediment records document how today's high mountain tree species like spruce and fir were growing at much lower elevations during the colder climate of the last ice age, before moving upslope as the world's climate moved into the current warmer interglacial period about 11,000 years ago. Similarly, plant macrofossils preserved in the middens of ancient packrat nests directly show how much, and how fast, the ranges of plant species have expanded and contracted geographically, moving north and south, and locally upslope and downslope, in response to climate variations (Betancourt and others 1990). These pollen and macrofossil records also show that southwestern vegetation communities in the past often consisted of combinations of plant species unknown today (Betancourt and others 1990; Weng and Jackson 1999; Anderson and others 2008a).

Linked changes in climate, vegetation, and fire activity are evident in paleoecological records from this region. For example, documented midden evidence of ponderosa pine (*Pinus ponderosa*) is almost non-existent in the Southwest during the last ice age, but with the early post-glacial warming and the associated development of our summer monsoon climate after about 10,000 years ago this pine expanded across the region to eventually become a widespread forest species (Betancourt and others 1990; Weng and Jackson 1999). During this same time period, the abundance of charcoal deposited in lakes and bogs increased markedly across the region (Anderson and others 2008a, 2008b; Allen and others 2008), reflecting increased frequency and extent of fire activity on Southwestern landscapes, which likely also favored the expansion of fire-adapted and fire-fostering species, like ponderosa pine (Weng and Jackson 1999). Numerous charcoal records over the past 1,000 years in the West and Southwest generally show the modulating effects of climate on fire activity, with modest increases in charcoal concentrations during the Medieval Warm Period, and also some significant decline during the Little Ice Age (Marlon and others 2012); millennial tree-ring fire histories from giant sequoia (*Sequoiadendron giganteum*) groves show similar temporal patterns (Swetnam and others 2009). The world's greatest regional concentration of tree-ring studies is from the Southwest, including tens of thousands of precisely dated fire scars from hundreds of forest sites across the region—these reconstruct fine-resolution spatial and temporal patterns of fire extending back 400+ years, documenting high levels of frequent and widespread fire activity that were closely tied to climate patterns until ca. 1900 (Swetnam and others 1999, 2011; Falk and others 2011).

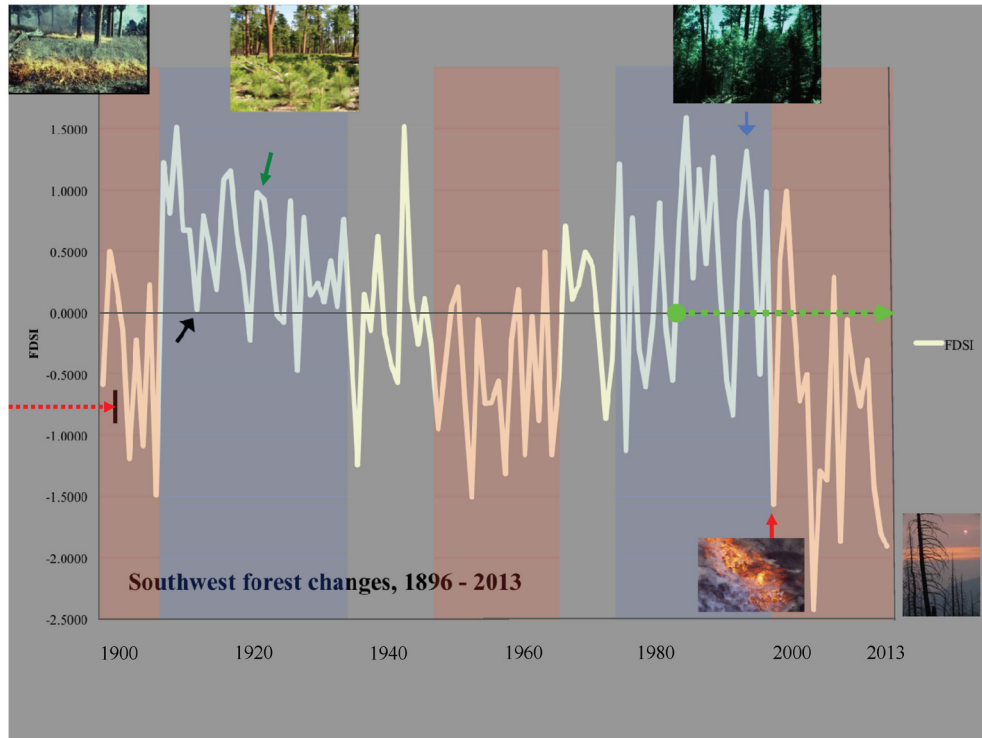
These pre-1900 fire-climate relationships are consistent with those that we see today (Swetnam and Betancourt 1998; Swetnam and others 1999), with much higher levels of fire activity in warm dry years. For about two-thirds of the fire scars we can even estimate the season that the fire scar formed, documenting that most pre-1900 fire spread occurred in the dry spring and early summer period, just as today, before the July onset of summer rains. Tree-ring reconstructions document that frequent, low-severity surface fires characterized the pre-1900 fire activity in the widespread ponderosa pine and dry mixed-conifer forests that predominate in much of the Southwest (Swetnam and Baisan 2003). Climate variability synchronized fire activity across the region, with large portions of most Southwestern mountain

ranges burning in some extreme fire years—for example, 1748 is the most widespread fire year known in the Southwest (Swetnam and others 1999) and West-wide (Swetnam and others 2011). Still, note that there is great diversity of forests and associated fire patterns across the substantial elevational and regional landscape gradients present in the Southwest (Swetnam and others 2011; Vankat 2013). For example, mixed-severity and high-severity stand-replacing fires naturally occurred in cooler and wetter mixed-conifer and spruce-fir forests, which occupy relatively limited high-elevation portions of this region (e.g., Fulé and others 2003; Margolis and others 2007, 2011; Margolis and Balmat 2009; O’Connor and others 2014). Tree-ring studies also show that major climate relationships with tree establishment, growth, and death have been rather consistent for the past 1,000 and more years. That is to say, forest trees in the Southwest grow better and reproduce in pulses during wetter periods, whereas during periods of extended warm drought trees experience high levels of drought stress and mortality (Swetnam and Betancourt 1998; Allen and Breshears 1998; Swetnam and others 1999; Brown and Wu 2005; Breshears and others 2005; Falk and others 2011; Williams and others 2013).

## **HISTORICAL INTERACTIONS AMONG CLIMATE, LAND MANAGEMENT, AND FOREST CHANGE IN THE SOUTHWEST**

Over the past 150 years, regional forest landscapes and disturbance regimes (fire, drought stress, insect outbreaks) have responded to changes in human land use and land management in concert with patterns of climate variability (Figure 6). The prehistoric pattern of widespread, high-frequency surface fire regimes across the Southwest initially collapsed in the late 1800s, because with the entry of railroads to this region there was an associated buildup of domestic livestock herds that interrupted the former continuity of grassy surface fuels by widespread overgrazing, trampling, and trailing (Swetnam and others 1999; Allen 2007). This mostly inadvertent suppression of surface fires by overgrazing then transitioned into active fire suppression and exclusion efforts by land management agencies in the early 1900s, which have continued with ever-increasing effort and expenditure to the present (Stephens and others 2012). Since forest types historically characterized by high-frequency surface fire regimes (ponderosa pine and dry mixed-conifer) are a substantial majority of Southwest forests (about 70%, based upon vegetation area estimates from Vankat 2013), over a century of fire suppression has greatly affected most forests in the Southwest.

After the late 1800s collapse of surface fire regimes in most Southwestern forests, the multitude of young trees that periodically established no longer were thinned out by naturally frequent surface fires that previously had favored relatively open forest conditions with grassy understories. As a result, woody plant establishment and forest densification exploded during the 20th century, particularly fostered by two favorable wet climate windows for tree regeneration (Savage and others 1996; Brown and Wu 2005) and growth in the early and late 1900s (Figure 6). Increasingly intensive fire suppression efforts by land managers during the 20th Century also were necessary to enable the general pattern of regional “woodification,” with widespread expansion regionally of trees into grasslands and meadows (Swetnam and others 1999), along with substantial increases in the densities of most (although not all) southwestern forests and woodlands. For example, in some of the most common forest types—like various ponderosa pine and dry mixed-conifer forests—tree densities commonly increased ten-fold or more, often from less than 100 to over 1,000 trees per acre (Covington and Moore 1994; Allen and others 2002), and with greater proportions of relatively shade-tolerant but more fire-sensitive tree species such as white fir (*Abies concolor*).



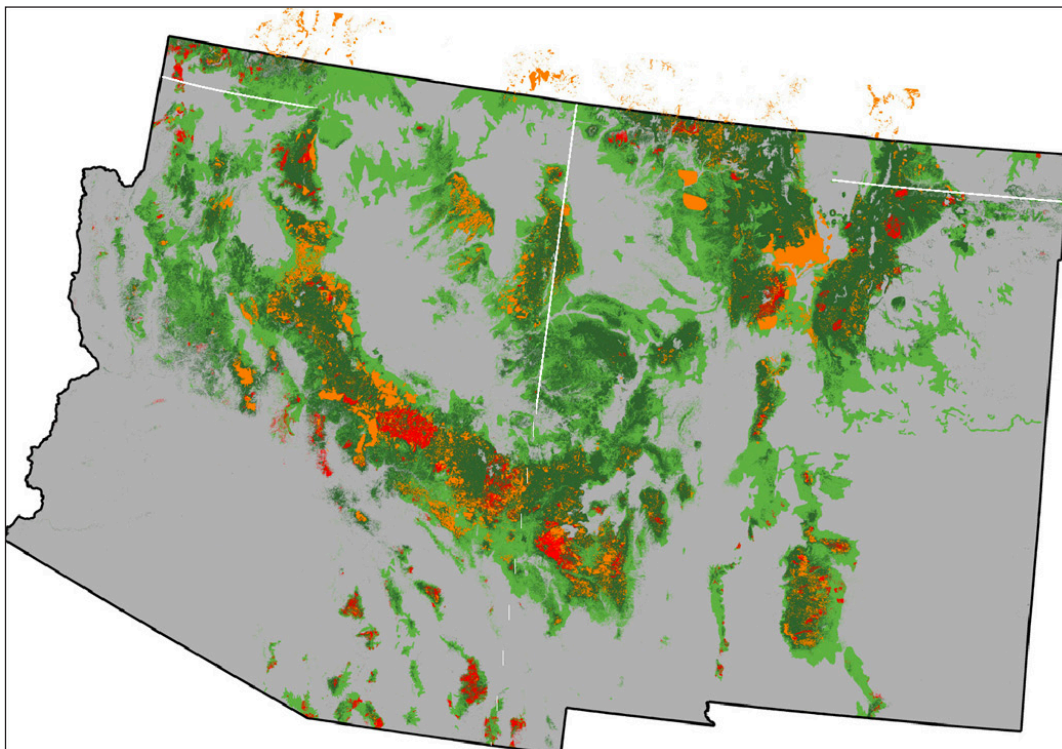
**Figure 6.** Historic sequence of interactions among climate, land-use, disturbance regimes, and forest change in the Southwest, showing: graph of regional Forest Drought Stress Index (FDSI) for 1896-2013 (updated from Williams et al. 2013); wet periods (blue shading) and dry periods (red shading); former period of widespread high-frequency surface fires (dashed red arrow) ends in late 1890s (black bar); onset of fully institutionalized fire suppression ca. 1910 (black arrow) early in a wet period that supported abundant tree regeneration (1919, green arrow); late 1900s wet period with maximal development of dense high-biomass forests with widespread ladder fuels (blue arrow); and the onset of severe and persistent drought stress since 1996 (solid red arrow) that has driven regionally extensive wildfire and tree mortality. The dashed green arrow shows the period of fieldwork research conducted in the Jemez Mountains by the author (1982-present).

Such increases in forest density also were accompanied by huge increases in surface fuel loads and the widespread development of understory thickets of small, suppressed trees, with live crowns near the ground surface. These “ladder fuels” allow surface fires to easily spread upward into tree canopies, where the high energies liberated through combustion can generate strong convection that drives positive feedback toward more intense fire activity (Allen 2007). Severe regional drought in the 1950s (Figure 6) started to expose the potential for larger stand-replacing fires in the Southwest as more susceptible fuel structures began to emerge in ponderosa pine forests, but concurrent fire suppression advances generally kept a lid on extreme fire activity until drought stress moderated again. Generally wet conditions in the Southwest from the late 1970s through 1995 drove rapid tree growth and further buildup of forest biomass, and importantly, the wet conditions in this period also helped firefighters keep wildfires in check despite the hazardous fuel conditions that prevailed by this time (Figure 6). Thus, by the early 1990s many southwestern forests likely were near their maximum possible levels of tree density, biomass accumulation, and leaf area at both stand and landscape scales; the former fire-maintained mosaic of mostly low-density forests (with interspersed patches of thicker forest and open meadows) across diverse Southwest landscapes had morphed into a relatively homogenous blanket of dense forests with vertical and horizontal fuel structures that could



support the initiation and extensive spread of explosive high-severity canopy fires. Yet during this late-1900s wet period, forest growth was strong and forest disturbances (e.g., fire and bark beetle mortality) were limited—southwestern forests seemed to be resilient and secure.

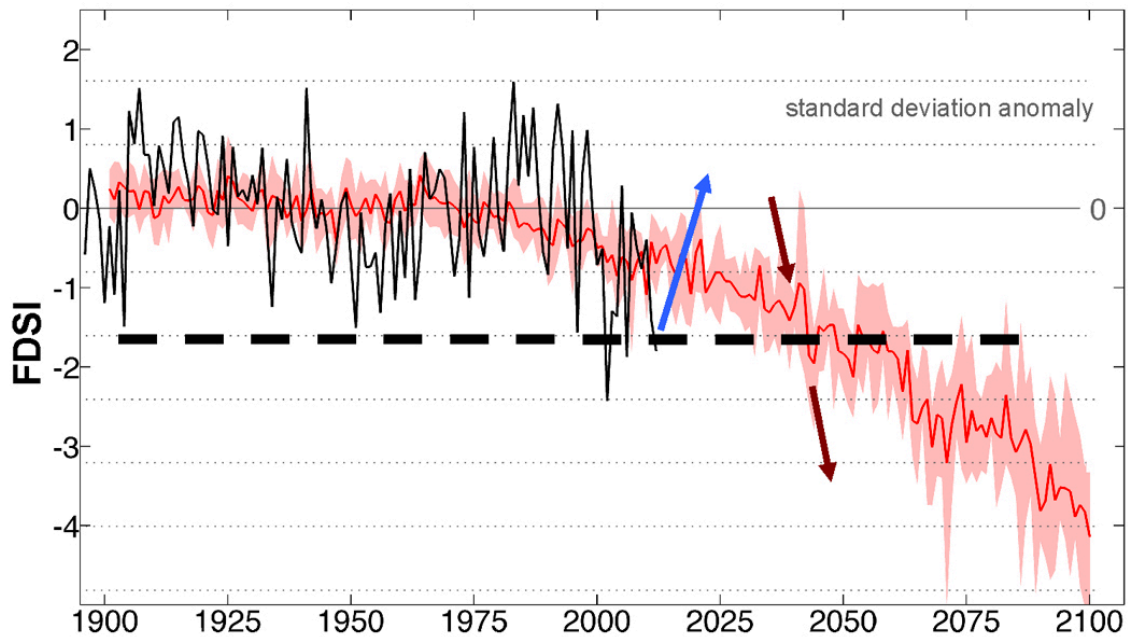
Drier winter conditions abruptly returned to the Southwest in 1996, with near-continuous and ongoing drought since 2000, along with historically novel warmer temperatures. As a result, over the past 17 years southwestern forests and woodlands have been subject to reduced plant-available water, sharply reduced tree growth, much more extensive and severe fire activity (e.g., figures 2-5) and major pulses of drought-induced tree mortality (including associated bark beetle outbreaks). About 20 percent of regional forests have been affected by significant tree mortality from combinations of drought stress, bark beetles, and high-severity wildfire between 1984 and 2012 (figure 7). The scale of these recent tree-killing forest disturbances is unprecedented in the Southwest since historic record keeping began around 1900, and almost certainly is unprecedented since the regional megadrought of the late 1500s (Swetnam and Betancourt 1998). The size of recent high-severity fire patches in southwestern ponderosa pine forests (e.g., Figures 2,3) quite possibly is unprecedented (Fulé and others 2014) since modern regional patterns of climate, vegetation, and fire regimes established by ca. 9,000 to 6,000 years ago (Anderson and others 2008).



**Figure 7.** Forest (dark green) and woodland (light green) extent in Southwestern U.S. uplands, with areas affected from 1997-2011 by high levels of tree mortality from bark beetles and drought stress (orange) and severe wildfire from 1984-2012 (red) cumulatively mapped as almost 20% of regional forests. (Updated from Williams et al. 2010.)

## GROWING RISKS OF POSTFIRE CONVERSION FROM FOREST TO NON-FOREST ECOSYSTEMS

Given that substantially warmer temperatures and greater drought stress are projected for the Southwest in coming years (figure 8; Seager and Vecchi 2010; Williams and others 2010, 2013), we should expect even greater increases in mortality of drought-stressed trees, high-severity fire, and ultimately conversion of current forests into different ecosystems, ranging from grasslands and shrublands to new forests dominated by different tree species (Williams and Jackson 2007; Jackson and others 2009). Increasingly frequent and severe droughts and fires favor plant life-forms that can survive above-ground stem dieback and fire damage by resprouting from below-ground tissues—these are traits exhibited by many grass and shrub species (Figure 5). In contrast, after high-severity fires successful regeneration of the main conifer tree species in the Southwest primarily depends upon the local survival of enough mother trees to serve as seed sources. The broadleaf tree quaking aspen (*Populus tremuloides*) is a prominent exception on cool/moist sites in the Southwest, as it is well-adapted to large stand-replacing fires by resprouting from long-lived clonal root systems as well as by long-distance seed dispersal (Margolis and others 2007, 2011). However, ongoing climate-driven aspen declines in the Southwest (Worrall and others 2013) suggest risks of substantial loss of regional aspen area due to projected climate stresses in this century (Rehfeldt and others 2009; Worrall and others 2013).



**Figure 8.** Climate model projections of Forest Drought Stress Index (FDSI) for the Southwest United States, 1900-2100 (updated from Williams et al. 2013). Observed FDSI 1896-2013 (black line), mean of ensemble model projections (red line), and inner quartile of ensemble projections (light red shaded band). Hypothetical deviations from this projection due to decadal-scale climatic oscillations (e.g., PDO) are shown by arrows. The dashed line indicates the upper bound of the driest 50% of years of the 1580s megadrought, representing tree-killing levels of drought stress.

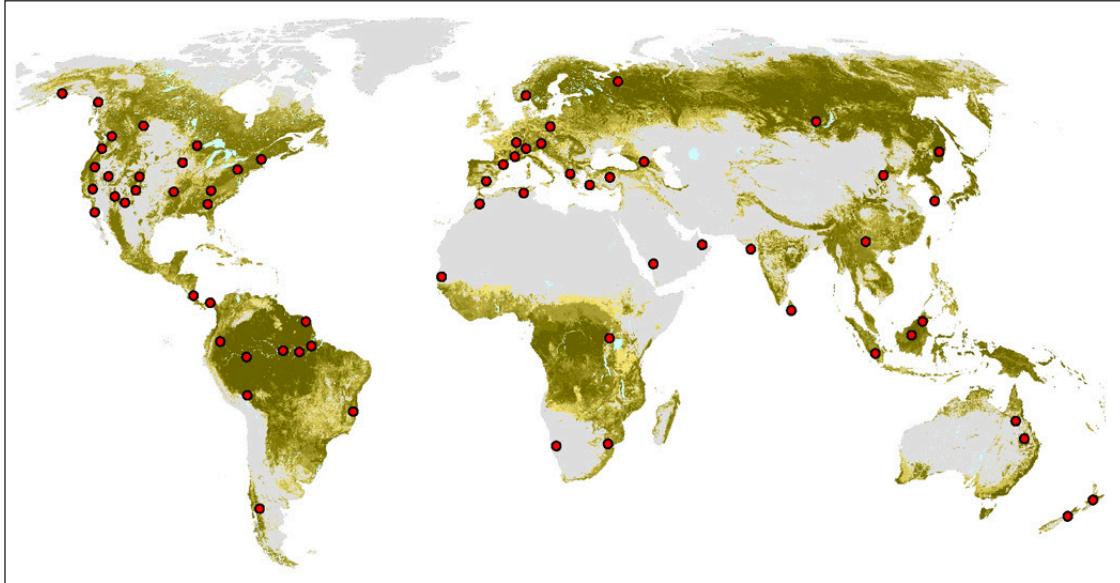
Recent observations and studies document postfire vegetation type conversions from forest to non-forest ecosystems in the Southwest (Barton 2002; Savage and Mast 2005; Goforth and Minnich 2008; Savage and others 2013). These conversions can be caused by large, high-severity fire patches where essentially all tree seed sources are killed across tens of thousands of acres, as increasingly observed in some recent fires (Figures 2, 3). Such large stand-replacing fire patches greatly limit recolonization rates by some of the most common southwestern tree species such as piñon (*Pinus edulis*), ponderosa pine, and Douglas-fir (*Pseudotsuga menziesii*), allowing dense grasslands or shrublands of resprouting species to achieve dominance before conifer trees can re-establish. It is also beginning to be observed that once large areas of resprouting shrubs, like Gambel oak, become heavily mixed in and around surviving post-fire conifer tree populations, a subsequent hot reburn through the shrubs can then kill nearly all of those adult tree survivors and associated young regeneration (Figure 5). In this way, a sequence of hot burns can eliminate local tree seed sources over extensive areas (Figures 2, 3, 5).

In addition, millions of hectares of forest and woodland in the Southwest have been affected by high levels of tree mortality since 2000 (Figure 7) from combinations of drought and heat stress, amplified by tree-killing biotic agents, particularly various bark beetle species (Breshears and others 2005; Raffa and others 2008; Williams and others 2010, 2013). The growing extent and severity of recent forest disturbances in this region, and the minimal tree regeneration across some extensive sites after severe fires, are evidence that we already may be reaching tipping points of regional forest ecosystem change, changes that are new in the historical era.

## **BROAD-SCALE IMPLICATIONS—REGIONAL, CONTINENTAL, GLOBAL**

Similar patterns of recent climate-amplified tree mortality and fire activity also are occurring more broadly in western North America (Westerling and others 2006; Raffa and others 2008; Meddens and others 2012), with major consequences for ecosystem services ranging from water supply and biodiversity to carbon sequestration (Hicke and others 2012, 2013). In addition, the first global overview of drought and heat-induced tree mortality (Allen and others 2010) compiled many examples of extensive forest die-off from all major forest types worldwide (Figure 9), ranging from tropical rainforests in the Amazon to African savannas, from Mediterranean forests to boreal and steppe ecotone forests of inner Asia, and from aspen in many portions of North America to varied eucalypt forests in opposite corners of Australia. While all major forest types globally are observed to be vulnerable to high levels of tree mortality during periods of drought and heat stress, we cannot yet determine if forest die-off processes are increasing overall at a worldwide scale due to the absence of long-term baseline information on global forest health conditions, and the continued absence of a globally coordinated observation system (Allen and others 2010). Still, as climate continues to warm there is growing evidence of reasons to expect more tree die-off events like those recently observed (e.g., Bentz and others 2010; McDowell and others 2011; Choat and others 2012; Worrall and others 2013; Williams and others 2010, 2013). Interactions between changes in climate and human land uses also are driving increasingly severe fire activity in many regions around the world (Bowman and others 2009, 2011; Pechony and Schindell 2010).

Every plant species has a particular range of climatic conditions across which it can reproduce and grow. As local climates (and associated disturbances like fire and insect outbreaks) shift beyond the tolerance limits of the historically and currently dominant species, today's dominant plants will increasingly die, thereby opening space for new species that are better adapted to the



**Figure 9.** Locations of substantial drought- and heat-induced tree mortality around the Earth from 1970-2009 (red dots), documented by peer-reviewed studies compiled and summarized in Allen and others (2010). Global forest cover and other wooded regions based on FAO (2005).

altered climate conditions—see Brusca and others (2013) for a Southwest example. There is, however, a major gap in scientific knowledge about precisely how much drought and heat stress various tree species can tolerate before dying. In other words, scientists do not yet know how to “kill” trees in models with the realism necessary to confidently project how much change in climate conditions they can tolerate before widespread mortality occurs (McDowell and others 2008, 2011; Allen and others 2010). Despite the uncertainties, there is growing observational and experimental evidence that tree mortality is amplified by warmer temperatures (McDowell and others 2011). Recent experiments on *Pinus edulis* demonstrate that when warmer temperatures accompany drought, trees die much faster (Adams and others 2009). Other new research demonstrates that the growth of multiple conifer species in the Southwest United States is highly sensitive in negative (and predictable) ways to warmer daytime temperatures during the growing season, likely due to water stress associated with greater atmospheric vapor pressure deficits from warming (Williams and others 2013). This work also shows strong correlations between forest drought stress and area affected annually by high-severity fires and bark beetle infestations in the Southwest (Williams and others 2013). Warming temperatures could drive forest drought stress in the Southwest to unprecedented levels by the 2050s (Figure 8), which likely would render large areas of current forest climatically unsuitable for their present dominant tree species. Note however that decadal-scale oscillations that affect Southwest precipitation and temperature (McCabe and others 2008; Pederson and others 2013) might slow or even reverse the overall aridity and warming trends for a few decades (Chylek and others 2013), as suggested hypothetically in Figure 8. While such ocean-driven oscillations could bring some decadal-scale relief from aridity to the Southwest in coming years, when the inevitable oscillation back toward aridity recurs a few decades later one might expect climate stresses to become even more extreme than the central tendency of ensemble climate model projections (Figure 8).

The observed recent ramp-up in the extent and severity of climate-related forest disturbances across the Southwest (Figures 3,4,6,7; Williams and others 2010, 2013) may represent the

beginning of substantial reorganization of ecosystem patterns and processes into new configurations (Barton 2002; Goforth and Minnich 2008; Jackson and others 2009; Brusca and others 2013; Worrall and others 2013), as southwestern forest landscapes transition toward more open and drought-resistant ecosystems in response to recent climate forcing. If the climate projections of further rapid warming and drought for the Southwest are correct (e.g., Seager and Vecchi 2010), then in coming decades southwestern forests as we know them today are expected to experience ever-growing levels of vegetation mortality (Figure 8; Williams and others 2013), driving the emergence of transformed ecosystems with new dominant species (Williams and Jackson 2007). One particular outcome of such mortality-mediated forest change is that old-growth trees and ancient forests likely will be lost, as multicentury-aged trees become increasingly unsuited to emerging new climates.

While a unique combination of geography, climate, land use, and disturbance histories have driven the recent period of high-magnitude forest stress and disturbance in the Southwest United States, similar patterns of forest change could emerge more broadly as projected climate changes progress at continental and global scales. Similar interactions among drought, heat, and land use are widely observed to be drivers of major fire and forest die-off episodes more broadly in western North America (Westerling and others 2006; Raffa and others 2008; Littell and others 2009; Bentz and others 2010; Allen and others 2010; Meddens and others 2012; Williams and others 2013; Hicke and others 2013) and globally (Bowman and others 2009; Allen and others 2010; Pechony and Schindel 2010; McDowell and others 2011; Matusick and others 2013; Worrall and others 2013). Given projections of substantial further global warming (IPCC 2013) and increased drought stress in coming decades for much of western North America (National Climate Assessment 2014) and many areas globally (IPCC 2013), the recent emergence of high levels of forest drought stress and associated disturbances (fire, die-off) in the Southwest United States (Williams and others 2013) may foreshadow future forest trends globally in the Anthropocene.

## CONCLUSION

Despite these recent disturbance trends and emerging risks for forests in the Southwest, there are a variety of forest management approaches available to buy time for our forests through increasing their resistance and resilience to growing climate stress, in order to restore and maintain historically sustainable patterns of forest structural conditions, species compositions, landscape-scale patterns of fire hazard, and ecological processes (Sisk and others 2006; Fulé 2008; Finney and others 2005, 2007; Ager and others 2010; Stephens and others 2012). For example, combinations of mechanical tree harvesting, ground mulching, and managed fire treatments can reduce forest densities and hazardous fuel loadings, decreasing between-tree competition for water (Grant and others 2013), thereby reducing overall forest drought stress and risk of high-severity fires (Finney and others 2005; Ager and others 2010) and providing protection to mountain watersheds (TNC 2014). Such treatments also can restore historical forest ecological conditions that were sustainable for at least many centuries prior to 1900 in many Southwest forest types (Swetnam and others 1999; Allen and others 2002; Sisk and others 2005; Fulé 2008; Stephens and others 2012; Fulé and others 2014).

In summary, forests as we know them today in the Southwest United States are changing rapidly from amplified tree mortality and high-severity fire due to increasing drought and heat stress. The recent increases in regional forest drought stress, the greater extent and severity of

forest disturbance, and the lack of post-disturbance tree regeneration on some sites all suggest that if modeled climate projections of a warmer and drier Southwest come to pass, we can expect to see regional forest ecosystems change beyond the historical and observed patterns of the past few centuries. Forest management practices have potential to improve forest resistance and resilience to climate stressors and associated disturbances. Finally, this observed convergence of climate, human land use patterns and histories, and disturbance trends in the southwestern United States may presage widespread forest ecosystem changes more broadly in North America, and globally.

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# Increasing Resiliency in Frequent Fire Forests: Lessons from the Sierra Nevada and Western Australia

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***Abstract:** This paper will primarily focus on the management and restoration of forests adapted to frequent, low-moderate intensity fire regimes. These are the forest types that are most at risk from large, high-severity wildfires and in many regions their fire regimes are changing. Fire as a landscape process can exhibit self-limiting characteristics in some forests which can assist managers in mitigating large, severe wildfires. In mixed conifer forests in Yosemite National Park, when the amount of time between successive adjacent fires is under nine years, the probability of the latter fire burning into the previous fire area is low. Analysis of fire severity data by 10-year periods (from 1975-2005) revealed stability in the proportion of area burned over the last three decades; this contrasts with research demonstrating increasing high-severity burning in many Sierra Nevada forests. There is also evidence that intact fire regimes can constrain fire size. One of the world's best examples of a prescribed fire program designed to reduce unwanted fire effects can be found near Perth, Australia. Approximately 8,500 prescribed burns have been conducted burning a total area of 15 million ha since 1950. Over this time an inverse relationship between the area burned by prescribed fire and wildfire has been established. However, the annual area of prescribed burning in this region is trending downwards since the 1980s while the annual area burned by wildfires is trending upwards. In contrast to crown-fire adapted ecosystems, areas that are adapted to frequent, low-moderate intensity fire regimes can be managed today to reduce their susceptibility to high severity fires and increase ecosystem resiliency. The current pace and scale of fuel treatments and managed wildfire are inadequate to increase ecosystem resiliency in forests in the western United States. Continued funding reductions for fuel reduction treatments is one of the most serious issues facing federal resource managers in the western United States working to increase forest resiliency.*

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## INTRODUCTION

In forests in the western United States, fire hazard reduction treatments have become a priority as the size and severity of wildfires have been increasing in some forest types (Miller and others 2009; Westerling and others 2006; Miller and Safford 2012). However, both the scale and implementation

rate for fuel treatment projects is well behind what is necessary to make a meaningful difference across landscapes (USDA Forest Service 2011; North and others 2012). This issue is particularly relevant as wildfire size and intensity are projected to increase in many parts of the western United States based on climate-fire modeling (Lenihan and others 2008; Westerling and others 2011; Yue and others 2013).

In contrast to crown-fire adapted ecosystems, ecosystems that once experienced frequent, low-moderate intensity fires can be managed to reduce their susceptibility to high severity wildfires (Fulé and others 2012) and increase ecosystem resiliency (Stephens and others 2012a, Stephens and others 2013). Research has determined that there are few unintended consequences of forest fuel reduction treatments across forests in the United States, because most ecosystem components (vegetation, soils, small mammals and song birds, bark beetles, carbon sequestration) exhibit very subtle or no measurable effects at all (Stephens and others 2012a). Similar results were found in Western Australia forests and shrublands that were repeatedly prescribed burned over 30 years (Wittkuhn and others 2011). In surface-fire adapted ecosystems, management actions including fuel treatments and managed wildfire (lightning ignitions allowed to burn for resource benefit) can be taken today to reduce the negative consequences of subsequent wildfires (such as large, high severity patches—Collins and Roller 2013) that also meet restoration objectives (North and others 2009).

Of the three principle means of fuels reduction, mechanical, prescribed burning, and wildfire, the latter is often the most expensive (North and others 2012). U.S. Forest Service (USFS) mechanical treatments (thinning, mastication) costs vary widely (Hartsough and others 2008) but costs on average were 3.5 times higher than prescribed fire in large part due to expensive service contracts for removal of small, noncommercial biomass. Wildfire costs were highest but vary tremendously between burns. In general, costs per acre increased as access became more difficult but decreased with fire size (North and others 2012).

Managing fire for multiple objectives instead of a narrow focus on fire suppression is producing some positive outcomes such as when fire exhibits self-limiting characteristics (reduce area and severity) in some ecosystems (Figure 1). Recurring fires consume fuels over time and can ultimately constrain the spatial extent and lessen fire-induced effects of subsequent fires. In montane forests in Yosemite National Park, United States, when the amount of time between successive adjacent fires is under nine years, the probability of the latter fire burning into the previous fire area is low (Collins and others 2009).

Our analysis of fire severity data by 10-year periods revealed stability in the proportion of area burned over the last three decades among fire severity classes (unchanged, low, moderate, high). This contrasts with increasing high-severity burning in many USFS Sierra Nevada forests from 1984 to 2010 (Miller and Safford 2012), which suggests that freely burning fires over time in some forests can regulate fire-induced effects across the landscape (Figure 2) (Stephens and others 2008; Miller and others 2012). It should be noted that the USFS has not used prescribed fire or managed wildfire to the degree that the U.S. National Park Service has which has influenced current burning patterns.

Current wildfires are burning large areas, but there is some evidence that intact fire regimes (those minimally affected by fire exclusion for several decades) can constrain fire size (Stephens and others 2013). For example, in montane forests of Yosemite National Park, where lightning fires have been allowed to burn under prescribed conditions for 40 years, a pattern of intersecting



**Figure 1.** Jeffrey pine forests that have been repeatedly burned by managed wildfire in the Illilouette Creek basin in Yosemite National Park. Re-introduction of a functioning fire regime in 1973 has produced a forest that is resilient to fire and climate change. Photo by Scott Stephens.

fires emerged that limited the extent of subsequent fires to less than 4000 ha (9884 acres) (van Wagtenonk and others 2012). However, wildfires have grown to over 40,000 ha (98,842 acres) on areas in or adjacent to the park where fires have been routinely suppressed and the resulting burn severity patterns (especially large patch sizes) are not within desired ranges to conserve ecosystem resiliency (Miller and others 2012).

### ***Fire and Fuels Management in USFS Lands in the Sierra Nevada***

A recent analysis determined that fuels reduction was occurring on USFS lands in the Sierra Nevada at very low rates (North and others 2012). With less than 20% of USFS lands in the Sierra Nevada receiving needed fuels treatments, and the need to frequently re-treat many areas, the current pattern and scale of fuels reduction is unlikely to ever significantly advance restoration efforts. One means of changing current practices is to concentrate large-scale strategic (Finney and others 2008) fuels reduction efforts and then move treated areas out of fire suppression into fire maintenance. A fundamental change in the scale of fuels treatments is needed to emphasize treating entire firesheds and restoring ecosystem processes (North and others 2009, 2012). Without proactively addressing this situation, the status quo will relegate many ecologically important areas (including sensitive species habitat) to continued degradation from either no fire or wildfire burning at high severity (North and others 2012).



**Figure 2.** High severity patch in upper elevation mixed conifer forest in the Illilouette Creek basin is in Yosemite National Park. Median high severity patch size in this forest is < 4 ha (Collins and Stephens 2010) and the amount of high severity fire has not changed since the early 1970's (Collins and others 2009). Photo by Scott Stephens.

Ironically, current USFS practices intended to protect resources identified as having high ecological value often put them at a greater risk of large, high-severity fire (Collins and others 2010, North and others 2012). A policy focused on suppression, which ultimately results in greater wildfire intensity, means that fuels reduction becomes the principle method of locally affecting fire behavior and reducing severity (Collins and others 2010). Forest areas identified as having high conservation value, such as riparian conservation areas (van de Water and North 2010, 2011) and protected activity centers (PAC) for threatened and sensitive wildlife often have management restrictions and higher litigation potential, resulting in minimal or no fuels reduction treatment (North and others 2012). Stand conditions in these protected areas often consist of multi-layered canopies with large amounts of surface fuel, resulting in increased crown-fire potential (Spies and others 2006; Collins and others 2010). Following a particularly high-intensity 2007 wildfire in the Sierra Nevada (Moonlight), riparian and PAC areas had some of the greatest percentage of high-severity effects of any area within the fire perimeters (Safford and others 2009). In contrast, low- and moderate-severity wildfire and prescribed burning in Yosemite National Park maintained habitat characteristics and density of California spotted owls (*Strix occidentalis*) in late successional montane forest (Roberts and others 2011).

Recent estimates determined that at current treatment rates, the deficit of forestland “in need” of treatment would be approximately 1.2 million ha (approximately 30 million acres) in the Sierra

Nevada (approximately 60% of USFS lands in the Sierra Nevada), of which 670,000 ha (16.5 million acres) are ponderosa (*Pinus ponderosa*) and Jeffrey pine (*Pinus jeffreyi*) dominated forest types (North and others 2012). This is a very conservative estimate of the deficit because it assumes that mechanical, prescribed fire, and wildfire areas never overlap and that all wildfires are restorative in their ecological effects, which is not the case. Although current policy recognizes the importance and need for managed wildfire (FWFMP 2001; USDA/USDI 2005; FWFMP 2009) studies have found very low rates of implementation. In 2004, land management agencies only let 2.7% of all lightning ignitions burn (NIFC 2006), consistent with a recent analysis in the Sierra Nevada that less than 2% of USFS lands were burned under managed wildfire between 2001–2008 (Silvas-Bellanca 2011). The most significant factor associated with USFS District Rangers using managed wildfire was personal commitment, while the main disincentives were negative public perception, resource availability, and perceived lack of agency support (Williamson 2007).

With less than 20% of the landscape that needs fuels treatments receiving them and the need to re-treat many areas every 15–30 years depending on forest type (Stephens and others 2012b), the current pattern and scale of fuels reduction is unlikely to ever significantly advance restoration efforts, particularly if agency budgets continue to decline. Treating and then moving areas out of fire suppression into fire maintenance is one means of changing current patterns (North and others 2012).

As fuel loads increase, rural home construction expands, and budgets decline, delays in fuel treatment implementation will only make it more difficult to expand the use of managed fire after initial treatments. Increases in managed wildfire may be criticized given current constraints but at least it could stimulate discussions between stakeholders, air quality regulators, and forest managers about current and future management options (North and others 2012). Without proactively addressing some of these conditions, the status quo will relegate many ecologically important areas to continued degradation from fire exclusion and high severity wildfires. In some forests, revenue generated in the initial entry (Hartsough and others 2008) may be the best opportunity to increase the scale and shift the focus of current fuels reduction toward favoring long-term fire restoration (North and others 2012).

### ***Fire and Fuels Management in Western Australia***

One of the world's best examples of a fire management program designed to reduce wildfire impacts can be found in Australia (Boer and others 2009). In the fire-prone forests and shrublands of south-west Western Australia, prescribed burning of native vegetation is an important management strategy for achieving conservation and land management objectives (Wittkuhn and others 2011). Prescribed burning done at the appropriate spatial and temporal scales reduces the overall flammability and quantity of fuels in the landscape, thereby reducing the intensity and spread rate of wildfires (Stephens and others 2013).

Broad area fuel reduction burning as a key asset protection strategy has been implemented in south-west Western Australia since the mid-1950s (Figure 3). Approximately 8,500 prescribed burns have been conducted burning a total area of 15 million ha (37 million acres) (Stephens and others 2013). Over this time, an inverse relationship between the area burned by prescribed fire and wildfire has been established (Boer and others 2009), i.e., prescribed burning has reduced



the impact of wildfires by reducing their size and intensity. This Australian example could be of interest for regions that continue to focus solely on fire suppression.

However, the annual area of prescribed burning in the south-west Western Australian region is trending downwards since the 1980s (mainly because of the reduced area of prescribed fire), while the annual area burned by wildfires is trending upwards (Stephens and others 2013). In recent years there has been a spate of wildfires that have not been experienced in the region since the 1960s. Key drivers of these trends are (Stephens and others 2014):

- Climate change. Since the 1970s, the climate has become warmer and drier (Bates and others 2008) reducing the window of opportunity for safely carrying out prescribed burning. Longer periods of hotter, drier weather result in longer periods of high fire risk.
- Population growth in the urban-wildland interface. More people are living in fire-prone settings. In many instances, local by-laws and land use planning policies do not adequately consider the risk of wildfires, or are not adequately enforced. People are building and living in dangerous locations and often are not taking adequate fire protection measures.
- Fire management capacity. Resources and personnel for fire management have not kept pace with the increasing demands and complexity of managing fire. Additional staff is needed and training programs are necessary to allow this new group to become familiar with prescribed fire planning and operations.



**Figure 3.** Prescribed fire in mixed eucalyptus forests near Busselton, Western Australia. Note the variety in fire severity with some areas unburned and others burned at high intensity which is the common goal in this area. Regrowth is already occurring only two months after the prescribed fire. Photo by Scott Stephens.

- Smoke management. Managing air quality and the impacts of smoke on adjacent land users or home-owners further narrow burning windows and reduce the size and number of prescribed burns that can be conducted.

Effective management of wildfire risk will require the incorporation of larger-scale management processes across landscapes (at the 10,000 - 30,000 ha scale, 25,000-75,000 acre scale) (North and others 2012; Stephens and others 2014). This can be done with large scale prescribed burning programs, mechanical fuel treatments, combinations of mechanical and fire treatments, or allowing wildfires to burn under desired conditions. Managed wildfire probably has the greatest ability to meet restoration and fuel management goals in the western United States because it can be implemented at moderate-large spatial scales with the lowest cost (North and others 2012) whereas in Australia, the Mediterranean Basin, the U.S. Great Plains, and the Southern United States, prescribed burning is preferable (Stephens and others 2013). Regardless of how a fire is ignited, smoke will likely be a large concern, especially its impact on human health. However, it is important to contrast the human health effects of smoke from prescribed fires and managed wildfires with those of large, severe wildfires, which can affect large regions for weeks or months.

## CONCLUSION

Federal forest managers have a great challenge in promoting forests that are resilient to changing climates. Forests that once experienced frequent, low-moderate intensity fire regimes can be managed today to reduce the negative impacts of subsequent wildfire. Increased use of fire and fire surrogates treatments (McIver and others 2009; Schwilk and others 2009; Stephens and others 2012a) and increased use of management wildfire for resource objectives are the only possibilities for managers to achieve desired conditions. Current rates of treatments on federal lands in the western United States are inadequate to conserve forests into the future (North and others 2012). This treatment deficit has the potential to adversely impact critical ecosystem services that are derived from U.S. forests.

One of the largest challenges faced by U.S. federal land managers is the continued reduction in funding for fuels programs which subsequently emphasizes managed wildfires as their primary management option. Funding for prescribed fire, thinning, and mechanical fuels treatments has been reduced in the last two years and the 2013 U.S. federal budget reduces it by over 85% in comparison to resources allocated in this area in the early 2000's. Managed wildfire is appropriate in wilderness, roadless areas, and other remote areas but is not applicable to large areas of federal land because of human infrastructure. Managing wildfires for weeks or months can produce positive ecological outputs but is much riskier than performing fuels treatments over relatively short time intervals. Managers need access to all forest management options to increase resiliency in the forest areas of the United States; removing options will further increase the back-log of areas in need of restoration.

California can learn from a successful prescribed fire program in southwestern Western Australia (Sneeuwjagt and others 2013). While the ecosystems in these two areas are different they both evolved with frequent fire in Mediterranean climates. Southwestern Western Australia has successfully implement a prescribed fire program that has reduced the incidence of wildfires (Boer and others 2009) while conserving ecosystems (Wittkuhn and others 2011). The challenge is for California managers to produce a similar outcome for frequent fire ecosystems in the Sierra Nevada.

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# Planning the Future's Forests with Assisted Migration

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***Abstract:** Studies show that changes in climate may exceed plant adaptation and migration. The mismatch in rates between climate change and plant adaptation and migration will pose significant challenges for practitioners that select, grow, and outplant native tree species. Native tree species and populations that are planted today must meet the climatic challenges that they will face during this century. Anticipated shifts in climate call for the revision of ethical, legal, political, and economical paradigms, as well as changes in the guidelines for growing and outplanting trees to maximize survival and curtail maladaptation. Growing trees that survive may be more important than growing perfectly shaped trees and may require selection of adapted genetic material and/or movement of plant populations (for example, assisted migration). We review and explore assisted migration as an adaptation strategy, present some working examples, and provide resources for consultation.*

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## INTRODUCTION

If the climate changes faster than the adaptation or migration capability of plants (Zhu and others 2012; Gray and Hamann 2013), foresters and other land managers will face an overwhelming challenge. Growing trees that survive may become more important than growing perfectly formed trees (Hebda 2008) and may require selection of adapted plant materials and/or assisting the migration of plant populations (Peters and Darling 1985). Agencies, land managers, and foresters are being advised to acknowledge climate change in their operations, but current client demands, policies, and uncertainty about climate change predictions and impacts constrain active measures (Tepe and Meretsky 2011). For example, the practice of restricting native plant movement to environments similar to their source has a long history in forest management (Langlet 1971), however, transfers must now factor in climate change because plant materials guided by current guidelines and zones will likely face unfavorable climate conditions by the end of this century.

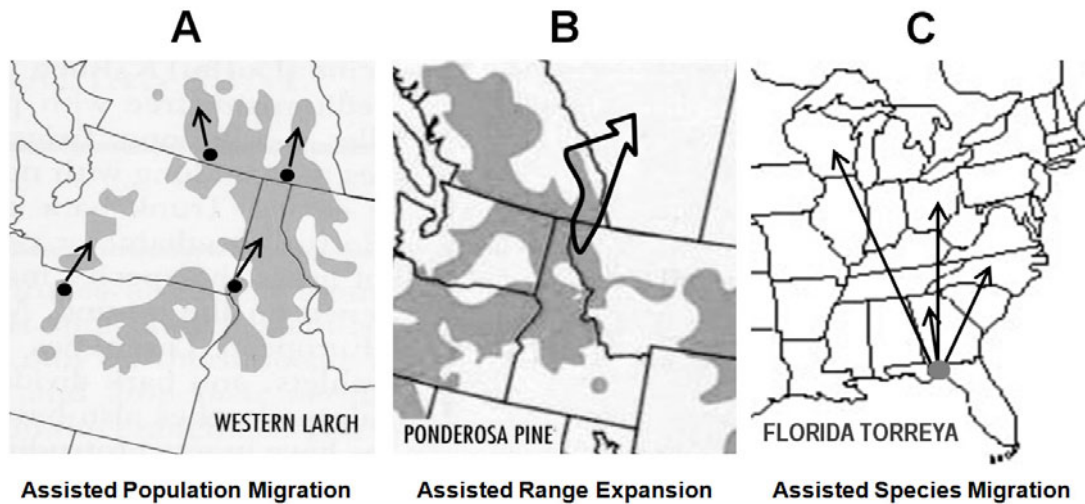


To facilitate adaptation and migration, we will need to rethink the selection, nursery production, and outplanting of native trees in a dynamic context, such as modifying seed transfer guidelines in the direction of climatic change to suit target species and populations. A challenge lies in the matching of existing plant materials (that is, seed, nursery stock, or genetic material) with ecosystems of the future that have different climate conditions (Potter and Hargrove 2012). To alleviate the challenge, strategies such as assisted migration (also referenced as assisted colonization and managed relocation) have been proposed in adaptive management plans (for example, USDA Forest Service 2008), but without specific guidance. In this article, we summarize the main mechanics of assisted migration, discuss the societal issues, and present some working examples with resources to help generate dynamic guidelines.

## MECHANICS OF ASSISTED MIGRATION

Foresters have been moving tree species and populations for a very long time. Usually, these movements are small and properly implemented by using seed transfer guidelines. Occasionally, these movements are drastic and intercontinental to support commercial forestry (for example, exporting Monterey pine [*Pinus radiata*] from the United States to New Zealand). The concept of assisted migration, first proposed by Peters and Darling (1985), builds on this forestry legacy of moving species and populations, but deliberately includes management actions to mitigate changes in climate (figure 1) (Vitt and others 2010). This does not necessarily mean moving plants far distances, but rather moving genotypes, seed sources, and tree populations to areas with predicted suitable climatic conditions with the goal of avoiding maladaptation (Williams and Dumroese 2013). How far we move plant materials to facilitate migration will depend on the target species and populations, location, projected climatic conditions, and time. For a species or population, this may require target distances across current seed-zone boundaries or beyond transfer guidelines (Ledig and Kitzmiller 1992). Target migration distance is the distance that populations could be moved to address future climate change and foster adaptation throughout a tree's lifetime (O'Neill and others 2008). Target migration distance can be geographic (for example, distance along an elevation gradient), climatic (for example, change in number of frost-free days along the same elevation gradient), and/or temporal (for example, date when the current climate of the migrated population equals the future climate of the outplanting site). Instead, evaluating species that might naturally migrate is an option. For example, Alberta, Canada is considering ponderosa pine (*P. ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*), now absent in the province but occurring proximate to the province, as replacements for lodgepole pine (*P. contorta*) because it is predicted to decline in productivity or become extirpated under climate change (Pedlar and others 2011).

Moving plants has been practiced for a long time in human history, but the movement of species in response to climate change is a relatively new concept (Aubin and others 2011). As an adaptation strategy, assisted migration could be used to prevent species extinction, minimize economic loss (for example, timber production), and sustain ecosystem services (for example, wildlife habitat, recreation, and water and air quality) (figure 1) (Aubin and others 2011). Assisted migration may be warranted if a species is at high risk of extinction or if loss of the species would create economic or ecosystem loss, establishes easily, and provides more benefits than costs (Hoegh-Guldberg and others 2008). Reducing fragmentation, increasing landscape connections, collecting and storing seed, and creating suitable habitats are all viable options (depending on



**Figure 1.** Assisted migration can occur as assisted population migration where seed sources are moved climatically or geographically within their current ranges, even across seed transfer zones (A). For example, moving western larch (*Larix occidentalis*) 200 km north within its current range. Seed sources can also be moved climatically or geographically from current ranges to suitable areas just outside to facilitate range expansion (B), such as moving seed sources of ponderosa pine (*Pinus ponderosa*) into Alberta, Canada, hypothetically. In an assisted species migration (or assisted long-distance migration) effort (C), species are moved far outside current ranges to prevent extinction, such as planting Florida torrey (*Torrey taxifolia*) in states north of Florida. Distribution ranges are shaded gray; terms from Ste-Marie and others 2011; Winder and others 2011; Williams and Dumroese 2013 and distribution maps from Petrides and Petrides 1998; Torrey Guardians 2008.

the species and population) to facilitate adaptation and migration. Some species may migrate in concert with climate change, thus conserving and increasing landscape connections should take precedence over other management actions. Other species may adapt to changes in climate, while other species may have limited adaptation and migration capacities. Assisted migration needs to be implemented within an adaptive management framework, one that assesses species vulnerability to climate change, sets priorities, selects options and management targets, and emphasizes long-term monitoring and management adjustments as needed.

Frameworks, tools, and guidelines on implementation (table 1) (Beardmore and Winder 2011; Pedlar and others 2011; Williams and Dumroese 2013) have been introduced to make informed decisions about climate change adaptation strategies. Programs such as the Climate Change Tree Atlas (Prasad and others 2007), Forest Tree Genetic Risk Assessment System (ForGRAS; Devine and others 2012), NatureServe Climate Change Vulnerability Index (NatureServe 2011), System for Assessing Species Vulnerability (SAVS; Bagne and others 2011), and Seeds of Success program (Byrne and Olwell 2008) are available to determine a species' risk to climate change. Species most vulnerable to climate change are rare, long-lived, locally adapted, geographic and genetically isolated, and threatened by fragmentation and pathogens (Erickson and others 2012). Listing species as suitable candidates—those with limited adaptation and migration capacity—is a practical first step, but requires a substantial amount of knowledge about the species and their current and projected habitat conditions. Provenance data exist for several commercial tree species and should be used to estimate their response to climate scenarios. The Center for Forest Provenance Data provides an online database of tree provenance data (St. Clair and others 2013).



**Table 1.** Resources related to forest management, native plant transfer guidelines, climate change, and assisted migration for the U.S. and Canada. Most programs are easily located by searching their names in common web browsers. All URLs were valid as of 15 October 2013.

Resource or Program	Description	Authorship
Assisted Migration Adaptation Trial <a href="http://www.for.gov.bc.ca/hre/for/gen/interior/AMAT.htm">http://www.for.gov.bc.ca/hre/for/gen/interior/AMAT.htm</a>	Large, long-term project to evaluate the response of 15 tree species to climate change and assisted migration	Ministry of Forest and Range, BC
Center for Forest Provenance Data <a href="http://cenfor.gen.forestry.oregonstate.edu/index.php">http://cenfor.gen.forestry.oregonstate.edu/index.php</a>	Public users are able to submit and retrieve tree provenance and genealogical data	Oregon State University and USDA Forest Service
Centre for Forest Conservation Genetics <a href="http://www.genetics.forestry.ubc.ca/cfcg/">http://www.genetics.forestry.ubc.ca/cfcg/</a>	Portal for forest genetics and climate change research conducted in British Columbia, Canada	The University of British Columbia
Climate Change Response Framework <a href="http://climateframework.org/">http://climateframework.org/</a>	Collaborative framework among scientists, managers, and landowners to incorporate climate change into management	Northern Institute of Applied Climate Science
Climate Change Tree Atlas <a href="http://www.nrs.fs.fed.us/atlas/tree/tree_atlas.html">http://www.nrs.fs.fed.us/atlas/tree/tree_atlas.html</a>	An interactive database that maps current (2000) and potential status (2100) of eastern US tree species under different climate change scenarios	USDA Forest Service
Forest Seedling Network <a href="http://www.forestseedlingnetwork.com">http://www.forestseedlingnetwork.com</a>	Interactive website connecting forest landowners with seedling providers and forest management services and contractors; includes seed zone maps	Forest Seedling Network
Forest Tree Genetic Risk Assessment System (ForGRAS) <a href="http://www.forestthreats.org/research/projects/project-summaries/assessing-forest-tree-risk">http://www.forestthreats.org/research/projects/project-summaries/assessing-forest-tree-risk</a>	Tool to identify tree species risk of genetic degradation in the Pacific Northwest and Southeast	North Carolina State University and USDA Forest Service
MaxEnt (Maximum Entropy) <a href="http://www.cs.princeton.edu/~schapire/maxent/">www.cs.princeton.edu/~schapire/maxent/</a>	Software that uses species occurrences and environmental and climate data to map potential habitat; can be used to develop seed collection areas	Phillips and others (2006)
Native Seed Network <a href="http://www.nativeseednetwork.org/">http://www.nativeseednetwork.org/</a>	Interactive database of native plant and seed information and guidelines for restoration, native plant propagation, and native seed procurement by ecoregion	Institute for Applied Ecology
Seed Zone Mapper <a href="http://www.fs.fed.us/wwetac/threat_map/SeedZones_Intro.html">http://www.fs.fed.us/wwetac/threat_map/SeedZones_Intro.html</a>	An interactive seed zone map of western North America; user selects areas to identify provisional and empirical seed zones for grasses, forbs, shrubs, and conifers; map displays political and agency boundaries, topography, relief, streets, threats, and resource layers	USDA Forest Service
Seedlot Selection Tool <a href="http://sst.forestry.oregonstate.edu/index.html">http://sst.forestry.oregonstate.edu/index.html</a>	An interactive mapping tool to help forest managers match seedlots with outplanting sites based on current climate or future climate change scenarios; maps current or future climates defined by temperature and precipitation	Oregon State University and USDA Forest Service
SeedWhere <a href="https://gfc.cfsnet.nfis.org/mapserver/seedwhere/seedwhere-about.php?lang=en">https://gfc.cfsnet.nfis.org/mapserver/seedwhere/seedwhere-about.php?lang=en</a>	GIS tool to assist nursery stock and seed transfer decisions for forest restoration projects in Canada and the Great Lakes region; can identify geographic similarities between seed sources and outplanting sites	Natural Resources Canada, Canadian Forest Service
System for Assessing Species Vulnerability (SAVS) <a href="http://www.fs.fed.us/rm/grassland-shrubland-desert/products/species-vulnerability/">www.fs.fed.us/rm/grassland-shrubland-desert/products/species-vulnerability/</a>	Software that identifies the relative vulnerability or resilience of vertebrate species to climate change; provides a framework for integrating new information into climate change assessments	USDA Forest Service

Bioclimatic models coupled with genetic information from provenance tests and common garden studies in a GIS can be used to identify current and projected distributions (for example, Rehfeldt and Jaquish 2010; McLane and Aitken 2012; Notaro and others 2012). These forecasts can assist land managers in their long-term management plans, such as, where to collect seeds and plants. Although modeled projections have some uncertainty in future climate predictions and tree responses (Park and Talbot 2012), they provide an indication of how climatic conditions will change for a particular site.

## **ECOLOGICAL, ETHICAL, AND LOGISTICAL ISSUES**

The movement of species in response to climate change does not come without economical, ecological, ethical, and political issues (Schwartz and others 2012). Assisted migration is a sensitive strategy because it disrupts widely held conservation objectives and paradigms (McLachlan and others 2007). Adoption requires us to balance conservation of species against risks posed by introduced species (Schwartz 1994). Current natural resource management plans were not written within the context of climate change, let alone rapid changes in climate. The U.S. Forest Service anticipates using assisted migration of species to suitable habitats to facilitate adaptation to climate change (USDA Forest Service 2008). But, these management statements imply that assisted migration should only be implemented in cases where past research supports success (Erickson and others 2012; Johnson and others 2013). Assisted migration is essentially incompatible with existing U.S. state and federal land management frameworks (Camacho 2013). For example, in current tree-improvement programs in the United States, seed transfer guidelines and zones are used to determine the safest distance that a population can be moved to avoid maladaptation (Johnson and others 2004). For most jurisdictions in the United States, the guidelines and zones prohibit the movement of seed sources between and among zones. As they currently stand, seed transfer policies do not account for changes in climate, even though research has identified that suitable habitat for some important commercial tree species will shift north and to higher elevations during this century (Aitken and others 2008; Rehfeldt and Jaquish 2010). The existing policies hamper any formal actions and may encourage more privately-funded operations, such as the Florida torreyia (*Torreya taxifolia*) project in southeastern United States. Since 2008, it has been planted on private lands in five southern states in an effort to curtail extinction (Torreyia Guardians 2012).

Even so, the debate about its implementation is largely focused on an ecological assessment of risks and benefits (see Ricciardi and Simberloff 2009; Aubin and others 2011; Hewitt and others 2011; Lawler and Olden 2011). We cannot reliably predict future climates so it is difficult to know which or how ecosystems will be affected. We have limited knowledge about establishing native plants outside their range in anticipation of different climate conditions let alone the impact of climate change on ecosystem properties important to the survival and growth of trees (for example, photoperiod, soil conditions, and pollinators). To further complicate matters, we know little about the long-term ecological effects of assisted migration, such as, invasiveness, maladaptation, and site stability (Aubin and others 2011). Uncertainty about future climate conditions and risks, such as genetic pollution, hybridization, impairment of ecological function and structure, introduction of pathogens, and bringing on invasive species are major constraints to consensus and implementation (Gunn and others 2009; Aubin and others 2011).

Economic costs and ecological risks will vary across assisted migration efforts (figure 1) and likely increase with migration distance (Mueller and Hellmann 2008; Vitt and others 2010; Pedlar and others 2012). Establishment failure could occur if the species or population is moved before the outplanting site is climatically suitable or if the seed source is incorrectly matched with the outplanting site in a projected area (Vitt and others 2010). Assisted migration to areas far outside a species current range would carry greater costs, management responsibilities, and ecological risks than assisted population migration and assisted range expansion (Winder and others 2011). Principle to reforestation success is using locally adapted plant materials, so the greater the difference between seed origin and outplanting site the greater the risk in maladaptation. An increase in distance (either geographic or climatic) is usually, but not always, associated with loss in productivity, decrease in fitness, or mortality (Rehfeldt 1983; Campbell 1986; Lindgren and Ying 2000).

Forest tree species are highlighted most often in the assisted migration literature because of their economic value and focus in climate change research, however, assisted migration conducted for economic rather than conservation reasons is cited as another major barrier to implementation, meaning that economic benefit may be an insufficient justification (Hewitt et al. 2011). On the contrary, the forestry profession is well suited to evaluate, test, and employ an assisted migration strategy given its long tradition of research, development, and application of moving genetic resources through silvicultural operations (Beaulieu and Rainville 2005; Anderson and Chmura 2009; McKenney and others 2009; Winder and others 2011). For commercial forestry, assisted migration could address health and productivity in the coming decades (Gray and others 2011) because operational frameworks already exist.

## **ASSISTED MIGRATION IN ACTION**

Forest management policy drafts to allow assisted migration and trials of assisted migration are currently underway in North America. The Assisted Migration Adaptation Trial (AMAT) is a large collection of long-term experiments undertaken by the British Columbia (BC) Ministry of Forests (Canada) and several collaborators, including the U.S. Forest Service and timber companies, that tests assisted migration and climate warming (Marris 2009). The program evaluates the adaptive performance of 15 tree species collected from a range of sources in BC, Washington, Oregon, and Idaho and planted on a variety of sites in BC. Important components of the trial test how sources planted in northern latitudes perform as the climate changes and evaluate endurance of northern latitude sources to warmer conditions in southern latitudes. For decades in the southeastern United States, some southern pine seed sources have been moved one seed zone north to increase growth (Schmidting 2001). Similarly, Douglas-fir has been planted around the Pacific Northwest to evaluate their growth response to climatic variation (Erickson and others 2012). The only known assisted species migration project in the United States is a grassroots initiative to save the Florida torreyia, a southeastern evergreen conifer, from extinction by planting it outside its current and historic range (McLachlan and others 2007; Barlow 2011). The project has prompted the U.S. Fish and Wildlife Service to consider assisted migration as a management option for this species (Torreyia Guardians 2012).

Assisted migration will be best implemented where seed transfer guidelines and zones are currently in place and most successful if based on climate conditions (McKenney and others 2009). Provenance data, seed transfer guidelines, and seed zones can be used to facilitate the adaptation

of trees being established today to future climates of tomorrow (Pedlar and others 2012). In Canada, several provinces have modified policies or developed tools to enable assisted migration. Seed transfer guidelines for Alberta were revised to extend current guidelines northward by 2° latitude and upslope by 656 ft (200 m) (NRC 2013) and guidelines for some species were revised upslope by 656 ft (200 m) in BC (O'Neill and others 2008). Policy in BC also allows the movement of western larch (*Larix occidentalis*) to suitable climatic locations just outside its current range (NRC 2013). To test species range limits in Quebec some sites are being planted with a mixture of seed sources from the southern portion of the province. Canada and the United States have tools to assist forest managers and researchers in making decisions about seed transfer and matching seedlots with outplanting sites (for example, Optisource [Beaulieu 2009] and BioSim [Regniere and Saint-Amant 2008] in Quebec, Seedwhere in Ontario [McKenney and others 1999], and the Seedlot Selection Tool in the United States [Howe and others 2009]). Seedwhere can map out potential seed collection or outplanting sites based on climatic similarity of chosen sites to a region of interest. The Seedlot Selection Tool is a mapping tool that matches seedlots with outplanting sites based on current or future climates for tree species such as Douglas-fir and ponderosa pine.

Target migration distances must be short enough to allow survival, but long enough to foster adaptation toward the end of a rotation, or lifespan of a tree plantation (McKenney and others 2009). Preliminary work in Canada on most commercial tree species demonstrates that target migration distances for populations would be short, occurring within current ranges (O'Neill and others 2008; Gray and others 2011). For some tree species, target migration distances are < 125 miles (< 200 km) north or < 328 ft (< 100 m) up in elevation during the next 20 to 50 y (Beaulieu and Rainville 2005; O'Neill and others 2008; Pedlar and others 2012; Gray and Hamann 2013). Target migration distances are needed for short and long-term planning efforts and will require adjustments as new climate change information comes to light. Methods using transfer functions and provenance data have been developed to guide seed movement under climate change (for example, Beaulieu and Rainville 2005; Wang and others 2006; Crowe and Parker 2008, Thomson and others 2010; and Ukrainetz and others 2011). Bioclimatic models mapping current and projected seed zones have been assessed for aspen (*Populus tremuloides*) (Gray and others 2011); lodgepole (Wang and others 2006), longleaf (*P. palustris*) (Potter and Hargrove 2012) and whitebark (McLane and Aitken 2012) pines; dogwood (*Cornus florida*) (Potter and Hargrove 2012); and western larch (Rehfeldt and Jaquish 2010).

The lack of genetic, provenance, and performance data on which seed transfer guidelines and zones are based impede making informed decisions about assisted migration for non-commercial species. At best we can consult provisional seed zones (for example, Seed Zone Mapper - table 1) developed from temperature and precipitation data and Omernik level III and IV ecoregion boundaries (Omernik 1987). Furthermore, we can shift the focus to producing plant materials that grow and survive by modifying past and current projects and implementing studies and strategies. Many existing projects, such as provenance and common garden studies can be transformed with little modification to look at adaptation and response to climatic conditions (Matyas 1994). Information such as where the plant comes from, where it is planted on the site, and how it performs (growth, survival, reproduction, and so on) can guide forestry practices to increase the proportion of species that survive and grow well (McKay and others 2005; Millar and others 2007; Hebda 2008).

## CLOSING REMARKS

Climate change poses a significant challenge for foresters and other land managers, but given its long history of selecting and growing trees, the forestry profession has the knowledge and tools to test and instigate assisted migration; we need dynamic policies that allow action. The frameworks and techniques for production and outplanting already exist, therefore researchers and practitioners can work with nurseries to design and implement adaptive measures that consider assisted migration and hopefully curtail significant social, economic, and ecological losses associated with impacts from a rapidly changing climate. The science and practice of growing trees to sustain ecosystems will greatly benefit with collaboration (McKay and others 2005). The Adaptive Silviculture for Climate Change (Linda Nagel, project lead) is one such collaborative effort in the United States that focuses on the understanding of long-term ecosystem response to adaptation options and to help forest managers integrate climate change into silviculture planning (Northern Institute of Applied Climate Science, table 1). Framing the discussion to identify objectives and produce frameworks, such as the Climate Change Response Framework, that lead to practical and dynamic strategies is pertinent. Changing policies will require collaboration and discussion of how predicted conditions will affect forests, how managers can plan for the future, and how landowners can be encouraged to plant trees adapted to future conditions, such as warmer conditions and variable precipitation patterns (Tepe and Meretsky 2011).

Assisted migration may not be appropriate for every species or population. Whatever the chosen adaptive strategies, foresters need to be included in the dialogue with scientists and land managers in climate change planning. We have little time to act given current climate change predictions and uncertainty regarding the adaptation and migration capacities of species and populations. Establishment of healthy stands is vital now to prepare forests as changes occur. This might entail small-scale experiments, such as planting fast-growing trees adapted to projected climate in the next 15 to 30 years (Park and Talbot 2012) or randomly planting a variety of seed sources in one area and monitoring their adaptive response (similar to provenance testing) (Pedlar and others 2011). Planting the standard species or stocks in regions highly sensitive to climate change will be unwarranted (Hebda 2008), given that reductions in fire frequency from 100 to 300 y to 30 y have the potential to quickly shift some forest systems to grasslands and woodlands (Westerling and others 2011). Instead, we need to shift our focus to plant species adapted to the novel conditions and/or those anticipated to migrate into these areas. Implementation of complementary actions, such as ecosystem engineering (for example, using drastically disturbed areas as sites to test assisted migration), increasing landscape connectivity, emphasizing genetic diversity in seed source collections, targeting adaptive traits, and focusing on ecosystem function and resilience rather than a historical reference are also necessary considerations for any climate change strategy (Jones and Monaco 2009; Lawler and Olden 2011; Stanturf and others, in press).

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# Invasive Plants, Insects, and Diseases in the Forests of the Anthropocene

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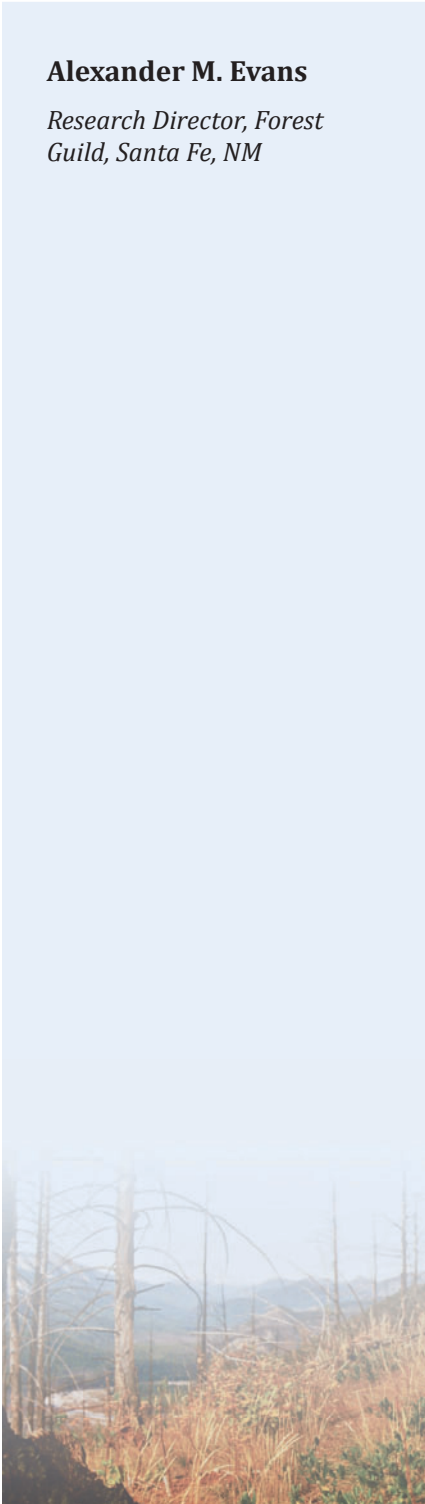
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***Abstract:** Invasive species, non-native plants, insects, and diseases can devastate forests. They outcompete native species, replace them in the ecosystem, and even drive keystone forest species to functional extinction. Invasives have negative effects on forest hydrology, carbon storage, and nutrient cycling. The damage caused by invasive species exacerbates the other forest stresses of the Anthropocene: increased human intrusion throughout natural landscapes, the fragmentation of forests, and a changing climate. Warming will open new areas for ecological invasion while the rising concentration of CO<sub>2</sub> (carbon dioxide) in the atmosphere gives many invasives an edge over native species. Storms and extreme climatic events are likely to become more frequent, and these events will facilitate the introduction and spread of invasive species. The cumulative effect of these stressors is impaired ecosystems that can no longer provide all the services on which humans rely. Because these changes are not possible without humans to facilitate the introduction and spread of new species, the impact of invasives is a defining element of the Anthropocene.*

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## INTRODUCTION

The unprecedented mixing of species from across continents and ecosystems is one of the profound changes of the Anthropocene. Species introduced into completely different ecosystems are freed from the constraints that limited their growth and expansion in their home systems (Phillips and others. 2010). For example, plants can escape the herbivores adapted to feed on them, insects can escape the pathogens that limited their population growth, and newly introduced species can find new opportunities such as hosts with little resistance to their attack (Liebhold and others. 1995). The combination of fewer constraints and new opportunities allow some introduced species to flourish in their new environments to the detriment of native species; in short, to become invasive species (Torchin and others. 2003). Executive Order 13112 (1999) defines invasive species as alien species whose introduction causes economic or environmental harm or harm to human health. In many cases, the introduction of species into new ecosystems is an unintended consequence of human movement and trade



(Bradley and others. 2011). Some invasives were introduced intentionally to bring useful plants and animals to new places for the benefit of humans (Reichard and White 2001). However, once introduced into a new ecosystem, invasive species are able to expand in that ecosystem without human assistance (e.g., Gibbs and Wainhouse 1986). As invasive species expand their range, they can create novel ecosystem interactions and unforeseen outcomes (Hobbs and others. 2006; Mascaro and others. 2011).

In addition to their ecological costs, exotic forest invaders have a large economic impact on both forest products and ecosystem services (Pimentel and others. 2005; Holmes and others. 2009). For instance, a mere three invasive insects cause approximately \$1.7 billion dollars in damages in the United States annually (Aukema and others. 2011). By one estimate, the United States spends about \$1.3 million dollars a year on surveillance to keep just one pest, the Asian gypsy moth (*Lymantria dispar*), from invading (Work and others. 2005).

The negative impact of invasive species is likely to expand during the Anthropocene. Their effect is exacerbated by the warming climate (Bradley and others. 2010), more frequent extreme climatic events (Diez and others. 2012), large and severe fires (Ziska and others. 2005), and forest fragmentation (Dewhurst and Lutscher 2009). Moreover, it is not just the invasive species already in our forests that will thrive as the climate changes as the introduction of new species is almost inevitable. As global trade continues to move vast cargos across the world, the chance of new introductions is high. Work and colleagues (2005) estimate that about seven species are introduced to the United States each year via refrigerated maritime cargo alone. Even native insects, plants, and diseases may act more like invasive species in the Anthropocene under new climate conditions (Weed and others. 2013).

Invasive species will help define the forests of the Anthropocene, hence it is vital to understand the types of invaders we face, their impacts, and how they interact in natural ecosystems. While all ecosystems have been altered by invasive species, this discussion is limited to plants, insects, and diseases affecting forested ecosystems. Though animals such as the brown tree snake (*Boiga irregularis*) or feral pigs (*Sus scrofa*) have detrimental impacts on forested ecosystems, they are excluded from this paper in an effort to limit an already expansive topic. For the same reason, this paper also excludes invasion of wetland and coastal communities. While all the examples and most of the research cited is drawn from the United States, the issue of invasives in the Anthropocene is, of course, international (e.g., Yan and others. 2001).

## OVERVIEW

### *Plants*

Humans are enthusiastic about importing new species of plants for economic benefit or aesthetic appeal, but these introductions frequently go wrong and result in exotic plants invading native forests (e.g., Forseth and Innis 2004). By one estimate, the horticultural trade is responsible for over 80 percent of invasive plants in the United States (Reichard and Hamilton 1997). Other common pathways include accidental introduction with crop seeds and purposeful introductions for soil erosion control (Reichard and White 2001). Many of the invasive plants in the United States are agricultural weeds; in other words, plants that interfere with crop production or grazing, but these are generally outside of the scope of this paper. Though the focus of this paper is

on forests, the list of invasive plants is still long. In the northern forests of the United States, the major invasive plants of concern include the following species among many others (Shifley and others. 2012):

- spotted knapweed (*Centaurea biebersteinii*),
- tree-of-heaven (*Ailanthus altissima*),
- Russian olive (*Elaeagnus angustifolia*),
- multiflora rose (*Rosa multiflora*),
- garlic mustard (*Alliaria petiolata*),
- Japanese knotweed (*Fallopia japonica*), and
- bush honeysuckle (*Lonicera* spp.).

In the forest of the Southeast, the list includes (Hanson and others 2010):

- mimosa trees (*Albizia julibrissin*),
- kudzu (*Pueraria lobata*),
- Asian bittersweet (*Celastrus orbiculatus*),
- cogon grass (*Imperata cylindrica*), and
- Japanese stiltgrass (*Microstegium vimineum*).

In western forests, invasive species of concern would include (Cal-IPC 2006; Gray and others 2011):

- cheat grass (*Bromus tectorum*),
- salt cedar (*Tamarix* spp.),
- toadflax (*Linaria* spp.),
- spotted knapweed (*Centaurea maculosa*),
- Scotch broom (*Cytisus scoparius*),
- leafy spurge (*Euphorbia esula*), and
- knapweeds (*Centaurea* spp.).

Unfortunately, these 19 species are just a small sample of all the invasive species in the United States Forests and readers are encouraged to refer to publications specific to each region or state to identify invasive plants (e.g., Olson and Cholewa 2009; Miller and others. 2010; Gray and others. 2011). Mapping from programs such as the Early Detection and Distribution Mapping System ([www.eddmaps.org/distribution/](http://www.eddmaps.org/distribution/)) shows that invasive plants cover the entire United States. Though not every forested acre has been invaded by non-native plants, at the county scale, invasive plants are ubiquitous in the coterminous United States. For example, a study of 24 northeastern and mid-western states found 66 percent of all plots had at least one invasive plant (Schulz and Gray 2013). Disturbed areas, particularly roadsides, accumulate invasive plants because many invasives are adept at colonizing open growing space (Aikio and others. 2012).

Invasive plants disturb ecosystems in a number of ways. Out of the 1,055 threatened plant species in the United States, about 57 percent are affected by invasive plants (though often in combination with other stressors) (Gurevitch and Padilla 2004). Invasive species outcompete and overwhelm native plant species. For example, kudzu covers some 7.4 million acres in the United States, where it shades out and crushes other plants (Forseth and Innis 2004). Similarly, stiltgrass outcompetes native plants, reduces herbaceous diversity, impedes native woody species regeneration, and creates extensive stiltgrass monocultures (Oswalt and others 2007; Adams and Engelhardt 2009). Invasive plants can disrupt plant reproductive mutualism such as pollination or seed dispersal, causing population reductions (Traveset and Richardson 2006). An example of a less visible influence of the presence of invasive plants is the allelopathic effect of tree-of-heaven, which has a detrimental impact on red oak regeneration (*Quercus rubra*), an important tree both economically and ecologically in the eastern United States (Gómez-Aparicio and Canham 2008). Another example is melaleuca (*Melaleuca quinquenervia*) which has converted wetlands to uplands through increased litter inputs over many years (Strayer and others 2006).

Invasive plants often negatively impact water quantity because they tend to grow fast and use more water than native species (Brauman and others 2007). Invasive plants alter, usually negatively, habitat for wildlife. Some reduction in habitat quality is to be expected where animals have adapted to a plant community that is subsequently disrupted by invasives. For example, birds that nest in honeysuckle and buckthorn (*Rhamnus cathartica*) experience higher predation rates than those that nest in native plants (Schmidt and Whelan 1999). Even when invasive species like buckthorn provide fruits for animals (birds in this case), these fruits are often less nutritious than those provided by the native species displaced by the invaders (Smith and others 2013). About 28 percent of birds listed as threatened are negatively affected by invasive plants (Gurevitch and Padilla 2004).

### **Insects**

There are some 455 invasive insects in U.S. forests, though only about 62 cause significant ecosystem damage (Aukema and others 2011). Of those insects that have a significant impact on forested ecosystems and feed on trees, about a third feed on sap, a quarter are wood borers, and the remainder feed on foliage (Aukema and others 2010). Over the last century, an average of about 2.5 non-native insects were detected in the United States per year (Aukema and others 2010) and Koch and colleagues (2011) predict new alien forest insect species establishments every 5–15 years in select urban areas. Not every foreign insect that establishes in the United States becomes a destructive invasive, but many have. Some of these insects, such as the gypsy moth, have been in this country for over a century, and many have spread through the entire range of their new hosts. Mapping tools such as the Alien Forest Pest Explorer ([www.nrs.fs.fed.us/tools/afpe/](http://www.nrs.fs.fed.us/tools/afpe/)) illustrate that at least one, but often many, invasive forest insects infest every forested region in the United States.

Many invasive insects are specialists that feed on, or live in, one particular tree or shrub species or genus. For instance, hemlock woolly adelgid (*Adelges tsugae*) feeds only on species of hemlock. Others, such as the gypsy moth, attack a broad range of tree species. The Northeast and Appalachian forests have a particularly high number of destructive insects, in part because of their proximity to busy eastern ports and in part because of the large number of tree species that

can support a large number of species-specific invaders (Liebhold and others 2013). In contrast, western interior forests have fewer different species of invasive insects (Liebhold and others 2013), perhaps because of their distance from ports of entry and because they have fewer species of trees and shrubs.

Insect populations often expand and collapse in response to environmental conditions. For native insects, populations can be very low and individuals difficult to find until conditions are right for an outbreak. The population then crashes due to declines in the host, lack of available food, climate shifts, predator response, or pathogens that spread easily at high population densities. Invasive species can build large, outbreak-type populations as they invade new areas because of the lack of constraints in the new environment. Because these are novel outbreaks, native trees are ill equipped to resist or recover from them. For example, populations of hemlock woolly adelgid can be very high once they have established in a new area, but even though adelgid populations decline as the health of hemlock trees decline, the outbreaks result in significant hemlock mortality (McClure 1991).

Polyphagous insects can cause a reduction in tree growth through massive defoliation, but species- or genus-specific invaders can also have disastrous impacts on forested ecosystems. By 2006, some 15 million ash trees had been killed by the Emerald ash borer (*Agrilus planipennis*) (Poland and McCullough 2006). This widespread mortality has cascading effects through the ecosystems with ash trees, including the loss of native insects (Gandhi and Herms 2010b). The death of hemlocks from hemlock woolly adelgid affects herbaceous plants (Eschtruth and others 2006), nutrient cycling (Cobb and others 2006), stream temperatures, fish communities (Ross and others 2003), bird diversity (Tingley and others 2002), and habitat for deer and other mammals (DeGraaf and others 1992). More generally, by removing important trees from U.S. forests, invasive insects have the potential to affect fundamental forest composition, structure, and function (Ellison and others 2005; Gandhi and Herms 2010a). The complexity of interdependencies within ecosystems makes it difficult to trace the full impact of invasive forest insects (Kenis and others 2009).

### **Diseases**

There are likely many more non-native disease-causing organisms in the United States than have been identified because they are often difficult to detect. As with non-native insects, those we are most aware of are those that cause serious damage. For example, an early introduction, chestnut blight (*Cryphonectria parasitica*), functionally removed American chestnut (*Castanea dentata*) from its ecological role as a dominant tree in eastern forests by the 1950s (Tindall and others 2004). Though the list of significant invasive forest diseases is shorter than that of insects, diseases cover most forested regions of the United States (Aukema and others 2010). Chestnut blight, Dutch elm disease (*Ophiostoma* spp.), and butternut canker (*Sirococcus clavignenti-juglandacearum*) cover the entire range of their host trees (Evans and Finkral 2010). Beech bark disease (*Ophiostoma* spp.) has spread through forests where beech trees (*Fagus americana*) are most dense (Morin and others 2007). Based on past spread rates, it is likely that other significant diseases including sudden oak death (*Phytophthora ramorum*), dogwood anthracnose (*Discula destructiva*), laurel wilt (*Raffaelea lauricola*), and phytophthora root rot (*Phytophthora cinnamomi*) will likewise expand to fill their ecological niche in the United States (Evans and Finkral 2010).

A lack of coevolution between host and pathogen can result in limited resistance in the host tree and excessive aggressiveness (i.e., greater host mortality) in the pathogen, which in turn causes disease outbreaks (Brasier 2001). For example, there is very limited genetic resistance of tanoaks (*Notholithocarpus densiflorus*) to sudden oak death (Hayden and others 2011). Because genetic resistance to invasive diseases may vary in a native tree population, identifying and protecting potential resistant individuals is an important management response (Schwandt and others 2010). Selection and breeding presents a possible route to increasing resistance to beech bark disease in American beech populations (Koch and others 2010). Diseases introduced to forests have removed dominant tree species, reduced diversity, altered disturbance regimes, and affected ecosystem function (Liebhold and others 1995, Mack and others 2000). The cascading effects of the removal of important trees species are similar to the effects of invasive insects and influence forest structure as well as the animals and plants connected to the diseased trees.

### **Synergies**

The previous sections discussed invasive plants, insects, and diseases separately, but of course they interact with each other and with other forest stressors. An invasion by one species can facilitate other invaders (Green and others 2011). For example, the tree-of-heaven's allelopathy facilitates the secondary invasion of another invasive plant, Fuller's teasel (*Dipsacus fullonum*), by suppressing native competitors (Small and others 2010). There are numerous examples of insect invaders facilitating invasion by plants. The emerald ash borer helps buckthorn and honeysuckle invade forests by opening the canopy (Hausman and others 2010). Japanese barberry (*Berberis thunbergii*), Asian bitter-sweet, and honeysuckle often invade forests after hemlock woolly adelgid has caused canopy mortality (Small and others 2005). Defoliation by gypsy moth helped tree-of-heaven spread through the forests of Pennsylvania (Kasson and others 2013). Though less well-documented, it is likely that invasive forest diseases have also facilitated the invasion of plants by creating canopy openings. Diseases also help insects by sapping tree defenses (e.g., Parker and others 2006). The synergy between invasives that aggravate the impact on native ecosystems has been labeled "invasional meltdown" (Simberloff and Von Holle 1999). Unfortunately, evidence is beginning to accumulate that this invasional meltdown is already occurring in some ecosystems (Simberloff 2006).

## **INVASIVES IN THE ANTHROPOCENE**

Humans are tightly linked with invasive species. They are a key factor in the introduction of invasive species as discussed above, but they are also a key factor in their spread. For example, the transportation of firewood has been identified as an important vector for invasive insects, particularly long-distance dispersal (Bigsby and others 2011; Koch and others 2012). Human development and infrastructure also help invasive species flourish. Many invasive plants such as Asian bitter-sweet and multiflora rose (*Rosa multiflora*) thrive in disturbed areas and the open edge habitat created by human development (Yates and others 2004; Kelly and others 2010). The trees of these disturbed, edge habitats may also be more stressed, and hence more susceptible to insects and diseases. For example, in one Ohio study, 84 percent of new emerald ash borer infestations were within 0.6 miles (1 km) of major highways (Prasad and others 2010). Even low-density residential areas are associated with a greater density of invasive plants (Gavier-Pizarro and others 2010). The effect of human land use on invasives lasts a long time, as demonstrated

by a study that links invasive plants in North Carolina with historic land use and reforestation (Kuhman and others 2010).

### **Human Development**

Human development is expanding in the Anthropocene and with it the opportunity for invasives expands as well. About one third of the coterminous United States was human-dominated in 2001, and an additional 35,600 square miles (92,200 km<sup>2</sup>, or roughly the size of Indiana) are likely to be converted from natural cover to development by 2030 (Theobald 2010). About 15 percent of the current acreage of southern forests could be converted to housing and other uses by 2040 (Hanson and others 2010). Although the long-term trend in the Northeast during the 20th century was one of increasing forest cover, this trend has recently reversed, and the total number of forested acres has started to decline again (Drummond and Loveland 2010). As much as 909,000 acres (368,000 hectares), or about two percent of forest land, could convert from forest to other land uses in Maine, New Hampshire, Vermont, and New York by 2050 (Sendak and others 2003). This growing human presence and increased fragmentation is a significant driver in the spread and domination of invasive species in U.S. forests (Lundgren and others 2004; Gavier-Pizarro and others 2010; Schulz and Gray 2013). An indirect effect of fragmentation and suburbanization is the population growth of animals that thrive in human environments. For instance, deer (*Odocoileus virginianus*) populations have grown significantly in many suburban/forest interface zones. The high deer populations help spread invasives and, at the same time, hamper the regeneration of native species (Evans 2008; Williams and others 2008).

### **Climate Change**

Not only is human development making the landscape more available to invasives, but in addition, human-driven changes to the climate benefit invasives. A warming climate opens new ecosystems to invaders previously limited by cold. Warming will facilitate the spread of invasive plants such as kudzu and privet (*Ligustrum sinense*) as far north as New England by 2100 (Jarnevich and Stohlgren 2009; Bradley and others 2010). In general, invasive plants have been far better able to respond to recent climate change in New England than native species (Willis and others 2010). Warming will also facilitate the spread of invasive insects such as hemlock woolly adelgid (Evans and Gregoire 2007). Two or three times more forest in Canada will be at risk from gypsy moth by 2060 because of a changing climate (Régnière and others 2009). Similarly, climate changes will modify forest pathogen dynamics and may exacerbate some disease problems (Sturrock and others 2011). For instance, sudden oak death has potential to expand its range under a warming climate (Venette and Cohen 2006). Increasing summer temperatures appear to exacerbate outbreaks of cytospora canker (*Valsa melanodiscus*) and mortality of alders (*Alnus incana*) in the Southern Rocky Mountains (Worrall and others 2010).

A changing climate means more than just warming temperatures. Other climate changes such as increased CO<sub>2</sub> (carbon dioxide) concentrations and more frequent and more powerful storms will benefit invasives. Rising CO<sub>2</sub> concentrations commonly give invaders an extra edge in competition with native species (Manea and Leishman 2011). For example, cheatgrass is able to take advantage of increased CO<sub>2</sub> concentrations by increasing productivity (Smith and others 2000). Higher CO<sub>2</sub> levels help kudzu and honeysuckle tolerate cold temperatures and hence expand these species' capacity for invading new forests (Sasek and Strain 1990). Extreme climatic



events are likely to increase as the climate changes, and these events will facilitate the introduction and spread of invasive species (Diez and others 2012). Hurricanes, ice storms, wind storms, droughts, and fire can all create forest disturbances that invasive species can capitalize on. Many invasive species grow rapidly and can take advantage of the increased sunlight in forest gaps faster than can native species. A study in Florida found that nearly 30 percent of the species regenerating after Hurricane Andrew were invasive and that invasive vines negatively affect the regeneration of native plants (Horvitz and others 1998). Similarly, tufted knotweed (*Polygonum caespitosum*) and mile-a-minute weed (*Persicaria perfoliata*) were able to expand after Hurricane Isabel hit Maryland (though garlic mustard decreased because of the increased light) (Snitzer and others 2005).

The warming and, in many regions, drying predicted for the United States will increase the area burned in the United States over the next century (Moritz and others 2012). These predictions match the trend from the last few decades of increased fire activity in the United States (Westerling and others 2006). Some invasive species contribute to the increase in fire activity. Cheatgrass provides surface fuel that spreads fire more frequently than before its invasion (Ziska and others 2005). Sudden oak death also encourages fire by killing trees and creating more heavy fuel (Valachovic and others 2011). This synergy between sudden oak death and fire has caused a fourfold increase in the mortality risk for redwood trees (*Sequoia sempervirens*) (Metz and others 2013). While many native species are adapted to fire, altered fire regimes (more frequent or more severe fires) can benefit invasives. Uncharacteristically severe fire kills dominant vegetation that would have survived more natural fire and can create growing space for invasives.

### ***Native species under new conditions***

In addition to the effects on invasives, climate change affects native species in unforeseen ways. With a changed climate, native species may be able to expand their range to new areas and may act like invaders in these new regions. Climate change has the potential to disrupt predator-prey relationships and permit outbreak conditions (Logan and others 2003). Temperature increases will shift native species ranges northward so new areas are affected, but at the same time, some previously affected areas may no longer be suitable for certain species (Ayres and Lombardero 2000). Warmer, drier conditions have helped drive insect outbreaks in the Southwest and Alaska (Logan and others 2003). Spruce budworm outbreaks in eastern Canada are predicted to be longer and more severe because of the changing climate (Gray 2008). Not only will mountain pine beetle be able to expand its range into much of the boreal forest, but it may be able to expand eastward by infesting jack pine (*Pinus banksiana*), a new host (Carroll and others 2006). Other previously obscure native insects such as the red oak borer (*Enaphalodes rufulus*) may become serious pests under new conditions (Riggins and Londo 2009).

## **HOPE FOR FORESTS IN THE ANTHROPOCENE**

Is there any hope for native forest ecosystems in the Anthropocene? For conservationists, ecologists, foresters, wildlife biologists, and all those who work in the woods, the answer must be yes. The first key element in any response to invasive species should be concerted effort to limit new introductions (Hayes and Ragenovich 2001; Lodge and others 2006). Increased surveillance at ports and other introduction pathways can limit the growth of the invasive problem. Improved early detection strategies directed at a quarter of U.S. agricultural and forest land would likely

be able to detect 70% of invaded counties (Colunga-Garcia and others 2010). If an invasive species avoid detection, a rapid response can help limit establishment (Anderson 2005). Similarly, policy or management actions that limit fragmentation and carbon emissions will reign in the negative interactions between invasives and these other forest stressors. There are steps that forest land owners and managers can take to increase ecosystem resistance to the effects of climate change and resilience to negative impacts of invasive pests and plants (Waring and O'Hara 2005). Eradication is impossible for many invasives and management should focus on those invasives that cause the most damage or those that can be effectively removed (Ellum 2009). A cornerstone of forest management in the face of the uncertainties of the Anthropocene is maintaining species diversity (Linder 2000). Maintaining or restoring species diversity on a site can increase the likelihood that some native species will flourish in this new epoch. Intact, diverse forest ecosystems may be more resistant to invasion (Jactel and others 2005; Huebner and Tobin 2006; Mandryk and Wein 2006). For example, the impact of sirenid wood wasp has been less dramatic in the diverse forests of the United States than in the single species plantations in the southern hemisphere (Dodds and others 2010).

Even in the Anthropocene invasives are not invincible. Much of their competitive advantage comes from escaping the predators, pests, and pathogens of their region of origin. When those predators, pests, and pathogens catch up with an invader in a new region, the invader is less able to cause unusual damage or disrupt ecosystems. For example, *Entomophaga maimaiga*, a fungus that attacks gypsy moth, appears to have begun to limit the extent and impact of outbreaks in the areas longest infested by gypsy moth (Andreadis and Weseloh 1990). Similarly, a leaf blight has been discovered on stiltgrass that can cause reduced seed production, wilting, and, in some cases, death of stiltgrass plants (Kleczewski and Flory 2010). In a third example, an insect pest that can significantly retard the growth of kudzu has recently been found in Georgia (Zhang and others 2012). Once predators, pests, and pathogens have caught up with a non-native species in its new region, the label 'invasive' may no longer be appropriate. As with biological control of invasive plants and insects, human intervention may be able to change the dynamics of some invasive pathogens. New transgenic techniques hold promise for engineering resistance into tree such as elm and chestnut to battle exotic diseases (Merkle and others 2007).

As climate change alters ecosystems, there is the possibility that new restoration opportunities may emerge. For example, canopy openings created by hurricanes and other storm events could provide ideal planting sites for the restoration of American chestnut (Rhoades and others 2009). In addition, climate change may render some areas unfavorable to invasives that previously seemed entrenched. Models suggest that cheatgrass will no longer be viable in some areas of the western United States as the climate warms (Bradley and Wilcove 2009). In these locations, cheatgrass could be replaced with native species. Managers should be ready to seize these novel restoration opportunities if and when they emerge during the Anthropocene.

Though it can be considered heresy, invasive species may not be all bad. Some can provide ecosystem services, while others might fill novel ecological niches created by climate change and inaccessible to native species. For example, invasive tamarisk provides habitat for the endangered willow fly catcher (*Empidonax traillii*) (Shafroth and others 2005). With the recent introduction of the tamarisk leaf beetle (*Diorhabda carinulata*), which reduces tamarisks competitive advantage (Pattison and others 2011), it is worth reconsidering tamarisk's potential positive role in riparian ecosystems. A study in Hawaii demonstrates that though invasives caused the decline of

native tree species, the new species were able to maintain some ecosystem functions (Mascaro and others 2011). While protecting against new invasives and fighting the spread of existing invasives are both important, it may be time to accept some non-native species.

Protecting refugia, such as parks and preserves, where threatened native species face fewer stressors may help those native species survive through the Anthropocene. Outside of parks and preserves, management that fosters diversity at both the stand and landscape scales can help minimize the threat of invasives. Managers must be ready to embrace any opportunities for proactive restoration that may emerge because of a warming climate, species shifts, or disturbances. For entrenched invasives, conservationists may have to move from denial to acceptance and adapt forest management to a new mix of species. Though invasives are a significant threat to forests in the Anthropocene, all is not lost.

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# Indigenous Experiences in the U.S. with Climate Change and Environmental Stewardship in the Anthropocene

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**Abstract:** *The recognition of climate change issues facing tribal communities and indigenous peoples in the United States is growing, and understanding its impacts is rooted in indigenous ethical perspectives and systems of ecological knowledge. This foundation presents a context and guide for contemporary indigenous approaches to address climate change impacts that are comprehensive and holistic. Tribal communities and indigenous peoples across the United States are re-envisioning the role of science in the Anthropocene; working to strengthen government-to-government relationships in climate change initiatives; and leading climate change research, mitigation and adaptation plans through indigenous ingenuity. Unique adaptive capacities of tribal communities stem from their ethics and knowledge, and help frame and guide successful adaptation. As documented in the Special Issue of the Climatic Change Journal on the impacts of climate change to U.S. indigenous communities (Maldonado and others 2013), these issues include the loss of traditional knowledge; impacts to forests, ecosystems, traditional foods, and water; thawing of Arctic sea ice and permafrost; and relocation of communities. This collaboration, by more than 50 authors from tribal communities, academia, government agencies, and NGOs, demonstrates the increasing awareness, interest, and need to understand the unique ways in which climate change will affect tribal cultures, lands, and traditional ways of life. Climate change is expected to affect animal and plant species that indigenous people depend on for their livelihoods, health and cultural practices. The impacts of climate change on forests and other ecosystems that are home to many of these species require tribal engagement in climate change research, assessments, and adaptation efforts. This paper synthesizes key issues and case studies related to climate change impacts on tribally valued forest resources and tribal adaptive responses to climate change.*

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## **INTRODUCTION**

The Anthropocene epoch is often defined as a time when the collective actions of humans have an unprecedented influence on natural systems. In the case of climate change, the Anthropocene is predicted to be a period characterized by environmental changes that are more

rapid and patterned differently than what human societies have experienced in the past (Kolbert 2010). In response to this prediction, it is important to try to anticipate how diverse societies in North America will uniquely experience the Anthropocene. Particular social, political, cultural, and economic circumstances define the unique vulnerabilities of different communities. Foresight of vulnerabilities can help communities develop local capacities for successful adaptation to climate change. A complete understanding of vulnerabilities and capacities can help land management and other agencies modify existing policies and create new policies more relevant to particular communities. In this paper, we focus on the vulnerabilities and capacities of tribal communities and indigenous peoples in the United States (and refer to tribes and indigenous peoples synonymously throughout the paper). Below we describe the context in which indigenous communities find themselves in a climate change era, provide an overview of the role of traditional knowledges in climate change initiatives, and expand on some of the ways indigenous vulnerabilities and strengths are being manifested in policy development and research. Later, we examine specific ways in which indigenous communities may be uniquely vulnerable to climate change impacts affecting the reciprocal relationship these communities have with the spiritual and living ecosystems of their region (in this case, forests). We follow this by assessing some of the unique sources of climate change resilience within tribes, particularly political and cultural capacities that may serve as catalysts for successful tribal climate change adaptation. In particular, we explore two examples of tribal adaptive capacity: the application of tribal practices and traditional knowledges into land management (Wabanaki), and the development of innovative collaborative relationships with state, federal and scientific entities (Pyramid Lake Paiute Tribe). We also assess the value of federal-tribal partnerships. We conclude by providing broad insights for federal land management agencies and other conservation professionals seeking to engage tribes in the development and implementation of resource management policies that are relevant to tribes in the Anthropocene.

## CONTEXT

The Intergovernmental Panel on Climate Change (IPCC), as well as the 3<sup>rd</sup> National Climate Assessment (forthcoming), recognizes present socio-political environment, high rates of unemployment and poverty, and disease and risks to public health are factors that make indigenous peoples of North America disproportionately vulnerable to climate change (Field and others 2007). For example, damage caused by extreme weather events forced communities in Alaska, including Shishmaref and Newtok, to consider relocation because the cost of road and building repairs overwhelmed the limited resources of tribal governments (Bronen 2011; Larsen and others 2008; Maldonado and others 2013; Shearer 2011). Perhaps equally significant is that indigenous peoples are spiritually and culturally invested in the Earth's freshwater, and terrestrial and marine resources and systems. As such, many tribal identities, values, and cultural traditions are embedded in the land, water, and air (Daigle and Putnam 2009; Lynn and others 2013; Voggeser and others 2013; Wildcat 2013). The cultural and subsistence relationships that indigenous peoples maintain with the Earth's resources and systems are defined by the traditions and beliefs practiced by indigenous peoples. For example, an indigenous community may use spiritual ceremonies, educational traditions, and coming of age rituals to ingrain practical knowledge and ethical principles about how to hunt in ways that do not exhaust species populations and ensure adequate food for individual community members (Reo and Whyte 2012).

Houser and others (2001) estimates 1.2 million (60 percent) U.S. tribal members live on or near reservations, and many pursue lifestyles with a mix of traditional subsistence activities and wage labor and have strong connections with freshwater, terrestrial, and marine resources and systems. Wild foods such as fiddleheads, berries, mushrooms, rice, deer, moose, elk, fish, and seafood provide not only subsistence, but also cultural connections through storytelling, harvesting, processing, and sharing of food resources. It is this strong and multifaceted dependence on natural resources and systems that makes indigenous populations particularly vulnerable to climate change (Daigle and Putnam 2009). Changes in the range and distribution of culturally significant plant and animal species will severely affect tribal cultures, economies, and resources for governance (Lynn and others 2013; Voggeser and others 2013).

In the United States and around the world, indigenous peoples are affected by more than just impacts to physical infrastructure and natural resources; at risk are cultural and traditional ways of life (Abate and Kronk 2013; Maldonado and others 2013). Climate change and the very idea of the Anthropocene epoch brings to mind large-scale human impacts on the Earth, specifically, increased greenhouse gas emissions to the atmosphere through industrialization and deforestation. These impacts result from activities that benefit those who view freshwater, terrestrial, and marine resources and systems as commodities for extraction and exhaustion to support energy-intensive middle and upper class lifestyles. In contrast, indigenous perspectives are often founded on a relationship of reciprocity—the relationship of mutual responsibilities shared between indigenous peoples and the living and spiritual inhabitants and systems of the Earth (Williams and Hardison 2013; Whyte 2013). Indigenous worldviews are predicated on being attentive to happenings over time in unique natural environments and acknowledging that humankind does not stand above or outside of Earth's life system (Wildcat 2009). That is, many cultures who see responsibilities that bind all living and spiritual beings also recognize a tremendous imperative to learn as much as possible about how one can exercise responsibilities toward these beings. Indigenous ethics of reciprocity entail systems of creating and maintaining useful knowledge of how humans can be good stewards of the Earth. Indigenous knowledge of stewardship interconnects ceremonies that express respect for species and promote conservation practices that ensure species' health and sustainability (Reo and Whyte 2012; Trosper 2009; Kimmerer 2000; McGregor 2012).

The IPCC Fourth Assessment Report (AR4) noted that indigenous knowledge is “an invaluable basis for developing adaptation and natural resource management strategies in response to environmental and other forms of change.” This was reaffirmed at the 32nd Session of the IPCC in 2010: “indigenous or traditional knowledge may prove useful for understanding the potential of certain adaptation strategies that are cost-effective, participatory and sustainable” (IPCC 2010). Additionally, in the last year, there has been an increasing realization that observations and assessments of indigenous peoples and marginalized populations provide valuable regional information, offer regional verification of global scientific models and satellite data sets, and provide the basis for successful adaptation and mitigation strategies (McLean and others 2011).

### ***Traditional Knowledges***

Traditional knowledges play an important role for many tribes in understanding how climate change impacts and adaptive strategies are affecting culturally important species.

“Climate impacts on tribal cultural resources will affect the formation and use of Traditional Ecological Knowledge (TEK). TEK, the indigenous way of understanding relationships among species, ecosystems, and ecological processes, can play a vital role in climate change assessment and adaptation efforts that bridge human and environmental systems” (Whyte 2013; Williams and Hardison 2013 in Voggeser and others 2013).

The role of and protections needed for traditional knowledges in climate change and environmental arenas are currently being explored at national and international levels. In this document, we refer to traditional knowledges (TKs), recognizing that other concepts, such as traditional ecological knowledge, native science, indigenous knowledge, and indigenous knowledge of the environment are commonly used in a diverse range of literatures and settings. Traditional knowledges offer a pathway for indigenous peoples to identify and interpret the potential impacts of climate change, as well as develop culturally relevant adaptation strategies. Riedlinger and Berkes (2001) describe five convergent areas that bring together TKs and western science, including local-scale expertise, climate history, research hypotheses, community adaptation, and community-based monitoring. Additionally, in the policy document *Weathering Uncertainty: Traditional Knowledge for Climate Change Assessment and Adaptation* (Nakashima and others 2012), Nakashima and others write that such “community-based and local knowledge may offer valuable insights into environmental change due to climate change, and complement broader-scale scientific research with local precision and nuance” (p. 6). While these TKs may offer understanding of impacts and solutions beyond indigenous communities, protections are needed to ensure that TKs are not misappropriated. International resolutions such as the United Nations Declaration of Rights of Indigenous Peoples and the Convention on Biological Diversity recognize the need for indigenous peoples and knowledge holders to give their Free, Prior and Informed Consent when sharing traditional knowledges in any manner (Williams and Hardison 2013).

Indigenous knowledge systems and ethical perspectives present a context and guide for contemporary indigenous approaches to address climate change (Williams and Hardison 2013). In this way, traditional knowledges represent opportunities to understand vulnerabilities indigenous peoples may face in the context of climate change, as well as adaptive strategies for addressing climate impacts. These indigenous approaches are making way for a comprehensive and holistic understanding of climate change impacts to indigenous peoples (Williams and Hardison 2013). Traditional knowledges and systems of reciprocity offer more than historical perspectives; they offer guidance on integrated and holistic approaches for use today and into the future. Based on this guidance, indigenous peoples across the United States are re-envisioning the role of science in the Anthropocene by strengthening their engagement in indigenous and non-indigenous climate change initiatives and playing leading roles in research, mitigation and adaptation plans through indigenous ingenuity (Wildcat 2013). Indigenous peoples, then, should be seen as having unique capacities, stemming from their ethics and knowledges that frame and guide their potential for successful adaptation in the Anthropocene.

### ***Policy and Research***

The vulnerabilities and adaptive capacities described above are playing a key role in policy development and policy-related literatures arising from native and non-native scientists, scholars, and environmental professionals (Maldonado and others 2013). In 2014, for the first time, the National

Climate Assessment report included a dedicated chapter on climate change impacts on tribal lands and resources, and documents many of the issues currently experienced by indigenous communities in the United States because of climate change (NCA, forthcoming). This report is required by Congress every four years as part of the Global Change Research Act of 1990 and serves to identify and communicate climate change science and impacts in the United States. Climate change impacts addressed in the tribal chapter include: loss of traditional knowledges; impacts to forests, ecosystems, water, and traditional foods; thawing of Arctic sea ice and permafrost; and relocation of indigenous villages and tribal communities (NCA, forthcoming). In light of understanding these diverse and numerous challenges, the tribal chapter of the National Climate Assessment (forthcoming) called for a more in-depth examination of indigenous climate change observations, experiences, and adaptive strategies around the United States. In response, nearly 50 authors representing indigenous and tribal communities, academia, government agencies, and NGOs in the United States wrote a Special Issue edition for the journal *Climatic Change*, “Climate Change and Indigenous Peoples in the United States: Impacts, Experiences and Actions” (Maldonado and others 2013). One particular article in this special issue edition of *Climatic Change* focuses on the impacts of climate change on tribally-valued forest resources (Voggesser and others 2013). This article will expand upon impacts to tribally-valued forests and will focus on the importance of understanding indigenous cultural values related to forests, and the potential for climate change to pose significant threats to those resources and values.

## **CLIMATE IMPACTS ON TRIBAL FOREST RESOURCES**

According to the 2013 Indian Forest Management Assessment (IFMAT), more than 18 million acres of tribal forests are held in trust by the United States (IFMAT 2013). Tribal access to forest resources are threatened by climate change impacts including increased frequency and intensity of wildfires, higher temperatures, extreme changes in ecosystem processes and forest conversion, and habitat degradation (NCA forthcoming, Voggesser and others 2013). Climate change impacts on tribally-valued forests will affect the composition and distribution of plant, animal, and fungi species that many tribes rely on for culture, economy, traditional foods, nutrition and health (Lynn and others 2013; Voggesser and others 2013). The shift in the range and extent of species, or changes to the timing of availability of cultural resources could result in reduced access to culturally-important species, and the subsequent loss of traditional knowledges (Swinomish 2010; Turner and Clifton 2007).

Climate change will continue to alter most U.S. fire regimes (Cohen and Miller 2001; Trostler and others 2012). Specifically, longer fire seasons and the damage caused by wildfires will affect not only particular species, but also the cultural uses and tribal traditions dependent on those species (Voggesser and others 2013). An example of climate impacts on specific species is in the West, where wildfires and drought changed and reduced forage for elk and deer, consequently impacting wild game that is critical for tribal livelihoods (DeVos Jr. and McKinney 2007). Traditional practices and TKs form the basis for tribal adaptation strategies to changing fire regimes. Traditionally, tribes used fire to increase the predictability of resources and ecosystem resilience, for crop management, basketry, range-browse improvement, communication/signaling, warfare, rituals, fireproofing valued resources, clearing travel routes, driving game/prey, clearing riparian areas, and increasing water yield (Stewart 2002; Voggesser and others 2013; Williams 2002). Cultural fire regimes based on TKs and traditional use of fire can serve

as a model for achieving ecosystem resilience and cultivating cultural resources (Voggesser and others 2013). Today, tribes use silvicultural treatments and fire to reduce potential losses from projected increases in climate-related wildfires (Rose 2010; Wotkyns 2013). And in some cases, tribes and federal agencies are working together to address a range of issues related to potential climate impacts to forests, including invasive species, wildfire, and other related threats (Voggesser and others 2013).

### **Case study: Climate-related impacts from invasive species and pests**

The relationship between invasive species and climate change is more and more important to understand as environmental changes create more suitable conditions for invasive species and will accelerate landscape-level change. Tribes may be forced to alter subsistence or ceremonial practices in response to the compounded stressors of climate change and invasive species (Voggesser and others 2013). Specific impacts involve the loss of traditional resources and changes in the geographical range of species. Invasive insects, pathogens and fungal diseases can kill trees valued for food or materials, and restructure the composition, structure and function of forests (Dukes and others 2009; Sturrock and others 2011).

Compounding climate change impacts to tribes are the multi-scale effects of invasive species as animal and plant pests, pathogens, and diseases directly affect subsistence and ceremonial practices, health and safety (Voggesser and others 2013). Sudden Oak Death, or SOD (*Phytophthora ramorum*), first detected in coastal northern California in the mid-1990s, is now threatening oak-dominated forest ecosystems (McPherson and others 2010; Valachovic and others 2011). As SOD spreads, it will diminish tribal opportunities for utilizing forest resources (Voggesser and others 2013). Many of the pathogen's hosts are trees or shrubs utilized by tribes for foods, materials, and medicines (Ortiz 2008). In the Midwest and eastern United States, the invasive emerald ash borer (EAB), which is a green beetle native to Asia and Eastern Russia, is creating landscape-level change and impacting cultural practices of indigenous peoples who use the black ash (*Fraxinus nigra*), a medium-sized deciduous tree. Figure 1 illustrates the Cooperative EAB Project and the initial county detections of EAB in North America as of February 2014. Despite aggressive eradication efforts, EAB, first discovered in Michigan in 2002, has spread to 20 states and two Canadian provinces, with a recent detection being last year (2013) in New Hampshire (USDA APHIS 2014).

For the Wabanaki nations of Maine (the Penobscot Indian Nation, Passamaquoddy Tribe-Pleasant Point, Passamaquoddy Tribe-Indian Township, Aroostook Band of Micmacs, and the Houlton Band of Maliseet Indians), black ash serves critical roles in the social, cultural and economic spheres of contemporary life. The cultural importance of black ash is reflected in Wabanaki origin stories, wherein Gluskabe, the Wabanaki trickster hero, shot an arrow into the basket tree (the black ash), giving rise to the people who came into the world singing and dancing. Given this context, there is no substitute for the *Fraxinus* or ash in Wabanaki culture. Moreover, baskets made of black ash are the oldest art form in New England and represent an original “green,” value-added, sustainable forest product. The loss of ash and the associated basketry tradition would have deep economic, cultural, and spiritual effects on tribes. Sales of ash basketry exceed \$150,000 each year and many tribal household incomes are partially dependent upon this resource (Daigle and Putnam 2009). More than 95 percent of tribal basketmakers in Maine live on or near reservations—many at or below the poverty level.

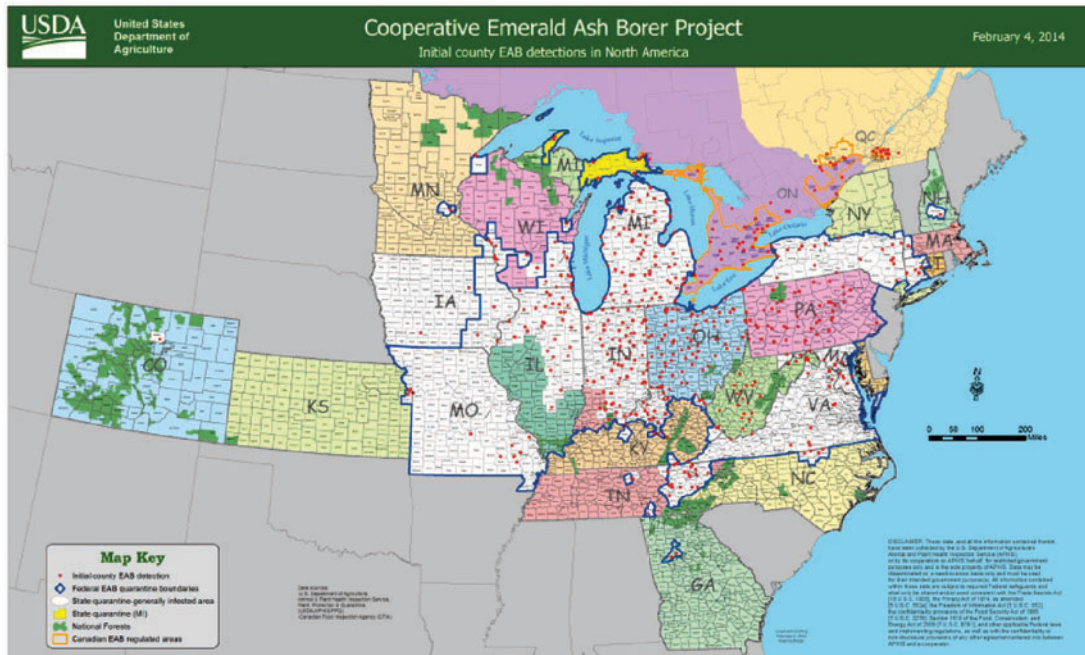


Figure 1. Cooperative Emerald Ash Borer Project

## TRIBAL ADAPTIVE STRATEGIES

### *Tribal Adaptation to Forest Changes and Wildfire Threats*

When indigenous peoples shape climate policies, foster strong economies, engage in sustainable development, and are part of natural resource management decisions, indigenous communities and livelihoods become more resilient (Daigle and Putnam 2009; Field and others 2007; Wildcat 2009). There have been increasing calls for tribes to be “at the table” as decisions are made about natural resource management, research design and implementation, and future policies (Galanda 2011; Grijalva 2011; Tsosie 1996). Indigenous peoples’ participation and involvement in research is extremely important when planning for invasive forest pests such as the Emerald Ash Borer (EAB) in Maine (Ranco and others 2012). Indigenous peoples are also focusing their efforts on bringing to light the climate change experiences of indigenous communities region-wide in North America and the Pacific Islands (First Stewards 2012). Collaboration between tribal and government entities with trust responsibilities, as well as collaborations between tribes and non-governmental entities, emerge as important themes. Strengthening mutual respect between traditional knowledge holders and western scientists, and developing a better understanding of the relationship between the two approaches can strengthen future natural resource management collaborations.

Recently, tribal initiatives and activities have increased to address climate impacts and large-scale environmental changes on forests through research collaborations, public awareness, information campaigns, and restoration projects, including forest management treatments, hazardous fuels reduction and prescribed burns (Mason and others 2012; Ranco and others 2012). For example, indigenous basketmakers and black ash harvesters in Maine are working collaboratively with university researchers, state and federal foresters, landowners, and others, to prevent, detect, and respond to the invasive EAB (Ranco and others 2012). This collaboration combines extensive



indigenous history, traditional knowledges that identifies quality grade “basket trees”, and geographic information systems (GIS), to initiate state-wide planning for protection and management of black ash resources.

Tribal governance and communication networks with tribal councils are being integrated in emergency response planning efforts in the event of an outbreak of EAB. Tribal natural resource agencies are initiating efforts to collect and preserve ash seeds, as well as record voice and field methods to identify high quality grade “basket-trees” to help retain traditional knowledges for future generations. These proactive initiatives are supplemented with coordinated information and education campaigns, such as national public television programming. These programs bring awareness of contemporary cultural traditions and highlight the importance of ash resources to Wabanaki tribes. These programs also raise awareness of other actions, including a law that prohibits the transportation of firewood into the state; firewood is a major contributor to the spread of EAB throughout the Midwest and Northeast United States.

### ***Federal-Tribal Partnerships***

Many of the efforts described above are accomplished through federal-tribal partnerships that provide tribes with an opportunity to engage in identifying resource management strategies to manage for and conserve culturally important species on and off-reservation. A strong government-to-government relationship must be in effect to ensure that consultation is occurring between the highest level of agency and tribal leadership so that tribal concerns and priorities are reflected in agency management plans (Harris 2011). Some policy and administrative mechanisms are in place to help achieve meaningful government-to-government relations, such as Executive Order 13175, November 6, 2000 (Consultation and Coordination With Indian Tribal Governments) and the Tribal Forest Protection Act, which, authorizes the Secretaries of Agriculture and Interior to give consideration to contracts or projects proposed by tribes on Forest Service or Bureau of Land Management (BLM) lands that border or are adjacent to Indian Trust Land (PL 108-278, 2004).

The importance of the federal-tribal relationship in addressing tribal access to forest resources is evident in the 15-year report evaluating the effectiveness of federal-tribal relationships under the Northwest Forest Plan, which adopts a coordinated management strategy to produce timber products while protecting and managing impacted species on lands administered by the BLM and Forest Service within the range of the Northern Spotted Owl (Harris 2011). The 15-year report suggests that Memorandums of Understanding (MOU) contribute to strengthening government-to-government relationships by defining federal trust responsibilities and establishing frameworks for how consultation (and collaboration) should occur (Harris 2011). A key finding from this report demonstrates that beyond just protocols for federal-tribal consultation, MOUs can be key components in effectuating strategies for communication, coordination, information sharing, and collaboration intended to meet the goals of protecting and restoring natural and cultural resources (Harris 2011).

The 2013 Indian Forest Management Assessment (IFMAT) also emphasizes the role of federal funding to support tribal climate change planning, assessment, and adaptation. The IFMAT report discusses climate change threats to tribal forests including wildfire, insects and diseases, among other issues. IFMAT policy recommends requiring “the allocation of federal agency funds for

climate change response and develop processes and criteria to assure a more equitable distribution of funding to tribes” (IFMAT 2013).

### **Case study: Pyramid Lake Paiute Tribe**

The case of the Pyramid Lake Paiute Tribe (PLPT), the largest tribe in Nevada, exemplifies tribal vulnerabilities as a result of climate change. Located in the Truckee River Basin, PLPT’s tensions regarding water rights are high, and climate change may upset the delicate balance between growing water demands of off-reservation users while simultaneously maintaining the health of a tribally-valued ecosystem of Pyramid Lake. PLPT is culturally and economically dependent on Pyramid Lake, which is located at the terminus of the Truckee River (Figure 2). The river begins at Lake Tahoe with headwaters in California’s Sierra Nevada Mountain Range and flows through the semi-arid Reno-Sparks metropolitan region before terminating at Pyramid Lake. Pyramid Lake is extremely important for biodiversity, sociocultural traditions, recreation-based revenue sources, the federally-listed endangered fish cui-ui (*Chasmistes cujus*) and the threatened fish Lahontan cut-throat trout (LCT; *Salmo clarkii henshawi*).

The Pyramid Lake Paiute Tribe’s name in Paiute is *Kooyooee Tukadu*, or cui-ui eaters, named after the Pyramid Lake sucker fish, which was one of their main food sources before its drastic decline in the early 1900’s due to upstream diversions at Derby Dam for irrigation, upstream water use, and drought. Culturally, the Paiute origin story is based on Pyramid Lake and its tufa-rock formation, called the Stone Mother that represents a woman with a basket whose tears created the lake (Wheeler 1987). Today, fishing and recreational activities are central to PLPT economy. Like many Native American tribes, PLPT is especially vulnerable (Smith and others 2001) to both climatic and non-climatic stressors because of their reliance on natural resources for spiritual and socio-cultural practices (Jostad and others 1996); dependence on local natural resources (Adger 2003; Thomas and Twyman 2005); and poor socio-economic conditions (Sarche and Spicer 2008). Besides technical western approaches, understanding PLPT’s vulnerability to climate change requires thoughtful consideration of values, history, and other local socio-economic and political contexts. Byg and Salick (2009) underline the importance of the local perception of climate change, impact assessment, and adaptation planning.

Socio-economic vulnerability factors of PLPT to climate change consider internal and external factors. Internal factors, like the local response capacity at the local scale include human capital (e.g., education and employment, climate change perceptions, institutional capacity, and technology), physical capital, economic resources and financial capital, social capital, and natural capital. External factors at the larger scale are linked to outside social, economic, legal, and environmental processes such as federal support and entitlement, power relations and legal stressors, and job opportunity and migration. The education and economic wellbeing of PLPT members is slightly better than the national average for Native Americans (from the U.S. Census 2010, 34 percent of PLPT members surveyed attained a 2 or 4 year college degree versus 23 percent of Native Americans), and PLPT’s degree attainment rate is close to the mainstream U.S. rate (38 percent). From a survey of 687 households on the PLPT reservation with a 16 percent response rate, about 80 percent of PLPT members were aware of climate change and observed changes in their environment (Gautam and others 2013). Uncommon among tribes, in 2007, PLPT received “Treatment in the Same Manner as a State” (TAS) status by the Environmental Protection Agency (EPA) to implement Water Quality Standards (WQS) and as a result, PLPT gained a seat at the decision-making



**Figure 2.** Truckee River Basin Showing Pyramid Lake Indian Reservation (Credit to Karl Musser)

table regarding impacts to the Truckee River and limiting pollutant discharge. PLPT is largely dependent on federal support, which is extremely limited and underfunded (e.g., Indian Health Service). For example, in 2010, only 0.007 percent of the funding that states received from U.S. Fish and Wildlife Service (FWS) was available competitively to 565 federally-recognized tribes. Federal projects are responsible for most of PLPT’s basic infrastructure. However, PLPT has a strong network of fish hatcheries to maintain cui-ui and LCT populations. There is a strong sense of individual tribal members desire to safeguard tribal interest and entitlement (e.g., 72 percent of surveyed tribal members vote in tribal elections). In addition, several active religious and social organizations show potential for emergency mobilization under extreme events or disasters. In addition to protecting the ecosystem of the lake, the natural capital of PLPT include groundwater and surface water, rangeland, wetlands, and agriculture which face concerns of decreasing water supplies, invasive species, and droughts.

While not specifically prepared for climate change impacts, within the past several years, there has been a strong willingness and common desire among PLPT tribal managers to include climate change in their respective programs. The prospects of geothermal and other solar energy projects on the reservation and, more importantly, potential use of the Truckee River Operating Agreement

(TROA) settlement fund for PLPT's economic development show some prospect for a diversified economy and may enhance the adaptive capacity to cope with climate change. Another positive factor demonstrating PLPT's adaptive capacity was the ability of PLPT to partner with universities, government agencies, non-profits, and other tribal nations and tribal consortiums to address climate change impacts. Native American reservations are nested within states and thus share and compete for natural resources with other resource users. While entitlement and access to resources can greatly determine the ability to adapt, there may be legal or institutional barriers that impede tribal entitlement and access to resources. PLPT went through a relentless legal battle for water rights for fisheries and succeeded through the listing of cui-ui as an endangered species in 1967 and LCT as a threatened species in 1975. Despite pressure for municipal and industrial needs in the Reno-Sparks area, Stampede Reservoir was designated as an upstream storage reservoir for the conservation of cui-ui and LCT. Recently, through the Preliminary Settlement Agreement of 1989 and Public Law 101-618, after the minimum in-stream flow in the Truckee River is maintained and all Orr Ditch Decree Rights are satisfied, then water can be stored in the Stampede Reservoir. This legislation also designates funds for PLPT to buy additional water rights, thereby enhancing tribal adaptive capacity. Reduced water supplies as a consequence of climate change would result in a compounded reduction of inflows to Pyramid Lake, thus potentially impacting the spawning and sustenance of a cultural livelihood, the cui-ui fish. Meanwhile, limited economic opportunities and dwindling federal support constrain tribal adaptive capacity. Factors that contribute to tribal adaptive capacity include: sustainability-based values, technical capacity for natural resource management, proactive initiatives for the control of invasive-species, strong external scientific networks, and remarkable tribal awareness of climate change.

PLPT faces multiple challenges for the protection of the quality and quantity of water reaching Pyramid Lake that is important to tribal values and economic activities and motivates PLPT to reach out to federal programs and science communities to build adaptive capacity. Gautam and others (2013) suggest multiple ways in which PLPT created collaborative partnerships with western scientists with whom some tribes have historically had tense relationships. Gautam and others (2013) emphasizes the importance of networks and indigenous rights frameworks like TAS. But a key lesson here is that programs like TAS are only effective if they are truly implemented such that tribes have the same opportunities as states. It is not sufficient for tribes simply to have the possibility of being treated like a state. There have to be sufficient options for gaining that authority and receiving funding that is appropriately equal to what states receive for setting up similar programs. As a growing amount of literature shows, knowledge networks like those highlighted by Gautam and others (2013) are crucial for climate change adaptation (Bidwell and others 2013). Guided by their culture and values, indigenous peoples are initiating knowledge networks with groups they previously have not worked with. They are also identifying challenges with federal programs that prevent tribes from having the flexibility and capacity needed for adaptation.

## **CONCLUSION**

The Anthropocene epoch is a historical period when large-scale human impacts, such as increased greenhouse gas emissions to the atmosphere through industrialization and deforestation, influence earth systems in major ways. Some scientific and policy circles anticipate climate change to rapidly change the environment in the next 100 years in ways to which human societies are unaccustomed. Many indigenous communities are already observing and adapting to such changes (Swinomish

2010; Wotkyns 2013). While these changes may present certain opportunities for some societies, indigenous peoples must prepare for how to absorb substantial economic costs, threats to cultural practices, and increased political pressures. From this perspective, we must explore what capacities need to be developed by indigenous peoples in order to best cope with a rapidly changing world.

The vulnerabilities and potential negative impacts of climate change on tribal forests, water, and other natural systems can be understood as both ecological and governance issues. They can be described as ecological issues in the sense that they involve environmental changes that have ramifications for the relationships between natural systems and human cultural systems. For example, invasive species in forests threaten the sustainability of intrinsically valuable relationships that tribal members have maintained with certain species since time immemorial.

At the same time, ecological issues are often deeply interwoven with governance issues, particularly when it comes to tribes. For example, the Pyramid Lake Paiute Tribe (PLPT) case emphasizes the importance of governance institutions such as rights to protect Pyramid Lake, treatment as state (TAS) status, and networks with nonindigenous partners. Institutions such as TAS status may be problematic if the structures are not equitable for tribes. Additionally, rights to protect the lake may not be enough to control the ecological conditions required for spawning of cui-ui under climate change impacts. In these cases, there are governance concerns regarding whether tribal political relations with federal, state, and local governments and agencies are adequate to give tribes the space to exercise their culturally-motivated adaptation strategies and to influence the strategies of their non-indigenous partners. When such relations are insufficient—whether due to inadequacies in funding, unclear policies, force of policy mandate, or inflexible implementation plans—the ecological issues compound and become substantial burdens on tribal communities. This highlights the need to strengthen governance institutions such as government-to-government relationships, tribal consultation, and networks with non-indigenous parties in order to improve tribal governance and maximize tribes' adaptive capacity.

In addition to strengthening governance institutions, we must also expand our understanding of indigenous governance to account for unique situations that may arise in the Anthropocene. Climate change will alter relationships between culturally significant species, natural systems, and practices, as well as the jurisdictions of tribal governance. For example, species moving off reservation or outside a treaty area challenge these jurisdictions. As is illustrated in the PLPT case, tribes may find that an effective way to deal with these problems is to develop networks with partners from a broader geographic scope and with whom they may have never worked before. Expanding how we understand indigenous governance will be necessary to account for situations in which historic jurisdictions do not afford tribes the abilities to exercise their capacities as stewards of their cultural landscapes. The MOU and collaborative arrangements described by Daigle and Putnam (2009) and Harris (2011) represent a strong step forward in this direction, as do the networks discussed in the PLPT case. While not compromising on the longstanding meaning of the government-to-government relationship, MOUs, collaborative arrangements and networks add the sensitivity and flexibility that are needed for tribes to address climate change more successfully. It is important to note, however, that there are also potential challenges in these new relationships and partnerships because the particular parties may have little experience working with indigenous peoples.

Another key insight in both of the presented cases is that tribal cultures, practices, and knowledges possess abundant adaptive capacity, an example of which is illustrated in indigenous uses of fire.

These are human systems that can generate adaptive strategies even in an Anthropocene epoch in which the environment differs significantly from that which supported the development of many indigenous cultures. In this article, we point to two different approaches by which tribes pursue adaptive strategies. In the first approach, tribal practices, such as burning practices derived from traditional knowledges, are appropriate practices in the Anthropocene and offer alternatives to non-tribal strategies developed in contexts that may be inapplicable to tribes and may not be trusted by tribal members. In the second approach, tribes, motivated by their culture and values, foster new and strong collaborative relationships with state, federal and scientific parties that aim to provide the capability and flexibility for adaptation. This second approach also involves tribes taking action to ensure that federal programs are accessible to tribes to meet the challenges of climate change, and draws from tribal experience with federal programs and working with federal agencies through a government-to-government relationship.

For land management agencies, these points should illustrate that in this Anthropocene epoch, it will be critical to tailor governance instruments, including policy, to facilitate and support rather than obstruct tribal capacities to pursue their own adaptive strategies in numerous ways. The above cases demonstrate that we must renew efforts to create robust governance structures suggested by tribes for many years now, such as the government-to-government relationship and treaties. These governance institutions must be re-envisioned, taking into account the challenges of the Anthropocene as seen from a tribal perspective.

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# Journeying into the Anthropocene— Scots Pine and Eastern Hemlock Over the Next 400 Years

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***Abstract:** Our native trees are much loved and valued components of our forests and fields, towns and cities. For a host of reasons—conservation, landscape, shade, and their sheer visual glory, we want our trees to grow big and old. But it takes time—often several centuries—from planting a tree to the desired outcome. This means that we need to choose trees today, which can grow successfully long into the Anthropocene era. In forest conservation, the standard view is that only locally native trees will deliver the objectives of conservation. The examples of Eastern Hemlock and Scots pine illustrate the challenge of the uncertain Anthropocene future—we cannot guarantee the long-term viability of these (or any) trees. Yet traditional forest conservation approaches do not offer any robust alternative to maintain the functions of those trees. If our aim is to pass on the benefits of big old hemlocks and pines to our descendants, we can no longer place all our eggs in one basket. A key way to reduce the risk of failure is to add diversity and redundancy—to grow a broader range of tree species including non-natives that have similar attributes.*

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## INTRODUCTION

On 20<sup>th</sup> April 2013, the Governor of Pennsylvania joined 150 volunteers on a cold, sunny Saturday to plant memorial trees at the Flight 93 National Memorial in Somerset County, Pennsylvania, USA. The first tree to be planted, laden with symbolism and garlanded with history, was a seedling grown from a parent tree living on the Gettysburg Battlefield. It is an Eastern Hemlock (*Tsuga canadensis*), the state tree of Pennsylvania. Earlier in 2013, in Edinburgh, a new ‘State tree’ was being proposed: the Scottish Parliament received a public petition asking that Scots pine (*Pinus sylvestris*) should become the National Tree of Scotland (Macnab 2012).

What links both these actions is a sense that trees can be monuments: predictable in growth, timeless and constant once mature, a well-designed structure reliably delivering the functions we require. Trees can remain relatively unchanged over the short arc of human lives (or attention spans)—our experience up to the beginning of this

century was that trees tended to be robust against natural stresses of weather, pests and diseases, with the example of Dutch Elm Disease (and in some places chestnut blight), being the only example in most people's experiences in either the eastern USA or the UK. As we've moved into a more unstable growing environment, the view of trees as robust, long-lived and highly predictable monuments is being increasingly challenged by the reality of unexpected tree health problems (Allen and others 2010; Anderegg and others 2013; Changhui and others 2011; Cullingham and others 2011; Mantgem and others 2009), and we are only at the beginning of a very long period of unpredictable change. The next few Anthropocene centuries are the future which today's tree seedlings will inhabit, and in choosing to grow long-lived trees in our conservation or multi-use forests, we are choosing paths forward into a wilderness of uncertain and unexpected combinations of opportunity and peril. Given that uncertainty, what trees should we grow?

Eastern hemlock in the eastern USA, and Scots pine in Scotland make good illustrations of the difficulties facing us—much loved native trees acting as the foundations of whole ecosystems, threatened by combinations of climate change and novel diseases, and yet valued for their long, long lives. They also make good examples of the way our feelings about our trees have lagged behind the understanding of threats and uncertainty about the future. It's hard to imagine that the Governor and his volunteers planted that memorial tree in the expectation that it will soon be infested with a non-native bug and either die, or survive only through an insecticide life-support recently banned across Europe. Equally, the petitioners at the Scottish Parliament had presumably not selected Scots pine as the national tree because it was showing a novel and worrying susceptibility to a needle fungus, with significant levels of infection in some places.

Designing our forests for their journeys into this uncertain Anthropocene wilderness requires some clear objectives. One approach to tree health and forest adaptation has focussed on preserving populations of tree species through spatial change, moving species or genotypes which are likely to decline to more suitable future destinations. This tactic has stimulated a vigorous debate over the value of assisted migration (AM) and its many synonyms (Hewitt and others 2011; Loss and others 2011). While such action may provide threatened tree species with a new home, we also value them for the functions they provide for us in their current location, including providing habitats for biodiversity as well as cultural, landscape, hydrological and carbon ecosystem functions. For example, an expansion of Scots pine within the boreal forest into higher Arctic latitudes in Norway and Finland (Reich and Oleksyn 2008) is not likely to be seen by Scots as adequate compensation for a decline of Scotland's Caledonian pinewood. Therefore, this paper focusses on how to sustain, in place, the forest functions likely to decline if Scots pine and eastern hemlock decline. This is not to downplay the importance of resolving other threats to these forest systems such as unsustainable logging, development or grazing, but these are comprehensively covered in other work, and are outside the scope of this paper.

### ***Scots pine in the Caledonian pinewoods of Scotland***

Scots pine (SP) has an enormous range, from Scotland and Portugal to Greece, Northern Finland, and eastern Siberia. In Scotland it is the primary and defining component of the Caledonian pinewoods, a western, oceanic outlier of the great boreal forests sprawling eastwards from Scandinavia. It is the only large native coniferous tree in Great Britain. SP in the Caledonian pinewoods faces a number of current problems. The overall area of ancient or old growth pinewood is only about 19000 ha (46,950 acres)—1percent of total woodland area, and is somewhat

fragmented (Patterson and others 2014). It has commonly undergone a long period without regeneration, leading to stands dominated by old trees without younger successors (Summers and others 2008). These structural problems have been recently joined by an unexpected increase in infection from *Dothistroma* needle blight (Brown 2012), possibly driven by weather impacts related to climate change (Watt and others 2009). This disease (aka Red Band needle blight) can progressively defoliate a range of pine species, weakening, and in some circumstances killing, SP and other pines in Scotland, especially Lodgepole (*Pinus contorta*) (Forestry Commission 2013). Looking to the future, the forecasts for climate impacts are restricted by the available modelling to the next 70-90 years, and predict a range impacts on SP from moderate (Ray 2008) to large (Reich and Oleksyn 2008). There are no forecasts available for future pest and pathogen impacts. Finally, any threats to SP carry serious consequences to the forest and its functions since it has no natural redundancy—there are no similar native species nearby that could significantly fulfil its functions. Furthermore, there is no possibility of natural range expansion by other similar species because of Britain’s island status.

### **Eastern Hemlock in Eastern USA**

Eastern Hemlock (EH) occupies about a million hectares in eastern North America, distributed in small groves and riparian strips within the generally broadleaved eastern forest, and as a larger component in New England. It has an important foundation role in the wider ecosystem (Ellison and others 2012) with trees living several centuries and when mature providing important functions including the support of stable streamflow in summer. Although it occurs in a more diverse forest than the Caledonian pinewood it has a unique set of characteristics which mean that there is no real redundancy within the system—no similar species can naturally expand to fill its role if it is lost.

Since the 1980s EH and the related Carolina Hemlock (*Tsuga caroliniana*) have been seriously affected by the Hemlock Woolly Adelgid (HWA), an insect accidentally imported from Japan. The HWA has rapidly moved through the southern part of the range, where it threatens the almost total loss of the hemlocks (Orwig and others 2002). Its northerly progress has been slowed, probably by winter temperatures, but the predicted warming trend in winter is likely to allow its further impact beyond Massachusetts over the next century (Orwig and others 2012). Even if HWA impacts can be controlled or somehow attenuate to allow EH to persist, its long-term future over the lifespan of today’s seedlings carries the same uncertainty as Scots pine—with forecasts of climate change impacts on eastern United States forests similarly limited to just the next 90 years or so (Rustad and others 2012).

## **CONSERVATION OBJECTIVES**

Timber production is generally dependent on younger trees, harvested in their adolescence or early middle age. For most other functions, especially biodiversity, trees become progressively more valued as they age, with big old trees living through their long natural lives seen as the most valuable of all. Studies also show humans just seem to like big old trees for their visual, landscape and recreational values (Donovan and others 2013; Edwards and others 2012; Gundersen and Frivold 2008; Ribe 1989). A recent analysis (Lutz and others 2012) produced a succinct summary:

*Large-diameter trees dominate the structure, dynamics, and function of many temperate and tropical forest ecosystems and are of considerable scientific and social interest... [and] continue to contribute disproportionately to forest ecosystem structure and function after they die.*

The functions and values we associate with Caledonian pinewoods and EH within the great eastern forests of North America fit within this general pattern. In the Caledonian forest, SP has a maximum lifespan of around 400 years (Fish and others 2010), with many biodiversity functions dependent on or more abundant in SP stands older than 100 years (Mason 2000) and in large deadwood that develops after mortality from 200 years onwards (Summers 2004). The role of EH in providing shade and reduced evapotranspiration to maintain stream flow and thus aquatic biodiversity and fish populations (Brantley and others 2013; Snyder and others 2002) is dependent on mature EH, as is the production of large dimension deadwood. An analysis from the northern end of its range in Ontario's Boreal-East Forest Region defined *Old Growth* status as having EH at least 180 years old, which are likely to endure for a further 500 years (Uhlir and others 2001).

So, some key functions of these native forests depend on big, old SP and EH. This generally becomes conservation objectives to follow the template of our inherited natural forests by protecting existing big old trees, and to meet our responsibilities to future generations by ensuring the future succession of SP and EH to great age and large sizes. We know little of the environmental conditions looking far into the future; given the vagueness of the few estimates of long-term multi-century climate change (Rogelj and others 2012) and the potential for novel pest or pathogen problems (Aukema and others 2011; Brasier 2008; Levine and D'Antonio 2003), we face considerable difficulties in assessing the viability of today's SP or EH seedlings over their desired lifespan.

Environmental changes have already begun and are causing widespread and significant health problems and mortality for many native trees, including the most valuable large old individuals (Lindenmayer and others 2014, 2012). Even if SP and EH overcome their current threats, we expect these trends to continue, and it seems likely that we will see further tree mortality and decline—indeed potentially on much larger scales as the departure from the 20<sup>th</sup> century baseline widens, and the cumulative environmental changes approach fundamental species or genotypic limits. A number of authors have pointed out that the effects of climate change on trees go beyond abiotic effects ('climate envelopes') to a range of inter-related biotic impacts (Lindner and others 2010; Sturrock and others 2011). For example, possible impacts of climate on insect pests of trees include changes in insect dispersal, development rates, voltinism, mortality, as well as changes in the resistance of trees through drought, waterlogging or storm stresses, and alterations in the palatability of leaves driven by changes in atmospheric CO<sub>2</sub> concentrations (Netherer and Schopf 2010). The impact of environmental changes on tree growth becomes essentially unknowable beyond the next few decades, because predictions of the drivers of change are too short or too vague—and unravelling the consequences of those changes is extraordinarily difficult. This leads to two troubling conclusions:

- We can neither guarantee nor predict the long-term viability of trees we start to grow today
- Conservation objectives that depend on the long-term viability of any single tree species run the risk of failure, particularly if the intended lifespan is long in relation to environmental change

### ***Delivering our conservation objectives—existing big old trees***

Maintaining our existing big old trees includes straightforward conservation tasks like preventing their intentional destruction, for example by avoiding large-scale felling. Reducing the threat from biotic and abiotic health issues could be helped by effective biosecurity and a significant reduction in the pace of greenhouse gas emissions, but these entail greater public motivation than simply forest conservation. For SP and EH, as for many other tree species, improvements in forest condition and the health and vigour of the trees is likely to help them resist damaging health impacts, or at least slow down the rate of spread or mortality. But the recent trends of tree health problems include primary pests and pathogens (including those currently affecting EH and SP) that can kill healthy trees. Faced with such antagonists, improving forest condition may do no more than delay the inevitable, and perhaps not even that. Finally, treatments such as pesticides or biological controls receive initially enthusiastic media coverage, but tend to be ineffective or too costly for forest-scale application (Orwig and others 2002), or are too much of a multi-year commitment to retain public support. Finally, even in the most hopeful scenarios, natural mortality will eventually take our existing big old trees, so sustaining the forest functions provided by these large trees requires us to choose their successors through planting or regeneration management.

### ***Delivering our conservation objectives—growing the future big old trees***

Since the early days of forest conservation the question of what trees should be grown generally meets the same answer—locally native genotypes and species, using the template derived from post-glacial or pre-settlement eras. In the Caledonian pinewoods for example, strenuous efforts have been made to ensure that only Scots pine of local origin is grown. In order to define ‘local’, 7 seed zones have been established across Northern Scotland (the smallest being only a few miles across), and only SP grown from seed collected within that zone should be planted there (Forestry Commission Scotland 2006). Such rules are designed to maintain the genetic and compositional status quo for a future of stable environmental conditions. Given we expect substantial, unpredictable and chaotic changes in the growing environment, it isn’t easy to make a new justification for this exclusive approach that explicitly incorporates the changes we foresee. So, what are the options for improving our chances of successfully passing on viable trees to become the big old trees for future generations?

Doing nothing is always an option. Beyond a simple panglossian view—‘it will probably all work out OK’—is a more thoughtful argument that we know that tree species decline and recover, and perhaps we should simply accept our current difficulties as cyclic processes. Both our example species have suffered substantial declines in prehistory, with EH declining precipitously 5000 years ago, probably through a pest or pathogen impact combined with changing climatic conditions (Foster and others 2006). The recovery to pre-decline levels, measured by pollen records, took some 1900 years (Allison and others 2013). SP experienced a significant decline around 4400 years ago, principally driven by a climate which became cooler and wetter, leading to the formation of extensive peat deposits (Bennett 1995), and has never recovered the lost ground. A wider perspective perhaps should consider that the vast majority of all species that ever lived are extinct, and an assumption of likely eventual recovery is little more than a guess. Even if recovery does occur, the species in decline will not be providing their forest functions for long periods—so long that they may be functionally lost in terms of human objectives. In forest

systems where the declining species have significant redundancy—where their functions can be delivered by other species that fill the vacated space—then perhaps a non-intervention approach has a stronger justification. However, for our examples that backup role is not available, because there are no species that can provide this redundancy—so any decline means their forest functions decline as well.

A variation on doing little requires the adoption of a luckily-timed and affordable future technological fix. This allows us to continue with the status quo (perhaps using short term or unsustainable measures to buy time), and rely on currently unavailable technologies that may allow us to protect our native forests. This might include defanging specific pests or pathogens, modifying the tolerances of individual trees, or reversing the momentum of climate change. But just as the continual postponement of nuclear fusion power shows the limits of technological promises, placing all our hopes on such a *deus ex machina* requires accepting the decline of tree species and their functions if the technological fix does not become available.

Numerous forest climate change adaptation strategies focus on actions that fit within conservation's native-ness and natural processes principles (Anonymous 2009; National Fish and Partnership 2012). These commonly include: improving forest condition by reducing stresses; encouraging range adjustments and the removal of migration barriers and forest fragmentation; and relying on future natural selection or tree breeding to produce trees successively well adapted to future environments. However, as noted in the section above, the current health problems of SP and EH are, like many other recent examples, caused by primary pests and pathogens capable of killing healthy trees. For this reason, improving the condition of our conservation forests cannot provide the basis of an effective strategy. In terms of range changes, the maximum natural rate of tree migration is too slow to track climate change (Aitken and others 2008), and for SP and EH there are in any case no candidates with similar functions which are near enough or without insurmountable barriers. Finally, a strategy based on growing successively different genotypes each adapted to the conditions of the time can only deliver big, old trees if the rate of environmental change is slow compared to the time required to grow such trees. Such a strategy is reasonable in timber plantations, where the trees are felled and replanted quickly (often <50 years)—but a poor strategy where we want to grow individual trees for 150-400 years.

### ***Sustaining forest function through adding diversity and redundancy***

The electricity supply for a major hospital is a perhaps a better model for the kind of resilience we need in our forests. Few such hospitals rely only on the external electricity supply. Instead, they will commonly have backup generation systems to maintain at least their key functions during a power outage. Such a backup system requires *diversity*—i.e., separate systems that can work independently, and *redundancy*—i.e., systems that provide at least the critical functions—i.e., continuing electrical power. For forests, a resilience strategy following this approach (formally 'robustness', see Morecroft and others 2012) aims to ensure the continuity of the ecosystem functions that depend on big old trees, by ensuring that sufficient big old trees are continuously present. It essentially pre-empts tree health crises by making changes now (i.e., developing backup systems) that reduce the future impacts of environmental stresses to acceptable levels.

Both our forest examples lack natural redundancy—they have functions that other nearby species cannot replicate. Even if they shrug off their current health issues they remain highly

vulnerable to future health threats over their long slow lives because they have no backup systems. Therefore any diversity added for resilience can only come as non-native genotypes and species. This approach thus becomes a direct challenge to the ubiquitous conservation view that promotes the exclusive use of locally native species.

A native tree in a natural forest is a package of functions and relationships that is unlikely to be replaceable as a single unit, and some of our forest functions may be exclusively reliant on a unique characteristic only found in a single tree species or genotype. But other functions we value depend on characteristics which can also be found in non-native species, suggesting that partial functional analogues can be found (Mascaro and others 2012; Schlaepfer and others 2011). For example, crested tits (*Parus cristatus*), naturally nest in cavities in larger SP—but will readily breed in nestboxes (Summers and others 1993), implying no strong obligate relationship to SP. Red squirrels (*Sciurus vulgaris*) in the Caledonian pinewoods will readily eat—and even thrive—on a wider range of conifer seeds (Bryce and others 2002) than just those of SP including Norway Spruce (*Picea abies*). In terms of the landscape and visual function of SP, the characteristic orange upper bark and growth habit has a striking similarity with that of Ponderosa pine (*Pinus ponderosa*). For EH, both Chinese hemlock (*Tsuga chinensis*) and hybrids between EH and Chinese hemlock have been seen positive early results in terms of growth and adelgid resistance (Evans 2012). Another candidate might be Norway spruce, planted and present in New England for many years and having some structural and shade qualities similar to EH.

A core part of forest research has been the exploration of the characteristics of different genotypes within tree species, and provenance trials (see Persson and Beuker 1997; Schmidting 1994) have been used to consider the impact of anticipated climate change on those genotype. In terms of the conservation concepts of native-ness, using a non-native genotype of a native tree is an unresolved issue—to do so might offer some adaptation benefits but at the cost of the likely permanent loss of local genotype through gene flow from the non-natives. Perhaps more importantly, using such trials to match species or genotypes to future projected climates requires both reasonably accurate knowledge of those future climates (which is, as previously noted, not available on the multi-century timescales needed for big old SP and EH) and an assumption that pests and pathogens will not intervene. A striking example of this issue was noted in (Aitken and others 2008), ‘...Lodgepole pine should be one of the species least affected by climate change. However, the recent climate-associated population explosion of the mountain pine beetle and the resulting decimation of vast tracts of Lodgepole pine forest...underscore the difficulty of predicting complex ecological interactions and the limitations of the models described herein.’

Finally, there may be a trade-off between redundancy and diversity: using non-native genotypes of native species is likely to provide very good redundancy, and can be used to anticipate some near-term climatic changes, but they may not provide effective diversity and share vulnerabilities with their native cousins.

The use of non-native species, genotypes, or novel hybrid constructs carries potential disadvantages and risks. Backup genotypes and species will inevitably take space from the natives. Any single such backup may not be viable in the longer term and fail to provide our desired functions—thus requiring multiple backup genotypes and species. They may deliver those functions less well than the natives, and introductions may carry some risk of invasive consequences or, more commonly, the simultaneous introduction of ‘passenger’ pests and pathogens (Ricciardi



and Simberloff 2009). While good research and carefully controlled actions should minimise unintended consequences, there are probably unavoidable costs—perhaps best considered in the same way as insurance premiums, or the cost of maintaining a backup generator system—i.e., the price of resilience. Also, to consider the risks and costs of a diversity/redundancy approach without including risks to the viability of native species is to make an unfair comparison. Over coming decades and centuries we expect rapid change which may eliminate or diminish native tree species, or uncouple their mutualistic relationships. The status quo is no longer likely to sustain the same conservation value as the ecosystem loses species, continuity and complexity or may only do so through repeated interventions which implicitly erode a claim to native or natural status. Essentially, the future may allow us no native or natural forest—our choice is whether we seek changes that help to sustain the functions we like—or to accept unpredictable changes that are less likely to include big old trees.

## CONCLUSION

This problem—selecting trees that will be viable through the unpredictable conditions of the next centuries—is as challenging as any conservation dilemma. The long development time of big old trees means we have to take decisions well before we can be certain of the nature and timing of any threats. Many of the proposed adaptation strategies carry significant risks, and no approach guarantees success.

We can and should use what we know—our understanding of trees and the factors that cause them to grow or die—to create a framework for our decisions. We can and should build in risk assessments and assumptions based on our experience and the predictions available. However, the complexity of forest ecosystems, and our difficulty in projecting knowledge forward by many decades or centuries suggests that this framework is inadequate for a mechanistic decision-making process. Our recent experience of ‘black swan’ type events (like the abrupt spread in 2009 of *Phytophthora ramorum* from *Rhododendron* species to Japanese larch (*Larix kaempferi*) (Brasier and Webber 2010) supports this view. Can we remedy the inadequacy of our knowledge and risk framework to the point where we can plant a long-lived tree with confidence? This is an important question worthy of deeper consideration, but it seems very challenging given the tree growth timescales involved, the long residence time of CO<sub>2</sub> in the atmosphere, the lag between changes in emissions and climatic effects and the influence of politics, trade and technology. When even the IPCC offers predictions on the basis of a series of very different climate scenarios, the chances of a clear understanding of the consequences to individual trees seem small. As an example of the difficulty, provenance trials have been very useful in illustrating the characteristics of different tree genotypes, and we should certainly use this in thinking about our choices. But without reliable information on climate, weather extremes or pests and pathogens occurring in (say) 100 years’ time, that genotypic knowledge is hard to apply with precision or certainty. A related issue to the difficulty of predicting tree viability centuries into the future is that any assessment of the reliability of such predictions is rather hard, and likely to offer a range of answers subject to differing assumptions used in the frameworks or models.

If we can’t rely on a knowledge and risk framework to give us unequivocal answers, then we have to supplement these with values and judgements of risk. A confidence in technological advancement might prompt leaving problems to some future technological fix, whilst a focus on today’s values of native-ness might regard future species losses and functional breakdowns as a

gamble worth taking. An expectation of damaging impacts of environmental change on native trees, or a view that we would have only a weak ability to predict the viability of tree genotypes more strongly suggests a diversity/redundancy approach—as a necessary backup for a system facing much uncertainty and an intolerance of functional breakdown.

Since all approaches carry uncertainty, and are influenced by individual values and judgements, we probably should not settle for *any* single approach. A reasonable set of approaches spread across our landscapes might include:

- a suite of reference native stands and forests, allowing species losses such as EH and SP to occur without excessive interference
- investing in modest assisted migration-style genotype movements within existing ranges, for example, perhaps making better use of the enormous natural range of SP
- native forests with varying proportions and numbers of additional non-native species, to provide backup diversity and redundancy

It also seems wise to continue development of better technologies to respond to tree diseases—especially ways to buy time to develop and implement responses.

Unless we can quickly improve our knowledge and risk framework (or develop a consensus on its limitations) we run a risk of an extended period of debate where fundamental uncertainties mean that no resolution is available, and no action is taken other than the status quo. The discussions over AM perhaps provide an example of this. Perhaps we can make faster progress by acknowledging that none of the perspectives or approaches are flawless—and seeking to match each approach to the different perceptions of decision-makers to create ‘coalitions of the willing’ to implement the range of actions described above across our forest landscapes. Within this uncertainty-driven approach there will be much work for researchers to populate and extend the framework of our understanding, and a need for an adaptive management approach incorporating regular review of our priorities and techniques. Maybe from this composite approach comes an energising sense that forest conservation can do more than despairingly watch the loss of our big old trees—that we have more options to deliver conservation objectives if we can re-define these more positively as sustaining forest functions rather than simply avoiding any non-native species.

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# Mitigating Anthropocene Influences in Forests in the United States

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***Abstract:** Anthropogenic and other climate changes, land use changes, forest structure changes, and introduced organisms are difficult to isolate with respect to their cumulative consequences. Similar changes have occurred before with undesirable effects and the currently high human population could suffer greatly if they happen again. Active forest management can help avoid dramatic, unfavorable changes. We can anticipate some effects from current geographic and weather patterns and forest ownership sizes, species compositions, and age class distributions. Less known are what foreign species might invade and cause trouble; how much forests will be converted to agriculture to replace the drying farm lands; and what wood demands, equipment, and incentives will be directed toward the forests. Many silvicultural activities can mitigate the undesirable effects of climate changes. The silvicultural expertise can be applied if the infrastructure of labor, equipment, and markets and the will of the people exist to support such activities with finances and legislation.*

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## THE ISSUES AND CONCERNS

Changes to forests during the Anthropocene are difficult to isolate between those generated by human-induced climate changes, land use changes, and movements of species. And, in fact, all three factors may be involved. It is also difficult to separate human-induced changes from those that would happen even if people never existed. Many of the dramatic changes today have been preceded by analogous events:

- About 30 species of large mammals became extinct in North America about 5 to 2 million years ago, destroying the “American Serengeti” presumably as a result of rapid climate change (Flannery 2001);
- Between about 10,000 and 6,000 years ago, species in North America moved northward roughly at a rate of 25 miles per century. A fir species separated into two genera—balsam fir (*Abies balsamea* (L.) Mill.) and Fraser fir (*Abies fraseri* (Pursh) Poir.)—as some individuals moved up the Smokey Mountains and others moved northward to Canada. Undoubtedly,



some species became extinct. And, others remained in topographically cool “refugia” far south of their contiguous ranges.

- Species have been moving to new continents for millions of years, with the raven family now occupying all continents (Flannery 2001), for example.
- Native species have created local epidemics, such as the pine butterfly (*Neophasia menapia* C. Felder & R. Felder) which killed old growth Ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) trees over 150,000 acres in eastern Washington in 1893-1895 (Scott 2012).
- Extreme hurricanes and ice storms have impacted many forests throughout the eastern United States for over 400 years (Oliver and Larson 1996).

People have also dramatically changed North America’s forests for several thousands of years. Many North American mammal species became extinct after people colonized America after the last glacial maximum—the saber-tooth cat, flat-nose bear, North American camel, and others. The eastern United States has undergone extensive forest clearing for agriculture before Europeans arrived, re-expansion of forests when the native populations declined, re-clearing when English colonists occupied the land, and re-expansion of forests in the 19<sup>th</sup> and 20<sup>th</sup> century as agriculture moved west (Mann 2005). Such land use changes also cause extinctions. These earlier changes indicate what can happen again. Even if future changes are no worse than previous ones, there is still reason for concern and for action to prevent further human hardship and loss of forest values. The values at risk referred to in this paper include the “Criteria of Sustainability” (Guldin 2008).

This paper will address ways of ensuring that forests of the contiguous United States continue to function and so provide the many values in light of recent and anticipated Anthropocene changes. Fire-prone forests of the interior western United States are also being addressed elsewhere in this general technical report. Vose and others (2012) have also addressed the United States forest changes in detail. The activities targeted to the forest are under the discipline of “silviculture.” However, silviculture can only be done in appropriate coordination with other disciplines. This paper will address:

- Anticipated changes in forest behavior with continued climate and other changes;
- Other human responses to climate change that may affect forests;
- Specific silvicultural activities that can be done to maintain forest values and functioning;
- The importance of other influences needed to ensure the success of silvicultural activities.

## **ANTICIPATED FOREST BEHAVIOR WITH CLIMATE CHANGE**

Based on the past climate warming of about 10,000 years ago, North American plant and animal species can be expected to move to cooler climates both to the north and at higher elevations as the climate warms. Previously, the species’ contiguous ranges moved northward at a rate of about 25 miles per century (Davis 1981) or to higher elevations at the same latitude at about 130 feet per century (Hopkins 1920).

At the same time, the world is already entering a period of drying at lower latitudes caused by more intensive equatorial sunlight, based on orbital patterns (Milankovitch Cycles; Pielou 1991)

and has caused the shrinking of forest areas and the change of the Sahara and Arabian grasslands to deserts during the past few thousand years. The earth is expected to re-enter a period of cooling at the poles caused by less intensive sunlight there sometime within the next few thousand years; and Pielou (1991) has suggested that polar species may already be migrating southward. At about the same time, we would ordinarily expect continental glaciers to form and expand over Canada and northern Europe, sea levels to recede, and a cooling of the earth including low latitudes. If/when this glacial expansion occurs, the world's forest and cropland area will shrink to a relatively narrow belt between cold polar temperatures and arid, cool equatorial climates.

It is uncertain if the recent climate changes are the beginning of this broader cycle. And, it is uncertain if the human-induced climate change will prevent the continental glaciers from forming. This paper will consider the northward migration of species in the United States, but not consider the southerly migration of species in Canada—or the overall southerly migration of species if the continental glaciers begin to form. It will be important to monitor the possibility that such changes could occur.

Plant species do not migrate as communities. That is, species found together as a community at one latitude now were probably not together at a lower latitude when the climate was cooler and will probably not be together at a higher latitude in the future (Davis 1981). Instead, a plant community is simply an assemblage of plants that are migrating from and toward different places, but happen to be in the same location when observed. Plant species migrate simply by individual seeds becoming established and outcompeting other species at a given time and place. Plant movement occurs



**Figure 1.** The unusual mixture of Douglas-firs (*Pseudotsuga menziesii* [Mirb.] Franco), mountain hemlocks (*Tsuga mertensiana* [Bong.] Carriere), and Pacific silver firs (*Abies amabilis* [Douglas ex Loudon] Douglas ex Forbes) growing together at 3,000 feet elevation in the North Cascades of Washington is a result of the different climates when each species became established (from Oliver and others 1985). 1) Foreground Pacific silver fir, 5 ft tall, 110 years old became established at a slightly cooler climate than present. 2) Tree to right of center is mountain hemlock (growing about 1000 ft lower than it usually germinates at present) about 200 years old (established during Little Ice Age). 3) Large Douglas-fir person is leaning on typically becomes established about 1000 feet lower at present and is about 800 years old, established during the Medieval Warming period. (Photo credit. C. Oliver)

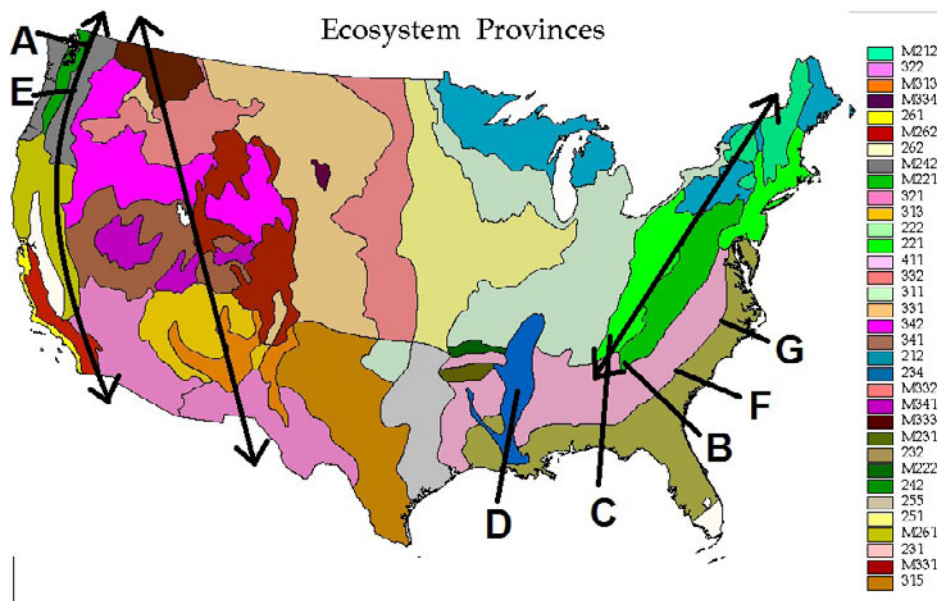


primarily after a disturbance, when growing space is available for the plant to become established in the new location. Plant survival during germination and initial growth seems quite sensitive to climate; and, long-lived trees that begin growing under one climate can survive in the same place even after the climate has changed. Many tree species may actually be living in places where they can no longer become established (Brubaker 1986; Figure 1).

Species can become established on favorable slopes—sunny slopes in the cool, northern end of the range and shady, north slopes in the southern end. Species also become established at slightly higher and lower elevations in response to climate changes. The opportunistic nature of plant establishment and migration means a species' range may fragment if some individuals move to higher elevations, others move northward, and some remain as isolated “refugia” on favorable microsites. These fragmented habitats can lead to the isolated groups evolving along such different trajectories that they become different species—the “species pump” concept (Huston 1994).

The current warming of climates tends to force species northwards, especially on gentle terrain and where mountain ranges lie north-south (Figure 2), as in much of North America (Flannery 2001). Here, the species can easily migrate to more amenable locations slightly to the north. Other factors tend to keep species positions more stationary (Figure 2). A mountain range can keep a species nearly stationary as it moves slightly uphill to re-establish in a cooler climate (with 400 feet elevation having a similar climate change to 70 miles of latitude; Hopkins 1920). Some species that move up mountains to cooler climates may eventually become isolated in “Sky Islands” similar to those in the Southwestern United States (Warshall 1995) and possibly in the Smokey Mountains; and, species may be eliminated if the mountain is not tall enough to provide suitably cool climates.

The generally North-South mountain orientation in the United States allows species to move latitudinally quite readily with climate change; however, steep east-west valleys along the Pacific Coast have prevented—and may continue to prevent—species migrations northward (A, Figure 2). The



**Figure 2.** Features affecting species movement and stability in the contiguous United States, overlain on Bailey’s Ecosystem Provinces (Bailey 1995). (Letters refer to discussions in text. Arrows show north-south orientations of mountains.)

east-west valleys of the Pacific Coast may explain the region being a “biodiversity hotspot” (Myers 2000) with global concern over the extirpation of species.

Mountain ranges also affect rainfall patterns, cold periods, and ice storms. The orographic precipitation belt at the southeastern base of the Smokey Mountains (B, Figure 2) will probably not move with climate change. And freezing rain storms will probably continue at the Cumberland Plateau (C, Figure 2). Similarly, the Mississippi River and its floodplains may continue to be a barrier to the east-west migration of species (D, Figure 2). And, the crest of the Cascade and Sierra Ranges (E, Figure 2) will probably continue to create a division between humid ecosystems to the west and arid ecosystems to the east.

On the other hand, the freezing rain belt that limits slash pine’s (*Pinus elliottii* Engelm.) northern range in southern South Carolina (F, Figure 2) may move northward (Baldwin, 1973). The sandy soils (Sand Hills) of the upper coastal plain (G, Figure 2) in the southeastern United States will not move, and so longleaf pines (*Pinus palustris* Mill.), scrub oaks, and other species well adapted to those soils will probably not move northwestward into the adjacent, clay soils; however, species may move farther north within the Sand Hills. Similarly, species adapted to floodplains may move northward within floodplains, but not move to other soil types very much.

The above description suggests that some species changes can be anticipated; however, it is impossible to predict all changes—especially behaviors of insect and disease pests such as the pine butterfly-bark beetle outbreaks in the Pacific Northwest (Scott 2012), or the native bark beetle outbreaks with warming climate in central British Columbia (Astrup and others 2008).

Ideally, we would monitor the forests and facilitate the migration of each species to more suitable areas; however, the overwhelming numbers of species would make such an endeavor impossible. Alternatively, we can focus on the viability of all ecosystems—the “coarse filter” approach to biodiversity conservation (The Nature Conservancy 1982)—recognizing that they will reorganize with different component species in the future. As they reorganize we can reclassify the ecosystems and concentrate on maintaining their viability. If all current and future ecosystems are viable, it is highly likely that most species will also be viable, although differently arranged. We can also monitor a subset of key species of trees, herbaceous plants, and animals to ensure they are thriving—the “fine filter” approach to biodiversity conservation (The Nature Conservancy 1982).

## **NON-FORESTRY POSSIBLE HUMAN INFLUENCES**

A concern is that a unique ecosystem may become extremely small, resulting in component species become exterminated by chance local events. On a coarse scale, this concern is probably not substantive in the eastern United States. Most ecological provinces in the eastern United States contain over 50% of their areas in forests (Bailey 1995; Figure 3 and Table 1); consequently, much of the issue will be ensuring the forests are in appropriate condition, rather than creating forests. Exceptions are the Eastern Broadleaf Continental Forest and the Lower Mississippi Riverine Forest, both of which have been extensively cleared for agriculture; and the Everglades, which may always have had lesser amounts of forests. The Lower Mississippi Riverine Forest province is of special concern because it is a small area to begin with; and the Ozark Broadleaf Forest-Meadow and Ouachita Mixed Forest-Meadow provinces are also small and, although currently forested, will need attention to avoid their extirpation of species. The Everglades is already receiving attention,

**Table 1.** Ecosystem province names and abbreviations used in Figure 3 (Bailey 1980).

<b>Ecosystem province name</b>	<b>Abbreviation</b>
Laurentian Mixed Forest Province	212
Adirondack-New England Mixed Forest—Coniferous Forest—Alpine Meadow Province	M212
Eastern Broadleaf Forest (Oceanic) Province	221
Central Appalachian Broadleaf Forest—Coniferous Forest—Meadow Province	M221
Eastern Broadleaf Forest (Continental) Province	222
Ozark Broadleaf Forest—Meadow Province	M222
Southeastern Mixed Forest Province	231
Ouachita Mixed Forest—Meadow Province	M231
Outer Coastal Plain Mixed Forest Province	232
Lower Mississippi Riverine Forest Province	234
Everglades Province	411

and the Eastern Broadleaf Continental Forest and the Lower Mississippi Riverine Forest provinces may be difficult to address because increasing the forests here will shift agriculture to larger areas of less productive soils.

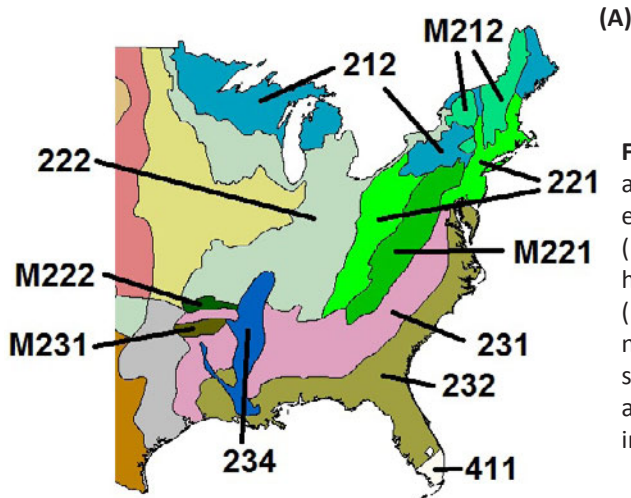
Extensive clearing of some eastern forests for agriculture could occur if the Ogallala aquifer providing irrigation for the “farm belt” in the Great Plains dries up with climate change. Irrigation and modern farming techniques could make eastern forests productive for agriculture, but would create problems maintaining extensive forests and their values.

The eastern forests are already fragmented with highways, cities, and farmlands that make migration difficult for plant and animal species. Such issues as connectivity to allow migration with climate change will need to be addressed (Redondo-Brenes 2007).

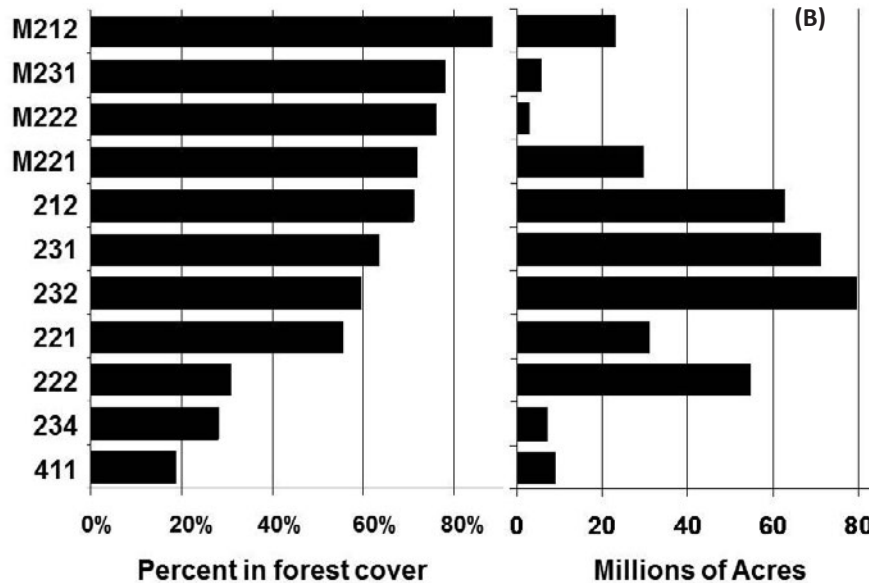
Some introduced species become benign parts of the ecosystem, while others are more harmful because they eliminate some native charismatic tree species and restrict the ranges of others. Problems with these harmful introduced species is increasingly creating problems both in the United States and abroad as increased global trade is moving more predators to locations where the hosts are not resistant. As the number of tree species in an area declines, the food diversity of animals also declines. It is uncertain if the overall behaviors of these introduced species will create different kinds of problems as the climate changes. Native species may also exhibit different behaviors with a changed climate (Warren and Bradford 2014; Urban and others 2012), and currently benign species may aggressively displace their long-time neighbors.

## **SILVICULTURAL ACTIVITIES TO MAINTAIN FOREST VALUES**

Two features of the forest are highly important to monitoring, sustaining, and possibly facilitating migration of species: current and future condition of the forest and our ability to manipulate the forest. Figure 4 shows the recent age class and diameter distributions of the U.S. forests in different regions (Smith and others 2009). Figure 4 also shows the mean global temperature when each age class became established (Soon 2005). To the extent that species are most compatible with their climate at the time they initiate as discussed earlier, Figure 4 shows which age classes—and

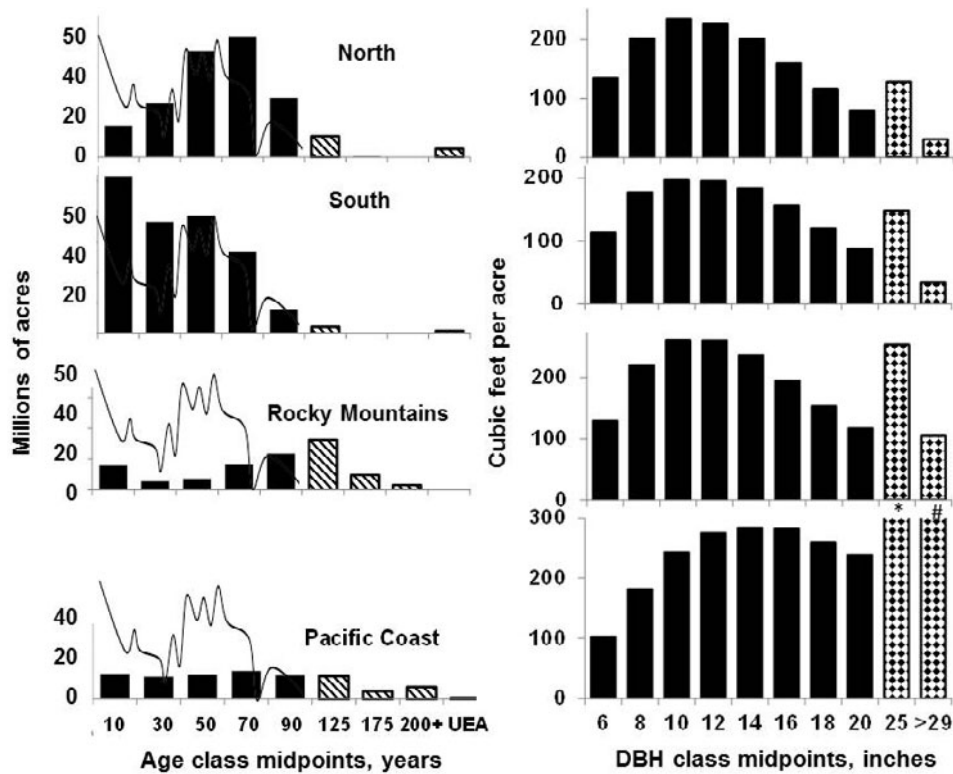


**Figure 3.** Locations (A) of ecosystem provinces and forest proportions and areas (B) within each province in the eastern United States (Bailey 1983, 1995). Only a few ecosystems have small proportions or areas of forests. (Unlike eastern forests, western forests are not continuous, but are mixed with natural shrublands, grasslands, deserts, and alpine areas.) (See Table 1 for key to letters/numbers in Figure 3.)



which proportions of each region’s forest—are living in compatible and incompatible climates. The 40-to-80 year age classes became established during the warm period in the first half of the 20<sup>th</sup> century when the climate was somewhat similar to present; consequently, plants in these forests may survive well in the warming climate. Forests less than 40 years old and over 80 years may be more vulnerable to the warming climate because these forests became established when the climate was cooler. Consequently, much of the western forests are growing in climates much warmer than they began in, and so may not be physiologically well adapted. Older forests in the North also may be out of synchrony with their climate, but nearly all forests in the South, being young, began in warm climates similar to the present and anticipated future.

The forests in each region will probably be most resilient to loss of functioning with climate change if they are maintained in a diversity of stand structures (Oliver and Larson 1996; Figure 5). Since each structure supports many, different species (Oliver and O’Hara 2004), the diversity means that large, uniform populations of native hosts or pests are less likely to develop. The variety of structures also makes the forests less susceptible to catastrophic fires and more suitable for water

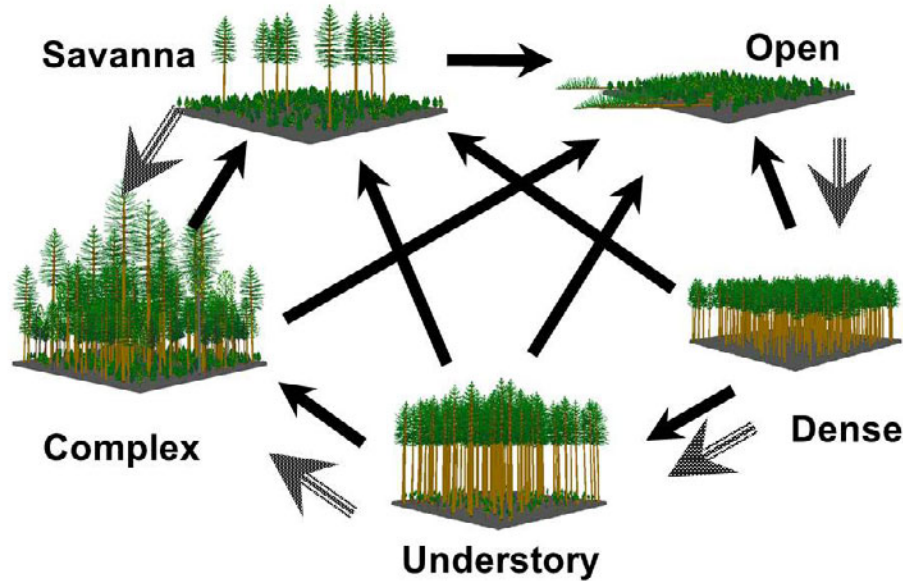


**Figure 4.** Distributions of forest age and diameter classes in the four major forest regions of the contiguous United States (Smith and others 2009). Line graph (Soon 2005) superimposed on age classes shows relative temperature compared to present (far left) when each age class initiated. (“UEA = uneven-age; “\*” and “#” indicate even higher volumes than shown.)

infiltration. Open and savanna structures evapotranspire less water than the other structures that have more leaf area; consequently, more water flows through the soil to aquifers or streams. And, the constant need for “open” and “savanna” structures gives opportunities for available growing space where species can become established and thus migrate to more suitable climates.

Each structure also will have issues that will need silvicultural attention with climate change. The older, understory and complex forests may contain trees that are physiologically weakened by the warmer climate and/or susceptible to associated storm or other weather patterns. On the other hand, these forests are needed by some animals and plants. And, these structures take a long time to replace. It may be appropriate to focus especially on protecting those old forests in cool and moist topographic positions. And, it may be appropriate to remove old forests where their demise may provide a human hazard, such as alongside roads where wind and ice storms can destroy power lines and block roads. It may be appropriate to begin planning areas of future old forests within the cooler parts of the current tree ranges, as permanent “reserves” while the younger forests are managed to respond to climate change (Seymour and Hunter 1999). This planning may give an opportunity to promote understory and complex forests in the Southeast, where relatively few of them currently exist.

All regions contain many crowded stands of small diameter trees in the dense structure (Figure 4; see also Oliver 2002). These crowded stands pose problems of insect and disease infestations and



**Figure 5.** Forests naturally contain stands in a variety of structures that change with growth and disturbances. Each structure provides habitat for some species, so a forest maintains the most diversity—as well as being resilient to catastrophic disturbances and climate change—if all structures are maintained (Oliver and Larson 1996).

subsequent fires, especially in conifer stands. Monitoring and thinning these stands can maintain these stands and avoid the catastrophes.

The savanna and open structures are among the structures that contain the most species (Oliver and O’Hara 2004). Both structures are generally needed for the complete suite of species because some species utilize the large savanna trees and others avoid them. Creating these two structures allows tree and other plant species to invade or be introduced that are suitable for the climate, and so assists in migration. On the other hand, these structures also allow unwanted, introduced and native plants to become established, and so care is needed.

Special measures, such as “assisted migration” of plants to allow them to cross the east-west valleys of the Pacific Coast, may be called for in some areas. Such measures need to be taken with caution and monitoring since the species may not survive or, conversely, become an aggressive pest outside of its current range.

The silvicultural knowledge and techniques exist to manage the forests in ways that maintain its many values during the Anthropocene changes. Silviculture has changed from identifying a single “system” for managing each species and community. It now considers that each stand can develop naturally through any of a large number of possible “pathways” that are the result of both growth and disturbances (Botkin 1991; Oliver and O’Hara 2004). A stand’s pathway can be directed by using silvicultural operations that avoid and/or mimic disturbances and regeneration at key times to provide targeted structures and values at later key times. Silviculturalists can mix the many pathways of different stands within a landscape to ensure a diversity of structures and values are continuously provided. Individual structures can be placed and moved on a landscape so they are least susceptible to unwanted disturbances or

pests. In the process of implementing the diversity of pathways, various species and species combinations can be regenerated in favorable habitats. In addition, various “protected areas” can be designated not only for endangered species but also for aesthetic (e.g., the “golden spruce”; Vaillant 2005) or scientifically unique species or as parts of corridors that allow species to migrate. Such corridors can be created in managed forests and other landscape features (Redondo-Brenes 2007).

A major issue will continue to be introduced species, especially insect and disease pests (Zavaleta and others 2001). We have seen elimination of the American chestnut (*Castanea dentata* [Marshall] Borkh.) and possibly its return, as will be discussed later. Now, we are seeing the possible elimination of the Carolina hemlock (*Tsuga caroliniana* Engelm.), American ash (*Fraxinus americana* L.), and sugar maple (*Acer saccharum* Marshall). For those pests currently in the United States, we are already undertaking a mixture of quarantining them, developing resistant trees, and introducing analogous species (Oliver 2014). Once developed, resistant and analogous species still need to be reintroduced into the forests, which would be done in the savanna and open structures.

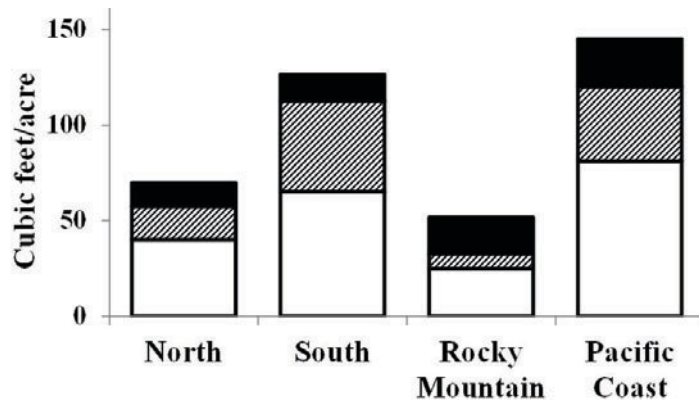
## **OTHER INFLUENCES TO ENSURE SUCCESSFUL SILVICULTURAL ACTIVITIES**

### ***The Need for a Forest Infrastructure***

All of the silvicultural knowledge and technology to avoid catastrophic forest problems associated with climate change are insufficient without the financial backing and an infrastructure of appropriate labor and equipment to do the needed operations. And, markets for the wood removed are needed to keep the operations from becoming prohibitively expensive.

Currently, there is a shortage of labor and forest management equipment (Knight 2013) in much of the United States. And, there is little incentive to invest in such equipment because very much more wood is growing than is being utilized in the United States (Figure 6)—and in the rest of the world (Oliver and others 2014). Consequently, wood is a “buyer’s market,” and most stands are not being treated. In addition, much of the present orientation of forest operators is toward equipment that is too large to do the needed operations such as removing small trees in thinnings or operating on small forest tracts (Cushing and Straka 2011).

The infrastructure could be developed by a concerted effort to harvest and utilize more wood sustainably for wood construction, with the residues used for wood energy. Such greater wood use would also reduce the world’s CO<sub>2</sub> (carbon dioxide) emissions and fossil fuel use (MGB 2012; Oliver and others 2014). A paradigm shift toward greater logger skill and smaller, less expensive equipment that can operate more carefully could allow more stands to be managed in an appropriate way (Scott 2013). And, active public incentives and forest management programs similar to tree-planting incentives, the “Land Care” program in Australia, the Florida state forest fire prevention program, and a counter-cyclic program similar to the Civilian Conservation Corps could both provide labor and financing for the needed forest management and help provide productive employment (Oliver 2014).



**Figure 6.** Forests in all regions of the United States are accumulating biomass (Smith and others 2009). (white = net growth), with relatively little harvest (diagonal = harvest), and some mortality (black = mortality).

### ***Broader Issues Needing Adjustment***

Silviculture, including the infrastructure, can be important but needs to be done as part of a broader effort rather than as a series of stand-alone mandates. First, the silviculture activities need the “dynamic” perspective described by Botkin (1979, 1991), rather than the now-outdated “steady state” perspective. The “steady state” perspective tended to separate management from some preferred “natural” development that would occur without human intervention (Colwell and others 2012). We now appreciate “natural” trajectories are random and may not protect biodiversity or provide other forest functioning and values. A similar issue is the potential legal liability if a forest fire or other catastrophe occurs following “active management,” whereas a fire burning in an unmanaged forest could be considered an “act of God” and so incur no blame. This obstacle could be similar to the issue of a passing medical doctor helping victims of a traffic accident and then being sued for any lingering injury.

Second, we need to reduce the public’s confusion between science and advocacy. A sincere debate among scientists is healthy; however, decades ago, legal actions against the tobacco and automobile industries made industry as a whole very disciplined in its statements. A similar discipline needs to be instilled in environmental organizations. Both industry and environmental organizations are important; however, neither should be misinterpreting science.

Third, we need a new, creative economic paradigm for sustaining forests and other natural resources. The “sustained yield” economic paradigm served well (Davis and others 2001), but proved problematic in the long term because the world is dynamic, rather than stable. Critiques of sustained yield defaulted to short-term profitability, such as following price signals, as an alternative (Dowdle 1984). Such short-term management is similar to the cutting of all trees on Easter Island for short-sighted advantage, as described by Diamond (2005). Under the justification of “fiduciary responsibility to the owners,” it has probably led to the decline in wood consumption, logging infrastructure, and profits of forest ownership. We need an economic/business paradigm in resource management that bridges the best of both the long term and short term.

Fourth, we need to look at forestry from the landscape level (Oliver 1992; Boyce 1995; Heilig 2001) since single stands only provide parts of the values. For small landownerships, it will be helpful for many owners to work together to provide all values. Such cooperation may also enable marketing and managing benefits through the economies of scale. Each landscape has different properties (Oliver and others 2012), so local knowledge will be needed for appropriate management.



Fifth, introduced aggressive organisms such as those attacking trees are often extremely vigorous at first; however, over time populations of species that prey on them can build and keep their aggressiveness in check. A gradual approach of trying to slow each aggressive species may give time for these predator populations to grow and limit the harm of the aggressive one. This gradual approach may be combined with “Integrated Pest Management” (Kogan 1998), which also combats pests through a combination of monitoring and taking increasingly severe actions only as needed. Together the two approaches may be very effective.

Finally, more stringent measures may need to be taken to prevent new pests from entering North America—or leaving it. Since many regions of the world are facing losses of species and money with these introduced pests, it may be prudent to stop overseas shipping of raw organic materials (Oliver 2014). This action would prevent “hitchhiker” pests on these raw materials, and ensure that secondary manufacture occurs in the region where the organic material is grown. This approach may have an additional benefit of stimulating economies throughout the world by helping them develop value-added products instead of exporting raw materials (Acemoglu and Robinson 2012).

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## **Section III:**

Developing and Implementing Adaptation  
Strategies for Biodiversity Conservation on  
Large Landscapes and Varying Patterns of  
Public and Private Ownership

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# Challenges and Opportunities for Large Landscape-Scale Management in a Shifting Climate: The Importance of Nested Adaptation Responses Across Geospatial and Temporal Scales

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***Abstract:** The Yellowstone to Yukon Conservation Initiative (Y2Y) was established over 20 years ago as an experiment in large landscape conservation. Initially, Y2Y emerged as a response to large scale habitat fragmentation by advancing ecological connectivity. It also laid the foundation for large scale multi-stakeholder conservation collaboration with almost 200 non-governmental organizations working together. In recent years, the Yellowstone to Yukon Conservation Initiative has taken on the issue of climate adaptation as climate impacts span large landscapes. Yet, these impacts are highly variable across 25 degrees of latitude and various local topographies. This presents a challenge to climate adaptation implementation methods as the response mirrors the complexity of the impacts. As such, climate adaptation approaches at large scales may require nested landscape methods that vertically coordinate smaller to larger areas of ecological concern, in combination with considerations of multiple temporal scales for specific spatial scales. In the Southwestern region of the Crown of the Continent Ecosystem in the vicinity of the Bob Marshall Wilderness of Montana, the US Forest Service, the Wilderness Society, and their many partners are prototyping large scale resilient forestry through the Collaborative Forest Landscape Restoration Program. Working across 1.5 million acres (600,000 hectares), the Southwestern Crown Collaborative seeks to test various hypotheses about forest conservation and management in the age of changing climate, uncertain futures, and shrinking economies. Drawing from our experience in collaborative forest restoration and management, here we examine the challenges and opportunities relating to climate adaptation implementation and larger scale conservation by focusing on specific lessons learned from a landscape-scale, on-the-ground project within the Yellowstone to Yukon region.*

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## **INTRODUCTION**

With the Holocene epoch giving way to a newly described Anthropocene, the ecological balance of the planet stands at the precipice of wholesale change. There

is great concern that the Earth's biosphere is approaching an ecological state shift (Barnosky and others 2012; Brook and others 2013). As a result, the operating space for human livelihoods and conserving biodiversity is narrowing as the expanding human footprint pushes toward 10 billion people by the year 2050 (Rockström and others 2009). More than 77 percent of the Earth's land surface is now composed of new ecosystem configurations as large scale land conversion is increasingly evident through agricultural enterprises, massive urban sprawl and infrastructure development, invasive species, and freshwater system eutrophication (Ellis and Ramankutty 2008; Ellis 2013). If global climate models and human population predictions prove correct, the planet and people will be pushed to the edge of sustainability. In this period, two global trends will reach critical inflection points—a plateau and downward trajectory of human population growth and a parallel response of decreasing greenhouse gas accumulation in the atmosphere and oceans. A few lucky infants born today may stand witness to this planetary challenge over the next one hundred years. Our call to arms now is to ensure that today's future centenarians prioritize human action to restore ecological balance of the planet and, with it, human well-being.

### ***The emergence of large landscapes as a focus for conservation and management***

In the face of global threats, large landscape conservation has emerged over the past three decades as a science-based response to increasing large-scale habitat fragmentation and degradation by advancing the concepts of ecological integrity, ecological connectivity, wildlife corridors and comprehensive landscape matrix conservation. More recently, large landscape conservation approaches have been embraced as a strategy to facilitate the adaptation of biodiversity to the impacts of climate change. In one sense, large landscape conservation is the evolution of the “beyond parks” conservation approach (Minteer and Miller 2011) in which species and ecological processes cannot be satisfactorily sustained within most circumscribed protected landscape parcels.

Conserving nature's parts and processes requires working at a landscape, ecosystem, or even bioregional scale. Hansen and DeFries (2007) demonstrate how even the vast spatial scales of our largest national parks are insufficient to fully support many ecological processes or prevent cross-boundary effects of surrounding human-dominated landscapes. Size does matter in ecology because of the scale of processes and impacts, and, in general, the larger the scale of focus, the better chance of conserving critical ecological processes, such as hydrologic function, natural disturbance regimes, species life cycles and functional trophic interactions (Lindenmayer and others 2008). Conservation at such large scales increases the complexity of decision making as collaboration and consensus among diverse stakeholders, with diverse values, is required. These processes not only sustain nature but provide vital ecological services that support human livelihoods.

Since the establishment of Yosemite and Yellowstone as protected areas in the 19<sup>th</sup> century, our knowledge of ecology and the practice of conservation have advanced substantially and are reflected in both policy and management. One insight included greater understanding of animal movement ecology. For instance, the Migratory Bird Treaty Act between US and Canada in 1918 set the stage for protecting large scale avian flyways and the eventual design of the North American Waterfowl Management Plan in 1986, which has facilitated the conservation of millions of hectares of wetlands and other bird habitats. In Yellowstone in the 1950s and 1960s, the concept of ecosystem-scale research gained traction through radio-collar research of scientists

such as the Craighead twins, who studied grizzly bear home range size and bear movement ecology. The Greater Yellowstone Coordinating Committee was established in 1964 to foster ecosystem scale collaboration among government agencies in the region, the same year that the Wilderness Act was passed. Further research of species movement ecology in later years led to the design of even larger conservation efforts such as the Yellowstone to Yukon Conservation Initiative, which recognized the inter-ecosystem movement needs of the region's medium-sized and large mammals, migratory birds and cold water fish within the Rocky Mountain Cordillera (Tabor 1996; Locke and Tabor 2005).

Since its inception in 1993, the Yellowstone to Yukon effort - through its network of 200 or so public and private organizations - has protected roughly 23 million acres (nine million hectares) of existing public lands through enhanced designations and roughly one million acres (400,000 hectares) of private lands through conservation easements and acquisitions. This includes one of the largest private land deals in the US: the wholesale purchase of Plum Creek timberlands within the railroad legacy checkerboard landscape, including nearly 50,000 acres (20,234 hectares) of the Swan and Blackfoot Valleys in the Crown of the Continent Ecosystem.

Yellowstone to Yukon was the first among a series of subsequent large scale efforts initiated in Canada, many facilitated by First Nations engagement, such as the Great Bear Rainforest in British Columbia, Plan Nord in Quebec and the Canadian Boreal Initiative. The latter effort stretches across six provinces and three territories and represents one of the largest landscape conservation initiatives in the world. In recent years within the US, various government-led large landscape responses have come to the fore. One of the more notable efforts was the 2008 Western Governors' Association initiative on crucial wildlife habitat and wildlife corridors, initiated in response to large scale energy planning and development. All 17 western states within the Western Governors' Association unanimously agreed on a shared policy framework to address the scale and scope of habitat and wildlife movement areas across their jurisdictions in the face of potential conflicts with planned development. This was a milestone event as states recognized the need to conserve their resources at a regional scale through interstate collaboration. Soon thereafter, in 2010, the US Department of Interior embraced a new landscape partnership program, the Landscape Conservation Collaboratives, which designated 22 large scale cooperative landscape management areas across the nation and adjoining transboundary regions in Canada and Mexico as part of a Department-wide coordinated adaptation response to climate change. At the same time, the All Lands Initiative and the US Forest Service's Collaborative Forest Landscape Restoration Program were established to more effectively address conflicts in natural resource management planning and development at large scales.

There has been an exponential growth of large landscape efforts in the past ten years, which, for the most part, reflects a growing conservation interest in maintaining ecological connectivity and wildlife corridors as an approach to address habitat fragmentation and heightened concerns about climate change impacts on species and habitats (McKinney and others 2010, Regional Plan Association 2012; McKinney and Johnson 2013). Large landscape efforts promote resilience to large scale stressors such as climate change, provide a range of potential climate refugia, and support species that can respond to changing environmental conditions with the opportunity to shift their geographic distribution. In reality, the story is more complex. Species interactions are likely to change as individual species respond differentially to climate stressors, and present day trophic structures may give way to novel species interactions and ecosystems in the future.



Moreover, not all species have the ability to shift their distributions to keep pace with the relatively rapid rate of climate change, and current understanding of the extent to which genetic plasticity may allow or prevent species from responding to climatic shifts in their current habitat is poor.

Within the Yellowstone to Yukon region at the international boundary between Canada and the US is the Crown of the Continent Ecosystem. This 18 million acre ecosystem surrounds Waterton Lakes and Glacier International Peace Park, the first international peace park, which was established in 1932. This landscape also bears the physical evidence of climate change as all remaining 25 glaciers in Glacier National Park are predicted to disappear within two decades after surviving for more than 7,000 continuous years (Hall and Fagre 2003). Triple Divide Peak within Glacier National Park connects three major continental river basins—the Columbia, the Missouri and Saskatchewan. The Crown of the Continent not only serves as a focal point for landscape impacts of climate change, it also serves as a focal point for US and Canada landscape collaboration and innovation. Within the southwestern portion of this ecosystem, a new large scale restoration effort is being prototyped, and this case study will inform the ideas for managing in the Anthropocene that are further elaborated in this paper.

## **A CASE STUDY OF COLLABORATIVE, LARGE LANDSCAPE MANAGEMENT**

The CFLRP began in August 2009 upon passage of the Public Lands Omnibus Bill. This Congressional Act established an annual budget of \$40 million to finance 10 collaborative, large landscape projects on Forest Service land across the United States. Thirteen additional CFLRP projects were added to the program in 2012 due to strong, bi-partisan support for the program (USDA Forest Service 2012). The goal of CFLRP is to carry out ecological restoration and fire management treatments in priority landscapes by encouraging collaborative, science-based ecosystem restoration projects.

Here, we provide one example of the many challenges, opportunities, and lessons learned related to landscape-scale management in a shifting climate: the Southwestern Crown of the Continent (SWCC) Collaborative Forest Landscape Restoration Program (CFLRP) project in Montana. The SWCC has been working to test various hypotheses about forest conservation and management in the age of changing climate, uncertain futures, and shrinking economies. This work falls under the auspices of a large landscape, forest restoration program initiated by Congress in 2010 and administered by the US Department of Agriculture's Forest Service. Spanning 1.48 million acres (600,000 hectares) of forested, mountainous habitat in three adjacent Forest Service (FS) Ranger Districts (Lincoln, Seeley Lake and Swan), the SWCC CFLRP project (one of 23 nation-wide CFLRP projects) includes portions of three of Montana's National Forests (the Helena, Lolo, and Flathead National Forests, respectively). Four years into the project, project partners are beginning to share lessons learned to identify best management practices for the Anthropocene in this landscape.

Under the CFLRP model of community forestry on our public lands, each project is expected to: (a) demonstrate the degree to which various ecological restoration techniques achieve ecological and watershed health objectives; (b) facilitate the reduction of wildfire management costs through re-establishment of natural fire regimes in back-country areas while simultaneously

reducing the risk of uncharacteristically severe wildfire near rural communities; and (c) encourage the use of forest restoration by-products (e.g., small-diameter timber) to offset treatment costs and support local, rural businesses and economies.

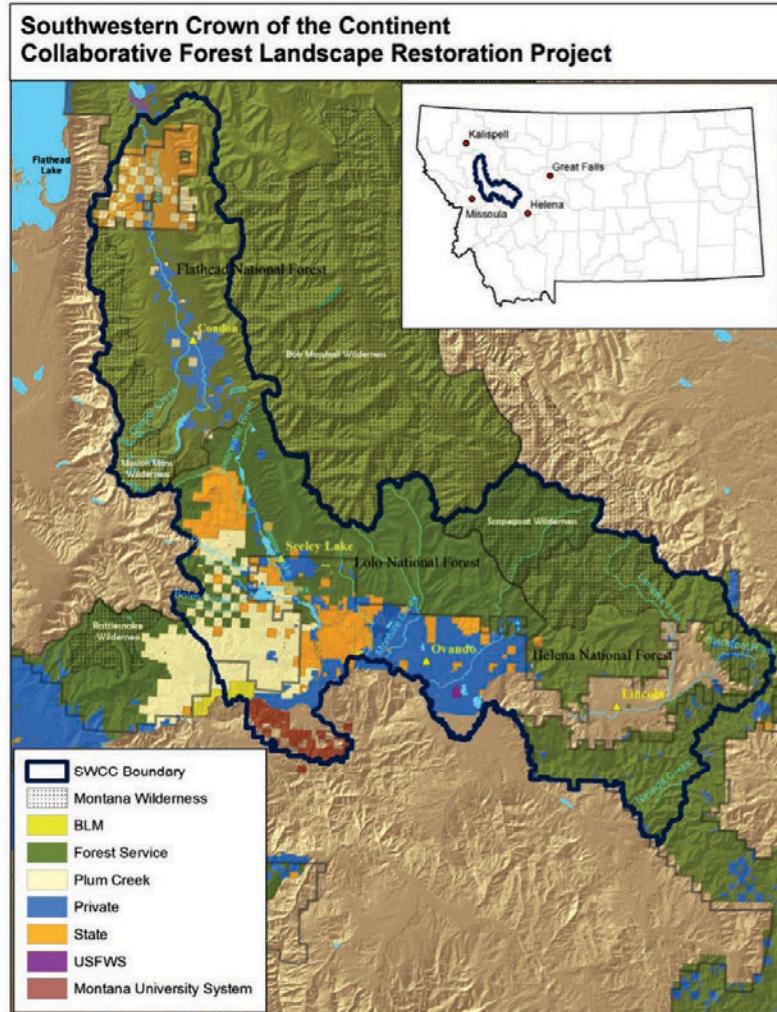
Through intensive, long-term work to improve forest health and resilience in an era of shifting climate, CFLRP projects are intended to sustain ecological, economic, and social benefits in rural communities that have traditionally relied on natural resources locally for their livelihoods, drinking water, and recreational opportunities. The Act strongly encourages a shift to adaptive management in these landscapes by requiring all 23 CFLRP projects to develop and implement a large scale monitoring program; a baseline inventory of natural resource conditions, coupled with short- and long-term evaluations of the effectiveness of restoration projects, is expected to create critically important information-feedback loops for managers in an increasingly uncertain future (Hutto and Belote 2013; Larson and others 2013b).

Through its selection for funding in 2010, the SWCC in Montana (<http://swcrown.org>) combined several existing local collaboratives into a new coalition comprised of U.S. Forest Service agency staff, university faculty, conservation organizations, and citizen groups. The SWCC is sited within the larger 18 million acre (7.28 million hectare) Crown of the Continent, renowned for its unusually high degree of ecological integrity. No known extinctions of plant or animal species have occurred since Lewis and Clark's travels through the region 200 years ago (Prato and Fagre 2007). In addition to the prime habitat provided for grizzly bear, elk, wolverine, deer, gray wolf, Canada lynx, forest birds and waterfowl within the forested mountain landscapes, the cold, clear streams of the Crown are home to a variety of native salmonid species.

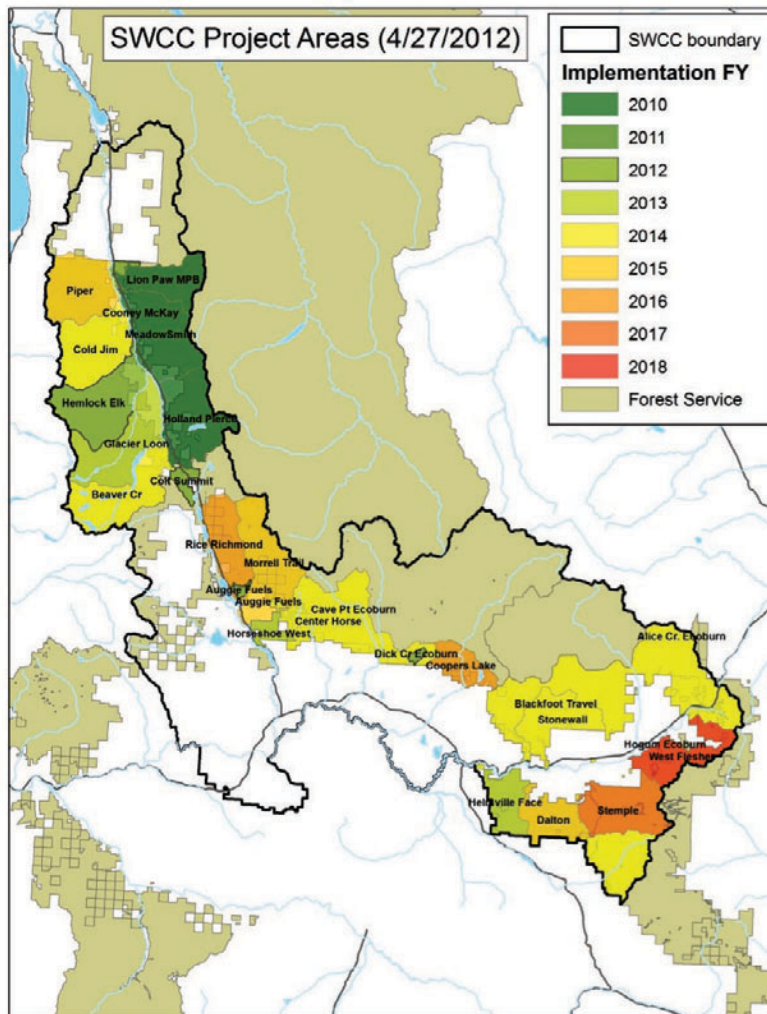
Nonetheless, major restoration needs exist. Noxious weeds and exotic fish species have invaded terrestrial and aquatic ecosystems across the landscape, thousands of miles of old logging roads fragment key wildlife habitat and lead to increased sedimentation in blue ribbon trout streams through erosion, and mining activities from an era gone by necessitate focused and expensive clean-up efforts in several places. Decades of fire suppression—a management response to catastrophic wildfires in Montana and Idaho during the “Big Burn” of 1910—have dramatically altered the ecology of Western forested ecosystems and resulted in unnaturally high accumulations of forest fuels (Arno and Fiedler 2005; Egan 2009).

While many of these restoration needs identified are common to Western landscapes of the United States and Canada, CFLRP project partners within the southwestern Crown of the Continent face further management opportunities and challenges associated with the Montana Legacy Project: an historic conservation deal in which 273,000 acres (110,479 hectares) of Plum Creek Timber Company-owned land was sold to a consortium of conservation organizations led by The Nature Conservancy and the Trust for Public Land, before being transferred into public ownership through the U.S. Forest Service. The checkerboard ownership pattern associated with the Montana Legacy Project (Figure 1) began a century ago when the lands were initially purchased by the transatlantic railroad, but remains visible from space today given major differences in the management of these and adjacent lands through time. The absorption of these commercial timberlands into the public domain highlights the significant, and often dynamic, challenges of developing conservation projects across jurisdictionally-fragmented lands.

**Figure 1.** Public/ private pattern of land ownership within the 1.5 million acre SWCC CFLRP project. Nested scales of partnership and coordination are critical to the work of any conservation management project in the continental United States given the degree of jurisdictional fragmentation typically found across all large landscapes, including those that remain relatively intact ecologically. For example, note the checkerboard pattern of land ownership associated with the Montana Legacy Project (green squares), a project in which approximately 500 square miles of former commercial timberland is being transferred from the Plum Creek Timber Company to public ownership under the jurisdiction of the U.S. Forest Service and the State of Montana beginning in 2010. Map courtesy of Cory Davis.



Prior to 2010, the SWCC had identified a detailed list of ecological restoration needs across 1.48 million acres (600,000 hectares) of the SWCC region. Proposed restoration included 43,000 acres (18,600 hectares) of forest land, removal of 400 miles (650 kilometers) of roads, restoration treatments influencing 937 miles (1,500 kilometers) of streams, treatments to reduce erosion on ~650 miles (1,000 kilometers) of roads, upgrading of 150 stream-crossing structures, reduction of non-native distributions in area lakes and streams, and noxious weed treatments on 81,000 acres (33,000 hectares). This projects simultaneously create 170 full- and part-time jobs each year, and contribute \$9.2 million annually in direct labor income to local communities in the southwest Crown (SWCC CFLRP proposal 2010; SWCC CFLRP landscape strategy 2010). Regional experts have worked to develop and implement the accompanying monitoring program required for the SWCC through collaborative “think tanks” on socioeconomics, aquatic ecosystems and fisheries, wildlife, and vegetation (a category that includes forest structure, noxious weeds, and fire) (SWCC CFLRP Annual Report 2012). In addition to the nested spatial scales of conservation work needed in the Anthropocene, the SWCC provides an excellent example of the nested temporal scales of planning and implementation required for landscape-scale projects; Figure 2 depicts the results of the SWCC’s collaborative planning processes across the landscape for the decade-long project.



**Figure 2.** Map of SWCC CFLRP forest restoration projects depicted across space and time for the ten-year, large-landscape restoration project. The design and implementation of each project requires years of coordinated work across nested scales of partnership. Map courtesy of Cory Davis.

While the focus of “restoration” assumes management will attempt to return ecosystem composition, structure, and function to historical ranges of variability, we suggest here that ongoing changes in climate in the region challenge the notion that a return to historical range of variability is the best approach to conserving the ecological values. Climate change may exacerbate existing stressors and disturbance agents on the landscape (such as pine bark beetle outbreaks), while simultaneously acting as a powerful new environmental stressor by itself (Pederson and others 2010). Years of intensive research and monitoring in the Crown have greatly expanded our knowledge of the impacts of a warmer, drier climate thus far: disappearing glaciers, shallower snowpacks, more rain on snow events each winter, earlier peak snow runoff events in the spring, and longer annual summer droughts. These effects have contributed to longer, more severe wildfire seasons, the creation of more suitable habitat for pernicious noxious weed species (e.g., cheatgrass) and novel pathogens (e.g., West Nile virus) as well as range distribution shifts by numerous wildlife species (see summary by Bay and others 2010). Yet, these impacts are highly variable across 25 degrees of latitude and various local topographies that span elevational gradients of 1,000 to more than 3,000 meters (Prato and Fagre 2007), further complicating the design and implementation of management responses across the landscape.

## COMING TO GRIPS WITH THE REALITIES OF LANDSCAPE-LEVEL WORK

Addressing restoration and climate adaptation challenges in the region requires explicitly dealing with the challenging issue of scale. Ecological processes operate across spatial scales where large scale patterns (e.g., climate regimes) govern small scale processes (e.g., seedling recruitment), while small scale patterns (e.g., stand-level structure of forest patches) also scale up to large scale processes (e.g., fire behavior and resulting emergent properties of landscape composition and arrangement, Hessburg and others 2013). Policy and management responses to coupled ecological pattern-processes span vast spatial scales as well (Table 1; Ban and others 2013). Understanding cross-scale patterns and mechanisms of linkages across spatial scales will be critical to sustain ecological systems in the Anthropocene. Given uncertainty surrounding the impacts of climate change across scales, how do policy makers and managers sustain ecological and social values? In the following sections we outline those approaches that we believe are needed to sustain ecological processes across scales through strategic and coordinated efforts to work across nested scales. When possible, we provide specific examples of ways the SWCC considers scale as it confronts challenges of forest management and restoration in the age of climate change.

**Table 1.** Examples of nested scales where key patterns and processes occur in ecological and socio-political realms. Understanding impacts of global changes at each scale and mechanisms that operate across scales is needed to sustain ecological services and conserve biodiversity in the Anthropocene.

Spatial scale	Area (hectares)	Ecological process example	Socio-political example
Global	51,000,000,000	Water, carbon, and energy cycling; global climate variability	G8 Global Summits on Climate Change and carbon emissions; geopolitical treaties and trade agreements
Bioregional	100,000,000	Long distance animal migrations, river basin hydrology, continental-scale climatic influences	River basin compacts, Canadian Boreal agreements, Landscape Conservation Cooperatives; Yellowstone to Yukon
Regional	1,000,000	Regional populations and genotypes of species	Forest Service Planning under new Planning Rule
Landscape	100,000	Habitat composition; contagious landscape processes (fire, insects, spread of invasive species); Large animal (e.g., grizzly bear) home ranges	Collaborative Forest Landscape Restoration Program
Watersheds	1,000	Hydrologic function; home range for small animals	Watershed Condition Class Framework
Stand-level	100	Local habitat for animal foraging and nesting; maintenance of tree diversity and local disturbance dynamics; seed dispersal	Local forest service districts and local restoration committees
Local-level	0.1	Regeneration niche; interactions between individuals (e.g., competition, mutualisms)	Contractor decisions and work; monitoring common stand exams; local restoration committees field trip visits

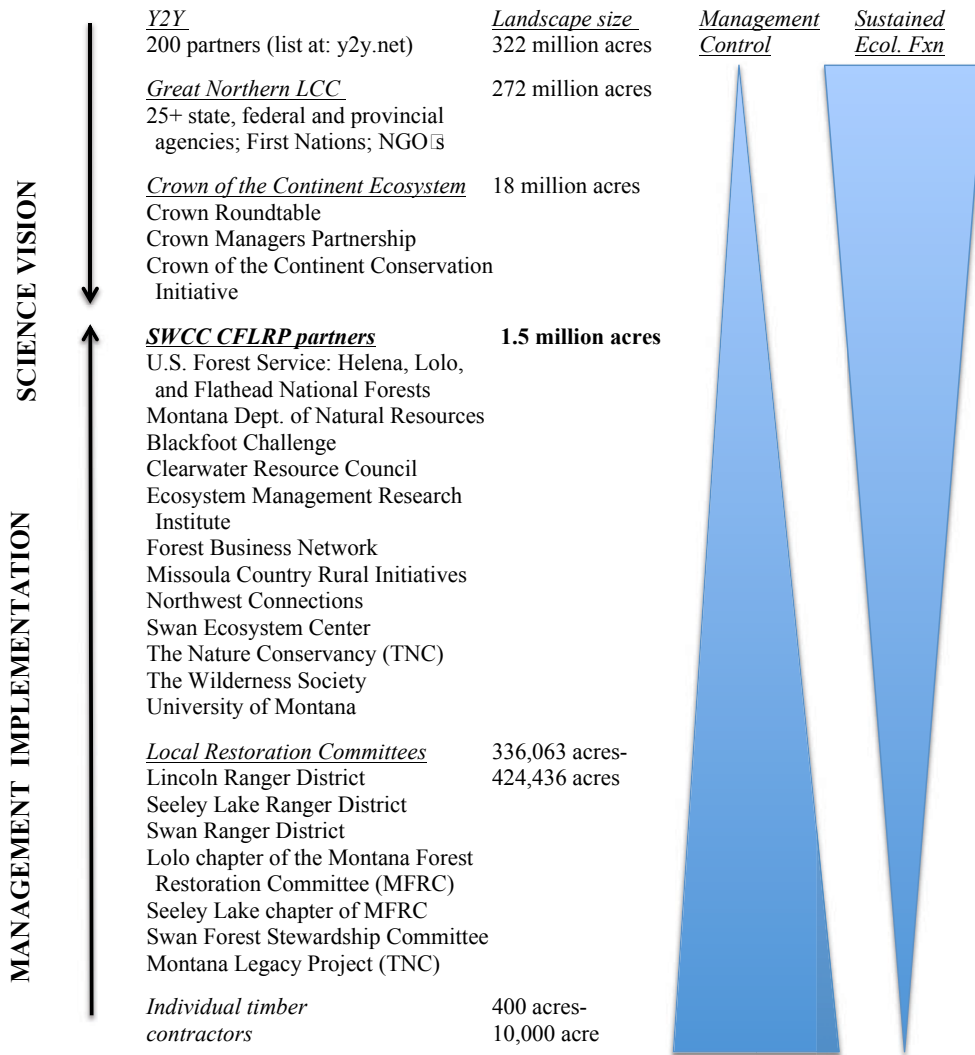
## ***Work across nested scales of space and time***

Working across scales requires an appreciation for different processes—both ecological and social—that operate at scales spanning orders of magnitude (Table 1). Managing ecosystem components with the best available understanding of interactions across scales will also be critical as climate change forces coupled patterns and processes at each scale. Project implementation and monitoring should consider various spatial scales that operate to sustain the things we value from nature (e.g., regenerating trees after disturbance and landscape composition and structure).

The Southwestern Crown of the Continent effort provides a concrete example of the necessity of collaborating and coordinating across nested scales to sustain ecological functions across geospatial scales. The SWCC continues to prototype much of the science and implementation for climate adaptation throughout the entire ecosystem (Figure 3). Consider, for example, the largest landscape-scale collaboratives in the region—Yellowstone to Yukon Conservation Initiative, the Great Northern Landscape Conservation Cooperative, and various Crown of the Continent coalitions. These groups generate much of the regional, scientific vision for sustained ecological functions across 25 latitudinal degrees of topographically-complex, mountainous ecosystems. They work collaboratively to establish and share data about the impacts of climate change and other stressors. Attributing phenomena to climate change impacts may only be detectable at regional scales (e.g., van Mantgem and others 2009). Regional monitoring programs—and their associated costs—may necessitate science consortia (e.g., Climate Science Centers) or national programs (e.g., National Phenology Network). Opportunities to attract and match funding are often highest at very large scales and most challenging at the smallest scales. Funding for the SWCC first came from the U.S. Department of Agriculture’s Forest Service, but has since attracted financial support from the corresponding Department of Interior large landscape initiative, the Landscape Conservation Cooperatives, while private foundations have been enthusiastic about the opportunity to leverage their private funding with public funding. Altogether, reasons for coordinating and collaborating across nested geospatial scales abound, although appreciation and funding for this vital function is often lacking.

At the other end of the spectrum are those projects and groups operating at smaller geospatial scales than the SWCC (e.g., local restoration committees, the Montana Legacy Project, Forest Service Districts, and individual timber contractors). Despite the significant amounts of time and effort required to coordinate with each group, these collaborative efforts have turned out to be absolutely critical given that management control is highest at local scales. From stand-level treatments to district level project planning, this is the scale at which extremely detailed knowledge of the threats and opportunities for treatments exists, and at which managers subsequently implement treatments on the land or intervene to manage wildlife populations that range across both public and private lands.

In the SWCC, treatments are still designed as traditional Forest Service-led projects conducted within one of three Forest Service Districts. Project boundaries are typically ~250-2,500 acres (100 to 10,000 hectares) in size, though not all areas are treated in the larger project boundaries. Treatments are still typically applied to stands ranging in size from ~5-250 acres (20 to 100 hectares), and projects are still designed by agency specialists. However, collaborative input has become more influential in designing projects and their treatments. While projects are still designed with “stands” as the primary unit of treatment, placing treatments in the context of



**Figure 3.** Levels of partnership and coordination required across nested geospatial and temporal scales for one large landscape project in Montana. The SWCC CFLRP provides a real-world example of the types of capacity and coordination required to successfully manage large landscapes in the Anthropocene, given that management control is highest at small geospatial scales, while sustained ecological function and connectivity are most effectively addressed at extremely large geospatial scales.

landscape processes is increasingly applied. Landscape modeling tools have provided both an idea of landscape characteristics within a historical range of variability as well as predicted landscape level effect of treatments on fire behavior and resulting landscape composition and arrangement. More work is needed to connect scales from <250 acres (100 hectare) patterns in stands to processes (e.g., fire, wildlife movement) operating at much larger (e.g., 2,500 acre or 10,000 hectares) scales, but the collaborative continually revisits the question about landscape function, rather than mere stand-level structure and composition.

Consideration of nested spatial scales may help move forest management beyond stands, but climate change also requires a consideration of temporal scales beyond traditional harvest rotation and schedules. A consideration of the “lifespans of treatments” now being implemented similarly should be factored into economic and ecological decisions, including plans for

adjusting management decisions following monitoring and evaluation of data. Re-entry into stands and landscapes may be required to sustain initial restoration and adaptation investments. Implementation of adaptive management strategies usually implicitly considers time, because *future* decisions should be adjusted as new information and understanding become available. Global changes require that actions and policies implemented today consider an uncertain future marked by altered climatic regimes and shifting species ranges, while anticipating ecological surprises (Williams and Jackson 2007). Perhaps most importantly, it is becoming apparent that some ‘work’ may be best addressed at very large scales (e.g., long-term planning, development of scientific datasets or tools for assessment of connectivity, monitoring of climate change impacts, funding) while other ‘work’ may be best coordinated at much more local scales (e.g., prioritization of on-the-ground projects, decisions about which scientific datasets and tools to use in informing project development, etc.).

### ***Work across jurisdictional boundaries***

As described above, conservation biologists have understood for decades that protected areas with boundaries may not sustain biodiversity because (1) global changes impact “protected” areas, and (2) populations of animals and plants need room to move and maintain genetic diversity. Addressing the second issue by working across land management jurisdictions remains one of the most challenging elements of landscape conservation. Lands adjacent to conservation reserves may enhance core regions for sustaining biodiversity or serve as regions of connectivity, especially as climate change shifts the geographic distribution of habitat.

Ecologically compatible land use approaches across patterns of land ownership have been labeled ‘matrix conservation’ (Noss 1983). In other words, matrix conservation considers protected areas to be embedded in a landscape matrix of land uses. UNESCO’s Man and Biosphere Program recognized this issue beginning in the early 1970s by advancing the implementation of landscape-scale conservation with ecologically intact core areas surrounded by gradients of increasing human use buffer zones. Noss and Cooperrider (1994) and Soulé and Terborgh (1999) improved on this design by advancing the concept of ecological connectivity or corridors between core protected areas—thus creating an interconnected ecological network of protected areas.

Ecological connectivity has become a major element of large-scale landscape conservation and is defined as the degree to which the landscape facilitates movement processes across habitat patches on multiple spatiotemporal scales (Taylor and others 1993). Over individual lifespans, daily and seasonal movements among patches ensure access to required resources (Dingle 1996); over generations, dispersal maintains metapopulation structure and provides rescue effects from population extinction (Harrison 1994); and, over multiple generations, long range dispersal sustains genetic diversity and the ability to respond to long-term trends, including climate change. Connectivity is now a major element in many revised State Wildlife Plans, the Western Governors’ Association Wildlife Corridors initiative, the U.S. Forest Service’s Planning Rule and the new national Fish, Wildlife, and Plans Climate Adaptation Strategy.

Connectivity is an ecological characteristic of landscapes, but achieving connectivity requires that conservation scientists and practitioners work across political boundaries. Connecting people to connect landscapes is the only approach that can sustain conservation outcomes through



the vagaries of political and fiscal cycles. Conservation across jurisdictions requires time-consuming, facilitated collaboration processes to bring key conservation stakeholder interests together. For instance, the Yellowstone to Yukon Conservation Initiative began as a bottom-up non-governmental organizational effort to connect conservation efforts with similar goals across an ecologically defined and relatively intact region. Today, there are nearly a dozen Crown of the Continent-wide ecosystem-scale initiatives that span the U.S.-Canada border and bring various stakeholder groups together from tribal nations, government, private land owners, businesses, watershed groups, local communities, universities, environmental educators and the non-profit conservation community.

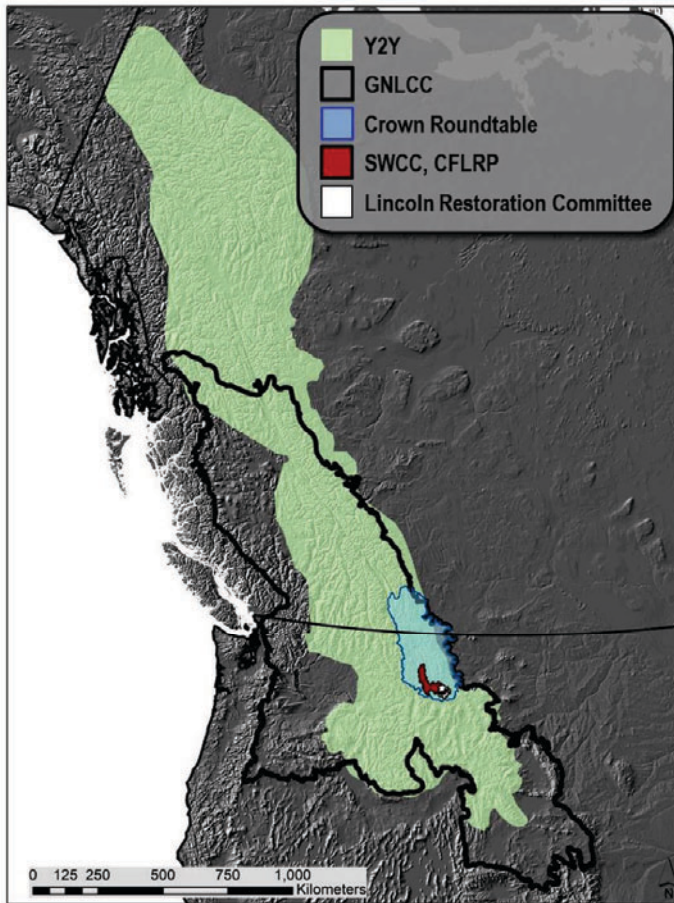
A landscape-scale network of all the ecosystem-wide initiatives, known as the Roundtable of the Crown of the Continent ([www.crownroundtable.org](http://www.crownroundtable.org)), was established in 2007. The Roundtable has created an informal governance structure based on a charter of common principles and shared goals that establishes a framework for multijurisdictional landscape conservation and land management collaboration; its purpose is to facilitate multi-jurisdictional, large scale, climate adaptation implementation across all major land ownership communities across the entire ecosystem.

Even at the smaller nested scale of the SWCC, cross-jurisdictional work is required. Ecological (e.g., fire and animal movement) and social (e.g., fire management, recreation) processes operate across diverse ownership boundaries in the region (Figure 3). Communication and collaboration among diverse jurisdictions from federal agencies to state lands to local land owners can be a challenge, but also offers great opportunity. Partnerships between groups, facilitated by local conservation groups, create the kind of information exchange needed for land stewards of various affiliations to respond to ecological impacts as climate changes (Figure 4; see also Wyborn and Bixler 2013 for another regional example of partnerships across scales). Without cross-jurisdictional partners, social responses to conservation challenges and threats across spatial scales would be stymied.

### ***Work across cultural and social ideologies***

Moving beyond historical ideological and social barriers is a necessity for effective conservation in the Anthropocene. The old rhetoric of “us versus them” should give way to embracing uncertainty and humility, trust building, and development of visions based on common values. In the SWCC, diverse stakeholders co-authored a landscape vision and proposal that articulates shared ecological, economic, and social values among diverse groups including conservationists, scientists, and loggers (see, for example, the SWCC charter: <http://www.swcrown.org/committee/committee-charters>). Achieving consensus on every issue has its challenges. However, time spent articulating desired outcomes builds trust and establishes common ground among individuals representing diverse interests.

We have found that two activities have been of particular use in building the trust required to work across cultural and social ideologies for SWCC partners: first, the group agreed to use a ‘zone of agreement’ developed by the Montana Forest Restoration Committee to guide forest restoration projects in western Montana from 2007 onward (<http://www.montanarestoration.org/restoration-principles>); this framework allowed individuals, organizations and agencies alike to work within the zone of agreement rather than having to evaluate every conversation, proposed



**Figure 4.** Map illustrating the geospatial scales associated across vertical nested conservation scales. Yellowstone to Yukon (Y2Y) connects conservation planning across bioregions. The Great Northern Landscape Conservation Cooperative (GNLCC) networks federal agencies and non-profits to handle complex conservation challenges across large regions. The Roundtable of the Crown of the Continent coordinates all stakeholders in the region. The Southwestern Crown of the Continent works to coordinate collaborative design and monitoring of landscape forest restoration. Nested with the SWCC, the local Lincoln Restoration Committee helps design on-the-ground projects, including use of experimental design of treatments as a way of implementing a science-based portfolio approach to restoration forest planning.

action, etc. against their own perspectives, missions or mandates. Rather, all of our missions and mandates were well represented within the zone of agreement, freeing partners to focus on the work at hand. Second, the partners have spent significant amounts of time out on the ground discussing proposed and completed restoration projects over the years, which has led to extremely honest and productive conversations that are firmly rooted in our values for the land and its resident wildlife: we recommend this approach whenever possible.

Reducing fuels in the wildland urban interface to reduce the risk of unmanageable crown fires near communities, sustaining populations of iconic wildlife species, and restoring landscape function and fire regimes are characters of the land that most individuals and groups agree are important to sustain or restore. The specifics on *how* to accomplish these goals and *what* science to rely on—especially when there is competing science—are sources of significant discussions and uncertainty. However, a common landscape vision that builds trust, embraces uncertainty, and moves beyond old ideological tensions has created an atmosphere that facilitates experimentation.

***Work across scientific disciplines and industries***

Collaboration across scientific disciplines is increasingly recognized as important to understanding complex socio-ecological systems (e.g., National Science Foundation’s Coupled Human Natural Systems Program; Resilience Alliance). This cross-disciplinary science

should not be limited to academe, but can also be used as a framework for implementation and monitoring of collaborative forestry projects. In the SWCC, we have developed a multi-disciplinary monitoring program that bridges economic, social, and ecological disciplines.

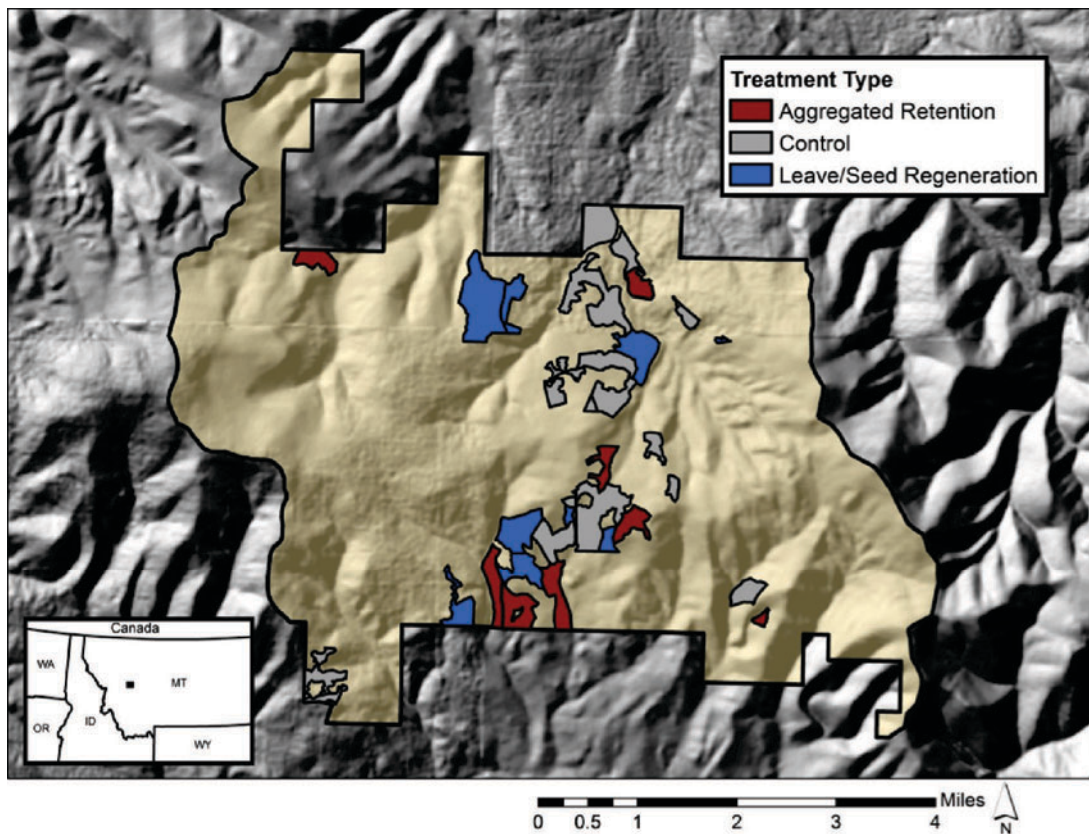
The monitoring program consists of scientists and management partners that together discuss and plan monitoring to address ecological and social questions. For instance, SWCC monitoring efforts collect data on vegetation responses to treatments in terms of crown fire risk, understory vegetation, and soil impacts, and will couple these ecological responses with economic and social questions. How much economic return is generated from projects; what are the perceptions of the collaborative work; and will reduced crown fire risk equate to less fire-fighting costs in the future? The Forest Landscape Restoration Act of 2009 calls for a coupled socio-ecological perspective. In response, the SWCC monitoring program has been designed to address diverse, collaboratively-generated questions on ecological, economic, and social fronts (see <http://www.swcrown.org> for annual SWCC project and monitoring program reports as examples).

***Adopt a portfolio approach that uses experimental design to learn and adapt more rapidly***

Uncertain impacts of climate change require new approaches and strategies. A nested portfolio approach using elements of experimental design continues to build trust, sets up resilient landscapes by focusing on diversity and heterogeneity at various spatial scales, and may be a way of hedging against uncertainty (see below; Millar and others 2007). The value of this approach is that it (1) is science-based and will allow management adjustments to be conducted with strong inference and understanding; (2) spreads risk by not doing the same thing everywhere; (3) honors various perspectives and empowers collaborative stakeholders; (4) confronts uncertainty head-on through the use of multiple treatments or experimentations; and (5) embraces uncertainty through humility. In the SWCC, we have designed two projects with a rigorous approach to experimental design (Figure 5; Larson and others 2013b).

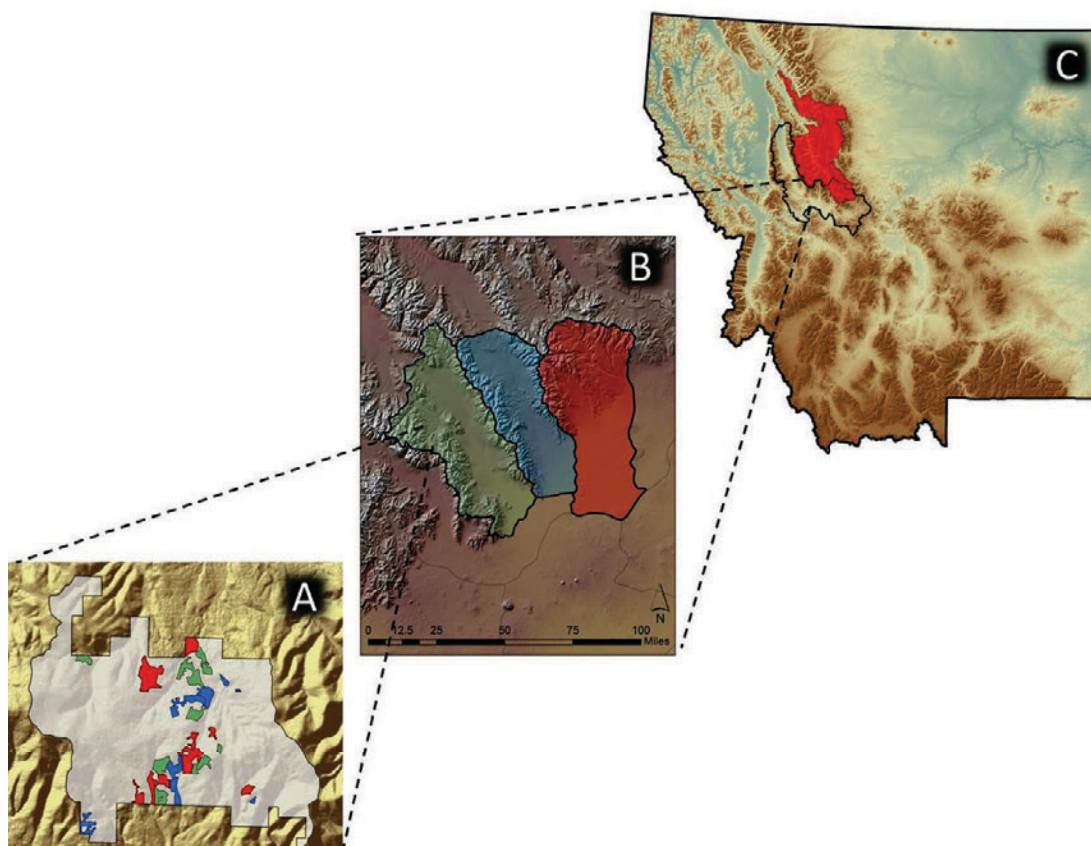
Using a robust experimental design, several projects of the SWCC will be implemented by turning diverse management perspectives into replicated treatments (Larson and others 2013b). For instance, the best method for restoring and sustaining forested values in lodgepole pine (*Pinus contorta*) landscapes where mountain pine beetle has caused significant mortality is a controversial topic. Lodgepole pine forests are typically considered to have been maintained historically by stand replacing fires. Whether mountain pine beetle, climate change, fire exclusion, or their convergence have altered landscape structure and composition, putting ecological and social values at risk of regime shift-inducing fires, remains an active area of research and controversy. Competing science and social perspectives have suggested that lodgepole stands and landscapes are either a very low or a very high priority for active management to restore structure and function. In situations of high scientific and social uncertainty, the SWCC and local restoration committee have begun designing a subset of projects as replicated experiments where various management options are viewed as experimental treatments (Figure 5).

Experimental approaches using stands and even small watersheds to replicate various treatments and monitor ecological responses helped move ecology from a descriptive to an experimental science (Bormann and Likens 1979). Additionally, nesting experimental applications of a



**Figure 5.** Map of the Dalton Mountain project area of the SWCC CFLRP where elements of experimental design (e.g., use of untreated controls, replication, and unbiased assignment of treatments) were collaboratively incorporated into treatment plans for 30 stands of lodgepole pine-mixed conifer forests. Figure courtesy of Larson and others, 2013.

portfolio of approaches can be accomplished across spatial scales ranging from 0.1 ha to entire landscapes (Figure 6), while simultaneously accommodating the legal framework associated with different land designations (e.g., Wilderness areas, roadless areas, etc.). This approach is consistent with a portfolio approach to managing climate risk (*sensu* Aplet and Gallo 2012). Such an approach would consider designated wilderness areas “observation zones” where managers can both accept and learn from climate-induced impacts. “Restoration zones” are areas managers resist climate-induced changes by working to restore resilience to degraded lands in the face of climate change. Existing lands administered by federal, state, and local agencies outside of wilderness would be good candidates for assignment to the restoration zone. Finally “innovation zones” would allow managers to attempt to facilitate transition to novel ecosystems given expectations that these ecosystems will undergo large scale, climate induced regime shifts (Aplet and Gallo 2012). The SWCC CFLRP project, for example, offers the opportunity to incorporate two of these three portfolio approaches at the landscape scale: the Bob Marshall Wilderness (in red, Figure 6 part C) is an “observation” zone in which managers are legally required (by virtue of the Wilderness land designation) to manage this area minimally, while the SWCC CFLRP project area (outlined in black, Figure 6 part C) is a “restoration” zone in which substantial intervention by managers could help reverse environmental degradation associated with a range of historic stressors and land use—thus sustaining key ecological values into the future.



**Figure 6.** A nested experimental approach to applying various treatment alternatives could be applied from stand scales (A), to watersheds (B), and landscapes (C). Each colored zone within a panel represents an approach or treatment intended to meet objectives at various scales with an eye toward the next highest and lowest spatial scales, and is consistent with a portfolio approach to managing climate risk (sensu Aplet and Gallo, 2012). That is, wilderness areas comprise “observation zones” where managers can both accept and learn from climate-induced impacts; “restoration zones” are areas where managers resist climate-induced changes by working to restore resilience to degraded lands in the face of climate change; and “innovation zones” would allow managers to attempt to facilitate transition to novel ecosystems given expectations that these ecosystems will undergo large scale, climate induced regime shifts (Aplet and Gallo, 2012). The SWCC CFLRP project, for example, offers the opportunity to incorporate two of these three portfolio approaches at the landscape scale: the Bob Marshall Wilderness (in red, Figure 6C) is an “observation” zone in which managers are legally required (by virtue of the Wilderness land designation) to manage this area minimally, while the SWCC CFLRP project area (outlined in black, Figure 6C) is a “restoration” zone in which substantial intervention by managers could help reverse environmental degradation associated with a range of historic stressors and land use.

Nesting experimental treatments of stands (Figure 6 part A) within treated watersheds (Figure 6 part B) and landscapes (Figure 6 part C) could help create a resilient landscape by implementing diverse approaches across scales while simultaneously creating a landscape set up to contribute to our understanding of best approaches in the Anthropocene. While not yet intentionally implemented by the SWCC, CFLRP projects offer a rare opportunity for pairing treated watersheds and landscapes with untreated controls.

### ***Continue to emphasize role of protected lands and wilderness core areas as a viable conservation strategy***

Untreated lands—where nature is left untrammelled—have come under increasing fire in recent years, as pernicious threats of global change (altered climate, invasive species, altered nutrient loadings, acidification, etc.) have impacted ecosystems once regarded as pristine. A hands-off approach to ecosystem management was once held as the preeminent conservation strategy. In the Anthropocene, it may be important for managers to intervene at the expense of untrammelled lands, but for the benefit of sustaining ecological patterns and processes upon which we depend. Does this new era called the Anthropocene render those reserves where nature is left untrammelled passé?

Here, we join Caro and others (in press, this volume) in arguing that wilderness and protected lands still constitute a viable conservation strategy in an age of shifting climate, as unmanaged wild lands serve many ecological and social purposes in rapidly changing conditions. Wilderness lands provide a benchmark by which to assess managed lands and various management strategies implemented in the nested portfolio approach described above. In fact, untreated control landscapes of ~250,000 acres (100,000 hectares) may be regarded as part of the experimental portfolio approach to climate adaptation project design. Uninterrupted or re-established fire regimes and top predator trophic interactions exist primarily within large un-managed wild lands, and the presence of large predators on the land is strongly correlated with significantly higher levels of biodiversity in ecosystems around the world (Stolzenburg 2009; Terborgh and Estes 2010). Wilderness therefore remains extremely important to managing in the Anthropocene.

In the SWCC, the unlogged forests in the Bob Marshall Wilderness where fire regimes have been re-established in recent years provide a compelling case study of how untrammelled (or untreated) “control” lands can provide insights into appropriate restoration strategies in a managed landscape (Figure 6 part C). Fire has returned to ponderosa pine, western larch, and mixed conifer forests of gentle terraces above the South Fork of the Flathead River. Effects of fire in terms of mortality, recruitment and composition of new trees, fuel loadings, spatial arrangement of tree clumps and gaps, and woody debris loads are currently being studied. These data indicate that some forest types may be more resilient to re-established fire than once perceived (Larson and others 2013a), while also providing insights into appropriate restoration treatments that could mimic nature’s patterns.

### ***Embracing diversity and heterogeneity at multiple scales to sustain resilience***

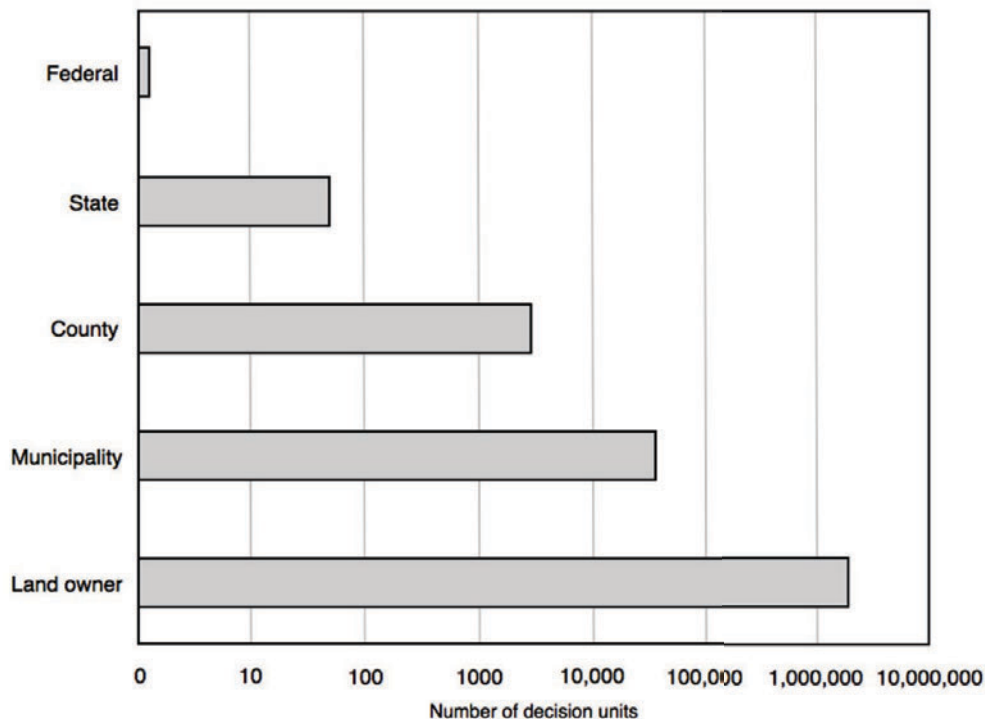
Sustaining nature’s parts and processes in the Anthropocene requires maintaining biological diversity across life’s hierarchy of organization. Growing numbers of studies link ecological function across scales of biodiversity from genetic diversity (e.g., Crutsinger and others 2006), to heterogeneity in the spatial arrangement of organisms (Larson and Churchill 2012), to landscape heterogeneity within and among ecosystems (Turner and others 2013). Therefore, to sustain these processes requires maintaining sufficient biological diversity across scales and levels of biological organization.

Biophysical diversity sets the stage for ecosystem and species diversity (Beier and Brost 2010), which occurs at various spatial scales (from diverse climatic regimes and landforms within and among continents to local edaphic and topographic effects). Local and landscape processes, such as species interactions and disturbance, further govern habitat and species diversity across more

local scales. Understanding the patterns and processes that give rise to and sustain species diversity across spatial scales has been a cornerstone of ecology for over a century and remains an important research theme of the science. Shifting climatic regimes, altered atmospheric chemistry, and introduced species may profoundly influence patterns of biodiversity distributions and ecosystem function. Basic understanding of the mechanisms that govern distributions and abundances of species and patterns of biodiversity should still provide important insights into best conservation approaches to sustain biological diversity—in all its forms—in the Anthropocene.

## NETWORKED SCIENCE AND GOVERNANCE ACROSS SCALES

The benefits of large landscape conservation lie within its inspirational vision and contextual management perspective, but these are countered by the realities of on-the-ground practice and socio-political constraints. The challenge of large landscape conservation is marrying the scale of how nature works with the scale of human decision making (Table 1). Landscapes are shaped by the decisions of multiple stakeholders. With this in mind, efforts to engage local stakeholders in landscape efforts and connect them through nested scales of conservation decision making and action are essential but often neglected in conservation investments. Similar to ecological trophic pyramids, there is a parallel land use decision making hierarchy in the United States (see Figure 7). Successful large landscape efforts need vertically integrated governance structures that link the scales of human decision making. Social agreement on shared goals and operating guidance is an essential element of landscape governance, as discussed in the SWCC example.



**Figure 7.** Land use decision-making hierarchy in the United States. This shows the number of jurisdictions (decision making units) with legal authority for making local land use decisions. Land owner is the number of large acreage agricultural land owners, a reasonable approximation of the potential number of land use decisions in the United States, which assumes that agricultural conversion is the primary form of land use change in the U.S. (from Theobald and others 2000).

There is an opportunity to bridge societal organizational scale with ecological scale through emerging network governance models. Equally so, information to assist large scale management efforts can be supported through networked science and monitoring approaches. If one critical goal of large landscape conservation is conserving ecological processes, the human response is similarly process oriented. Wise investments in stakeholder collaboration, trust building and connective organizational/community capacity will achieve this cooperative future. If information is the currency of social action, then the science community needs to engage stakeholders in research and monitoring from project inception. The technology and facilitative skill sets exist to link people and communities at large ecological scales. These collaborative efforts require long term vigilance and incentives for cooperative human action. The opportunity to establish long term conservation finance mechanisms to serve these enduring collaborative efforts have yet to be realized. Resilience funding mechanisms, similar to endowed conservation trusts, could support social engagement in large landscape conservation and leverage private and other public resources in order to sustain landscape efforts over the next century or longer.

## **CONCLUSIONS AND RECOMMENDATIONS**

Large landscape conservation is an emerging approach to address large scale impacts to the ecological integrity of the planet. Conservation within a landscape context sustains ecological processes across an array of land jurisdictions and helps to align diverse land management approaches so that ecosystem benefits and services are optimized. All land has ecological potential depending on how it is managed. Restoration practice is a key element of resilient land management. Wilderness and protected areas enhance the resilience potential of lands, especially in the face of climate change. Like some of our other colleagues in this volume (Caro and others in press), we argue that protected lands and wilderness areas continue to constitute an important conservation strategy in an era of shifting climate.

“How much is enough?” is a question that has vexed conservationists since the beginning of the modern conservation era. This question has little meaning in the Anthropocene as the planet edges towards an ecological regime shift. Ecological processes that sustain nature and humanity are dependent on functional ecology and the species interactions they depend on. The planet is now the scale of consideration and planning, and the solutions need to mirror the global impact of humanity.

Large landscape conservation requires local societal efforts to reach toward management scales that are novel and often challenging. While vision may guide these large scale efforts, social glue is required to maintain and cement them over time. New approaches to conservation need to be prototyped. In the Southwestern Crown of the Continent Ecosystem, a 1.5 million acre landscape within the much larger Yellowstone to Yukon region, we are prototyping such an approach. While relatively young in its inception, the Southwestern Crown of the Continent Collaborative is testing the following elements of large landscape conservation:

First, large landscape conservation is an approach nested within larger and smaller scales of science and implementation. Vertical integration of scales of action is needed and requires intensive work to connect individuals, institutions, and resources to perform this function. All land has ecological potential, even though the land has mixed ownership. For instance, the



Southwestern Crown of the Continent Collaborative is represented at larger scales of action through the Roundtable of the Crown of the Continent, the much larger U.S. Great Northern Landscape Cooperative, and the even larger Yellowstone to Yukon Conservation Initiative. At the same time, the SWCC embodies smaller scale initiatives such as the Blackfoot Challenge, three US Forest Service Districts and various local communities.

Second, large landscape conservation is a fusion of the spatial and temporal aspects of ecology and those of human society. Multijurisdictional facilitated processes are the new norm for conservation. Collaborative approaches to science and management that include stakeholder engagement and participation is essential. Professional conservation approaches need to empower stakeholders as conservation practitioner partners. Mechanisms that foster societal trust are essential to the success of these efforts.

Third, large landscape conservation will have a broad array of governance designs ranging from formal to informal approaches. The work in the Crown of the Continent suggests the role of network governance among stakeholder groups. The Southwestern Crown of the Continent Collaborative has developed a multi-stakeholder project implementation roundtable structure. A larger Roundtable structure exists in the Crown of the Continent to bring all ecosystem-wide efforts and stakeholders together. While a common set of principles and an organizing charter serve as collaborative touchstones for this coordination, these roundtable efforts are an example of network governance.

And finally, large landscape conservation science and monitoring integrates formal and informal information processes from rigorous experimental methods to traditional ecological knowledge. Interdisciplinary science is an essential element of this work. Science and monitoring should embrace a networked science approach where science, monitoring, metadata and local information is handled in a transparent and accessible fashion. This includes enlisting all stakeholders in the practice of science and monitoring.

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# Implementing Climate Change Adaptation in Forested Regions of the United States

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**Abstract:** *Natural resource managers need concrete ways to adapt to the effects of climate change. Science-management partnerships have proven to be an effective means of facilitating climate change adaptation for natural resource management agencies. Here we describe the process and results of several science-management partnerships in different forested regions of the United States (U.S.), including the Pacific Northwest, interior West, Pacific Southwest, and Upper Midwest and Northeast. Led by U.S. Forest Service scientists, these partnerships were developed to adapt resource management in National Forests, national parks, and land managed by other federal and state agencies to climate change and typically involved vulnerability assessments and science-management workshops to develop adaptation strategies and tactics. We discuss commonalities among these efforts, specific outcomes, and applicability to other regions and adaptation efforts.*

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## INTRODUCTION

Federal land management agencies in the United States are beginning to incorporate climate change into their management planning and operations. Department- and agency-level strategic plans and directives are increasingly recognizing the importance of incorporating climate change in agency activities. For example, Secretary of the Interior Order 3289, signed in 2009 and amended in 2010, suggests that potential climate change impacts necessitate changes in how the U.S. Department of the Interior (USDO I) manages natural resources and requires its agencies to incorporate climate change in planning, prioritization, and decision-making (USDO I 2009). Similarly, in the U.S. Department of Agriculture (USDA) strategic plan for fiscal years 2010–2015 (USDA 2010), one of four strategic goals is to ensure that National Forests and private working lands are conserved, restored, and made more resilient to climate change, and a 2011 Departmental Regulation (DR-1070-001) (USDA 2011), required the USDA and each agency within to prepare a climate change adaptation plan. More

recently at the executive level, President Obama issued Executive Order 13653, “Preparing the United States for the Impacts of Climate Change” (Obama 2013). The Executive Order requires the heads of the Departments of Defense, the Interior, and Agriculture, the Environmental Protection Agency, the National Oceanic and Atmospheric Administration, the Army Corps of Engineers, and other agencies to work with the Chair of CEQ and the Director of the Office of Management and Budget to, “complete an inventory and assessment of proposed and completed changes to their land- and water-related policies, programs, and regulations necessary to make the Nation’s watersheds, natural resources, and ecosystems, and the communities and economies that depend on them, more resilient in the face of a changing climate.” The assessments are required to include a timeline and plan for making changes to policies, programs, and regulations.

Agency directives have spurred a flurry of climate change-related activity in federal land management agencies over the last few years. From that activity, science-management partnerships have emerged as effective catalysts for development of vulnerability assessments and land management adaptation plans at both the strategic and tactical level (Cross and others 2013; Gaines and others 2012; Littell and others 2012; McCarthy 2012; Peterson and others 2011; Swanston and Janowiak 2012). Science-management partnerships typically involve iterative sharing of climate and climate effects information by scientists, and of local climate, ecological, and management information by managers. This iterative information exchange aids identification of vulnerabilities to climate change at the local scale and sets the stage for development of adaptation strategies and tactics, often developed through facilitated workshops.

The U.S. Forest Service (USDA FS) administers 78 million ha (193 million acres) of land in 155 National Forests and 20 national grasslands. The USDA FS is responsible for restoring, sustaining, and enhancing forests and grasslands while providing and sustaining benefits to the American people. Forest Service scientists and land managers are tasked with reducing the effects of climate change on ecosystem function and services (USDA FS 2008, 2011a). Partnerships among scientists in the Forest Service Research and Development branch, managers in the National Forest System, and other agencies and universities have played a major role in advancing climate change adaptation in the agency. Development of science-management partnerships is a performance measure in the USDA FS Climate Change Performance Scorecard (USDA FS 2011b), which rates National Forests on how well they are responding to climate change. Here, we describe the process and outcome of several recent science-management partnerships led by the USDA FS, identify key elements, and discuss future application to other regions.

## **ADAPTATION THROUGH SCIENCE–MANAGEMENT PARTNERSHIPS: STRUCTURE, PROCESS, AND OUTCOMES**

### ***Interior West***

As a part of the WestWide Climate Initiative (Peterson and others 2011), a science-management partnership was initiated among a research scientist from the USDA FS Rocky Mountain Research Station office in Fort Collins, Colorado; the regional ecologist from the USDA National Forest System, Rocky Mountain Region’s office in Lakewood, Colorado; and the resource staff officer from the Shoshone National Forest supervisor’s office in Cody, Wyoming. The partnership was initiated to determine the potential effects of climate change on Shoshone National

Forest and develop tools to help national forest land managers adapt their management to climate change. Over time, involvement from the regional office and Shoshone National Forest expanded to include experts in wildlife, water, ecology, and planning. The scientists at Western Water Assessment at Cooperative Institute for Research in Environmental Sciences and the University of Colorado became important partners. In addition, scientists from the U.S. Geological Survey (USGS) and several universities participated in partnership activities. Periodic briefings were held at the Shoshone National Forest and in the regional office to keep interested staff updated on activities.

Initial discussions identified the need to synthesize the literature on climate change specific to the Shoshone National Forest and surrounding area. A report, “Climate Change on the Shoshone National Forest, Wyoming: A Synthesis of Past Climate, Climate Projections, and Ecosystem Implications” was jointly written by Rocky Mountain Research Station and National Forest staff to synthesize current scientific information about prehistoric, recent, and future climate and how future warming may affect natural resources on Shoshone National Forest (Rice and others 2012). A focused review of the potential impacts of climate change on quaking aspen (*Populus tremuloides* Michx.) was also conducted in cooperation with other scientists in the WestWide Climate Initiative, because aspen is a high priority for management across the western United States (Morelli and Carr 2011).

Staff on the Shoshone National Forest expressed a desire to interact with scientists on specific topics and to have sufficient time for discussion of each topic. Thus, the Natural Resource and Climate Change Workshop was held in Cody, Wyoming in 2011. The workshop was attended by over 50 participants from Shoshone National Forest, other federal and state agencies, and private sector organizations. Topics covered in the workshop, selected by Shoshone National Forest staff, included climate change, snow pack, and vegetation models. Seven local experts in the fields of climate and climate change effects, water resources, snow and glaciers, ecosystem modeling, Yellowstone cutthroat trout (*Oncorhynchus clarkii bouvieri*), and recreation and tourism offered information about climate and potential effects in the Shoshone area (USDA FS 2011c).

Both during the workshop and afterwards, discussions among scientists, and regional and Shoshone National Forest staff led to the identification of key resources for further consideration. These high-priority resources included water availability, Yellowstone cutthroat trout, and quaking aspen, and partnership scientists and managers conducted a vulnerability assessment for each resource. The vulnerability assessment for water availability was developed to provide information about the effects of climate change on water resources in the Shoshone National Forest region, an important source of water for human uses. For the Yellowstone cutthroat trout, a customized vulnerability assessment tool was developed using indicators for climate change exposure as well as inherent landscape, anthropogenic, and ecological factors of sensitivity and adaptive capacity (Rice and others, in review). This tool provides information to guide adaptation strategy development and conservation and monitoring planning (Rice and others, in review).

Aspen in Shoshone National Forest currently occupies a fraction of its potential habitat based on climate, topography, and soils, which suggest that its distribution is constrained by other factors. The question of where aspen may exist in the future could not be completely addressed in the assessment, although the assessment pointed to the potential for an expansion of aspen because of projected changes in climate (Rice and others, in preparation). The effects of other factors,



such as conifer competition, fire regime, insects and pathogens, and wildlife browsing likely cause spatial and temporal variability of aspen distribution and abundance that may continue to be dynamic under climate change.

The results of the vulnerability assessments conducted through the partnership have informed conservation project planning for Yellowstone cutthroat trout, helped to inform the selection of hydrologic monitoring locations, and provide vulnerability information for the future management of water availability in grazing allotments. Rice and others (2012) was extensively used in the recent Shoshone National Forest planning process.

### ***Pacific Northwest***

In the first formal project to address climate change in a national forest, a science-management partnership was initiated by the USDA FS Pacific Northwest Research Station, Olympic National Forest, and Olympic National Park (Halofsky and others 2011b). Building on a long history of cooperation between a national forest and national park located on the Olympic Peninsula, this project engaged scientists and resource managers in a sequence of educational workshops, development of a vulnerability assessment, and compilation of adaptation options.

Early discussions among scientists and natural resource managers identified the need to increase awareness of climate change among federal natural resources managers on the Olympic Peninsula and assess the vulnerability of natural resources at Olympic National Forest and Olympic National Park. Four separate workshops were convened on the topics of hydrology and roads, fisheries, vegetation, and wildlife, with participants from different federal and state agencies, tribes, and other groups attending each workshop. At each workshop, scientists from the Forest Service and University of Washington provided state-of-science summaries on the effects of climate change on natural resources, and scientists and managers worked together to identify the most important impacts on the Olympic Peninsula. Smaller workshops were then convened with a core group of scientists and managers to review the vulnerability assessment and develop adaptation strategies and tactics for each of the four resource areas. All information was subsequently peer reviewed and published as documentation for management and decision making (Halofsky and others 2011b).

Building on knowledge gained from working with Olympic National Forest and Olympic National Park, the North Cascadia Adaptation Partnership (NCAP) was subsequently initiated in north-central Washington in 2011. The partnership covers 2.4 million ha (59 million acres) across the west and east sides of the Cascade Range and includes Mount Baker-Snoqualmie National Forest, Okanogan-Wenatchee National Forest, North Cascades National Park Complex, and Mount Rainier National Park (Raymond and others 2013; Raymond and others, in press). This diverse, mountainous region contains temperate rainforest, subalpine and alpine ecosystems, extensive dry forests subject to frequent fire, and shrub-steppe ecosystems. It also contains 17 000 km of roads and is adjacent to densely populated areas of western Washington.

The NCAP project started with one-day educational workshops at each of the four management units, which included resource managers, line officers, administrative personnel, and various stakeholders. Then, four two-day workshops were convened for all management units combined, with one workshop focused on each of the following topics: hydrology and access, fisheries,

vegetation and ecological disturbance, and wildlife. The first day of each workshop focused on developing summaries of resource sensitivities as components of the vulnerability assessment, with scientists leading the discussion and managers contributing data and information on specific locations. The second day of the workshop focused on adaptation to sensitivities identified for each of the four resource areas, with managers providing both adaptation strategies useful for planning and adaptation tactics useful for on-the-ground applications. Information discussed and written at workshops was compiled in peer-reviewed documentation that will be used by the National Forests and national parks (Raymond and others 2013; Raymond and others, in press).

The NCAP project was premised on an “all lands” approach that considered public, private, and tribal lands other than Forest Service and National Park Service lands. Individuals from about 40 different federal and state agencies, tribes, and conservation groups participated in the workshops and assisted with identification of resource issues and adaptation options. The NCAP catalyzed an ongoing dialogue on climate change in the North Cascades region that has persisted beyond the formal phase of the project. For example, additional workshops have been convened on how climate change will affect extreme flood events that have the potential to damage roads on the west side of the Cascades. Workshops have also been convened to focus on how climate change will affect fisheries and estuarine systems in the Skagit River basin, a major watershed in the NCAP project area.

### ***Pacific Southwest***

In 2009, as a part of the WestWide Climate Initiative (Peterson and others 2011), a science-management partnership was established between research scientists at the USDA FS Pacific Southwest Research Station and managers at Inyo National Forest and Devils Postpile National Monument in the Sierra Nevada, California. This effort aimed to develop tools and information to help forest and park managers adapt their management and planning to climate change. At the start of the project, Inyo National Forest was beginning revision of its land management plan, and Devils Postpile National Monument was beginning development of a general management plan to identify long-term desired conditions for the monument and guide park managers as they decide how to best protect monument resources and manage visitation. After initial meetings to determine the direction of the partnership, the team determined that facilitated sharing of knowledge about climate change and its effects through targeted workshops and assessment reports (developed by scientists) would help managers integrate climate change into planning and management.

Inyo National Forest staff had several specific requests of scientists in the partnership: (1) compile a summary of climate trends and adaptation options relevant to the eastern Sierra Nevada, (2) develop a regional bibliography of information on climate change, (3) establish a technical advisory board that includes climate scientists conversant in eastern Sierra Nevada regional issues, (4) prepare a report and field survey for a potentially novel climate threat to quaking aspen in the eastern Sierra Nevada, (5) participate in the public engagement process before the land management plan revision process, and (6) conduct facilitated climate applications workshops. A desired outcome of the partnership was for Inyo National Forest to implement resource treatments developed by partnership discussions and products, and to incorporate climate considerations in the land management plan revision.

Priorities identified by staff at Devils Postpile National Monument, whose lands are surrounded by Inyo National Forest, included a need for high-resolution climate monitoring and information on the potential role of the monument as a cold-air pool that could serve as a climate refugium for some species. The latter led to a request for scientists to develop an analysis of cold-air pooling in the upper watershed of the monument. Partnership activities at the monument had a strong focus on science, including a combined field and classroom workshop, summary of ongoing research, and synopsis of research and monitoring efforts needed to guide future adaptation efforts. A scientific technical committee was also convened to consult on general management plan development and advise on implementation of adaptation treatments.

The science-management workshop conducted at Inyo National Forest, “Evaluating Change in the Eastern Sierra”, was attended by a mix of federal, university, and other scientists, resource specialists, and concerned citizens. Scientists presented information on climate projections at the global, regional, and local scale, and discussed effects on other resources, such as vegetation (Morelli and others 2011). Implications for the Inyo National Forest were then discussed. For Devils Postpile National Monument, a science-management workshop was held with scientists from the USDA FS and USGS and managers from the National Park Service. The workshop included presentations on climate and hydrologic projections relevant to Devils Postpile National Monument as well as physical and ecological vulnerabilities and potential effects on visitors and infrastructure. Presentations were followed by a general discussion on implications for managing Devils Postpile National Monument as a refugium in an uncertain future.

In addition to education and training through facilitated workshops, outcomes of the science-management partnership in the eastern Sierra Nevada included several reports and tools. For Inyo National Forest, scientists developed a report reviewing aspen response to climate and describing an aspen screening tool (Morelli and Carr 2011). The Climate Project Screening Tool (Morelli and others 2012) was developed to provide a screening process to assess if climate change would affect resources involved in management projects in line for implementation. A report summarizing some of the latest data on climate change projections and effects relevant for eastern California was developed for use by land managers in the Sierra Nevada (Morelli and others 2011). In anticipation of the potential for Devils Postpile National Monument to serve as a climate change refugium, owing to its position at the bottom of a canyon with cold-air drainage, a network of temperature sensors in multiple-elevation transects and a climate monitoring station were recently installed to measure temperature patterns.

### ***Upper Midwest and Northeast***

The Forest Service in the Upper Midwest and Northeast created a structured approach to addressing the issue of climate change in forest management, led by the Northern Institute of Applied Climate Science. This approach, now called the Climate Change Response Framework (CCRF), needed to be responsive to the particularly diverse nature of the ownership patterns and forest practices within the region, in which National Forests and other federal lands comprise a small minority of all forested lands. The CCRF was designed to be a comprehensive program to support original science, literature synthesis, vulnerability assessment, education and outreach, adaptation planning, and adaptation implementation.

The goal was not to guide specific actions, but to instead foster climate-informed decisions in meeting a wide variety of management objectives. Meeting the needs of numerous land management organizations through an “all lands” approach required that the CCRF be flexible enough to be applied at multiple spatial and temporal scales, and address diverse management goals. Addressing the information and planning needs of the National Forests was thus a considered a core component of the CCRF, but providing information, tools, and outreach to the broader forestry community was equally critical. This was fully in keeping with the mission of the Forest Service and the explicit commitment of the Forest Service Eastern Region, Northeastern Area State and Private Forestry, and Northern Research Station to work together to support sound land stewardship across all lands ([http://www.na.fs.fed.us/stewardship/pubs/conservation/land-scale\\_conservation.pdf](http://www.na.fs.fed.us/stewardship/pubs/conservation/land-scale_conservation.pdf)).

The pilot for the CCRF was formally launched in northern Wisconsin in 2009, and the Chequamegon-Nicolet National Forest served as a “living laboratory” for the development of ideas, processes, and tools. The staff of the Chequamegon-Nicolet was absolutely essential to the evolution and success of the CCRF, providing valuable time, expertise, and often the hard voice of reality to the project. Likewise, their professional relationships in the broader forestry community helped the project grow in scope and experience. From the original pilot in northern Wisconsin, the CCRF is now being actively pursued in nine states in areas covering nearly 53 million hectares in the Northwoods (Michigan, Minnesota, and Wisconsin), Central Hardwoods (Illinois, Indiana, and Missouri), and Central Appalachians (Maryland, Ohio, and West Virginia). There are currently over 70 non-profit, private, county, state, tribal, and federal organizations partnering in the ecoregional CCRF projects.

A pilot forest ecosystem vulnerability assessment (Swanston and others 2011) and Forest Adaptation Resources book (Swanston and Janowiak, 2012) for northern Wisconsin have been published, and lessons learned from those efforts are being applied to five new vulnerability assessments (Brandt and others, in press; Handler and others, in press a/b) and an expansion of the Forest Adaptation Resources. The vulnerability assessments include chapters on 1) the contemporary landscape; 2) climate and climate modeling; 3) historic climate in the analysis area; 4) a range of projected, downscaled climates for the analysis area; 5) a literature synthesis of potential climate change impacts on forest ecosystems, and results of vegetation impact models from three different modeling platforms applied to the analysis area under a range of plausible climates (“bookends”); 6) an assessment of plausible regional climate shifts and corresponding ecosystem vulnerabilities; and 7) management implications of these shifts and vulnerabilities. A panel of ecologists, modelers, and land managers from numerous organizations were brought together through a structured expert elicitation process to produce the core of the actual assessment. They are led through a series of steps to identify and generate consensus on the vulnerability of key ecosystems being considered in the assessment, and then proceed to provide feedback on the subsequent vulnerability assessment chapters. The assessments do not make recommendations, but the Forest Adaptation Resources strategies menu and adaptation workbook can help managers choose the adaptation approaches most likely to meet their management goals.

Generating credible information about climate shifts and ecosystem vulnerability will inject critical information into the already enormous stream of information considered by land managers. However, generating clear examples of the application of that information in a realistic management context is necessary to operationalize climate-informed decision making. Creating

these examples on a variety of land ownerships pursuing a wide range of management goals is thus a major objective of the CCRF. A community website ([www.forestadaptation.org](http://www.forestadaptation.org)) serves as a common link between several sub-regional communities of practice, where these adaptation demonstrations can be briefly presented. Likewise, dozens of workshops, trainings, and conferences related to the CCRF have brought people together to discuss climate changes and forest and management responses. For those who are not interested in numerous seminars and want to get something done, the Forest Adaptation Planning and Practices training was designed to accommodate multiple organizations in a single training where participants bring real-world forest management projects and develop actionable adaptation steps using the Forest Adaptation Resources tools. Pre-work helps participants arrive ready to plan, and post-training follow-up aids organizations in their implementation processes.

The CCRF continues to grow, with new projects being planned in the Northeast and mid-Atlantic. Climate challenges can most effectively be addressed by a community, and the CCRF has successfully built a large-scale ecoregional network with widely diverse expertise, perspectives, and resources.

### ***Keys to Successful Adaptation Partnerships***

To date, all adaptation projects in National Forests and adjacent lands have used a number of common approaches and accomplished similar outcomes despite the fact that they were conducted in different geographic locations with varied natural resources issues and with different groups of managers (Peterson and others 2011). First, each project was developed on the foundation of a strong and enduring science-management partnership (Littell and others 2012) initiated by a Forest Service research station. Building these partnerships, which typically included other agencies (especially the National Park Service) and stakeholders (Table 1), required substantial time and energy to establish personal relationships and build trust. Having individuals to serve as liaisons between climate scientists and managers was critical, and the partnerships went well beyond simply providing climate data on a website or in a database for managers to access. The partnerships have persisted through time, even beyond the end of the original project, because of the effort that went into establishing relationships and providing information that can be directly applied to management.

Second, each project included an educational component in which natural resource personnel, line officers, and in some cases, administrative staff attended sessions in which they learned about the latest science on climate change and climate change effects, and shared their experiences with climate-related resource issues (Halofsky and others 2011a). This baseline of knowledge is critical for identifying key climate change vulnerabilities, developing adaptation plans, enhancing monitoring efforts, and generally incorporating climate change in planning and management.

Third, each project focused a great deal of effort on producing a peer-reviewed assessment of the vulnerability of natural resources to climate change (Table 1), in order to identify resources most at risk. These assessments, typically led by Forest Service scientists in collaboration with other agencies and universities, were state-of-the-science syntheses that focused on the topics considered by resource managers to be the most important (e.g., hydrology, fisheries, vegetation). Considerable effort was focused on downscaling and customizing information, often large scale and general in nature, to specific landscapes and resource management issues.

**Table 1.** Units involved, focus topics, and products for five science-management partnerships conducted with Forest Service Research and Development across the United States.

<b>Partnership name</b>	<b>Geographic region</b>	<b>Primary partnering units</b>	<b>Focus topics</b>	<b>Published tools and reports</b>
Inyo National Forest and Devils Postpile National Monument Case Study	Pacific Southwest	U.S. Forest Service Pacific Southwest Research Station, Inyo National Forest, and Devils Postpile National Monument	Quaking aspen, cold air pooling	Morelli and Carr 2011; Morelli and others 2011, 2012
North Cascadia Adaptation Partnership	Pacific Northwest	Forest Service Pacific Northwest Research Station, Mt. Baker-Snoqualmie National Forest, Okanogan-Wenatchee National Forest, North Cascades National Park Complex, and Mount Rainier National Park	Hydrology and access, fisheries, vegetation and ecological disturbance, and wildlife	Raymond and others 2013; Raymond and others, in press
Northwoods Climate Change Response Framework Project	Lake States	Forest Service Northern Institute of Applied Climate Science, Chequamegon-Nicolet National Forest	Forest ecosystems, carbon stocks	Swanston and others 2011; Swanston and Janowiak 2012
Olympic National Forest Case Study	Pacific Northwest	Forest Service Pacific Northwest Research Station, Olympic National Forest, Olympic National Park, University of Washington Climate Impacts Group	Hydrology and roads, fisheries, vegetation, wildlife	Halofsky and others 2011b
Shoshone National Forest Case Study	Interior West	Forest Service Rocky Mountain Research Station, Shoshone National Forest, National Forest System Rocky Mountain Region	Water availability, Yellowstone cutthroat trout, and quaking aspen	Morelli and Carr 2011; Rice and others 2012; Rice and others in review

Fourth, each project based the development of adaptation options directly on the vulnerability assessment and known principles of climate change adaptation (Joyce and others 2008, 2009; Peterson and others 2011). Scientists provided information on resource sensitivity to climate change for different scenarios, and resource managers responded with solutions for mitigating resource risk (Table 2). These responses typically included both an overarching adaptation strategy (conceptual, general) and a subset of adaptation tactics (specific, on the ground) for each strategy (Peterson and others 2011; Raymond and others 2013; Swanston and Janowiak 2012).

Commitment to regular, clear communication was a key to the success of all projects. Scientists spent many days on the ground in national forest landscapes and in offices where resource managers work. These conversations and experiences were critical for getting iterative feedback on the vulnerability assessment, management issues, and potential applications of climate change information. There is no substitute for scientists (typically with more discretionary time) working directly with resource managers (typically with minimal discretionary time) to ensure that the vulnerability assessment and adaptation options are relevant to local planning and management.

### ***Picking up the Pace: A Challenge for the Future***

Resource managers and leadership in National Forests and other lands where projects were conducted consistently cite the value of the projects in providing a new context for resource management and in enhancing “climate smart” thinking. However, implementation of information derived from climate change vulnerability assessments in national forest and national park resource assessments and monitoring is uncommon. Inclusion of climate change adaptation strategies and tactics in resource planning and project plans is just starting, even though current practices are often highly compatible with deliberate actions that enhance the ability of forests to adapt to climate change. More time may be needed for the climate change context of resource management to be incorporated as a standard component of agency operations.

At the national level, the federal agencies have a strong focus on advancing climate change issues. At the local scale, many management units would like to develop vulnerability assessments and adaptation plans. However, in the absence of a mandate to do so, the process of developing projects similar to those described above will continue to be slow. The USDA FS Climate Change Performance Scorecard requires development of climate change vulnerability assessments and adaptation plans, but the mandate is largely unfunded. Efforts to accelerate climate change implementation in National Forests come during a period of steep budget decreases, making it difficult to implement planned projects and initiate new projects. At the present time, relatively few National Forests have undertaken significant steps towards completing vulnerability assessments and adaptation plans, and the status of adaptation planning in other agency units is similar (Bierbaum and others 2013).

The slow pace of federal agencies in emulating the processes and applications described above (Peterson and others 2011) can be increased by mainstreaming (or operationalizing) climate change as a part of standard operations in the National Forest System and other federal lands. This transition has been enabled by various strategic documents in the Forest Service and other agencies. Concepts such as ecosystem-based management and ecological restoration that were originally plagued by skepticism and uncertainty evolved into operational paradigms. So too must climate change become incorporated in thought, actions, and management guidance; climate

**Table 2.** Examples of climate change sensitivities and related adaptation strategies and tactics. In science-management partnerships, sensitivities are typically communicated by scientists, and adaptation strategies and tactics are developed by land managers based on sensitivities.

Sensitivity	Adaptation strategy or tactic	
Increased opportunity for invasive species establishment	Implement early detection/rapid response for exotic species treatment	
Potential for mortality events and regeneration failures, particularly after large disturbances	<p>Develop a gene conservation plan for ex situ collections for long-term storage</p> <p>Identify areas important for in situ gene conservation</p> <p>Maintain a tree seed inventory with high quality seed for a range of species</p> <p>Increase production of native plant materials for post-flood and postfire plantings</p>	
Increased forest drought stress and decreased forest productivity at lower elevations	<p>Increase thinning activities</p> <p>Use prescribed burns and wildland fire to reduce stand densities and drought stress</p>	
Increased winter and spring flooding	<p>Implement more conservative design elements (more intensive treatments such as larger diameter culverts, closer spacing between ditch relief culverts and waterbars)</p> <p>Increase maintenance frequency of drainage features</p>	



change needs to become a standard component in strategic planning, project planning, monitoring, and implementation. This will likely come with increased awareness of climate change, understanding of the potential effects of climate change, and the development and awareness of effective responses to decrease resource vulnerabilities.

Scientific knowledge about the effects of climatic variability and change on natural resources is for the most part not a limiting factor in moving forward with climate change activities in National Forests and other federal lands. However, effective transfer of climate-related knowledge from the scientific to the management community is lacking, and thus so is the application of the information in natural resource management. Future efforts can therefore focus on the synthesis of relevant scientific information for specific landscapes (vulnerability assessment), effective transfer of that information to the management community, and then development of responses that reduce negative effects on resources (adaptation planning). This can be expedited in agencies like the Forest Service and National Park Service by institutionalizing science-management partnerships to facilitate climate change adaptation and associated processes. An ideal partnership in the Forest Service includes scientists from research stations, resource managers in National Forests, and subject matter experts from regional offices, along with scientists and managers from other agencies, universities and organizations. National Oceanic and Atmospheric Administration Regional Integrated Sciences and Assessments (RISA) program scientists were involved in the adaptation partnership developed with Olympic National Forest and Olympic National Park (Halofsky and others 2011b), in the NCAP effort (Raymond and others 2013; Raymond and others, in press), and in the Shoshone National Forest effort, and scientists from RISA centers and USDOJ Climate Science Centers could be key partners in future efforts. If participants in these partnerships work on multiple projects, they will accrue knowledge that will make each subsequent project more effective and efficient. In addition, vulnerability assessments and adaptation plans can be developed for clusters of National Forests and Parks (and, potentially, adjacent federal, tribal, and other lands) with similar biogeographic characteristics and management objectives, resulting in time and budgetary efficiencies. Different clusters of management units may be appropriate for different resources.

We are optimistic that climate change can be mainstreamed in the policies and management of the Forest Service and other federal agencies by the end of this decade. This can be expedited by considering climate change as one of many risks to which natural resources are subjected (Iverson and others 2012), and by considering adaptation as a form of risk management. This approach has been recently described for water resources, fire, carbon, forest vegetation, and wildlife (Peterson and others, in press; Vose and others 2012), and will be fully incorporated in future U.S. National Climate Assessments and assessments by the Intergovernmental Panel on Climate Change (Yohe and Leichenko 2010). We anticipate that evaluating climate change risks concurrently with other risks to resources will become standard practice over time.

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# Improving the Role of Vulnerability Assessments In Decision Support for Effective Climate Adaptation

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**Abstract:** *Vulnerability assessments (VA) have been proposed as an initial step in a process to develop and implement adaptation management for climate change in forest ecosystems. Scientific understanding of the effects of climate change is an ever-accumulating knowledge base. Synthesizing information from this knowledge base in the context of our understanding of ecosystem responses to natural/historical climate can be challenging. Little attention has focused on how information gathered in the vulnerability assessment phase actively facilitates the implementation of adaptation actions, that is, how and whether VA outputs actually are being used in resource projects. Given that financial and staffing resources remain critical barriers for natural resource managers, the assessment of vulnerability needs to be an effective and efficient process. We explore the success of VAs in motivating implementation of adaptation practices and offer recommendations on the development of future vulnerability assessments in natural resource management. Implementation of adaptation options may be more closely related to the extent that the VA and associated processes provided an opportunity for social learning.*

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## INTRODUCTION

The societal challenge associated with climate change involves not only improving our scientific understanding of the consequences of a changing climate but also communicating that understanding so that resource managers and the public can address the need for adaptation. The continually increasing additions of greenhouse gases to the atmosphere and concerns about consequent climate change have prompted resource managers to consider the need to include adaptation to climate change in the management of ecosystems (U.S. White House 2009; USDI 2009; USDA Forest Service 2012). Adaptation actions for ecosystem management on increasingly altered landscapes of the Anthropocene need a scientific basis (Peterson and other 2011). Initial motivation for understanding climate change began at the global scale (IPCC 1990), far from the scope of resource management; consequently developing adaptation options in resource

management necessitates sifting through the accumulated knowledge and applying it to a finer spatial scale.

Adaptation actions also need to reflect the experiential knowledge that forest managers have gained from implementing management in site-specific locations. Initial attempts to communicate the scientific understanding of climate change used descriptions such as ‘novel’, i.e., unlike anything seen in the past; reinforcing a perspective that past and current experience with climate, weather, and forest resources would have little or no relevance to the future. Further, resource managers often were not a part of the conversation that scientists were having in the multi-decadal accumulation of climate change research (Powledge 2008). This lack of recognition and participation disrupted possibilities for mutual sharing of scientific knowledge and experiential knowledge on climate change effects and natural resource responses. Similarly, cultural and institutional differences among concerned groups (scientists, resource managers, diverse members of the public)—even the way language is used—have impeded effective integration of knowledge into climate adaptation projects. This has been problematic especially when efforts were done with limited participation by different interest groups.

Recent reviews suggest that while adaptation actions have been implemented, much is still to be done across federal, tribal, state, and local governments and the private sector in the United States (Ford and Pearce 2010; Bierbaum and others 2013). In a survey of natural resource managers in Colorado, Utah and Wyoming, only 5 percent of the respondents reported that adaptation plans were currently being implemented or carried out (Archie and others 2012). Across the public and private spectrum, Bierbaum and others (2013) noted that the greatest barriers to implementing adaptation actions were mainly lack of funding, policy and institutional constraints, and difficulty in anticipating climate change given the current state of information on change. The greatest barriers identified by federal resource managers in the Pacific Northwest were insufficient climate change impacts information at scales relevant to regional or local level management; insufficient financial and staff resources; and insufficient support and/or knowledge from stakeholder groups (Jantarasami and others 2010). Information barriers were identified as three of the top five barriers to adaptation planning reported by federal resource managers in Colorado, Wyoming and Utah: lack of information at relevant scales, lack of useful information, uncertainty in available information (Archie and others 2012). In a comparison of public lands managers and municipal officials, Archie and others (2014) found that lack of information at relevant scales was a much stronger barrier for federal management than for rural communities.

An early step in nearly all adaptation planning frameworks (NRC 2010; Bierbaum and others 2013) is the assessment of vulnerability. This step accumulates and synthesizes information to develop an understanding of the potential changes in climate and the potential impacts of these changes on natural resources and the human communities. A variety of qualitative and quantitative approaches are being taken to assess vulnerability and risks from climate change, including case studies and analogue analyses, scenario analyses, sensitivity analyses, formalized scenario planning, peer information sharing, and monitoring of key species and ecosystems (Bierbaum and others 2013). However, little attention has focused on how information gathered in the vulnerability assessment phase actively facilitates the implementation of adaptation actions (Archie and others 2014), that is, how and whether VA outputs actually are being used in resource projects. Given that financial and staffing resources remain critical barriers for natural resource managers, the assessment of vulnerability needs to be an effective and efficient process.

We explore the success of VAs in motivating implementation of adaptation practices and offer recommendations on the development of future vulnerability assessments in natural resource management.

### ***Defining Vulnerability Assessments for Resource Management and for Climate Adaptation***

At this time, there is no standard definition of vulnerability with respect to climate change or a standard methodological approach for the vulnerability assessment of climate change (hereafter “VA”) (Fussler and Klein 2006; USGCRP 2011). Vulnerability with respect to disaster is couched in the context of the social construct of individuals and communities, characteristics such as income level, race, ethnicity, health, language, literacy, and land-use patterns. In natural resources, vulnerability has typically focused on sensitivity of plants, animals, and terrestrial and aquatic ecosystems to climate and other stressors, their exposure to these stressors, and the corresponding implied impact on humans from the resource effect (Glick and others 2011; USGCRP 2011; Furniss and others 2013). In many of the existing assessments, the social and economic effects of climate are under-represented (USGCRP 2011).

Guidelines have been developed for stand-alone VAs using the exposure, sensitivity and adaptive capacity framework (Glick and others 2011; Furniss and others 2013) and for VAs that are embedded in broader adaptation planning efforts (Nitschke and Innes 2008; Peterson and others 2011; Swanston and others 2012). Both Glick and others (2011) and Peterson and others (2011) identify the first step as determining objectives and scope of the assessment (Table 1). Glick and others (2011) stress that 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. To date, VAs in natural resources have been conducted as research studies (Hameed and others 2013), as stand-alone efforts (Coe and others 2012), or in science-management partnership settings (Swanston and others 2011). Goals of vulnerability assessments have been placed in the context of a larger adaptation planning effort (Raymond and others 2013; Swanston and Janowiak 2012) or as a single focused project related to an opportunity of the moment, funds or political will (Yuen and others 2013).

Gathering of relevant data and expertise, in particular to identify appropriate tools, is the second step in the VA process (Table 1). Relevant data are typically seen as scientific information or resource inventory information (Peterson and others 2011), and they can also include traditional knowledge (Laidler and others 2009), expert elicitation (Alessa and others 2008; McDaniels and others 2010; Moyle and others 2013), as well as the literature synthesis (for example, Johnston and others 2009; Lindner and others 2010; Erickson and others 2012). A wealth of quantitative tools has been developed and implemented either by the developer or a user (NatureServe tool: Young and others 2009, 2010, Amberg and others 2012, Wildlife Action Plan Team 2012; SAVs: Bagne and others 2011, Coe and others 2012, Bagne and Finch 2013, web-based tools: Treasure and others 2012; framework and tools: Swanston and Janowiak 2012; see also Table 2). In addition, assessments reports have been posted online by developers or accumulated on websites such as the State of California ([http://www.dfg.ca.gov/Climate\\_and\\_Energy/Vulnerability\\_Assessments/](http://www.dfg.ca.gov/Climate_and_Energy/Vulnerability_Assessments/)).



**Table 1.** Key Steps for Assessing Vulnerability to Climate Change (from Glick and others 2011)

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**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
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Vulnerability assessments can be qualitative or quantitative. This third step brings together the information developed and an understanding of confidence in this information (Table 1). Here also, the assessment begins to meld the understanding of vulnerability with the potential for adaptation. Stand-alone vulnerability assessments may complete the process with publication of results. Where the assessment is embedded in a broader adaptation planning process (step 4), the assessment can form the scientific basis for management actions under climate change. Too few examples exist to assess if stand-alone vulnerability assessments will be used in adaptation planning by land management agencies and clearly examples exist where the broader adaptation planning process has failed to develop adaptation actions (Yuen and others 2013). Extant VAs have been critiqued for a lack of clear definitions of vulnerability and adaptive capacity (ability to accommodate change; resilience), incomplete data or information, weakly described interactions between climate change and other stressors in the assessment, lack of tools to successfully prioritize among sensitive resources, and gaps in communication between experts conducting the assessment and the vulnerable groups (USGCRP 2011). Clearly, there is a need to establish a more rigorous link between information provided and information needed in the vulnerability assessment process.

**Table 2.** Vulnerability Assessments of species, habitats, and ecosystems in forested systems.

<b>Geographic focus</b>	<b>Participants</b>	<b>Methods</b>	<b>Science-management partnership</b>	<b>Adaptation actions identified or Opportunities for social learning outside of the assessment process</b>	<b>Citation</b>
Arctic region	State and federal scientists	Used existing data and the Delphi method to develop an index of vulnerability; engaged local experts to rate the indicators. Conducted three case studies to get community feedback on the index	No	Proposed as a tool that Arctic communities can use to assess their relative vulnerability—resilience to changes in their water resources from a variety of biophysical and socioeconomic processes	Alessa and others 2008
Canada’s tree species	Federal and province scientists	Literature review, modeling exercise	No	Management options identified	Johnston and others 2009
Bushfire vulnerability	Federal, non-governmental, and university researchers	Maps of relevant biophysical and socio-economic indicators to assess exposure, sensitivity and adaptive capacity	No	No adaptation actions identified in the study however results were later used by local governments in ICLEI’s Adaptation Initiative Pilot Program which provided these governments with additional opportunities to strategize about adaptation; Workshop setting to present results of the assessment; initial reactions did expand the involvement of stakeholders in the project. Reports released to media	Preston and others 2009
European forest ecosystems	University scientists	Summarizes the existing knowledge about observed and projected impacts of climate change on forests in Europe	No	No adaptation actions identified	Lindner and others 2010
Northern Wisconsin ecosystems	Federal, state, and university scientists, National Forest managers	Literature review	Yes	Provided few options; however the assessment was a component of the Climate Change Response Framework Project which also compiles strategies and approaches for responding to climate change in forests, provides tools for climate adaptation planning. As part of the larger project, several boundary-spanning partnerships were initiated	Swanston and others 2011

Wildlife and habitat, Massachusetts, Northeast states

Scientists and managers

Expert elicitation; index of vulnerability

Yes

Assessments were part of an effort to make “climate-smart” the northeast states’ existing State Wildlife Action Plan

Galbraith 2011

<http://www.mass.gov/eea/agencies/dfg/dfw/wildlife-habitat-conservation/climate-change-and-massachusetts-fish-and-wildlife.html>

Members of the MA assessment team worked with the State of Massachusetts to develop an adaptation plan that included natural ecosystems and this assessment information.

<http://www.dfg.ca.gov/biogeodata/projects/climate.asp>

Climate Change Vulnerability Assessment of Rare Plants in California

NatureServe tool; 156 rare species in California; on-line excel spread sheets of data on each species; as well as word documents on each species.

Dept of Fish and Game project began in 2011. Project funding and oversight from U.S. Fish and Wildlife Service, and CA Landscape Conservation Cooperative

West Kootenay Climate Vulnerability and Resilience Project, Canada

Conservation scientists and managers

Bioclimatic modeling, literature synthesis, expert elicitation

Yes

VA part of a larger project and a later report (Pinnell and others 2012) takes Assessment results and considers practical applications. Results presented at a managers workshop.

Utzig and Holt 2012

Pacific North-west forests

Scientists and Managers, FS and NPS

Educational workshops — Literature synthesis of climate change information, ecological models, Followed by workshops focused on developing adaptation options for hydrology and roads; vegetation, wildlife and habitat, fish and habitat

Yes

Development of adaptation options was integral part of this process. This work motivated NF staff to develop a tree species vulnerability assessment tool and apply to the National System Pacific NW Region.

Halofsky and others 2011

Table 2. Continued.

Geographic focus	Participants	Methods	Science-management partnership	Adaptation actions identified or Opportunities for social learning outside of the assessment process	Citation
Pacific Northwest tree species	National Forest System staff, State staff	Approach uses life history traits, distribution, and pest and pathogen data for individual tree species—combined with consensus regional climate projections—to rate each species' relative vulnerability. It does not include spatially explicit predictions. The model and data are available at: <a href="http://ecoshare.info/projects/ccft/">http://ecoshare.info/projects/ccft/</a>	No	Specific recommendations fall into three categories: 1. Learn about and track changes in plant communities as the climate changes 2. Maintain and increase biodiversity and increase resiliency 3. Prepare for the future	Aubry and others 2011, Devine and others 2012a,b
Wildlife and wildlife habitat, NV		NatureServe Climate Change Vulnerability Index used to assess 300 species			Wildlife Action Plan Team. 2012
Sky Islands, Coronado National Forest, AZ;	Federal scientists	Species Assessment Vulnerability (SAVs) tool to assess the vulnerability of vertebrate species; tool is online as are case studies: <a href="http://www.fs.fed.us/rm/grassland-shrubland-desert/products/species-vulnerability/">http://www.fs.fed.us/rm/grassland-shrubland-desert/products/species-vulnerability/</a>	No	Guidelines for using assessment results in adaptation planning given; no adaptation actions identified	Coe and others 2012, Bagne and others 2013
Fort Huachuca, AZ; Barry Goldwater Range, AZ;					
Middle Rio Grande Bosque, NM					
Two National Forests and two National Parks in the North Cascades Range, Washington	Federal, state, and local resource managers, federal and university scientists, other user groups	Educational workshop; two-day workshops focused on hydrology, roads, and access; vegetation and ecological disturbances, wildlife and habitat, fish and habitat	Yes: North Cascadia Adaptation Partnership	VA imbedded in an adaptation planning exercise	Raymond and others 2013
Point Reyes National Seashore	University scientists	Expert judgment, predictive vegetation mapping, predictive geophysical mapping, species-specific evaluations	No	No management actions identified; Engaged park managers in feedback twice over the development of the assessment using online survey where responses were anonymous	Hameed and others 2013

## THE RIGHT VULNERABILITY ASSESSMENT FOR THE JOB

### *Context and Priorities*

Who or what motivates the assessment influences the design of the assessment. Governments and institutions broadly mandate consideration of climate change and adaptation (U.S. White House 2009) but it is in the local or regional implementation that priorities and context are set. McCarthy and others (2010) stress the need to frame VAs by identifying key decisions that the assessment will inform, however many VAs have been conducted without consideration of context or use. Nearly all VA reports conclude that the results would assist in the prioritization of conservation or management priorities. However, the set of species, habitats, or ecosystems studied may be opportunistic for the scientist and of low priority for resource managers. For example, assessments often identify vulnerable landscapes where management is not possible (e.g., Wilderness) or where costs would be prohibitively great (suppressing wildfires in remote areas), or where priorities are very low compared to capacity to deal with the competing issues. In these cases, the VA may have little impact on adaptation, and the information is not actionable. To be useful to resource management, the context for the VA must be on species, habitats, or ecosystems that can be managed as part of agency mandates, or over which the institution can establish conservation priorities.

### *Goals*

From the outset, goals and objectives of the VA must be clearly identified, particularly in the context of agency or institutional structure (Glick and others 2011; McCarthy and others 2010). The scope and framing of these assessments, involving many partners from diverse backgrounds, may need to be negotiated, in that conflicting priorities, different world-views, and various degrees of technical understanding are the norm rather than the exception. What constitutes useful information may vary by stakeholder, but in general the more specific it is (e.g., in regard to location, project, resources, actions, costs, time required), the better. Further, initial goals may be revisited where funding is limited or new opportunities arise. For example, in the Western Port case study (AU), the initial goal was to assess both social and ecological consequences. However restriction of funding to human settlements led to a pragmatic decision to narrow the scope (Yuen and others 2013). Alternatively additional partners can bring in new skills and resources to expand the scope, as in the case of the North Cascadian Adaptation Partnership where two National Forests and two National Parks encompassed a geographic scope of over 2.4 million ha (Raymond and others 2013).

In that participants to a VA effort come from diverse backgrounds, Yuen and others (2013) suggest that vulnerability assessments can provide an opportunity for social learning so that collective action eventually can be taken to tackle a shared problem. Learning can be parsed into loops where single-loop learning entails technical changes to meet existing goals; second-loop learning involves reflection on current assumptions about goals/expectations; and triple-loop learning questions and potentially changes values and social structures that govern actions (Yuen and others 2013). In their review of vulnerability assessments, Yuen and others (2013) found that only single loop learning has been occurring in situations to date—i.e., adjustments and corrections of errors in current management practices. When natural resource managers were asked specifically about the hurdles associated with implementation of adaptation

activities, lack of perceived importance to the public and lack of public awareness (or demand to take action) were among the top 3 hurdles, with budget constraints identified as the greatest hurdle (Archie 2013). Webb and others (2013) found that integrating biophysical and socioeconomic assessments of vulnerability and directly incorporating stakeholders in adaptation identification and evaluation improves the efficacy of adaptation assessments in agricultural planning. Their process surfaces discordant views that may arise from differing management objectives among stakeholders, different adaptive capacity of the stakeholders, and different perceptions about the risk of climate change. Getting to adaptation actions will involve identifying and exercising opportunities to encourage second-loop and triple-loop learning during the vulnerability assessment process.

## **People**

The people involved in developing and using a VA ultimately determine the content and value of the end product. Scientists and resource managers have a role in ensuring that scientific information can be understood and applied in the context of specific assessments. Tapping into local and traditional knowledge can enhance scientific information (Fazey and others 2006). Stakeholders and decision-makers have long been recognized as important contributors to the VA (Schroter and others 2005; Turner and others 2003). Schroter and others (2005) defined stakeholders as people and organizations with specific interests in the evolution of specific human–environment systems. The increasingly altered landscapes of the Anthropocene may highlight a need to engage stakeholders more broadly in understanding the potential effects of climate change and of the Anthropocene, and to discern natural resource management decisions with respect to the evolution of these landscapes. Determining who ‘should’ be involved, how to identify who should be involved, and what processes to structure the interactions among these people are critical considerations.

Determining who to involve and how to identify people in the VA will be influenced by the scope of the VA and resources available. In addition to resource managers and providers of information, Glick and others (2011) included end users of resources/lands (e.g., hunters, birders, timber industry, oil and gas developers) and opinion leaders (influential and respected individuals within the region or sector of interest, members of special interest groups). Where the potential exists to plan and implement adaptation options, the stakeholder group expands to include the adaptation planners. Tompkins and others (2008) identified stakeholders in coastal management as those with a direct personal ‘stake’ or those with a role in governance of the resource and/or the area. In addition, those who are calling for the VA may also be important to include. Identification of individual people was an iterative process for Tompkins and others (2008), using published literature to identify experts, discussions with local councils and site visits by the research team.

How to involve people in the process can be as diverse as the VA topic. Engagement can be minimal where results are shared with the public to intensive where stakeholders become partners in the VA. Though VAs are a recent development, reviews suggest that it is important to evaluate the processes used to engage stakeholders. Insufficient discussion in VAs may limit the understanding gained through the VA to incremental solutions (Yuen and others 2013). Salter and others (2010) conclude that the stakeholder engagement must move from a transmissive or extractive model to co-development of knowledge in order to create socially robust solutions.

## ***Science-Management Partnerships***

These formal or informal collaborations are an attempt to bridge the development of knowledge with the use of that information. These partnerships have been implemented in conservation (Moore and others 2012) and more recently in addressing climate change (Peterson and others 2011; Littell and others 2012; Neely 2013). These partnerships can range from informal agreements to work together, even as simple as a one-time consultation, to more formal structured agreements with advisory committees (Halofsky and others 2011a,b; Peterson and others 2011; Halofsky and others in press). Initial steps in the partnership involve establishing and agreeing on specific and realistic goals and objectives. Initiating the dialogue can be a challenge; opening the discussion with a series of questions facilitates participant identification of their observations of change as well as goals (Table; see also Gaines and others 2012).

Several factors are critical in the successful application of science-management partnerships. Clear goals and objectives, agreed on by all parties, must be established for the partnership at the outset of a project (Peterson and others 2011; Littell and others 2012; Halofsky and others in press). Useful goals and objectives are those that are specific to time period involved, location, resource conditions, and financing. Goals and objectives should be developed not only for the natural resources under consideration but for the VA process itself—e.g., goals for the roles and responsibilities of the various members and groups, the planning calendar, and the communication processes should be stated. This shared vision needs to be articulated early, often, and kept prominently in the conversation when working through difficult phases (Webb and others 2010). Engagement among the partners is critical (Webb and others 2010) as regular interaction between scientists and stakeholders shapes the ways that knowledge is produced as well as the usefulness as perceived by the stakeholders (Lemos and Morehouse 2005). Co-location of staff as well as continuity of staff can facilitate interactions (Lindenmayer and others 2013). The partnership must create formal opportunities for sharing information, such as in workshops and conferences; but also encourage flexible opportunities and space for regular information exchange between parties, including sharing of experiences, discussion of new ideas, and joint problem-solving (Webb and others 2010; Peterson and others 2011).

Each partner's knowledge and experience needs to be recognized and incorporated where relevant (Peterson and others 2011; Halofsky and others 2011a); in addition their current beliefs, values, institutional roles and responsibilities should be honored (Ogden and Innes 2009; Webb and others 2010). Lemos and Morehouse (2005) identified the importance of interdisciplinarity in integrated climate assessments, scientists from different disciplines working together, as these assessments represent problems that cannot be solved by any single discipline. Such an understanding contributes to building trust and support among the partners (Lindenmayer and others 2013). Further, where differences in background and cultural context exist, clarity in communication and adherence to neutral language becomes critical for ultimate success (e.g., explaining abbreviations and acronyms, defining technical terms and content, avoiding advocacy language).

Collaboration can offer the opportunity to actively work together to achieve things that could not be done alone, such as implementing large-scale monitoring of environmental flows (Webb and others 2010), or addressing resource management challenges across large landscapes (Raymond and others 2013). Close collaboration between the managers and scientists was seen as greatly increasing the likelihood that the research findings or scientific information identified in the

process would be actively used to inform future decisions (Webb and others 2010; Raymond and others 2013; Lindenmayer and others 2013). In addition, Webb and others (2010) note that seeing research applied to practical management issues can be gratifying for scientists, and thus feeds back to motivate continued participation and learning.

### ***Expert Elicitation***

Expert judgment has been incorporated into the VA as a way to gather critical data on vulnerability and as a step to begin the linkage with management. Hameed and others (2013) developed a multi-functional assessment approach; however they noted that expert judgment was the most widely applicable and flexible assessment method. Jung and Choi (2012) developed vulnerability indicators and their weights with respect to sensitivity, exposure and adaptive capacity for small rivers using a Delphi process. The Delphi method is an anonymous iterative survey that allows experts to see other views and can produce a converged opinion in a short period of time. Lemieux and Scott (2011) sought to identify and evaluate climate change adaptation options across the primary management areas of a protected area agency in Canada. They used a policy Delphi to uncover both consensus and disagreement, in contrast to the conventional Delphi, which explicitly seeks to create consensus. McDaniels and others (2010) linked the VA to an evaluation of potential management actions, where the vulnerability assessment information was provided to scientific and management experts who then were surveyed on the potential management actions.

### ***Traditional Knowledge and Local Knowledge***

Vulnerability assessments can engage participants from the greater population beyond resource managers. When larger groups of stakeholders are involved, many different knowledge traditions emerge. Traditional ecological knowledge and local knowledge, for example by people who have lived and worked in rural communities for many years, are important to recognize. Laidler and others (2009) conducted a VA of Inuit vulnerability to sea ice change. Here indigenous knowledge, uses, and changes of sea ice from Inuit community were important perspectives in the dialogue with scientific information. This knowledge from the Inuit elders was formally cited in Laidler and others (2009) as contributions equally weighted and acknowledged as the academic sources. Science-management partnerships can facilitate this synthesis of local and traditional knowledge (Ogden and Innes 2009).

### ***Stakeholders***

Identifying how to involve people in the assessment process is an important step. McCarthy and others (2010) recommended that a broad-based set of partners be engaged in the VA, noting that with more partners, the process could take longer to complete. However, the end result could be better buy-in over the long run. Critically, Yuen and others (2013) noted that when some stakeholders are excluded from the process, such as those with knowledge of bureaucracies, this could result in critical knowledge/information being omitted.

How the public is involved in the VA and how scientific information is brought into the VA can influence the receptivity of the assessment information. For example, detailed spatial metrics were used to visualize potential wildfire risk under climate change in communities surrounding



Sydney, Australia and captured the attention of stakeholders at workshops where the information was presented (Preston and others 2009). However, stakeholders were reluctant to embrace these representations of vulnerability as they differed from their own perceptions of hazard. Not until the stakeholders were able to translate these metrics into their own perception of risk, which involved more public dissemination of the information and a process of validation of the assessment results, could the information be taken up in local government risk assessment and adaptation planning.

### ***Tools***

Tools that help the user focus on their specific resources, projects, and decision space will likely best assist them in developing adaptation options. A wide variety of tools have been developed to help structure the assessment of vulnerability for species, ecosystem processes, hydrological processes, and landscapes. Tools in this context can range from qualitative frameworks, such as the climate project screening tool (Morelli and others 2012) and decision-support flowcharts to quantitative climate and bioclimatic projections such as the Climate Wizard (Givertz and others 2009) and Tree Atlas (Prasad and others 2007). Selection of a tool should support the attainment of goals and objectives and produce actionable information. Importantly, the user should be aware of the tool's capacities and limitations, the inherent geographic and biological scope, capacity to include climate projections, handle uncertainty, and what expertise is needed to use the tool (Beardmore and Winder 2011; Wilsey and others 2013). Consulting with the developer about the use of a tool may facilitate a greater understanding on the tool's utility; this information is not always included in the user guide.

Stakeholder familiarity with the tools used in the vulnerability assessment can have an impact on the success of the projection. In Shire case study (AU), a participatory approach was used that engaged a diverse range of residents to contribute their knowledge of past climate-related events (flooding, fire) with the goal of using this experience to develop concrete solutions. Unfortunately, the project ran out of funding before concrete solutions could be identified and the local community was unsure of how to take the interviews and develop adaptation options (Yuen and others 2013).

Existing resource management tools, particularly ones that assess environmental risks, may overcome the need to learn new tools and offer an opportunity to incorporate climate change into the existing management practices ('main-streaming climate change considerations'). For example, through the science-management partnership on the Olympic National Forest, it was recognized that the current technique used to prioritize road maintenance could be enhanced with climate change information on increased risk of landslides and high intensity rainfall; thereby use an existing tool to evaluate increased risk associated with climate change (Halofsky and others 2011b). Modifying existing tools may also facilitate the comparison of climate change considerations with other non-climatic stressors or considerations.

### ***Climate Projections for Vulnerability Assessments***

An estimate of the change in climate is a fundamental component of the VA. To date, estimates in VAs have used qualitative descriptions (e.g., hot/dry), synthesized summaries of detailed climatological studies (e.g., 4° C increase in mean annual temperature), or a detailed suite of regional

or locally downscaled climate projections. In literature reviews or where indices of vulnerability are generated, the projected climate is typically summarized as expected changes in mean temperature and precipitation (annual or season) based on climatological studies of the area of interest (Lindner and others 2010; Galbraith 2011; Bagne and Finch 2013; Gardali and others 2012). In assessments where quantitative ecological models are the tool for analysis, downscaled climate projections are drawn from web portals or other sources (for example, Maurer and others 2007; Climate Wizard: Girvetz and others 2009).

The choice of which scenario and how many climate projections to use vary widely across VAs, and usually reflect the availability of models and the experience of the VA participants. Preston and others (2009) used a single projection, the mean projected change in average maximum January temperature in 2030, based on 12 different climate models and different emission scenarios. US BOR (2011a) used the available suite of 112 downscaled climate projections to analyze river hydrology in western United States. The use of different scenarios and models makes it challenging to compare across VAs in terms of likely impact and appropriate management responses. In addition, Harding and others (2012) warn that no matter what the criteria, selection of only a few projections will inevitably produce a bias in the climate projected and in the vulnerabilities identified. In other words, the specific projections selected will not represent the entire uncertainty space of known climate projections, and the assessment could reflect a future climate characteristic of only a small range of potential future climates.

The estimate of climate change used in a VA must be vetted from two different perspectives. First, that estimate must be understood in the context of the uncertainty space of available climate projections. Second that estimate must be relevant to the ecological sensitivity of the ecosystem or natural resources studied in the VA. Rarely are these concerns identified as part of the selection of climate scenarios for use in a VA, often resulting in the use of projections as if they were actual predictions of future conditions. Even where they are identified, the ability to estimate ecological response to climate futures involves far more uncertainties than with physical parameters. Thus, “mis-matches” between the level of resolution and/or precision in a climate model often cannot be met in ecological understanding and management response.

**Table 3.** General Questions to Facilitate Initial Dialogues on Climate Change Adaptation. These questions are intended to establish the local management context, elicit overarching management responses to climate change, and promote mutual learning within the science-management partnership. Questions can be designed to accommodate local interests and preferences (from Peterson and others 2011).

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- What are priorities for long-term resource management (e.g., 50 years)? How can climate change be integrated in planning at this time scale?
  - What is the policy and regulatory environment in which management and planning are currently done?
  - What are the biggest concerns and ecological/social sensitivities in a changing climate?
  - Which management strategies can be used to adapt to potentially rapid change in climate and resource conditions?
  - Which information and tools are needed to adequately address the questions above?
  - Which aspects of the policy and regulatory environment affect (enable, inhibit) management that adapts to climate change?
-

The uncertainty space of climate projections encompasses underlying assumptions about future emission levels, the atmospheric physics captured in the model, and the nature of the downscaling techniques used to develop projections at the local scale of interest. Guidance on the use of scenarios recommends obtaining as many climate projections (models and emissions scenarios) as possible, often made more useful by an ensemble that characterizes consensus or variability among projections (IPCC-TGICA 2007; Mote and others 2011; Glick and others 2011). However, if resources are such that only a single estimate of change (e.g., qualitative) or a few projections can be used, then the estimate of change or the selected climate projection(s) should be explicitly presented in the context of the agreement (or disagreement) among multiple climate models on the projected change in temperature and precipitation for the region of interest. In other words, the VA must identify whether the future climate studied is warmer or wetter than the outputs of many climate models. This is clearly an area where more collaboration between climate scientists, natural resource scientists working on climate change, and resource managers is needed. The existing tools to establish the context for selected projections or even the estimate of change are very limited and require technical facility with large data sets.

The estimate of climate change, whether qualitative or quantitative, must reflect the aspects of climate to which the natural resource is sensitive, as well as be relevant to the parameters of the specific ecological or physical resources being assessed. The objective of the VA is to discern the degree to which a system is susceptible to and unable to adjust to adverse effects of climate change. Climate variables that directly or indirectly affect the resource of interest may be known or can be identified using expert elicitation (McDaniels and others 2010), empirically (Walters and others 2013), or through the use of a conceptual model (Snover and others 2013). The VA should then explore a range of estimates or the outputs from multiple climate models so that the climate-related uncertainty is translated into the dynamic responses of the natural resource. This is also an area where more collaboration between climate scientists, natural resource scientists working on climate change, and resource managers is needed. Uncertainties need to be clearly communicated by authors of climate projections to resource managers to ensure that development of subsequent adaptation practices will correctly accommodate the inherent variances.

## **CHALLENGES AND OPPORTUNITIES FOR EFFECTIVE VULNERABILITY ASSESSMENTS**

### ***Lack of Vulnerability Science Relevant to Management***

Another possible reason why adaptation actions are not considered within the VA process is that the current wealth of scientific information on climate change focuses on impacts. Few established scientific fields explore scientific questions in the context of management (Jacobson and others 2013). Further, climate change science developed at scales far from the resource manager's decision space. Consequently at this time, very little climate change research focuses on the interactions of climate change/impacts and resource management or the effectiveness of management actions assisting in the adaptation or mitigation of climate change. Hence, the literature available to synthesize in the VA focuses on impacts and may have little or no bridge to resource management.

In most research fields related to natural resource management, the connections between resource manager and scientist in the past and at times now, were facilitated by a long-term partnership where the objectives/design of research were established collaboratively (McKinley and others

2012). In this relationship, the scientific understanding of forest was matched by the manager's experiential knowledge of implementing treatments on a particular landscape. Over time, for a variety of reasons, this close working relationship weakened. As scientific fields developed with their own standards for credibility, management and research separated further. For climate change research, there was never really a link with on-the-ground managers from the very start. This has made the link to on-the-ground challenging. While there is currently limited literature to glean in a VA about successful adaptation options, this lack of available information could be remedied by the recognition of experiential knowledge and a more cohesive effort among scientists and forest managers in the VA process.

Further, communication and translation of scientific knowledge is often limited to journal publications and/or online information and may not be effective in fostering an understanding of vulnerability, or facilitating implementation of adaptation actions. This situation has been described as the 'loading dock' problem, where scientific information is 'dropped on the loading dock' with no further discussion on use or implementation, resulting in manager's lack of understanding on how or what to use or concluding that the information is unrelated to their priorities or work/process/schedule (Cash and others 2006). Publishing only in scholarly journals that have peer science readers continues to promote science developing along the lines of what the scientist considers as important, which is not always what management sees as important. In the end, the scientific information is not useable (Dilling and Lemos 2011). This also could be remedied by a more cohesive effort among scientists and managers in the vulnerability assessment process.

### ***Focus of Assessments***

Most VAs are narrowly focused—typically on species, habitats, and in some cases, ecosystems and watersheds. While this narrow focus facilitates attention to some details, resource management encompasses many objectives and the entire physical, biological, and often also the relevant social system. This narrow focus presents challenges and limitations; scientists and resource managers know these challenges from past experience. As in the context of population viability assessments (PVA) and endangered species assessments (ESA), the fine-scale nature of assessing species or ecotype vulnerabilities can result in a situation of seemingly infinite needs. Cumulative effects and relative priorities must be considered during assessment. In the ESA context, the coarse-filter/fine-filter approach was developed, where coarse filter evaluations address general problems and umbrella solutions, while the fine filter focused on those few specifics that were urgent and addressable. The structure of current VAs seems to suffer similarly, in that coarse filter aspects have not been as much in focus as ecological specifics (fine filter).

An alternative or complementary approach is to focus on geophysical analyses of land and water to identify places of ecological resilience and biodiversity (Anderson and Ferree 2010; Beier and Brost 2010). In this approach, land characteristics are the focus with the assumption that a full spectra of physical stages or facets offer many microclimates and refugia for species and processes under a changing climate.

Including social indicators in VAs is important yet to date little integrated. Potential impacts to ecosystem services, availability of alternative resources, and resilience of rural and urban communities to change are as important to assessments as understanding ecological and physical dynamics. As the magnitude of climate change accumulates, natural resources will increasingly reach tipping

points where major shifts in state become inevitable. These must be planned for and met on the social side, where expectations of continuing flows of goods and services in perpetuity remain the norm.

### ***Baselines for Evaluations***

All VAs have a temporal baseline for evaluating the effects of climate change—it is either implicit or, better, explicit. The temporal baseline can be implicit in tools where literature is synthesized. Here the temporal period reflects the current state of knowledge, likely based on current dynamics of a species or ecosystem in recent historical conditions. Alternatively, many VAs have used specific historical conditions from observations as a baseline for evaluating change and sensitivity. In broad terms there are two categories of historical period that have been used as baselines or visions of healthy systems relevant to anthropogenic climate change. First is the recent past, e.g., the last 4-5 decades, which is a period of readily available observational data. Since the 1980s, temperature has been warming in most areas of the United States, such that there can be a distinct temperature signal in periods after 1980s but not necessarily before. Such a short time, however, captures little of the natural variability in Earth's climate system, and thus provides a very short-sighted view of change. Further, observational monitoring stations are often located in lowland areas, far removed from mountain and wildland situations of natural resource focus, making their relevance to VAs questionable.

McWethy and others (2010) stress that 'the last century is an inadequate reference period for considering future climate change because it does not capture the range of natural climate variability that vegetation responds to or the magnitude of climate change projected for the near future.' To this end, ecologists have also long used deeper baselines as references for evaluating vulnerability and assessing health of ecosystems. This is known as the historical range of variability (HRV) approach to characterizing dynamics of ecosystems. In these cases, long-term historic climate reconstructions, such as from tree-rings and sediment cores provide information about conditions over hundreds to thousands of years in the past. While this information is useful for informing scientists and managers about patterns and pace of natural climatic variability and ecosystem response, using HRV as a baseline for evaluating current health, or as targets for future ecosystem conditions is usually inappropriate. Changing climates over time means that the past does not resemble the present or future and that historic ecosystems adapted to different climate conditions than present climate (Jackson 2013; Millar 2014). Static views of ecological dynamics can hamper VAs and potentially lead to prescription of management treatments less effective for future conditions, such as prescriptions for reforestation that assume the same mix of species as in the past century will be adaptive in the future.

The use of historic conditions, thus, either the recent past (20<sup>th</sup> Century) or deeper time can be useful for understanding ecosystem dynamics, but also can hamper understanding of current and future vulnerability. The distinction between these roles for historic information must be clarified to all stakeholders at the onset of the evaluation process.

Pertaining to baselines also is the time horizon used in VAs for the future. The time span of ecological relevance often does not parallel institutional realities. In that climate projections often estimate conditions decades ahead (e.g., 2100), agency planning processes at best focus on 10-20 year futures, while budget cycles are predominantly annual. A partial solution is for VAs to project

outcomes at multiple temporal scales: detailed conditions for the near term (e.g., 1-5 years), and increasingly coarse detail at middle (10-20) and long (many decades) terms. This approach resembles the coarse-filter/fine filter but in a temporal context. Another issue regarding time that hasn't been adequately addressed relates to when in the adaptive management cycle a new VA is called for. This may be prescribed by official direction (e.g., as part of a formal national forest plan revision), or in response to natural-resource conditions. For instance, if changes in resources occurred more rapidly or in ways or magnitude not anticipated, a new VA would be appropriately undertaken.

### ***Evaluating Uncertainty and Risk; Anticipating Surprises***

Increasingly, VAs are attempting to capture uncertainty in some manner, even if only an acknowledgement of the nature of how uncertainty creeps into the quantitative analysis (US BOR 2011a,b), or where uncertainty reflects a consensus or lack of consensus in the scientific literature or a group of experts (Galbraith 2011; Bagne and others 2011). Even with these caveats, the assessment still provides a seemingly black and white picture of the future.

Most of the VAs tools currently available do not incorporate the potential for surprise, or even for reflection of surprise. Yet surprises have become an increasing result in the climate science literature; the rate of melting in the Arctic faster than climate models projected (Stroeve and others 2007), the counter-to-expectation downhill shifts in plant species as they tracked regional changes in water balance rather than temperature (Crimmins and others 2011); identification of highly vulnerable species that are not yet conservation concerns (Foden and others 2013), acute cold stress to montane mammals in winter from loss of insulating snowpacks (Beever and others 2010). Warming winter air temperatures in eastern US result in cooling soil temperatures, as snow depth changes and, under continued climate change, increased soil freezing, that will likely affect soil organisms (Groffman and others 2012) and could exacerbate soil cation imbalances already caused by acidic deposition (Comerford and others 2013). Invasive species might become key ecosystem drivers under future climates; however it is exceedingly difficult to project their behavior because their processes in the exotic landscapes are likely very different from life-history expectations in their native habitat.

How is it possible to anticipate surprises in VAs? Some of the unknowns can, in fact, become known-unknowns. Climate models often project changes, usually statistical probabilities, in frequency of extreme events, for instance, such as severe floods (Dettinger and others 2011), hurricanes (Webster and others 2005), and extreme heat waves (Meehl and Tebaldi 2004). In other situations, understanding of past natural conditions and ecological, both paleohistoric and recent history, can provide insight into the nature of infrequent disturbances, unusual combinations of conditions (e.g., unseasonal fires), or surprising ecological responses. Reviewing the historic literature prior to a VA and interviewing people with local experience over long times can help to identify potential unexpected vulnerabilities.

### ***Resistance Strategies; Need for Strategies to Assist Transitions***

Many VAs continue to recommend climate-resistance actions that prescribe “paddling upstream treatments” (Millar and others 2007). These derive from the desire to maintain status quo or historic baselines. In many cases these result in efforts to enforce and restore conditions that are not

longer what the land/climate can uphold naturally (i.e., conditions have changed). In the Sierra Nevada of California, for example, attempts are made routinely by land managers to maintain mountain meadows free of invading conifers by cutting seedlings. Although past human uses sometimes interact, studies clarify that climate is the main regional driver of ongoing conversions of meadows to forest in this region (Millar and others 2004). Consequently, increasingly aggressive effort is required to enforce the prescriptions, and, as climate trajectories proceed, success becomes increasingly unlikely.

Another example from the Great Basin is the concerted efforts underway by public land managers to remove pinyon pine and juniper recruitment into sage steppe ecosystems. Again, while historic suppression of fire and livestock grazing (including invasives) interacts, climate is a major force driving the conversions from sage steppe to pinyon-juniper woodlands in the northern Great Basin (Lanner and Frazier 2011). Efforts to remove—either manually or with managed fire—are unlikely to keep up with extensive force of the natural reproduction.

## **PUTTING VULNERABILITY ASSESSMENTS TO WORK—THE WAY FORWARD**

### ***Collective Learning***

Absorbing the current information on climate change is a challenging task for scientists who have had some link to this accumulating body of knowledge. Articulating the changes on the landscape as resource managers have seen them is a critical step in applying the current knowledge about how climate change will affect plants, animals, and ecosystems. It is the dialogue between these two knowledge systems that is fundamental in extending this knowledge to adaptation. Science-management partnerships can provide the setting for a two-way learning so that the current understandings about the impacts of climate change can be brought into the conversation. Further, the experience and practice of management can focus that understanding on how humans influence the environment as they attain ecosystem services. This two-way learning is a critical step in producing actionable information.

Completion of an assessment does not guarantee that a decision on adaptation is ready to be made. Implementation of actionable information likely needs the engagement of the public and decision makers in the vulnerability assessment or as part of the adaptation process. The nature of their engagement can be as participants in the vulnerability assessment (participatory research) or as part of the effort to determine scope, targets, and next steps on adaptation. Collective learning, information that emerges from experience and/or human interaction during which people's different goals, values, knowledge, and point of view are made explicit and questioned to accommodate conflicts, is the basis for identifying the collective action to tackle a shared problem (Yuen and others 2013). The challenge for vulnerability assessments and the larger effort developing and implementing adaptation actions is how to incorporate opportunities where the underlying ecological and social assumptions about resource production and management can be surfaced (second and third loop learning). The actual implementation of adaptation options may be more closely related to the extent that the VA and associated processes provide an opportunity for such social learning and through that learning, the identification of collective actions that the stakeholders and institutions can take.

## ***Case Studies Examples***

Case studies help to communicate model processes and highlight successful (and sometimes not) actions; Table 2 compiles a set of recent projects. Case studies where multiple site-specific assessments are on-going can serve as peer learning on data sources and techniques to assess vulnerability, as in the Watershed Vulnerability Assessments project where assessments were being completed on each of the 11 National Forests (Furniss and others 2013). Case studies also serve to engage participants who may then go on to implement the same type of VA or a modification of the VA, as in the Pacific Northwest example below. Reflections after a series of case studies offer the opportunity to evaluate what worked well and what did not, as was done after the Four Corners Assessments by The Nature Conservancy (McCarthy and others 2010).

In Massachusetts, expert elicitation was used to refine an initial assessment of habitats developed by scientists; scientists and resource experts were engaged in the process through a series of meetings and discussions (Galbraith and Price 2009; Galbraith 2011, see also Table 2). Findings from the habitat vulnerability report were also used in the Climate Change Adaptation Report for the State of Massachusetts (<http://www.mass.gov/eea/air-water-climate-change/climate-change/climate-change-adaptation-report.html>). In addition, the Massachusetts model served as a springboard to expanding the model to the entire Northeast area (Manomet Center for Conservation Sciences and National Wildlife Federation, 2012), and served as a template for a vulnerability assessment on the Badlands National Park (Amberg and others 2012).

In Halofsky and others (2011b), a workshop series approach was employed where the objective was to develop adaptation options for federal lands on the Olympic Peninsula. The framework consisted of sessions on climate change impacts and then sessions on management options for specific resource areas, such as hydrology and roads, fisheries, vegetation, and wildlife. Here the assessment of vulnerability involved meetings with managers from the Olympic National Forest and National Park and research scientists from the USFS and the University of Washington. In addition literature and available modeling output were synthesized and provided to the participants. Even though these sessions provided the opportunity for dialogue, some topics were more successful in terms of getting to actions that linked climate change with resource management on the ground. For the hydrology and roads topic, the interaction allowed resource managers to share their road management strategy and the tools associated with that strategy. With this understanding, scientists could identify how to add quantitative information on climate change. While the vegetation session might not have developed as concrete a set of climate adaptation actions, NF staffs were motivated to build on the work of Halofsky and others (2011b) and develop an assessment tool and conduct a VA more narrowly focused on tree species (Aubry and others 2011; Devine and others 2012a, 2012b). In this later effort conducted primarily by NF staff, adaptation options were developed with focused guidance for on-the-ground management of individual tree species. Opportunities for others to learn from these efforts can also result when such literature is recommended as reading for vulnerability/adaptation workshops [EcoAdapt, 2013, <http://ecoadapt.org/workshops/sierra-nevada-adaptation-workshop> identified recommended readings (Halofsky and others 2011a; Peterson and others 2011) for their workshop participants].



## ***Embedded Vulnerability Assessments***

To be most effective in implementing adaptation actions, VAs should be embedded in adaptation planning, and those embedded in general land and water management plans. If, as the literature repeatedly emphasizes, resource management will need to change in response to a changing climate, then VAs need to bring in how management is currently implemented and examine how the vulnerabilities of the socio-ecological system will be mitigated by resource management. Without the firm goal of developing adaptation to climate change guiding the VA, these efforts may serve the purpose of synthesizing the literature or quantifying the effects of climate change but fall short of facilitating adaptation planning or putting actions onto the ground. A question for reflection at the start of the VA might be: Will the information gathered be sufficient to change management?

A simple approach to evaluate the need for change in management prescriptions is the climate project screening tool (CPST; Morelli and others 2012). The CPST provides thought-cues for evaluating whether a project is likely to be influenced by changing climate, whether the existing project design adequately addresses those changes, whether modifications to the design need to be made prior to implementation, and whether the project should proceed to implementation or not. Boxes within the CPST form allow the specialist or deciding officer to document that appropriate considerations of various climate concerns have been made, and that evaluation to proceed as is, modify, postpone, or cancel a project has been made. The CPST review is best undertaken by a small group of specialists interacting in a science-management partnership. However it is adaptable, and can be used to assist a single specialist or a large team of peers in reviewing the climate vulnerability (or not) of projects, and thus to rank and prioritize them for funding and action.

Many currently identified adaptation actions build on current management experiences, often tied to current goals and objectives for management. Very little research has focused on testing the effectiveness of management under climate change. At this time, the dialogue between scientists and managers may be the first step in identifying potential interactions of current management and climate change effects. If different or novel ecosystem services become goals and objectives, then new management practices may be needed. Here is where scientist-management partnerships can make a significant contribution.

## ***Transformative Change***

Transformative change at the societal level will require a larger understanding in society about the potential effects of climate change and of the Anthropocene—suggesting that VAs and adaptation planning consider the role and objective of social learning in these activities. In the Anthropocene, VAs will need to address the entire socio-ecological system—plants, animals, and human society. Vulnerability assessments need to bring into the assessment how management is currently implemented to deliver the current set of ecosystem services. Humans have the capacity to influence the physical, biological and ecological dynamics in local, regional and global environments. Assessing the vulnerability of plants, animals, ecosystems to climate change leaves out the expectations and influence of humans on how these environments are to be managed—critical information that managers and decision-makers will face to develop adaptation options. If adaptation to climate change requires societal transformative change, then scientists and managers will need to be engaging in testing adaptation practices in the field.

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# Maintaining Forest Diversity in a Changing Climate: A Geophysical Approach

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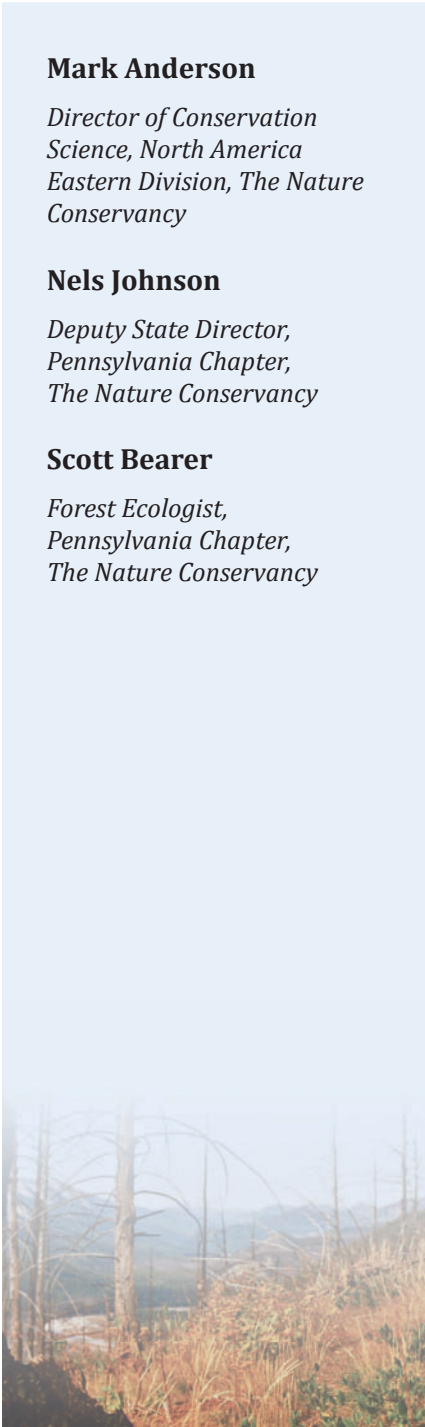
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***Abstract:** Forest conservationists need a method to conserve the maximum amount of biological diversity while allowing species and communities to rearrange in response to a continually changing climate. Here, we develop such an approach for northeastern North America. First we characterize and categorize forest blocks based on their geology, landforms, and elevation zones. Next, for each distinct geophysical combination we locate the forest blocks with the highest amount of internally connected natural cover, and that have complex topography and large elevation ranges increasing their micro-climatic buffering. We hypothesized that these blocks have the greatest resilience to climate change, and will maintain a diversity of species and processes into the future. Finally we identify a network of high scoring blocks representing all geophysical settings and we examine the potential connections among and between them to prioritize linkages where maintaining natural covers would likely facilitate important regional movements. By focusing on the representation of physical diversity instead of on the current species composition, we identify a network of sites that will represent the full spectrum of forest diversity both now and into the future. We advocate that this geophysical approach to identifying a network of core forest areas and key connectors be used to inform and augment the traditional conservation focus on large forest reserves nested within a matrix of well-managed forest.*

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## **INTRODUCTION**

Climate change in recent decades has already begun to affect the composition of forest ecosystems in the northeastern United States. Average annual temperatures have increased by nearly 1.8 degrees F since 1970 (Huntington and others 2009). Tree species migration appears indicated by much higher seedling densities for northeastern tree species in the northern parts of their ranges compared to central and southern parts (Woodall and others 2009). Climate-induced range shifts for other biota may also be underway. Bird species winter ranges in the eastern United States, for example, have shifted steadily north, although not as rapidly as temperature



shifts (La Sorte and others 2012). Projections of geographic ranges under various global climate model scenarios suggest most tree species will experience large range shifts in response to rising temperatures and more erratic precipitation regimes during the next century (Iverson and others 2012). Differential migration rates and varied abilities to cope with environmental gradients and human land uses are likely to dramatically re-sort the species composition of forest communities (Rustad and others 2012). Our ability to predict future species composition at any given location is extremely limited, calling into question the ability of current conservation networks to maintain biodiversity in the future.

We believe the strong correlation of geophysical factors with geographic patterns of biodiversity allows a new approach to designing conservation networks that will be effective even as species and communities continuously rearrange in response to climate change (Anderson and Ferree 2010). Here, we summarize such an approach for northeastern North America. We first review geophysical underpinnings of species diversity. The strong correlation of geophysical factors—number of geological classes, landform diversity, and elevation—with species diversity suggests that conserving geophysical settings is the key to conserving current and future forest biodiversity. We next review internal connectivity, which increases the ability of forest blocks to maintain species diversity and ecological processes, and regional connectivity, which facilitates regional movement in response to changing climatic conditions. By focusing on the representation of physical diversity instead of current species composition, plus accounting for internal and regional connectivity, we identify a resilient network of sites that have the potential to represent the full spectrum of forest diversity now and into the future. It should be noted that forests in less resilient areas, such as flat lands and coastal areas, are still important for a wide variety of benefits from watershed protection, carbon storage, wildlife habitat, and timber production. Actively maintaining diversity at the site level within a resilient conservation network brings in additional factors, such as structural diversity, soil replenishment, and space to accommodate disturbance regimes, which are important for local management. We conclude with summarizing strategies to manage for diverse forests at the landscape scale within a regional forest conservation network.

## **ELEMENTS OF RESILIENCY**

Site resiliency—that is the ability for ecosystems to retain species diversity and basic relationships among ecological features even as environmental conditions change—is driven by geophysical settings and landscape permeability in northeastern North America. Geophysical settings are important because they are the best predictors of species diversity at a regional scale, such as temperate northeastern North America (Anderson and Ferree 2010). While climate may be a better predictor of species diversity at a continental scale, most conservation decisions are made at regional, landscape, and site scales. In addition, landscape permeability and regional connectivity are critical elements of site resiliency since species and ecological processes will need to shift to new locations as temperatures and precipitation regimes affect their viability in any given location. Projections of tree species migration indicate many of today’s natural forest communities will be substantially altered by the end of this century (Prasad and others 2007), though forests will continue to be the region’s dominant ecosystem type. Assessing forest areas across the region based on their geophysical setting (e.g., geology, landform and elevation), internal patch permeability, and regional connectivity yields a potential network of natural

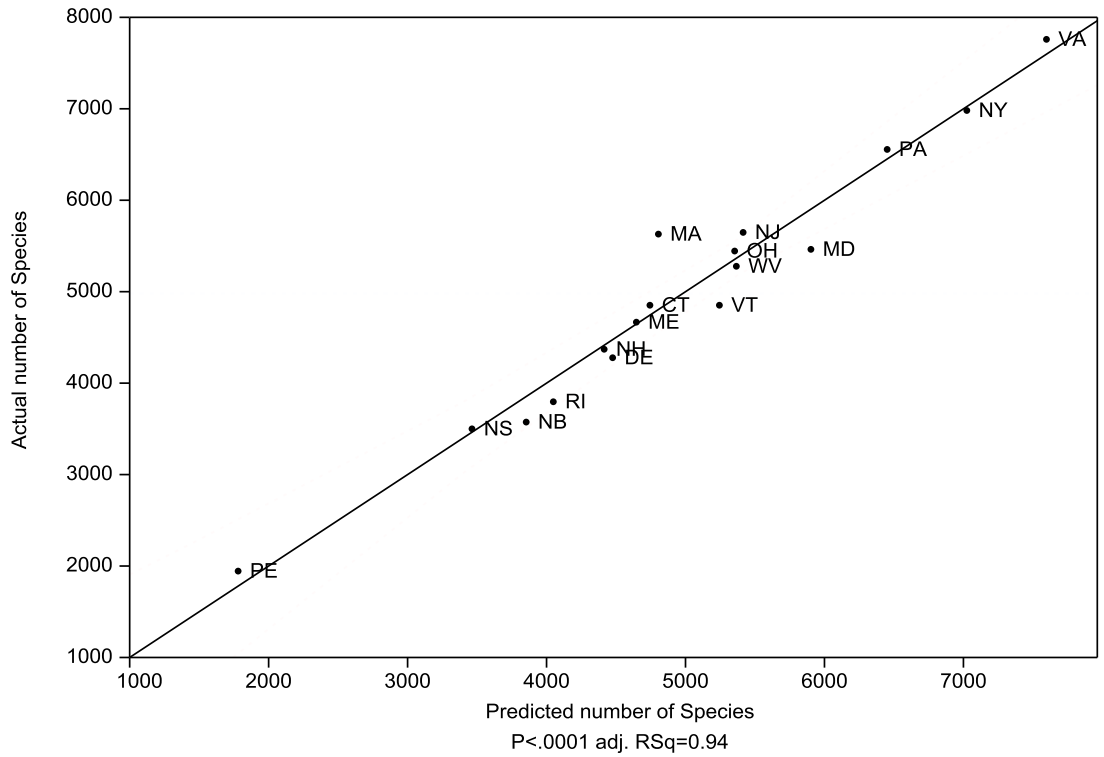
strongholds for future diverse forest areas. This network can be compared against the current network of secured forest lands and help focus future land protection and forest restoration efforts.

“Site resilience” is distinguished from species or ecosystem resilience because it refers to the capacity of a geophysical site (40 ha to 4000 ha [90 acre to 9885 acre]) to maintain species diversity and ecological function as the climate changes (definition modified from Gunderson 2000). This is important since neither species composition nor the ranges of variation of its processes are static in the context of climate change. Our working definition of a resilient site is a structurally intact geophysical setting that sustains a diversity of species and natural communities, maintains basic relationships among ecological features, and allows for adaptive change in composition and structure. Thus, if adequately conserved, resilient sites are expected to support species and communities appropriate to the geophysical setting for a longer time than will less resilient sites.

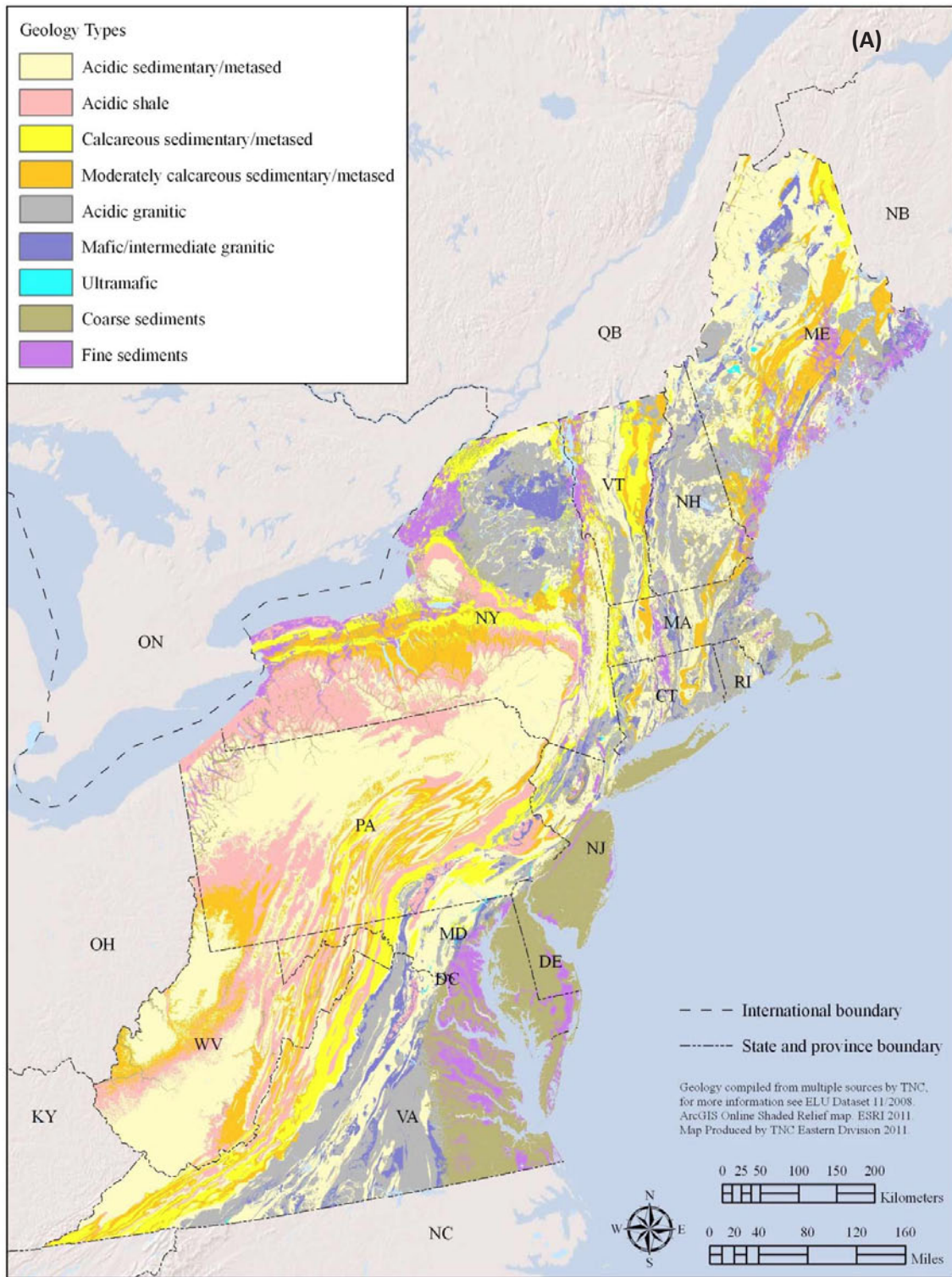
### ***Geophysical Settings***

Several factors—including *geologic classes*, *elevation range*, *latitude*, and *area of calcareous substrate*—are highly correlated with the distribution of terrestrial species diversity in the northeastern United States and adjacent Canadian Maritime Provinces (Anderson and Ferree 2010). Regressing the total number of species against these factors yields a strongly predictive relationship for terrestrial biodiversity across the northeastern United States and adjacent Canada (Figure 1). These factors work equally well for predicting species diversity across the region even though, for example, Virginia shares only 30 percent of its biota with Prince Edward Island and the region spans 1,400 km of latitude. Moreover, the region has been in flux during the past century with many range expansions and contractions, extinctions, and species introductions. These changes appear not to affect the basic relationship between species diversity and geophysical factors. As a result, conserving the full spectrum of geological classes stratified across elevation zones and latitude offers an effective approach to conserving forest diversity under current and future climates.

To capture the spectrum of geophysical settings in the northeastern United States, Anderson and others (2012) used 405 hectare (1,000 acre) hexagons to classify geology, elevation, and landform types. The region’s highly diverse geologic history is manifested in over 200 bedrock types which were grouped into nine geology classes based on shared genesis, weathering properties, chemistry, and soil textures (Robinson 1997). Likewise, elevation for the region, which ranges from sea level to 6,288 feet atop Mount Washington, NH, was divided into low, mid and high elevation classes. Finally, landform types have a major influence on species distribution and they were grouped into seventeen categories (see Figure 2).



**Figure 1.** Actual state/province total species diversity plotted against predicted diversity based on number of geology classes, hectares of calcareous bedrock, latitude, and elevation range for northeastern North America.



**Figure 2.** a) Geology classes; b) elevation zones, and; c) landform types that form the basis for classifying geophysical settings in the northeastern United States.

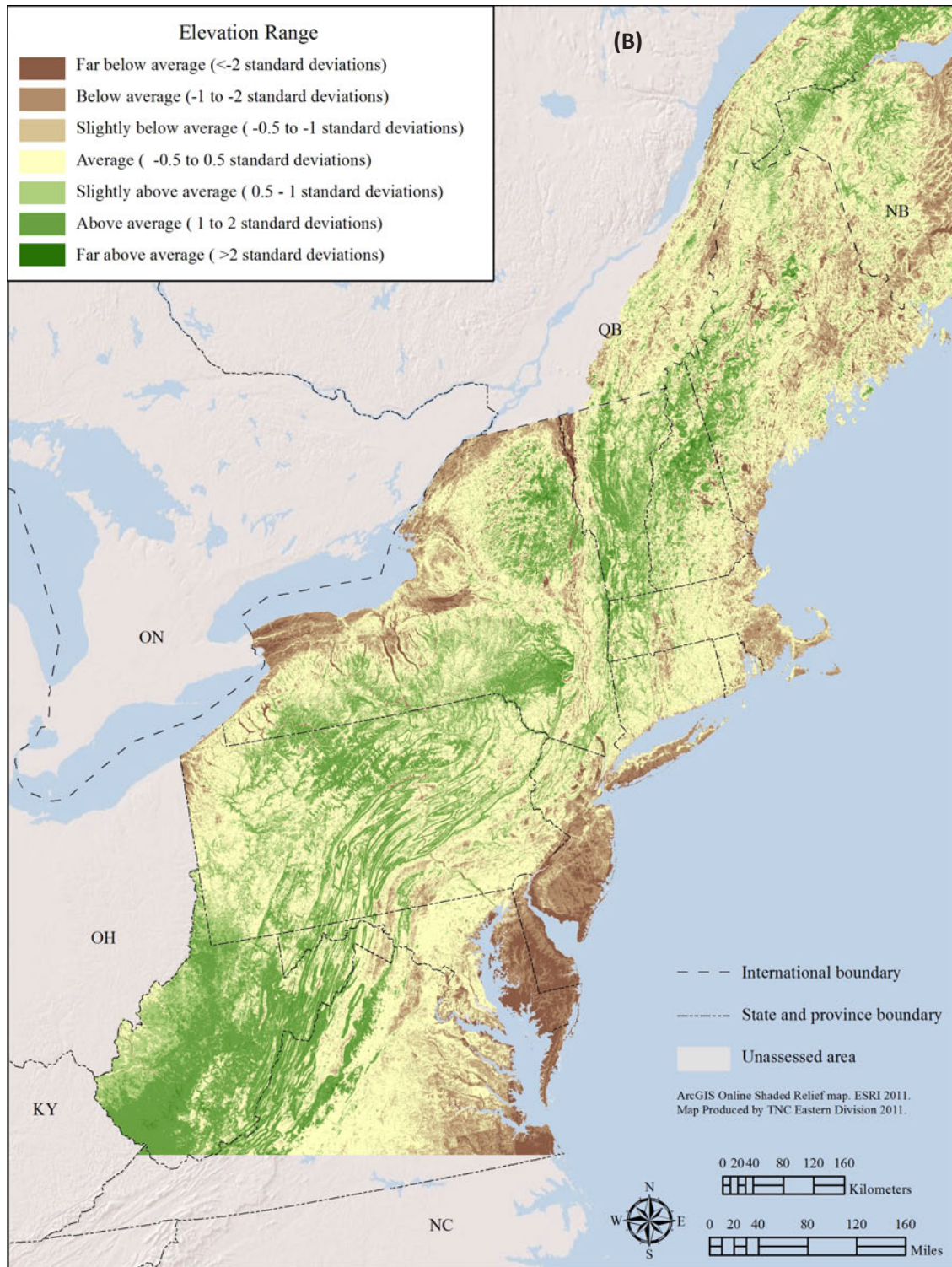


Figure 2. Continued.

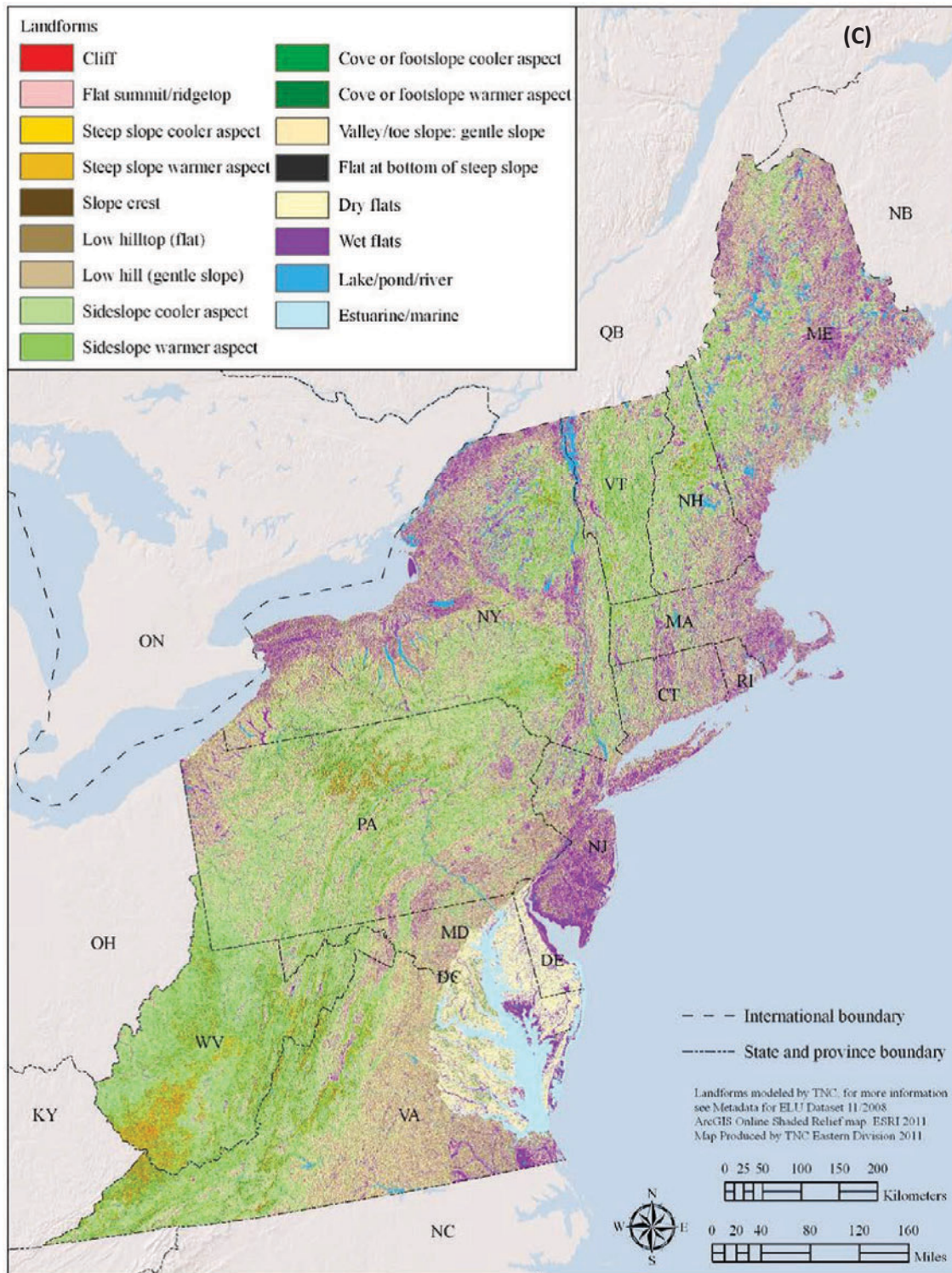


Figure 2. Continued.



Anderson and others (2012) then assigned each of the region's 156,581 hexagons—on the basis of hierarchical cluster analysis (McCune and Grace 2002) for similarity in terms of geology, elevation and landform—to one of 30 geophysical settings. These include 15 low elevation settings, 8 mid elevation settings, 6 high elevation settings and one miscellaneous high slope setting (see Figure 3). Examples of geophysical settings include “coastal coarse sand,” “low elevation fine sediment,” “mid elevation shale,” and “high elevation granitic.” Data from state natural heritage programs were used to identify natural community types associated with each geophysical setting. While the species at any given site are likely to change in response to a warming climate, the ecosystem types are likely to persist. Community types that have commonly been named after predominant plant species can now be referred to by their geophysical settings. For example, a Cattail (*Typha latifolia*)—Marsh Marigold (*Caltha palustris*)—marsh becomes a freshwater marsh ecosystem on shale at low elevation.

To assess the relative resiliency of sites associated with each geophysical setting, Anderson and others (2012) developed scores based on landscape complexity and local permeability (or connectivity), which are summarized below.

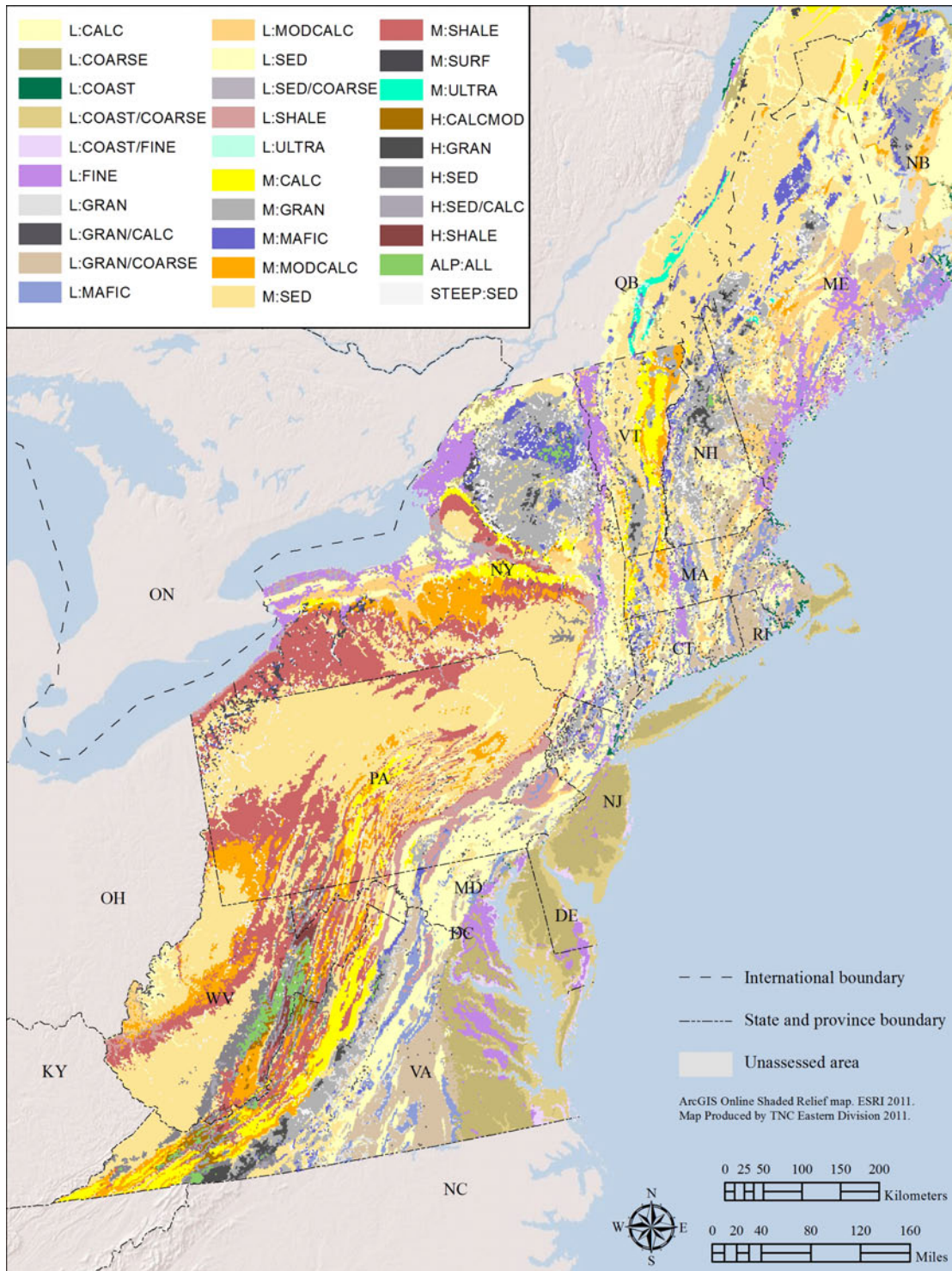
### **Landscape Complexity**

Landscape complexity is driven by an area's topography and associated landforms and the length of its elevation gradients. Landscape complexity creates micro-topographic thermal climate options that resident species can move to, buffering them from changes in the regional climate (Willis and Bhagwat 2009) and slowing the velocity of change (Loarie and others 2009). Under variable climatic conditions, areas of high landscape diversity are important for the long-term population persistence of plants (Randin and others 2008), invertebrates (Weiss and others 1988), and presumably for the more mobile species that depend on them. For example, Weiss et al (1988) measured micro-topographic thermal climates in relation to butterfly species and their host plants. They concluded that areas of high local landscape complexity—even at the scale of tens of meters—are important for long-term population persistence under variable climatic conditions. Because species locations shift to take advantage of micro-climate variation and stay within their preferred temperature and moisture regimes, extinction rates predicted from coarse-scale climate models may fail to account for topographic and elevation diversity (Luato and Heikkinen 2008; Wiens and Bachelet 2010).

A landscape complexity index was developed by tabulating the number of landforms and elevation ranges within a 40 hectare circular area around every 30 meter cell. It was assumed that sites with a larger variety of landforms would provide more microclimate options within their local neighborhoods. The number of landforms ranged from 1-11 (there are 17 landform types across the region). Elevation gradients for the cells ranged from 1 to 795 meters, which were log transformed for analysis since the gradients were heavily skewed toward narrow ranges. The landform and elevation information were combined using a weighted sum with landform variety given twice the weight of elevation (Anderson and others 2012). The final index was:

$$\text{Landscape Diversity} = (2*LV + 1*ER)/3$$

Where *LV* = landform variety, *ER* = elevation range



**Figure 3.** Thirty geophysical settings in the northeastern United States were classified on the basis of geology class, elevation zone and landform type.



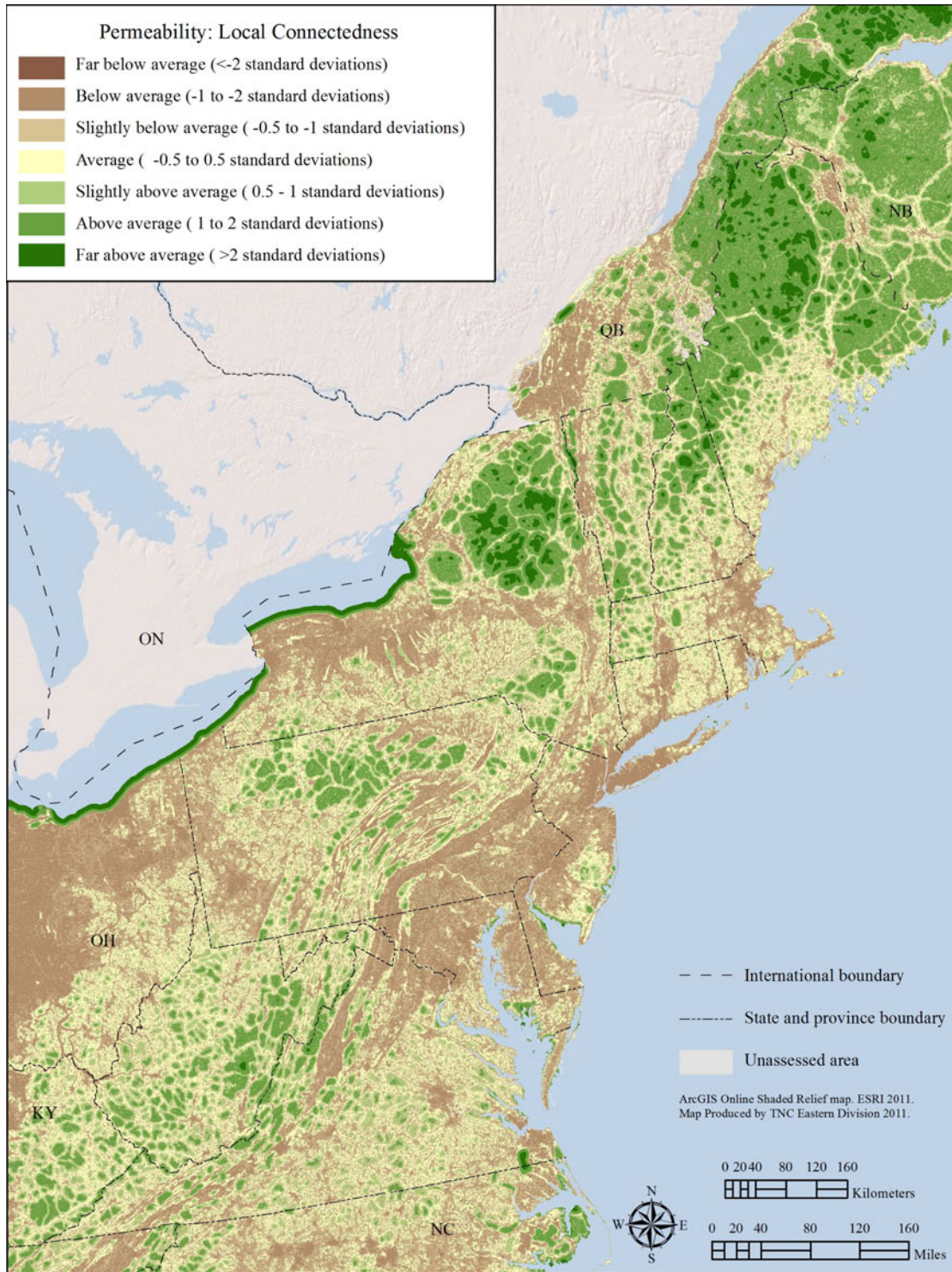
**Figure 4.** Landscapes with greater heterogeneity provide more options for species to move and rearrange at a given site.

### ***Landscape Permeability***

Landscape complexity is likely to offer less resilience if the site is geographically constricted since species populations and ecological processes could be overly confined as regional climate changes. Permeability is the degree to which a given landscape supports the movement of organisms and the natural flow of ecological processes such as water or fire (definition modified from Meiklejohn and others 2010). A highly permeable or locally connected landscape promotes resilience by facilitating local species movements and range shifts, and the reorganization of communities (Krosby and others 2010). Maintaining a connected landscape is a widely cited strategy for building climate change resilience (Heller and Zavaleta 2009). Botkin and others (2007) have suggested large landscape connectivity as an explanation for why there were few extinctions during the last period of comparably rapid climate change. Accordingly, our measure of permeability “local connectedness” is based on measures of landscape structure: the hardness of barriers, the connectedness of natural cover, and the arrangement of land uses.

To assess landscape permeability, Anderson and others (2012) used the resistant kernel analysis that assumes that the connectedness of two adjacent cells increases with their ecological similarity and decreases with their contrast (Compton and others 2007). The theoretical spread for a species or process out from a focal cell is a function of the resistance values of neighboring cells

and their distance from the focal cell out to a distance of up to three kilometers. A focal cell score for local connectedness is equal to the amount of spread accounting for resistance divided by the theoretical amount spread if there was no resistance. Cell scores are then multiplied by 100 to create a range from 1 to 100 and converted to standard normal distributions for the region. The resistance surface was based on a classified land use map with roads and railroads embedded in the grid (NLCD 2001; Tele Atlas North America 2012). Land cover was simplified into six types including *natural land* (evergreen, deciduous, and mixed forest, shrub/scrub, grassland, woody and herbaceous wetland), *water*, *artificial barrens*, *agriculture*, (pasture and cultivated), *low intensity developed* (developed open space, low intensity developed), and *high intensity developed* (medium density, high density and major roads). Natural land was given the lowest resistance score (10) and high intensity developed land was given the highest weight (100). Scores for the other land classes included artificial barrens (50), agricultural lands (80), and low intensity development (90).



**Figure 5.** Landscape permeability for forest blocks in the northeastern United States.

## RESILIENT FOREST CONSERVATION NETWORK

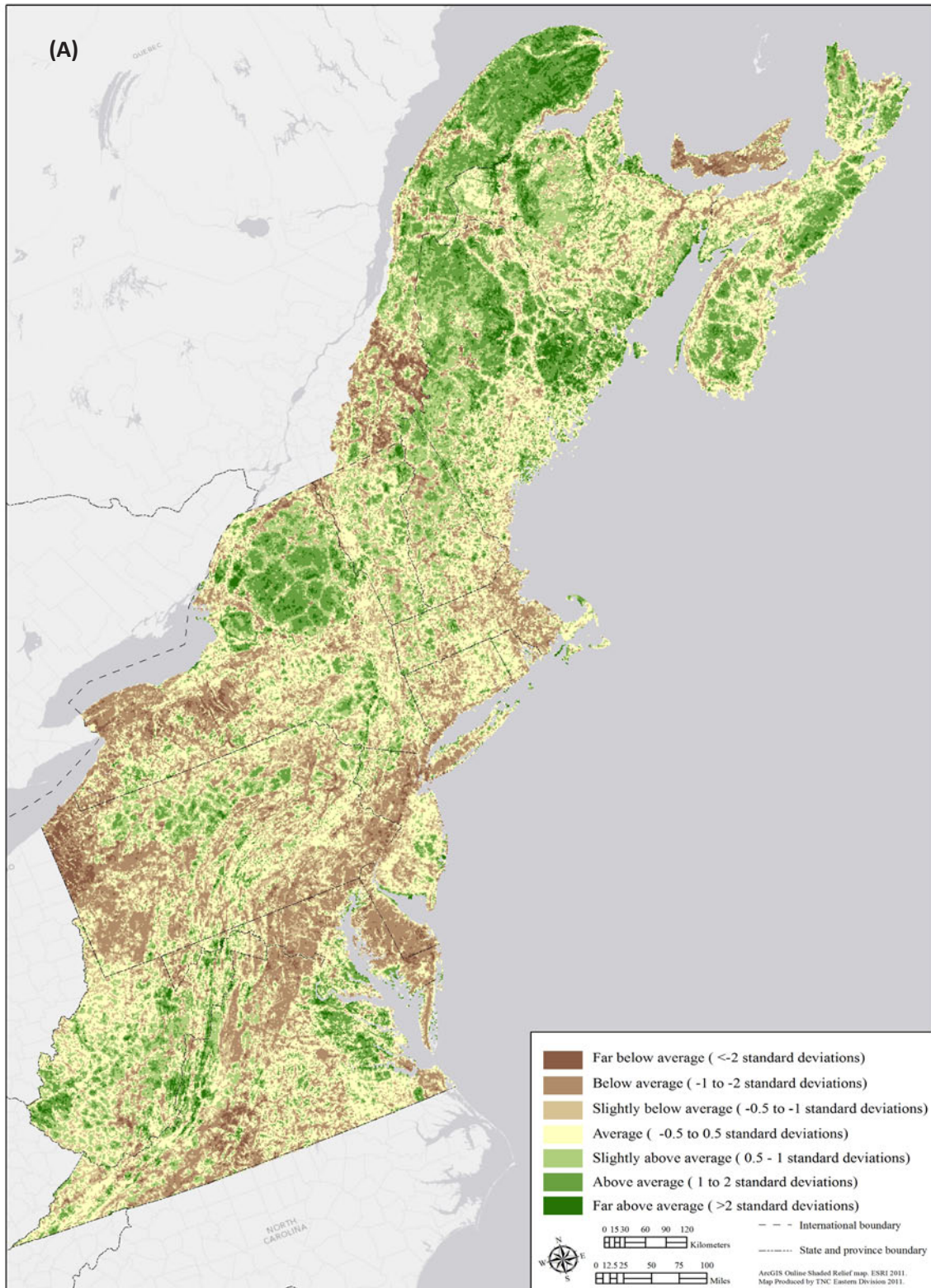
The landscape complexity and landscape permeability scores were combined to develop a single resiliency score for each 30 meter cell. The complexity and permeability scores were transformed into standardized normalized (Z-scores) in order to combine and compare resilience factors. Each factor was given the same weight in the integrated score:

$$\text{Estimated Resilience} = (LC1 + LC2)/2$$

Where *LC1* = local connectedness and *LC2* = landscape complexity

The results show a wide range of estimated resiliency for terrestrial ecosystems across the northeastern United States and Canadian Maritime Provinces (Figure 6a). The vast majority of areas with high terrestrial resiliency scores are forest ecosystems, although wetland and smaller patch communities are embedded within large blocks of resilient landscapes. A simplified map showing a regional network of resilient forest landscapes is shown in Figure 6b.

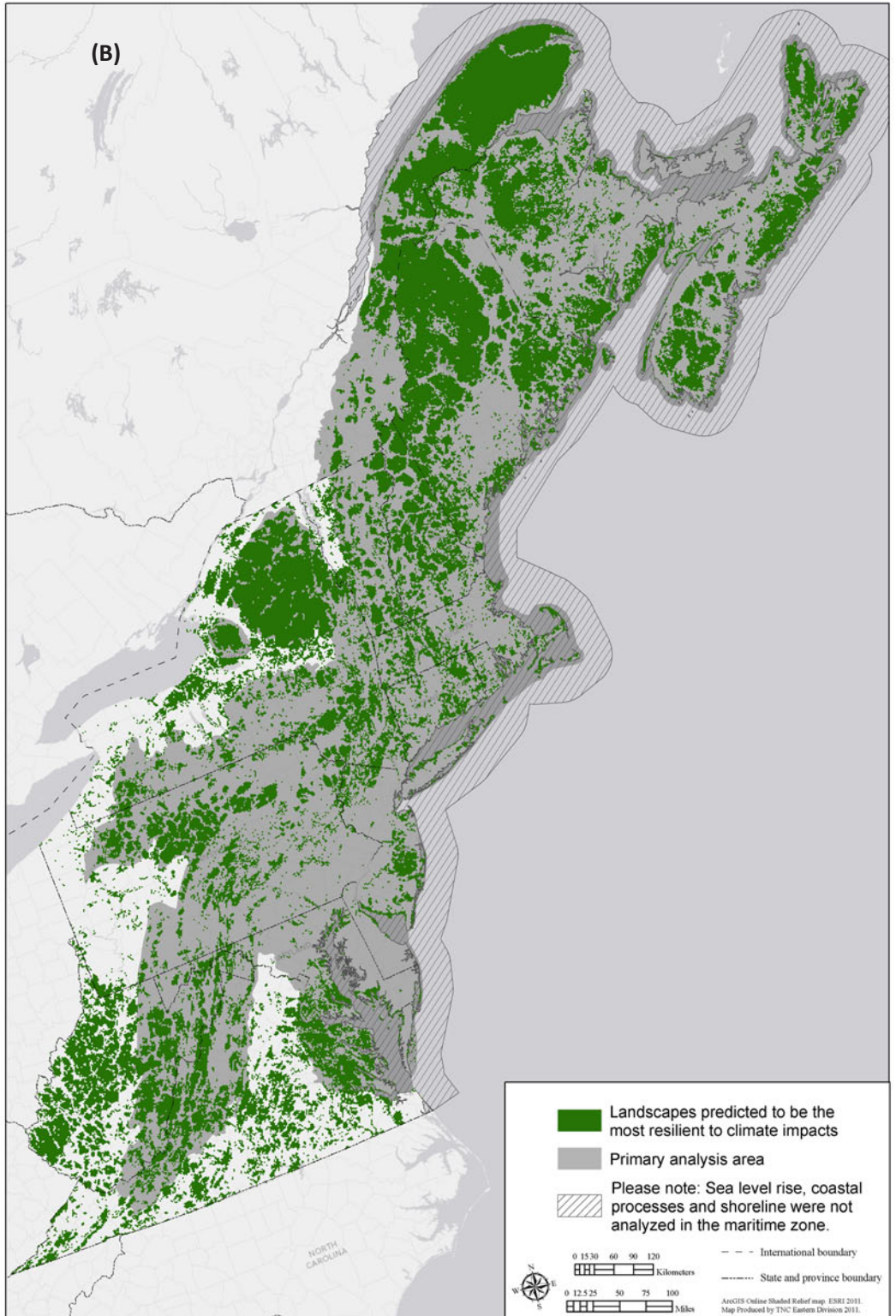
The last step in identifying a resilient conservation network is to locate regional linkages between large forest landscapes. Anderson and others (2012) used the Circuitscape software tool (McRae and Shah 2009), based on electric circuit theory, to identify potential larger-scale directional movements and pinpoint the areas where they are likely to become concentrated, diffused, or rerouted, due to the structure of the landscape. As with the local connectedness analysis, underlying data for this analysis includes land-cover and road data converted to a resistance grid by assigning weights to the cell types based on their similarity to cells of natural cover. However, instead of quantifying local neighborhoods, the Circuitscape program calculates a surface of effective resistance to current moving across the whole landscape. The output of the program, an effective resistance surface, shows the behavior of directional flows. Analogous to electric current or flowing water, the physical landscape structure creates areas of high and low concentrations similar to the diffuse flow, braided channels, and concentrated channels one associates with a river system. Three basic patterns can be seen in the output, as the current flow will: 1) *avoid* areas of low permeability, 2) *diffuse* in highly intact/highly permeable areas, or 3) *concentrate* in key linkages where flow accumulates or is channeled through a pinch point. Concentration areas are recognized by their high *current density*, and the program's ability to highlight concentration areas and pinch-points made it particularly useful for identifying the linkage areas that may be important to maintaining a base level of permeability across the whole region (Figure 7a). The Nature Conservancy's Central Appalachians Program has combined the regional resiliency and connectivity results into a network of "essential forests" and "key connectors" (Figure 7b).



## Regional Terrestrial Resiliency Score

Stratified by Setting with Regional Override

**Figure 6a).** Regional map showing ecological resiliency scores; b) Simplified map showing a network of resilient forest landscapes across the northeastern United States.

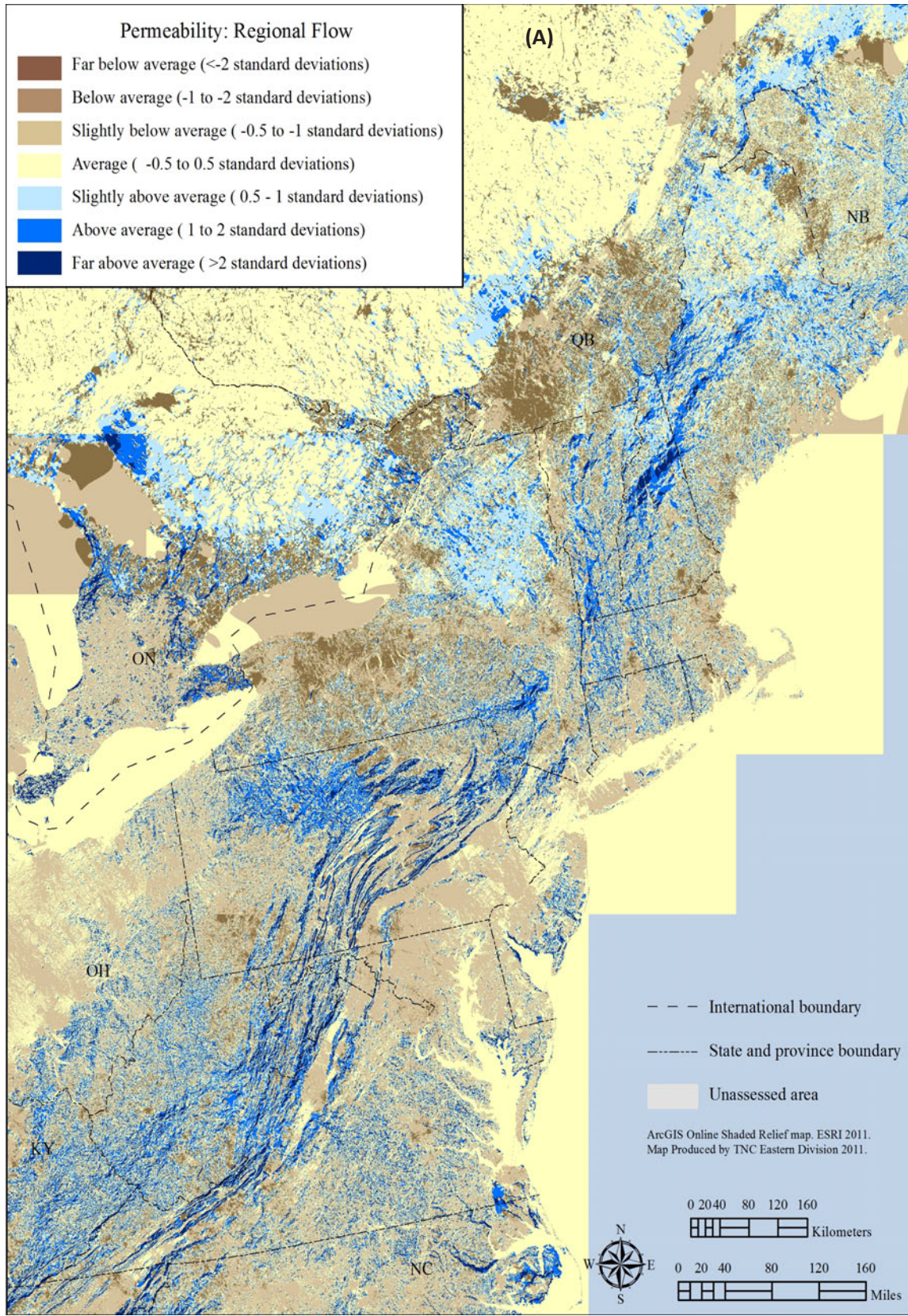


## Regional Terrestrial Resilience: Above Average Areas

Stratified by Setting and Ecoregion with Regional Override

Figure 6. Continued.





**Figure 7a).** Regional pinch points based on circuit theory (McRae and Shah 2009); b) Central Appalachians “essential forests” and “key connectors” network based on regional resiliency and connectivity analyses (Anderson and others 2012).

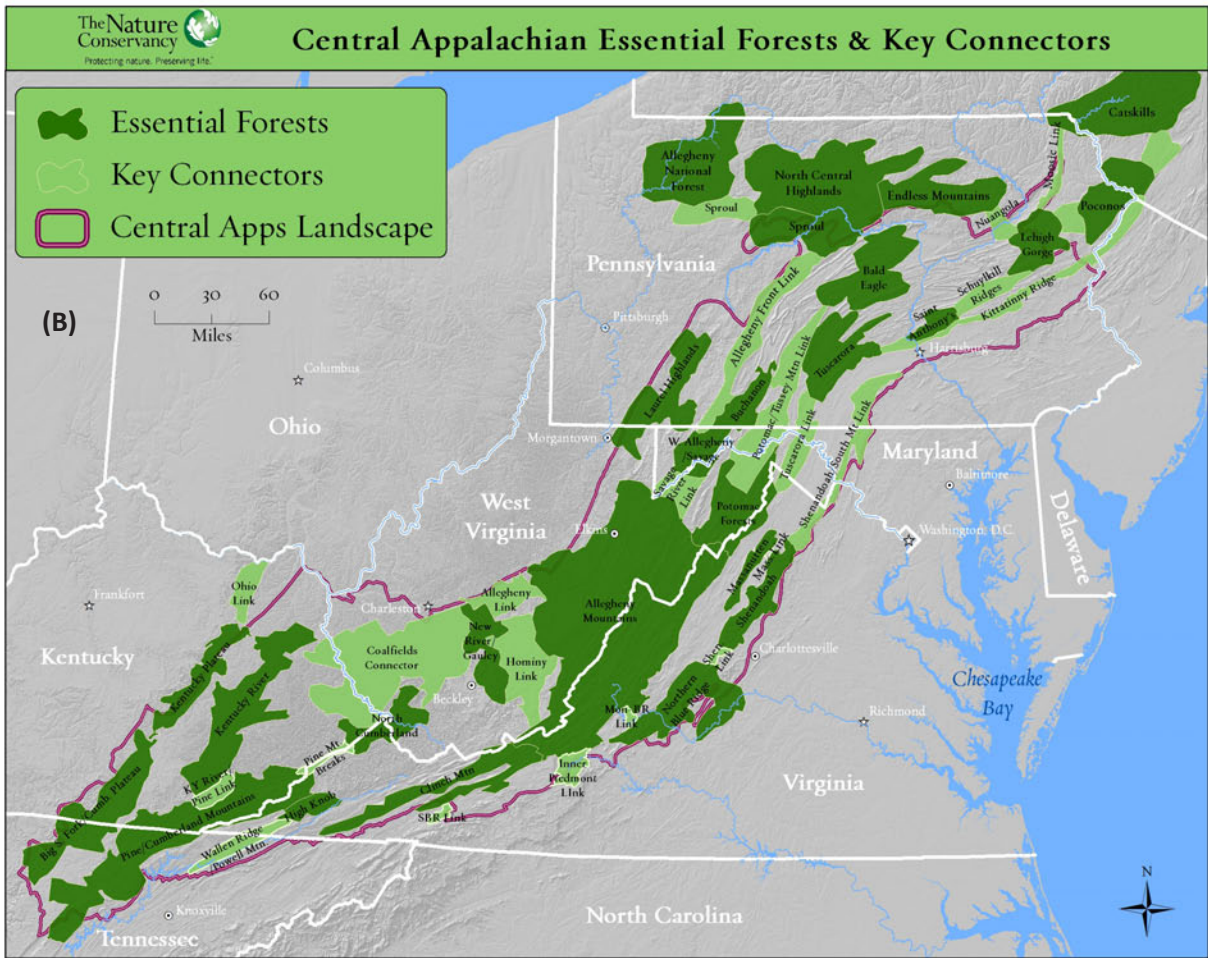


Figure 7. Continued.

## MANAGING FOR RESILIENT FORESTS AT THE LANDSCAPE SCALE

While geophysical factors are important for maximizing the potential for conserving forest diversity other factors—especially biological—are important for actively maintaining or restoring biodiversity at a given site. Some factors, such as reducing stress from forest pests and pathogens, have been traditional tools in landscape forest management. Others, such as selecting species on the basis of their tolerance for anticipated temperature regimes, introduce new approaches to managing today's forests so they remain diverse and productive decades from now.

A wide variety of recommendations have been made to help managers prepare for future conditions, including the considerable uncertainty that accompanies climate projections at the landscape scale (Millar and others 2007; Heller and Zavaleta 2009; Puettmann 2011; Cornett and White 2013). We've grouped strategies for maintaining and improving ecological resilience at the landscape scale into three categories, which are briefly summarized below:

- Promote Diversity
- Reduce Existing Stresses
- Anticipate Future Conditions

### **Promote Diversity**

Three dimensions of diversity can help forests be more productive and resilient at a landscape scale. *Species diversity* has been linked to ecosystem productivity and functioning by a variety of researchers (e.g., Tilman and others 1997; Chapin and others 2000, Flombaum and Sala 2008; Thompson and others 2009; MacDougal and others 2013). Because many forest species have very specific environmental requirements and functions (niche partitioning), their loss may lead to a reduction in productivity and/or function until the niche space is occupied by another similar species. Species diversity at the stand and landscape level is also associated with resistance to ecologically destructive disturbances such as severe fire and pest and pathogen outbreaks (Thompson and others 2009). Emphasis should be placed on increasing the native diversity of forest specialist and late-seral species associated with topographic and structural microclimates as opposed to generalist and non-native species associated with forest fragmentation. Management should increasingly consider model results (USFS Tree Atlas; LANDIS) and emerging data that provide information on which species may benefit from a changing climate (e.g., oaks, hickories) and which may suffer (e.g., beech, some maples, spruce). *Successional diversity* is another feature that can promote ecological productivity in the face of environmental change. A range of successional or age classes at the landscape scale promotes species and structural diversity by creating a mosaic of environmental gradients with respect to light, humidity, ambient temperature, and coarse woody debris. These gradients can help perpetuate a wider variety of disturbances, species and ecological functions that contribute to overall forest health than a landscape dominated by a single successional cohort (Franklin and others 2007). Likewise, *structural diversity* in forest ecosystems of any age class or mix of classes can promote forest ecological health as well as provide a wide range of habitats for a variety of species. Nurse logs, for example, facilitate the regeneration of moisture-sensitive species in northern hardwood forests. The acceleration of natural successional processes, such as the use of small patch cuts to simulate gap-phase dynamics, the creation of snags or the introduction of coarse

woody can improve the ability of forest ecosystems to adapt to changing conditions (Cornett and White 2013).

### ***Reduce Existing Stresses***

Most effects from a changing climate on northeastern forests will be expressed through stresses that already exist in the region. The dominant existing regional stressor—habitat fragmentation—makes forests more vulnerable to the spread of invasive species, wind damage along exposed forest edges and altered species movement. Invasive plant species, insect pests and disease pathogens have been a growing threat to forest diversity and health for the past century. Warmer and wetter conditions are likely to expand the range of many pests and pathogens, such as hemlock woolly adelgid, while more frequent droughts will exacerbate others, such as gypsy moth outbreaks in oak forests (Boitcourt and Johnson 2010). Increased droughts may also increase the potential for catastrophic wildfire in certain forest types that have had excessive fuel accumulation for decades. Deer populations have had severe impacts on forest regeneration in many areas of the northeastern United States. While there is little evidence that white-tail deer populations will increase as a result of climate change, the combined effects of excessive browse and other stressors (i.e., atmospheric deposition) could compound the regeneration challenge for many tree and understory species under a changing climate regime (Galatowitsch and Frelich 2009).

Many forest management programs at the stand and landscape scales already address existing stresses but climate change could change the relative threat each poses to forests. In order to respond to these potential threats, management should attempt to improve the forests' ability to resist pests and pathogens, work to prevent the introduction and establishment of non-native and/or invasive pest and plant species (and remove existing populations), and manage herbivory that impacts regeneration (e.g., establishing deer fencing). Management can also reduce the risk of catastrophic fire by establishing fuel breaks, altering forest structure to minimize risk and severity of fires, or conducting prescribed burns to reduce fuel loadings. Chapin and others (2009) suggest that management targets for existing stressors should be updated to incorporate trajectories of expected change rather than relying on historic ranges of variability. Given uncertainties about exactly how these threats will change increases the importance of establishing monitoring networks to detect unexpected changes in stress impacts and management responses to them (Joyce and others 2009). Conn and others (2010) provide several recommendations to reduce the total amount of stress on forest ecosystems. These include: 1) strengthening state and local programs to slow forest loss and fragmentation; 2) revising forestry best management practices (BMPs) to account for expected impacts from climate change to existing and new stressors; 3) working with sustainable certification programs such as the Forest Stewardship Council (FSC) and Sustainable Forestry Initiative (SFI) to promote integration of climate adaptation measures into their performance measures, and 4) expanding state and local capacity to monitor and respond to pests, pathogens, storm damage and fire risk.

### ***Anticipate Future Conditions***

Forest management actions taken today can anticipate future conditions and reduce the ecosystem's vulnerability to expected disturbance (Bolte and others 2009). Actions that can be taken to anticipate future impacts include selecting or promoting tree species with a wide environmental tolerance, maintaining and restoring habitat connectivity to facilitate species movement, and

stand/site design to minimize edges that are vulnerable to wind storms and invasive species. Current species that have a broad natural range with regard to temperature and moisture (i.e., oaks, *Tilia*, *Sorbus*, white pine) can be expected to do well (Iverson and others 1999). Species with a narrow range of ecological tolerance are likely to persist only in topographic microclimates, and attention to the recruitment dynamics within these microsites may be important to long-term persistence of these species in the forest. This may be preferable to selecting species not currently in the area that may or may not be adapted well to future conditions. Prioritizing and protecting refugia of unique habitats or populations of sensitive or rare communities should therefore be a goal of management. Ultimately, any management activities should attempt to protect the fundamental ecological functions of that system, including the protection of soil quality and nutrient cycling, and maintaining and restoring hydrological flows.

The U.S. Forest Service has developed an adaptive management framework based on an alternative set of strategy categories including those that help forests better resist impacts, or be able to recover more quickly from impacts, or respond to changing impacts (see text Box 1).

#### **Box 1. U.S. Forest Service Climate Change Response Framework**

The Climate Change Response Framework was established by the U.S. Forest Service's Northern Institute of Applied Climate Science ([climateframework.org](http://climateframework.org)) to help managers better understand the effects of stress on their forests and identify management options (Swanston and Janowiak, 2012). Their approach establishes an effective continuum of adaptation strategies, from developing fundamental management options, to developing strategies, approaches and tactics (Figure 8). In their continuum, adaptation strategies fall under three broad categories: resistance, resilience and response. Resistance actions—such as reducing invasive species impacts—improve the forests' defenses against anticipated changes or directly defend against disturbance to maintain relatively unchanged conditions. Resilience actions—such as promoting species and structural diversity—allow for some degree of change, but encourage a return to prior conditions after a disturbance, either naturally or through management. Response actions—such as moving species to new areas where they can remain within their climatic tolerances—intentionally accommodate change and enable ecosystems to adaptively respond to changing and new conditions (Swanston and Janowiak 2012).

**Figure 8.** A diagram of the process of the Climate Change Response Framework Adapted from Swanston and Janowiak 2012).



## CONCLUSION

Forest conservationists need methods to conserve the maximum amount of biological diversity while allowing species and communities to rearrange in response to a continually changing climate. By focusing on the representation of physical diversity instead of on the current species composition, we identify a regional network of sites that will represent the full spectrum of forest diversity both now and into the future. We advocate that this geophysical approach to identifying a network of core forest areas and key connectors be used to inform and augment the traditional conservation focus on large forest reserves nested within a matrix of well-managed forest. At specific sites within a resilient forest conservation network, forest managers should continue to do many of the things we have long known are important for maintaining healthy forest ecosystems. These strategies include: 1) managing for species, structural, and successional diversity; 2) reducing existing stress from invasive species, habitat fragmentation, altered fire regimes, and other factors, and; 3) making forest management decisions—such as selecting species with broad tolerances—that anticipate future climatic conditions. Since there is considerable uncertainty about the rate and degree of future change, managers will need to remain flexible, experimental and innovative. Adaptive management frameworks will be increasingly essential for sustainable forest management within a resilient regional forest conservation network.

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# Adaptation Approaches for Conserving Ecosystems Services and Biodiversity in Dynamic Landscapes Caused By Climate Change

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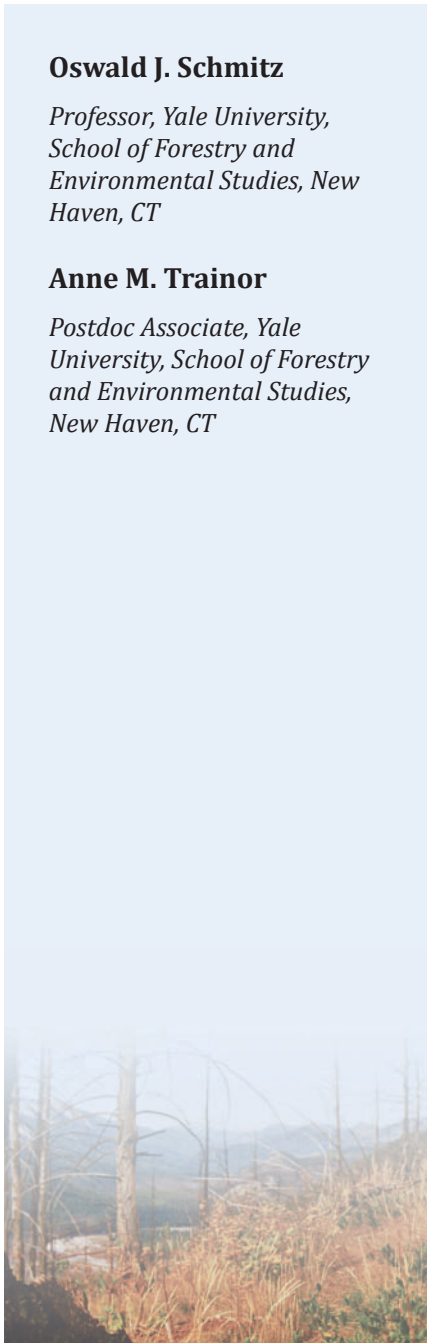
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**Abstract:** Climate change stands to cause animal species to shift their geographic ranges. This will cause ecosystems to become reorganized across landscapes as species migrate into and out of specific locations with attendant impacts on values and services that ecosystems provide to humans. Conservation in an era of climate change needs to ensure that landscapes are resilient by devising adaptation strategies to deal with such dynamism. This requires anticipating the future fate of species and ecosystems as well as implementing spatially explicit adaptation that enables species, ecosystems and their services to persist across vast landscapes. This paper describes a framework that highlights six spatially explicit adaptation approaches that emulate natural ecological resilience in support of landscape-scale adaptation planning. These include understanding and better sustaining concentrations of current biodiversity on landscapes and ecosystems services; anticipating where species will migrate so as not to develop landscapes in ways that impede their movement; and establish landscape connectivity between habitats and geophysical settings to ensure species can reach thermally favorable new environments as they are displaced by climate change. We discuss how to deploy the adaptation approaches in conservation assessments aimed at supporting land use planning for conservation and compatible land uses, highlighting the importance of using multiple approaches to develop coherent plans that address multiple stakeholder interests.

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## **INTRODUCTION**

Forest management is faced with the significant challenge of maintaining the integrity and functioning of forest ecosystems in the face of changing climate. This is a particularly formidable challenge because on-the-ground management activities are generally associated with specific geographic locations within fixed political jurisdictions. Yet species comprising ecosystems are expected to shift their geographic ranges toward more favorable climatic (i.e., temperature, precipitation) conditions (Hansen and others 2001; Iverson and Prasad 2001). Moreover,



these shifts may happen at differential rates depending on species' abilities or capacities to move (Hansen and others 2001; Malcolm and others 2002). Consequently, species that comprise forest ecosystems stand to become disassembled and reassemble into new configurations elsewhere (Hansen and others 2001; Malcolm and others 2002; Iverson and Prasad 2001; Zavaleta and others 2009), with attendant impacts on ecological processes and related ecosystem services (Schmitz and others 2003; Walther 2010).

To keep pace with this change, and maintain ecological integrity, management aimed at addressing the impacts of climate change must extend its purview. It has to shift from a traditional emphasis on local parcels of land with fixed boundaries to a more regional focus that strategically considers those local parcels of land as part of a larger portfolio of places that are integrated to build landscape-scale resilience as species and ecosystems move to adjust their geographic locations (Spittlehouse and Stewart 2003; Schmitz and others 2013). This further requires developing and implementing adaptation plans aimed at adjusting both natural and human systems in order to minimize the adverse effects of climate change on biodiversity (Spittlehouse and Stewart 2003; IPCC 2007; Mawdsley and others 2009). Such regional planning requires: (1) knowing what we have today; (2) understanding what a climate future might look like; and (3) adopting adaptation approaches that respond to current conditions and anticipated future change (Spittlehouse and Stewart 2003; Schmitz and others 2013). We present here a framework that addresses these three points to assist regional planning conserving biodiversity within dynamic landscapes caused by climate change.

The framework is the result of yearlong-deliberations by a scientific working group (see <http://yale.databasin.org/pages/panelmembers>) comprised of conservation biologists, modelers, and policy-makers charged with developing practical guidance for integrating climate adaptation approaches into conservation planning and policymaking. At the outset, the working group recognized that the conservation science community has made great strides in developing adaptation approaches to address climate change: there are upwards of 42 of them (Vos and others 2008; Galatowitsch and others 2009; Game and others 2011; Heller and Zavaleta 2009; Mawdsley and others 2009; Poianni and others 2011). But, in many cases, these approaches are presented merely as a menu of options. It was the working group's experience that such wide range of choices makes it difficult to decide which options should be implemented or to know which ones lead to complementary or contradictory outcomes for a given adaptation plan. Accordingly, in the face of such uncertainty important decisions and actions may be put off or avoided altogether, at the very time when action is critically needed (Spittlehouse and Stewart 2003; Brooke 2008; Poianni and others 2011).

The working group therefore distilled the choices down to seven promising adaptation approaches that are robust to uncertainty and can help maintain the functional integrity of biotic systems that are being managed (Schmitz and others 2014). The six approaches were chosen because they emulate natural ecological resilience; and they are spatially explicit to support action that must contextualize place-based action within regional, landscape contexts (Schmitz and others 2014). They are organized to address three levels of ecological organization (i.e., species, ecosystems and landscapes) and consider the need to consider existing as well as future conditions (Figure 1).

The six approaches are themselves complementary and broadly applicable to adaptation planning for a broad range of natural resource and biodiversity management concerns. As such, the framework complements and builds on existing climate adaptation frameworks (e.g., that developed by

Ecological Level			
Adaptation Approach	Species & Population	Ecosystem	Landscape
<b>A. Strengthen current conservation efforts</b>			
1) Protect current patterns of biodiversity	<ul style="list-style-type: none"> <li>Assess population sizes, viability, conservation status, and phenological trends</li> <li>Map species occurrences</li> </ul>	<ul style="list-style-type: none"> <li>Map terrestrial and aquatic ecosystems</li> </ul>	<ul style="list-style-type: none"> <li>Map genetic pattern across the landscape</li> <li>Map beta and gamma diversity</li> <li>Map biodiversity hotspots</li> </ul>
2) Protect large, intact, natural landscapes and ecological processes	<ul style="list-style-type: none"> <li>Identify and map extent of species occurrences in relation to their thermal tolerances, habitats and food resources</li> </ul>	<ul style="list-style-type: none"> <li>Map potential future patterns of fire, hydrology, carbon sequestration, and ecological integrity</li> <li>Map locations where ecosystem services provide human value</li> </ul>	<ul style="list-style-type: none"> <li>Map factors related to ecological integrity (e.g., fragmentation, distance from disturbance)</li> </ul>
3) Protect the geophysical setting	<ul style="list-style-type: none"> <li>N/A</li> </ul>	<ul style="list-style-type: none"> <li>Map areas of high ecological integrity</li> <li>Map land facets in relation to current climate patterns</li> <li>Map areas of high topographic complexity</li> </ul>	
<b>B. Anticipating and responding to future conditions</b>			
4) Identify and appropriately manage areas that will provide future climate space for species expected to be displaced by climate change.	<ul style="list-style-type: none"> <li>Forecast species and rare community vulnerability to climate change based on their capacity to adapt biologically</li> <li>Map future climate envelopes that will constrain distributions</li> </ul>	<ul style="list-style-type: none"> <li>Forecast ecosystem vulnerability to climate change</li> <li>Map locations that would support shifts in vegetation types and biomes</li> </ul>	<ul style="list-style-type: none"> <li>Forecast land use change</li> <li>Project sea level rise</li> <li>Analyze projected trends in climate variables (precipitation, temperature, etc).</li> <li>Project climate change</li> <li>Map potential future biodiversity hotspots</li> </ul>
5) Identify and protect climate refugia	<ul style="list-style-type: none"> <li>Identify areas that could harbor current species into the future</li> <li>Identify where species populations remain stable</li> </ul>	<ul style="list-style-type: none"> <li>Map habitats with high natural resilience to climate change (e.g. spring-fed streams)</li> <li>Map areas projected to experience little change in vegetation</li> </ul>	<ul style="list-style-type: none"> <li>Map drought refugia</li> <li>Map areas projected to maintain stable climate</li> </ul>
6) Maintain and restore ecological connectivity	<ul style="list-style-type: none"> <li>Identify areas critical to species movements in a changing climate</li> <li>Map movement corridors for species life-history and migration</li> </ul>	<ul style="list-style-type: none"> <li>Map connections between current and projected future locations</li> <li>Anticipate species invasions along planned corridors</li> </ul>	<ul style="list-style-type: none"> <li>Map connections between land facets, ecological land units, refugia or areas of high ecological integrity</li> </ul>

**Figure 1.** Six key climate change adaptation approaches for conservation planning at three levels of ecological analysis. The cells within the matrix list the kinds of scientific assessment needed to support adaptation planning and action.

the U.S. Forest Service [www.forestadaptation.org](http://www.forestadaptation.org) and the Nature Conservancy [Cross and others 2012, Groves and others 2012]) that are more focused to meet specific agency goals or specific resource planning needs. In presenting the framework here, we recognize that ultimately decisions about which adaptation approaches to implement depend also on the socio-economic and political context of the management issue (Spittlehouse and Steward 2003; Heller and Zavaleta 2009). Nevertheless, these decisions require first understanding the biophysical conditions determining the fate of the biotic systems being managed. To this end, we discuss here how to derive this understanding by describing how the different adaptation approaches can be used in conservation assessments to support regional planning for biodiversity conservation.

## FRAMEWORK FOR CONSERVING AND ADAPTING BIODIVERSITY

The adaptation approaches featured in the framework address three levels of ecological organization (i.e., species, ecosystems and landscapes) and consider the need to protect the integrity of existing conditions (i.e., ensure that current environmental conditions are maintained or improved) as well as anticipate future conditions to develop appropriate adaptation actions (Schmitz and others 2014). While the different approaches can be considered individually, we juxtapose them within a matrix that reveals the complementarity among ecological organization (Figure 1).

Doing this has tactical value. The framework is designed to simultaneously consider different approaches and organizational scales, thus encouraging the use of multiple approaches. This is based on the consensus that “climate-adaptive” conservation plans should be geared toward conserving not only species and their habitats, but should ensure that ecological and evolutionary processes can continue to operate across landscapes over the coming decades of changing climate (Zavaleta and others 2009; Zarnetsky and others 2012; Schmitz and others 2014). By contrast, most assessments that inform biodiversity conservation planning today continue to focus somewhat more narrowly on the upper-left section of this matrix (i.e., they map current and/or future species geographic ranges). Choosing and implementing several adaptation approaches from the matrix can help to ensure that there is coherence across ecological scales and organizational levels. For example, it helps to appreciate that conserving species may not only require maintaining existing habitats, reserves and protected areas but further appreciating the need for connectivity among those locations to facilitate species movements across landscapes. It further encourages anticipating locations where species may move in the future to identify and conserve those candidate locations and connect them with current locations inhabited by the species.

The framework also has strategic value by helping to foster collaboration and coordination among conservation and management agencies. Various conservation and management agencies have distinctive goals and expertise and as such often operate at different spatial scales or operate at diverse levels of ecological organization. The framework can help to envision how each agency’s efforts can be aligned to encourage inter-agency complementarity and synergism when developing regional adaptation policy and action. For example, coordinating the adaptation efforts of the U.S. Fish and Wildlife Service (USFWS)—a species-centric organization—with adaptation efforts of the U.S. Forest Service (USFS)—an ecosystem-centric organization—or the Bureau of Land Management (BLM)—a landscape-centric organization—can help to ensure that essential habitats are available for forest wildlife species (USFWS & USFS) or ensure that working landscapes designed to be resilient to climate change maintain or enhance the capacity for species of conservation concern to move across broad regions as they shift their geographic.

### ***Ecological scales of consideration***

The adaptation approaches apply to any or all of the following three levels of ecological organizations routinely considered in conservation and management (Schmitz and others 2014). (1) The species and population level focuses on spatial occurrences, population sizes, viability and conservation status and conservation concern. Adaptation at this level involves understanding current and future species geographic range distributions as well as population dynamics and movement patterns. (2) The ecosystem level recognizes that species and their habitats are integral components of ecosystems and, as such, influence ecological processes that provide services

to humankind and habitat for other species. This level begins to consider biodiversity in terms of its functional role and associated services in addition to more classical preservation values. (3) The landscape level recognizes that there are important patterns across multiple ecosystems that are determined by a combination of geographical features such as topography and soils (land facets and ecological land units), as well as by the degree to which species sort themselves into communities that comprise different ecosystems.

### ***Adaptation approaches***

The adaptation approaches fall into two broad categories. The first are those that enhance current conservation and management efforts, and the second are those that anticipate and respond to future conditions.

#### **Strengthen current conservation efforts**

The first three approaches build on conservation actions that are already in place. Once implemented, these approaches may also buy time to formulate adaptation actions once better understanding of future conditions is developed for any region of conservation or management concern. The first two approaches (Figure 1) are perhaps most familiar because they are used widely in conservation; the third is an emerging new approach that considers an additional suite of environmental variables that determine species distribution and diversity.

*1. Protect current patterns of biodiversity.* This represents a baseline objective reflecting Aldo Leopold's admonition that "the first rule of intelligent tinkering is to keep all of the parts." Even as climate change redistributes species, conservation will still need to ensure that species can persist where they are today. Without such protection, coexisting species may have little chance of persisting until other adaptation approaches can be implemented. Ensuring that critical natural habitat is maintained or enhanced across a landscape is key to such protection. This also helps to foster management actions that connect the places where species currently are to future locations with more favorable climatic conditions, using corridors, steppingstones, or working lands permeable to plant and animal movement (Thomas and others 2012).

*2. Protect large, intact, natural landscapes and ecological processes.* Shifts in the geographic range of species stand to reorganize species compositions of communities because they may become disassembled over time and space. This in turn may alter ecosystem functioning and the provisioning of environmental services (Schmitz and others 2003; Zavaleta and others 2009). Maintaining large areas reduces the potential for community disassembly because it helps to ensure that trophic interactions, disturbance regimes, intra-specific and inter-specific competition, and other large-scale processes can continue to generate and maintain high levels of biodiversity. As species move in response to changing climates, it will be more difficult to manage for species composition directly. Maintaining large spaces that can support the kinds of ecological and evolutionary processes offers a better way to protect a wide range of species moving at different rates. These areas are likely to contain a large complement of native species, including densities of top carnivores large enough to affect community structure. Such intact systems can also accommodate large-scale disturbance regimes (flood, fire, and windthrow). This adaptation objective thus considers the functional roles of species and takes a more dynamic perspective than the previous adaptation approach. It also recognizes that

species within communities are interdependent with each other and may provide important ecological services through those interdependencies. For example, native insect pollinator species diversity may be a key determinant of the success of high-value fruit and vegetable farming, especially when commercial species of pollinators such as European honeybees are in short supply. Plant species comprising coastal ecosystems buffer coastlines from flooding and erosion during storm surges and upland forest in watersheds control surface runoff and erosion while reserving drinking water quality. Conserving predators may be important not only to protect species with charismatic value but also to prevent loss of trees needed for watershed protection because predator species may prevent prey population outbreaks thereby protecting ecosystems from herbivore damage. The human-built environment may constrain the ability to protect single large areas, and so assembling a connected portfolio of smaller, undeveloped spaces may also protect many of the remaining natural landscapes as possible. In practical terms, this calls for considerably enlarging areas that are under active management for management or conservation (Sinclair and others 1995) combined with targeted restoration activities (e.g., reintroducing apex predators).

*3. Protect geophysical settings.* Species presence in a location can depend on a suite of factors including soil types, upslope drainage area, slope, elevation, aspect, and solar insolation (Hunter and others 1988). Such biophysical attributes—called land facets or geophysical settings—can sometimes account for spatial variation in biodiversity better than spatial variation in habitat attributes (Anderson and Ferree 2010). Even while climate changes, these locations are enduring features because soil types and geology are unlikely to change, and local climate gradients that are driven by topography will likely not change as quickly (Currie and Paquin 1987; Davies and others 2007; Anderson and Ferree 2010). Maintaining areas that contain a diversity of geophysical settings may help to conserve a diverse complement of species associated with these features under current and future climate regimes (Schloss and others 2011).

### **Anticipating and responding to future conditions**

This set of approaches (Figure 1) address changing climate futures. Through scenario analyses (Galatowitsch and others 2009) one can explore what influence climate change might have on species distributions and ecosystem functions and services. Anticipating geographic range shifts and alteration of ecosystem functions and services requires the use of models to project what areas may become suitable for species under future climates. Modeling helps locate areas on the landscape to protect for the future and areas needed to support range shifts between current and future locations (Lawler and others 2009).

*4. Identify and protect areas that will provide future climate space for species expected to be displaced by climate change.* Ample evidence shows that species are already undergoing shifts in their geographic ranges (Parmesan 2006; Barnosky 2009). While many shifts are comparatively small forays (e.g. 50-150 mile range extensions) arising from small (0.5°C) temperature increases over the last 50-100 years, larger range extensions can be expected if projections of even 1-3°C rise in mean temperature (IPCC 2007) come to pass over the next century. This approach identifies candidate locations to which species may migrate; and thus provides the impetus to determine if those locations are currently managed in ways that ensure species persistence after their migrations.

5. *Identify and protect climate refugia.* This adaptation approach recognizes that many species may have limited capacities to evolve tolerances quickly enough to match the rate of future climate change or have the capacity to migrate to new locations. One way to prevent potential losses of these species is to identify and protect climate refugia into which species can retreat. Refugia (e.g., mountain ranges, high plateaus, or areas of cold air drainage) are effectively safe havens on the landscape because climatic changes are expected to be relatively small there.

6. *Maintain and establish ecological connectivity.* Even if we succeed in conserving today's portfolio of large natural and semi-natural landscapes (Adaptation approaches 1-3) and have connected these areas with corridor networks some species will need to shift their range beyond those locations as climates change. Consequently, the connectivity network that was designed for current conditions may not be completely suitable for adapting to future conditions. Climate change induced species range shifts can be facilitated by anticipating where species will move (Adaptation approach 4), and connecting these new areas also with corridors. This approach thus identifies where species movement will likely take place across the landscape and accordingly identifies current and potential future travel routes and impediments (such as terrain, vegetation, human land use, and geological barriers) to movement. The connected areas can support gene flow among species populations, promote demographic flows that can prevent local extinction (demographic rescue), and facilitate recolonization after local extinction.

### ***Steps to applying the framework***

The framework (Figure 1) presents a suite of approaches that collectively support management to build climate resilient landscapes. It provides a systematic way to reason how different adaptation approaches and ecological levels may complement each other spatially. But, it is intentionally not prescriptive in order to accommodate the diversity of goals and objectives among different conservation and management agencies. It also helps identify critical information needs to characterize the current state-of-play as well as envision future outcomes through scenario analysis.

Scientific assessments in support of natural resource conservation and management gather and depict spatially explicit information about species and their habitats within ecosystems, and ecosystems across landscapes. This information is most effectively displayed through the use of maps. Developing maps as a product of assessments is a very useful way to foster scenario-building exercises and reveal decision options. The information in maps help policy-makers and managers visualize not only current but importantly potential future consequences of particular decisions that may be conflated or confounded by climate change.

Modern geographic information systems (GIS) technology is capable of providing the integrative environment needed for storing, accessing, and processing spatial data from such assessments by representing data from a broad range of sources into a single display. Maps can represent large volumes of disparate information in visual form where they would otherwise be buried in vast unconnected data sets, thus facilitating geospatial analyses among variables and features to produce a composite picture across landscapes.

Fundamentally, any assessment should be motivated by a clear articulation of the conservation problem and goal *before* choosing the adaptation strategy, analysis approaches, tools, and



data. Oftentimes, assessments are motivated simply because data and tools are readily available. Specifying goals and ensuring that the data and tools align with the goals ensures that assessment outcomes will meet the needs of planners; and hence reduces risks that inappropriate adaptation actions will be recommended. Once the goal is chosen, we suggest that a scientific assessment process supporting climate adaptation involves 5 steps: (1) Choose one or more adaptation strategy(ies) (the left column of Table 1) that may be appropriate depending on conservation planning goals. (2) Choose the level(s) of ecological organization (the top row of Figure 1). Ideally, more than just the species level of ecological analysis should be considered in assessments, for reasons explained above. The choice of adaptation strategy and level of ecological analysis then triangulate to a particular cell of the matrix, which in turn, leads to identifying appropriate analysis tools. (3) Choose the analysis tool(s). A menu of available tools for the different matrix cells, their description and explanation of their benefits and drawbacks can be found at <http://www.databasin.org/yale/using/matrix/lc/approaches>. (4) Choose the data sets. The choice of assessment tool dictates critical data needs, including deciding on the spatial extent and spatial resolution of the data. Assessments typically require the use of disparate abiotic, biotic and cultural datasets originating from multiple sources, and while numerous such datasets are available (see <http://databasin.org/yale/using/matrix>), integrating data from disparate sources to provide coherence is one of the toughest challenges in any assessment process. This step may require rescaling and reinterpreting datasets to a common spatial scale and development of common variable definitions. It further offers a way to identify and rectify data gaps. It also forces understanding and explication of uncertainties, which is among the most critical *aspect* of conservation planning (Lawler and others 2010). For example, data that are measured directly in the field or based on expert opinion may be more certain than data from satellite imagery that is not ground-truthed, or data outputs from models (e.g. projections of future climate). (5) Specify the assessment time horizon. The major effects of climate change on species and ecosystems are likely to be realized within the next 50 to 100 years (IPCC 2007). Yet, land-use planning for human systems often focuses on shorter (5-10 year) time horizons, although forest management planning may occur on somewhat longer time horizons. Regardless, any mismatch in the time horizon of climate change effects and management decisions can create irreversible, path-dependent land allocation outcomes (e.g., urban sprawl) because sequential short-term land-use plans often build upon existing land allocations that in turn may preclude land use options for management and conservation needed 20 or 30 years hence. For this reason, scientific assessments for future land management and conservation should be conducted for at least a 50-year time horizon. We encourage consideration of potential future scenarios over even longer time horizons in addition to the 50-year time frame, with the recognition that projections about future geographic range distributions of species as well as human demographics and land-use patterns become increasingly uncertain as the time horizon becomes longer than 50 years.

### ***Strengthen current conservation efforts***

Assessments in support of strengthening current conservation efforts include characterizing and inventorying the state of current conservation efforts. This can range from mapping the occurrence of single species of conservation concern, to mapping intact ecosystem types within a region (e.g., fir-hemlock forests, alpine, tallgrass prairie, riparian and associated riverine systems) or identifying geographic patterns and gradients in biodiversity concentrations across a landscape (biodiversity hotspots, beta and gamma diversity). Delineating the size and location of such large spaces involves different assessments for the different ecological levels (Figure 1). At

the species and population level, assessments identify and map species occurrences in relation to their needs (also called species distribution or niche modeling), such as their thermal tolerances, habitat requirements and prey species distributions. At the ecosystem level, assessments include mapping the spatial extents of disturbance regimes and ecological functions such as the spatial pattern in levels of production or carbon sequestration, watershed and hydrological regimes, and location and extent of wildfires. At the landscape level, assessments would include identifying and mapping landscape features such as high-elevation, low insolation slopes on calcareous soils, that can be strong surrogates for species diversity (Anderson and Ferree 2010) locations and extent of the human built environment, or degree of habitat fragmentation (e.g., Sanderson and others 2002; Theobald 2010).

### ***Anticipating and responding to future conditions***

Assessments to envision and respond to future conditions require the use of scenario analyses (Galatowitsch and others 2009) to explore what influence climate change might have on species distributions and ecosystem functions and services. Scenario analysis involves the use of predictive modeling and expert opinion. Generating future scenarios typically involves the sequential use of several or all of five kinds of models that project 1) future emissions of greenhouse gases, 2) how global atmosphere and oceans respond to these emissions, 3) how atmospheric processes affects habitats and biomes at smaller spatial extents, 4) species' responses to climate change (e.g., climate envelope models, physiological models) and 5) species movement and colonization (Pearson and Dawson 2003; Phillips and others 2008). Each of the models carries uncertainties because they employ uncertain data and assumptions to drive model projections. The sequential application of the models can compound these uncertainties because the output of each model is a crucial input into the next one. Nevertheless, one may still use scenario generation as a heuristic tool that, when combined with expert opinion, provides the means to envision and appropriately act in response to plausible future outcomes (Galatowitsch and others 2009; Lawler and others 2009; see also ***Coping with uncertainty***, below for more detail). Assessments enlist statistical modeling to project future locations with suitable biophysical conditions (niche modeling, climate envelope modeling), or enlist process-based models (physiological models) to identify locations that have climatically tolerable future environmental conditions, aka future niche space. Such single species models will provide the most robust insights for conservation planning especially if multiple scenarios are generated to cover a wide range of model uncertainty. This approach can also be used to make predictions for multiple species. Outputs for each species should be combined to generate a spatially coherent depiction of areas that will support future biodiversity concentrations. Because of the potential to compound uncertainties a more practical approach may be to consider ecological organization broader than individual species (i.e., ecosystems and landscapes; Figure 1) within each adaptation approach. Assessments in support of ecosystem level planning involve mapping future geographic locations of the dominant vegetation types or biomes that comprise different ecosystems (e.g., Neilson 1995; Iverson and Prasad 2001). This assumes that such vegetation provides critical habitat for animal diversity. One confounding factor is that biophysical conditions across broader landscapes may limit or preclude geographic range shifts of species. These constraining conditions include sea level rise and inundation, changes in land use regimes, and changes in the intensity and frequency of disturbances like fires and hurricanes. This requires contextualizing species and ecosystem assessments within anticipated biophysical landscape change. Assessments would also model the shifting climate space of individual species and overlay the individual species' projected

movements to identify landscape locations that may support range shift (Phillips and others 2008). Because this involves the same five kinds of models discussed above, it carries the same kinds of uncertainties. Newer coarse filter approaches can help reduce uncertainty by identifying potential corridors and connectivity areas on the basis of “natural blocks” or the degree of human modification (e.g., Spencer and others 2010; WHCWG 2010; Theobald and others 2012), geophysical settings (Brost and Beier 2012), or present-day climate gradients (Nuñez and others 2013). These approaches have their own uncertainties and assumptions (e.g. that areas of low human modification provide for movement of species and processes, or that future climate gradients will occur in the same locations as present day climate gradients—Nuñez and others 2013). Although these uncertainties are undoubtedly smaller than those involved in emission scenarios and general circulation models, the impact of such uncertainty needs to be quantified.

### ***Coping with uncertainty***

The six adaptation approaches carry uncertainty stemming from quantifiable errors in the measured or modeled data, assumptions of models used to project future climate change, and effects of climate change on species and ecosystems. It is easy to be paralyzed by uncertainty or invoke uncertainty to avoid making difficult decisions. We nevertheless advocate moving forward amidst uncertainty. Indeed, the first three proposed approaches (Figure 1) build on existing conservation approaches for which outcomes are known or relationships to biodiversity are well established empirically. So, they are likely to be good actions to take whether or not changes in climate play out as projected (Groves and others 2012). For those cases requiring greater use of modeling to conduct assessments (those projecting climate futures), several techniques can be employed to help reduce uncertainties. These include simulation analyses that account for the range of variability in the data, sensitivity analyses that explore robustness of models or adaptation approaches to various assumptions, and scenario analyses that examine a range of possible outcomes (Galatowitsch and others 2009; Glick and others 2011). Insights from modeling are extremely useful, especially when tempered by good expert judgment and opinion. One strategy to alleviate some uncertainty is to cross-walk between multiple adaptation strategies and ecological levels to evaluate when identification of priority conservation opportunities or future management actions are congruent or divergent. Indeed, those kinds of insights form the basis of many vulnerability assessments. Moreover, by providing vivid examples of the impacts of climate change, such assessments (e.g., Lawler and others 2009; Beever and others 2011) have motivated many managers and decision makers to treat climate adaptation as an urgent priority. Nevertheless, even with the best available data and models, uncertainties will always remain. Therefore, we recommend the use of adaptive management approaches that monitor and evaluate the performance of any implemented adaptation approaches (Lawler and others 2010; Cross and others 2012). This provides the kind of critical feedback needed to make continual amendments as new information and uncertainty arises.

## **CONCLUSIONS**

The framework provides a vision on how to build resilient landscapes by establishing strategic partnerships to align institutional capacity, data and analysis tools in a concerted effort to take action to protect biodiversity in an era of climate change. The Framework provides guidance on implementing any combination of six adaptation approaches at three distinct levels of ecological organization and the scientific assessments that are needed in support of their implementation.

This guidance helps to establish a baseline understanding of current environmental conditions; identify which ecological features will likely be most vulnerable to climate change; and visualize an act to meet the future needs species, ecosystems, and landscapes.

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# Section IV:

Water Resource Protection: Investment  
Strategies for Managing Risks From Wildfires,  
Pests/Pathogens, and Severe Storm Events

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# Adaptation: Forests as Water Infrastructure in a Changing Climate

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***Abstract:** Natural ecosystems like forests and wetlands provide a suite of water-related services that are increasingly critical for communities as the impacts of climate change intensify. Yet, these natural ecosystems are increasingly lost or degraded. In the face of growing water-related challenges in an age of fiscal austerity, investing in the conservation, restoration, and management of these ecosystems can represent a low cost alternative or complement to concrete-and-steel built infrastructure options and serve as part of a viable adaptation strategy. However, as they must with other forms of infrastructure, decision makers must understand the impacts of a changing climate on the provision of services from natural ecosystems. Impacts like changing species composition and increasing incidence of disturbances like wildfire, insects, and disease can affect the water-related function of upstream ecosystems, requiring additional and ongoing management interventions. This article lays out the basic underpinnings of investments in forests as an adaptation strategy for the provision of water-related services and the need for an iterative and flexible approach to managing those investments over time to ensure their sustainability in a changing climate.*

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## **INTRODUCTION**

As plainly stated in the draft 2013 National Climate Assessment: climate change, once considered an issue for a distant future, has moved firmly into the present. Climate change can have substantial implications for the provision of clean and abundant water that is so fundamental to public health, economic development, and prosperity. In some regions of the United States, heavy precipitation has increased over the last century. At the same time, the drought in western states over the last decade represents the driest conditions in 800 years (Karl and others 2009; Schwalm and others 2012). Changes in timing of snowmelt and associated streamflow have already reduced summer water supplies in regions like the Northwest (US EPA 2012).

All told, the costs to society of ongoing and expected water-related climate impacts are immense. They include escalated water treatment costs, lost economic activity

associated with water shortages, private property and public infrastructure damage, and losses in general human health and wellbeing. Drinking water and waste water utilities alone are expected to incur an estimated \$448-944 billion in infrastructure and operations and maintenance costs through 2050 in order to manage climate impacts (Association of Metropolitan Water Architects 2009).

As affected communities scope strategies to secure water resources in the face of a changing climate, investments to restore and maintain healthy forests should be carefully considered for the role forests can play in buffering against expected climate impacts. To this end, this paper presents a set of climate impacts that currently affect forests in the United States and the forest functions that can help mitigate these climate impacts. At the same time, investments should be shaped to take into account the sensitivity of forests to climate change and the new risks forests may face. To address this, the paper then outlines the risks of climate change to specific forest functions. This provides background for a discussion on opportunities for adapting forest management practices to ensure provision of water resources despite climate change. The two opportunities highlighted are the use of scenarios and robust decision making, and applying a water service lens to adaptation.

## FORESTS AS A FIRST LINE OF DEFENSE AGAINST CLIMATE IMPACTS

“Natural infrastructure” provides a first line of defense for communities as the impacts of climate change intensify. Natural infrastructure is defined as a “strategically planned and managed network of natural lands, working landscapes, and other open spaces that conserves ecosystem values and functions and provides associated benefits to human populations” (Benedict and McMahon 2006). Maintaining healthy, well-managed forested watersheds, for example, can reduce peak storm flows, maintain snow pack, shield water bodies from temperature extremes, and filter sediment, nutrients, and other pollutants in runoff (Gartner and others 2013). The manner in which forests are managed also has bearing on water resources. For example, robust forest road and stream crossing designs can help to mitigate sedimentation risks associated with extreme wet weather events, and maintaining forested riparian buffers is critical for combating elevated water temperatures.

While forests alone are not a panacea to climate impacts, they provide a suite of services that can help to buffer against those impacts (Peters and others 2011 as cited in National Climate Assessment 2013). Some of the most important of these services are summarized in Table 1 above and detailed below. By strategically investing in the conservation, restoration and management of ecosystems like forests, communities can build an *integrated and cost-effective system* of natural and built infrastructure to help adapt water provision systems to a changing climate.

**Table 1.** Forest Functions as a First Line of Defense against Climate Impacts

Climate Impact	Related Forest Function
Flooding and consequences of extreme precipitation	Erosion control and flow regulation
Increasing incidence of summer drought	Flow regulation and snow pack maintenance
Elevated water temperatures and lower flows	Cooling effect of forested riparian buffers

### **Climate Impact:** *Flooding and consequences of extreme precipitation*

Floods are expected to increase in most regions of the United States, even where average annual precipitation is projected to decline (Pan and others 2010 as cited in National Climate Assessment 2013). The largest increases in very heavy precipitation events have occurred in the Northeast, Midwest, and Great Plains (Karl and others 2009), damaging public infrastructure and private property and threatening human health and wellbeing. Meanwhile, earlier snowmelt in the Northwest, combined with more extreme precipitation events, has led to increased water flows and associated flood risk during the spring (Hidalgo and others 2009).

Additionally, as the rate of precipitation exceeds the ability of the soil to maintain an adequate infiltration rate, and as heavy precipitation increases, the kinetic energy of surface water, soils will erode (National Climate Assessment 2013). Accelerated erosion causes increased sedimentation and movement of nutrients, dissolved organic carbon (DOC), pathogens, and pesticides (Delgado and others 2011 in National Climate Assessment). For example, DOC in rivers and lakes is strongly driven by precipitation (Pace and Cole 2002; Raymond and Saiers 2010; Zhang and others 2010), and is expected to increase in regions where precipitation is expected to increase (National Climate Assessment 2013). Elevated levels of pollutants will drive both capital and variable costs of drinking water treatment—requiring investments in new and expanded treatment facilities as well as increasing levels of chemical additives. Increased sedimentation can also reduce the storage capacity in reservoirs needed for drinking water and hydropower generation, and can impact freight navigation.

### **Related Forest Function:** *Erosion control and flow regulation*

Forests have multiple layers of vegetation (Dohrenwend 1977) and have particularly thick litter layers that help to slow falling rain and reduce its erosive force during heavy rain events (Stuart and Edwards 2006). Sturdy, long-lived roots also help to anchor soil against erosion (Beeson and Doyle 1995; Geyer and others 2000). Multi-layered forest canopies have more interception (Brooks and others 2003; Briggs and Smithson 1986), greater photosynthetic area, and deeper roots than other plant communities, and so promote greater evapotranspiration and thus soil water deficits (de la Cretaz and Barten 2007). The forest litter layer promotes infiltration of water into the soil and provides a barrier that slows downslope water movement (Dudley and Solton 2003). These characteristics, together with the very high infiltration rates of forest soils created by complex pore structures, minimize stormflow peaks, minimize overland flow and associated erosion in intense storm events, and provide ample opportunity for nutrient uptake by plants and microbes in the soil (de la Cretaz and Barten 2007; Bormann and Likens 1979; Vitousek and Reiners 1975). In the Pacific Northwest, the forest canopy can minimize the impact of rain-on-snow events through interception. Rain falling on snow has been associated with mass-wasting of hill slopes, damage to river banks, downstream flooding, and associated damage and loss of life (U.S. Geological Survey 2013).

### **Climate Impact:** *Increasing incidence of summer drought*

Most regions of the United States are expected to increasingly experience drought in summer months. Impacts will be most pronounced in the Southeast (Zhang and Georgakakos 2011) and Southwest (Milly and others 2008; U.S. Bureau of Reclamation 2011), where longer term

reductions in water availability are expected with rising temperatures and general declines in precipitation (NCADAC 2013). These trends are occurring in confluence with growing population and demand for water in the Southeast, and increased competition for scarce water resources in the Southwest (Averyt and others 2011). In the Northwest, changes in the timing of snow melt and associated streamflow poses challenges for water availability in the summer months. Models indicate with near certainty that reductions in summer flow (by 38-46 percent compared to 2006) will occur by 2050 for snow-dense basins (Elsner and others 2010).

In addition to clear implications for the availability of drinking water, droughts also reduce the potential capacity for hydroelectric generation (NCADAC 2013) and can hamper other forms of energy production that consume large quantities of water such as shale and hydraulic fracturing. Drought has also created hardships for farmers and ranchers, reducing crop yields and forage available to livestock (Hedde 2012).

### **Related Forest Function:** *Flow regulation and snow pack maintenance*

While forests can reduce overall water yield through interception and transpiration (Hornbeck and others 1995), forests can also help to address summer droughts by regulating the timing of flow. Forest soils and debris can act as sponges, storing and then slowly releasing water. This process recharges groundwater supplies and maintains baseflow stream levels—although the overall effect must be measured against the “use” of water by forests.

Additionally, snowmelt is most sensitive to temperature and wind speeds (van Heeswijk and others 1996). Consequently, snowmelt is substantially higher in cleared areas than beneath forest canopies where wind speeds are lower (Marks and others 1998). Thus, forest cover can help to maintain snowpack and hedge against dry season water supply issues in regions like the Northwest that rely on snowmelt.

### **Climate Impact:** *Elevated water temperatures and lower flows*

Elevated stream temperatures and lower base flows can affect aquatic habitat for critical species (Spooner and others 2011; Xenopoulos and others 2005) and may require additional treatment by wastewater facilities to meet requirements under the Clean Water Act (US EPA 2011). It can also reduce the reliability of water withdrawals for electric power plant cooling and the efficiency of those cooling processes (Backlund and others 2008; Gotham and others 2012).

Rising stream temperature is also a factor, among others, in downstream lake temperature.

Within the past 40 years, lake temperatures have increased by an average of up to 1.5 degrees Celsius in over 100 lakes in Europe, North America and Asia (IPCC 2001). Warmer surface waters can lead to blooms of harmful algae (Paerl and Huisman 2008), which are estimated to impose costs of \$2.2 billion each year (Dodds and others 2009). Higher air and water temperatures are also decreasing lake mixing, decreasing dissolved oxygen and releasing excess nutrients, heavy metals, and other toxics into lake waters (NCADAC 2013). Increased evapotranspiration due to higher temperatures may also increase groundwater salinization in more arid regions, raising filtration and treatment costs for industrial plants, hydroelectric generators, and wastewater facilities (IPCC 2001).

### **Related Forest Function:** *Cooling effect of forested riparian buffers*

Many factors affect stream temperatures—for example, stream surface turbulence, shading, stream size, and stream water travel time (Bourque and Pomeroy 2001). Shade is a critically important—direct solar radiation has been found to be the largest contributor to changes in daily temperature in streams (Johnson and Wondzell 2005). Forested riparian buffers provide shade to streamwater and have been shown to prevent temperature increases (Groom and others 2011). Harvesting forests along streams can increase daily maximum and mean water temperatures by as much as 2 to 10 degrees Celsius (Bourque and Pomeroy 2001).

The examples described here illustrate a key two-fold point: while forests can address only some elements of expected and ongoing water-related climate impacts, investing in forests can be a timely and effective component of a broader community adaptation strategy as a “first line of defense.” Given the multiple benefits associated with healthy ecosystems—e.g., wildlife, recreation, property values, carbon sequestration, and air quality—investments in natural infrastructure can be a “win-win” measure that addresses parallel community needs.

## **CLIMATE RISKS TO FOREST FUNCTIONS**

As communities consider large-scale investments to conserve, restore, or manage forests and wetlands, however, decision makers must understand how a changing climate may impact their water-related functions. For example, changes in precipitation and temperature can contribute to changing species composition and increasing incidence of disturbance in forests. If not carefully managed, these impacts may affect the water-related function of upstream ecosystems, potentially compromising the ability of forests to serve effectively as natural infrastructure under a changing climate. Thus, even as we argue that the forest functions enumerated above help to mitigate climate risks to water services, we also call for attention to the pathways whereby climate change impacts may compromise water-related forest functions. To date, however, a limited body of literature directly treats the impact of climate change on the provision of ecosystem services. Here we highlight two climate impacts affecting the water-related functions of forests and associated management interventions to support maintenance of those functions as the climate changes.

### **Climate impact:** *Increased frequency and intensity of wildfire*

The increase in severe high temperature days in combination with dry air mass events—as well as fuel changes, successional growth, invasive species, insect and disease, longer fire seasons, and more severe episodic drought—is contributing to an increase in wildfire frequency and intensity in the Intermountain West and California (Sexton 2013; NCADAC 2013; Dietze and Moorcroft 2011). Eleven of the twelve largest fires in modern U.S. history have occurred since 2004 (Sexton 2013). These “mega-fires” are unprecedented in their social, economic and environmental impacts (NCADAC 2013).

### **Affected forest function:** *Erosion control and flow regulation*

Catastrophic wildfire can prime a watershed for dramatic surges in peak flows—documented to be up to 900 times greater than the unburned reference case for up to 15 years after a fire,

triggered by rainfall above a certain threshold (Martin 2013). These fires also disrupt the water quality-related functions of forests and elevated post-fire flows can cause massive sedimentation. Sediment exports due to wildfire are increased for up to one year following the fire; increased concentrations have been observed at well over 1,000 times the concentrations of unburned forested waterways. Similarly, multiplied concentrations of nitrogen and phosphorus have been observed to reach up to over 400 times the amount of the same, previously unburned waterways (Smith and others 2011). In some cases, post-fire runoff can also release potentially toxic “legacy sediments” into drinking water systems.

**Forest management technique:** *Prescribed burning and mechanical thinning*

Forest management activities like prescribed burning and mechanical thinning play a critical role in mitigating catastrophic wildfire risk. Historic fire suppression in fire-prone ecosystems like western forests led to the unnatural accumulation of fuels, a risk that is magnified by climatic trends. The behavior of fires that escape suppression is determined by available fuel, weather, and topography. The only one of these factors that can be controlled by forest managers is fuel (Thompson and others 2012). Management interventions like prescribed burning and mechanical thinning are geared to strategically reduce the fuel load in the forest in order to avoid catastrophic fires—for example by limiting canopy ignition by increasing the distance from surface fuels to flammable canopy biomass (Mitchell and others 2009). Fuels management can also protect human communities and restore fire-adapted ecosystems to natural function.

**Climate Impact:** *Changing species composition*

As the climate becomes increasingly variable, the impact of changing species composition on forest functions becomes more pronounced. Many species have already begun to be eliminated from areas that are dominated by human influence. A changing climate will further affect the species composition of forest ecosystems throughout the country, either causing species to migrate to cooler northern regions, or expanding vegetative ranges that sustain invasive species (Chapin and others 2000). Invasive species can displace native organisms while modifying habitat, altering ecosystem processes, and changing the interval of fire and water utilization (National Academy of Sciences 2008). It is likely that without intervention, invasive species will come to dominate migration in many places due to the water-intensive and resource consumption habits maintained by many non-native species. Such species are spread through climate-linked disturbances like flooding and wildfire and usually have traits that favor rapid establishment and population spread, high rates of seed production, and vegetative reproductive persistence in the soil seed bank (Watterson and Jones 2006).

**Affected Forest Function:** *Flow regulation and soil quality maintenance*

Invasive species outcompete native plants and organisms while altering the ecosystem functioning of forests. A forest hydrology report completed in 2008 by the National Academy of Sciences emphasizes an extreme hydrological sensitivity to species composition. As the genetic makeup of forests shifts through competition and predation, vegetation density is often impacted—although effective wildlife management can affect changing density by altering the intensity of browsing by herbivores (Gill and Beardall 2001). Vegetation density in turn affects transpiration rates of tree species. Partial or complete removal of forest canopy can reduce transpiration and

interception of rain, which can in turn increase soil moisture and water availability to plants. Increased saturation of the land reduces slope stability in the long run, while causing greater nutrient and sediment runoff and turbidity via erosion (National Academy of Sciences 2008). In some instances, the scenario might be reversed depending upon the type of tree displacement—eastern deciduous trees with higher transpiration rates and increased leafy surface area can severely deplete the water availability of forests. This suggests the importance of the delicate ecological balance of species in order to maintain forest functions (Brantley and others 2013).

For example, the hemlock wooly adelgid (*Adelges tsugae*) is an invasive insect whose population has been driven by temperature rises in the mid-Atlantic (U.S. Fish and Wildlife Service n.d.). The insect feeds on the keystone hemlock trees in eastern forests, allowing other deciduous species to replace them. This results in increased transpiration, reducing stream flow in the summer and increasing water discharge rates in the winter (Brantley and others 2013).

Certain invasive tree species also have higher rates of water consumption, thereby increasing regional water losses. According to an ecological model based in the northwest, the impacts of climate change are predicted to extend habitat suitability of the invasive *Tamarix* plant species (deep-rooted salt cedar shrubs) anywhere between 2-10 times its current level (Kerns and others 2009). *Tamarix* invasions in the Colorado River Basin have a detrimental effect on annual river flows. The plant spreads rapidly, forms dense thickets that remove water from adjacent streams, and remains more drought-tolerant than the native species that protect against streambank erosion (Chapin and others 2000). An economic study has estimated an annual loss of \$65-\$180 million in reduced municipal and agricultural water supplies due to the rapid evapotranspiration rate and sediment-trapping properties of the salt cedar. Obstructed stream flows throughout the western United States from the plant have yielded flood damages of an estimated \$50 million annually (Mooney and Hobbs 2000).

### **Forest Management Technique: *Holistic invasive species management***

To combat the detrimental hydrological impacts of species composition shifts on forest functions, a holistic adaptive management approach is needed to allow forests to recover from devastating disturbances and provide critical ecosystem services despite species composition shifts. Such a management approach includes enhancements to forest biodiversity and redundancy to act as a buffer against invasive species. Functional diversity in forests is directly related to production in the ecosystem (Chapin and others 1997); redundancy refers to the capacity of various forests to sustain abundant populations of the same species in order to ensure ecosystem functioning following an ecological disturbance. While several tree species have been lost or reduced in temperate forests, there has been relatively little or no loss of productivity in that ecosystem, which suggests compensation by other species (Thompson 2009). Biodiversity and redundancy contribute to forest resilience by maintaining productive capacity of existing species, allowing them to better utilize and partition resources. In complex systems, many organisms provide regular ecological processes (transpiration, decomposition, respiration) compared to simpler systems, where vacant niches are likely available to non-native organisms (Hooper and others 2005).

When controlling for invasive species, scientists and managers must collaborate across scales and jurisdictions to identify priority areas and critical species, and to establish a system of accountability that ensures efficient use of limited resources. In the past, Adaptive Management



Areas have been established in the Pacific Northwest with a focus on iterative learning, testing, and monitoring to ensure biodiversity and ecological resilience in the face of changing climate and land-use (Stankey and others 2003). The U.S. Department of Agriculture's *National Strategy and Implementation Plan for Invasive Species Management* identifies regulation through prevention, early detection and rapid response, control and management, and rehabilitation and restoration phases. Implementing these phases involves development of a national tracking system for invasive species, emergency response capabilities and technology, as well as shared education and outreach for proper protocols to limit the spread of non-native organisms (USDA Forest Service 2004).

## **ADAPTING FOREST MANAGEMENT FOR NATURAL INFRASTRUCTURE SERVICES**

Current best practices such as those outlined above for addressing two forest management challenges—wildfire and invasive species—are important inputs to adaptation planning that could enable forests to help safeguard water provision as the climate changes. Given pervasive uncertainties regarding the future impacts of climate change on forests, however, it may not be sufficient to incrementally expand and improve application of known management techniques.

Uncertainties around climate change impacts arise from three sources: a) unknown future levels of greenhouse gas emissions; b) scientific uncertainty associated with incomplete knowledge about future natural and social system dynamics; and c) natural climatic variability (Hallegatte and others 2012). These uncertainties compound the complexity of the interactions among the multiple drivers involved in a challenge such as forest fire or invasive species management and limit the usefulness of traditional “predict then act” approaches. For example, remaining uncertainty around interactions between climate change and an existing fire regime intersect with changes in land use that put more residences in harm's way, while increases in pests and diseases (some of which may also be affected by climate change) make the forest less fire-resistant.

Meanwhile, it is unclear how post-fire recovery of forest ecosystems may change under warmer temperatures, new precipitation regimes, or with a shifting species mix (Anderson-Teixeira and others 2013). Such complexity makes confident predictions about the implications of climate change for specific localities and regions a substantial challenge (Dessai and others 2009). While climate change and impact modeling continue to improve, it is unlikely that uncertainties at scales relevant to forest management will be reduced significantly in the near- to mid-term. In fact, the Intergovernmental Panel on Climate Change (IPCC) has warned that uncertainties in many instances will increase for some time to come as scientific inquiry diversifies and deepens (IPCC 2007). Here we discuss two ways in which climate change may demand strategic shifts in approaches to forest management.

### ***Using Scenarios, “Robust Decision” and Adaptive Management Approaches***

In response, a growing number of decision-makers are addressing climate change through the use of scenarios. The IPCC defines a scenario as “a coherent, internally consistent and plausible description of a possible future state of the world. It is not a forecast; rather, each scenario

is one alternative image of how the future can unfold” (IPCC 2007). Scenario planning and analysis is the process of evaluating possible future events through the consideration of a set of plausible, though not always equally likely, scenarios. Rather than relying on predictions, scenarios enable a creative and flexible approach to preparing for an uncertain future (Means and others 2005; Carpenter and others 2006; De Lattre-Gasquet 2006). Scenario planning can be conducted in many ways (Briggs 2007) and it is particularly useful for decisions that have long-term consequences, such as a forest management plan or a major infrastructure investment.

Scenarios are also used in “robust decision-making” (Lempert and Collins 2007), which is increasingly being applied to urban infrastructure investments (Lempert and others 2013). Under robust decision-making, each of a set of possible management options is tested against different future scenarios. Ultimately, a decision that fares well against a range of scenarios is chosen. In the absence of a robust option, the scenarios can also be used to identify the vulnerabilities of a potential adaptation, so that it can be modified or its risks otherwise addressed. It is important to note that robust decision-making does not weigh the scenarios with probabilities, nor does it depict the imprecise probabilities as a range. This is appropriate for the climate change context, in which probabilities typically are highly uncertain.

A study conducted for the Future Forest Ecosystem Scientific Council provides an example of how climate scenarios enable robustness to be used as a criterion in forest management decision making (Krcmar and others n.d.). The study created a conceptual framework for forest management decisions under climate change and used the Quesnel forest district in British Columbia as a case study. In the Quesnel case study it was important that the outcome address multiple competing interests threatened by climate change. To achieve this, the first step of the study was to develop multi-criteria forest models that addressed both timber supply and a tree diversity goal. The multi-criteria models were then used under two renewal options: a “status quo” option and an adaptation option that promotes resilience by allowing species composition changes. The models were “solved” for each of the climate scenarios identified and the authors identified two robust plans under the adaptation renewal option with criteria values that performed sufficiently well under all climate scenarios.

In the forest sector, scenarios are sometimes used for planning under the rubric of adaptive management (Cissel and others 1999). However, practical challenges abound, and adaptive management has not attained as widespread or as thorough application as may be needed in a changing climate. An analysis of the Northwest Forest Plan (Stankey and others 2003) highlighted how time lags confound experiments in forest management, and cited the need for greater coordination between regulators and managers under an adaptive management approach. Adaptive management also demands a willingness to acknowledge that current actions and beliefs might be wrong, and that the resources needed for iterative planning and implementation can be considerable. Despite these challenges, adaptive management will be an important strategy for ensuring that potential future climates are considered seriously in forest management, so that forests may help safeguard water benefits from climate change, rather than themselves falling victim to climate impacts. The approach needs renewed emphasis in general, new solutions to implementation challenges, and specific adjustments to consider potential climate change impacts and climate-related ecosystem thresholds.

## ***Bringing a Water Services Lens to Forest Adaptation***

Existing climate change adaptation efforts in the forest sector appear to be moving forward with limited attention to ecosystem services. Important recommendations for adaptation of forests focus on buffers and corridors, maintenance of large-scale ecosystem function, active management of species mixes, and improvements in monitoring. However, many of these recommendations come through a biodiversity lens, with little explicit attention to sustaining natural infrastructure functions for water (NFWPCA Partnership 2012; Heller and Zavaleta 2009).

In cases where forests are being used as part of a water infrastructure solution, adaptation planning should explicitly address infrastructural functions. This means focusing specifically on climate risks to water services, not only risks to the forest as a whole. Borrowing from emerging adaptation practice in the gray infrastructure realm, managers could consider charting a “decision map” or “flexible adaptation pathway” that links management decisions to key benchmarks for water provision over time, and enables monitoring of ecosystem services against expected levels of water demand (Fankhauser and others 1999). Such a “map” or “pathway” charts a risk management approach that can evolve as iterative risk assessments, evaluations and monitoring provide new information over time. London used this approach in designing its new Thames Barrier (Reeder and Ranger 2010), and New York City has used it for city-wide adaptation planning (New York City Panel on Climate Change 2009).

The development of a flexible adaptation pathway requires identification of critical thresholds beyond which key system functions are compromised. For example, a particular forest ecosystem may have thresholds for climate-induced fire risk or altered species composition beyond which the forest’s ability to provide water services becomes significantly impaired. Determining which thresholds are relevant is a significant challenge, but once they have been identified, having monitoring systems in place for these thresholds is central to implementation of the adaptation pathway. Given likely changes in species composition and potential geographic movement of the overall forest system, as well as shifting water demand, critical thresholds for water provision may, in part, be distinct from critical thresholds for the ecosystem as a whole. Climate change calls on forest managers to consider whether and how monitoring systems for natural infrastructure initiatives should differ from systems for monitoring the biodiversity functions of a protected area, or from general monitoring of forest health.

## **A CRITICAL MOMENT**

In the face of a changing climate and aging water infrastructure, never has it been more important to invest in water security. Increasingly, communities are looking to strategically invest in networks of natural and working lands like forests as natural infrastructure to secure the critical functions they provide. These efforts can contribute to community resilience by securing forests as a first line of defense against water-related climate impacts. While forests can provide several critical water services *now* and as the climate continues to change, as much as 34 million acres (13.75 million ha) of forest are projected to be lost in the lower 48 states by 2060 (USDA Forest Service 2012). Now is a critical moment to reverse this trend.

Yet, those forests face a number of climate-related risks that may affect the provision of ecosystem services like clean water and flood protection. While forest management practices are well

established for historical climate and ecological conditions, uncertainty will figure prominently in future approaches to management as the climate changes and ecosystems respond. To date, applications of adaptive management planning to natural infrastructure investments are in their infancy. Going forward, it is essential for researchers to further explore climate risks to the *water services* of forests, and for practitioners to incorporate an adaptive management approach in natural infrastructure investment programs.

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# Water Source Protection Funds as a Tool to Address Climate Adaptation and Resiliency in Southwestern Forests

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**Abstract:** Wildfire intensity in the Southwestern United States has increased over the last decade corresponding with dense fuels and higher temperatures. For example, in New Mexico on the 2011 Las Conchas fire, intense fire and wind-driven fire behavior resulted in large areas of moderate and high severity burn (42 percent of burned area) with roughly 65,000 acres (26,300 ha) left largely without green trees or seed sources. Monsoon rains fell in several drainages that sustained high-severity burn, and these moderate rainfall events triggered massive debris flows. Debris from one canyon deposited 70 feet of ash at the confluence with the Rio Grande. The cities of Albuquerque and Santa Fe stopped using river water for municipal needs for 40 and 20 days, respectively, demonstrating the significant impact of wildfire and post-fire debris flow on municipal water users. This paper examines two case studies in New Mexico that have applied or are seeking to apply the water fund model to watersheds dominated by national forest system lands. The first case study is the Santa Fe Water Source Protection Fund established in 2009, and the second case study is the Middle Rio Grande and Forested Watersheds Fund, expected to launch in July 2014. Both case studies illustrate multiple sectors of government and community interests responding to the need to protect water sources, and joining together to generate the financial resources for rapid action to improve forest resiliency in the face of climate change.

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## INTRODUCTION: ECOLOGICAL EFFECTS OF WILDFIRE IN SOUTHWESTERN FORESTS

The Southwest's fire-adapted forests are experiencing widespread changes as a result of a century of fire exclusion, climate change and various land uses, with an effect on water sources and supplies for people who live in the region. The historical fire regime in the Southwest's extensive ponderosa pine and dry-site mixed conifer forests was frequent, low-severity fire (Swetnam and Baisan 1996). Tree density increased significantly when humans removed fire from the ecosystem, resulting in ladder fuels and dense, continuous canopy fuels (Fule and others

1997; Allen and others 2002). In recent decades, rising temperatures have extended the length of the fire season. Currently, wildfire intensity has increased and caused a higher percentage of moderate- and high-severity burns, a consequence of the historic accumulation of dense canopy fuels and the current condition of fires burning during periods of higher summer temperatures (Westerling and others 2006; Williams and others 2010).

In New Mexico, the 2000 Cerro Grande Fire in the Jemez Mountains was considered large and destructive at the time, with a total size of 42,885 acres (17,350 ha) (Balice and others 2004). New records for the largest fire in the state were set in 2011 with the 156,593 acre (63,370 ha) Las Conchas Fire (Inciweb 2011). Another record was set in 2011 in Arizona, with the 538,049 acre (217,740 ha) Wallow Fire (Inciweb 2011). The New Mexico record was broken again in 2012, with the 297,845 acre (120,533 ha) Whitewater-Baldy Fire (Inciweb 2013b).

Analysis of wildfires from 1984-2006 showed that Southwestern fires typically resulted in 11 percent high severity, 27 percent moderate severity, 39 percent low severity and 23 percent unburned area (Quayle and others 2009). However, the trend in recent, larger wildfires is toward more high severity burn. For example, the Wallow Fire's burn distribution was 17 percent high severity, 14 percent medium severity, 47 percent low severity and 22 percent unburned (Wadleigh 2011). By contrast, the equally large and fast-spreading Whitewater-Baldy Fire had 13 percent high severity burn, 13 percent moderate severity and 74 percent low severity, due in part to frequent fires in the Gila National Forest (Southwest Fire Consortium 2012).

Southwestern forests are critical sources of water for people and play a key role in the hydrologic cycle. Most precipitation comes as snowfall and is stored in forested mountains until spring. Snow melt is the primary source of surface water for agriculture and municipal and industrial use (Leopold 1997). The recent large wildfires with significant areas of moderate and high severity burn have caused extensive and severe hydrologic damage in many watersheds across the region. The magnitude of post-fire flooding can be orders greater than pre-fire flows (Veenhuis 2002) and in some locations has resulted in catastrophic debris flows (Cannon and Reneu 2000). Rising temperatures are predicted to further threaten water supplies and forests, not only due to longer fire seasons with more large fires (Westerling and others 2006), but also through drought-induced forest die-off (Breshears and others 2005) and reduced snowpack and altered stream flow (Barnett and others 2008).

## **SOCIAL, POLITICAL AND ECONOMIC ISSUES OF WILDFIRE AND WATER SOURCE PROTECTION IN A CHANGING CLIMATE**

Community and political leaders responded to the 2000 Cerro Grande Fire with changes in national policy and local practices. A National Fire Plan was created in 2001 as a policy response to large fires such as Cerro Grande (McCarthy 2004). The National Fire Plan evolved as a result of the work of the interagency Wildland Fire Leadership Council, established in 2003, as large fires continued in western forests (U.S. Government Accountability Office 2009). The primary issue addressed in the National Fire Plan was protecting human life, homes and communities. Preventative efforts emphasized proactive treatments to cut and remove overgrown brush and trees around homes in natural areas; this work was to take place in what was termed the Wildland Urban Interface. National programs like FireWise and Community Wildfire Protection Planning were launched to increase local engagement in preparing for wildfire. The Healthy

Forests Restoration Act of 2003 was passed in part to simplify the environmental review process for thinning projects (U.S. White House 2003). The Collaborative Forest Landscape Restoration Act of 2009 created a funding mechanism for thinning and burning at a larger scale (Schultz and others 2012). After 10 years, the National Fire Plan was replaced with the Cohesive Strategy that is currently the guiding policy for fire management and forest restoration by federal and state agencies.

Studies of ponderosa pine and other forest types that historically experienced frequent, low-severity wildfires supported the thinning emphasis in national policy. Extensive research from sites throughout the west suggested that thinning to reduce tree density to historical levels, eliminate ladder fuels, and create canopy separation between trees or groups of trees, would change fire behavior to reduce damaging crown fire (Omi and others 2006; Ecological Restoration Institute 2013).

Congressional appropriations for the USDA Forest Service and Department of the Interior agencies were established for treatments in a Hazardous Fuels Reduction Program as part of the National Fire Plan (McCarthy 2004). Analysis of Congressional appropriations shows the level of funding for Hazardous Fuels Reduction increased significantly between 2001 and 2012, growing from about \$100 million to over \$500 million for the Forest Service and Interior Departments combined. However, even with these major increases, funding for Hazardous Fuels Reduction was insufficient to meet the full need for fuels reduction in western forests. Funding remained a fraction of the amount spent on fire suppression, which exceeded \$1 billion in 7 of the 10 years from 2002 to 2012.

Early in the National Fire Plan implementation, thinning treatments in Southwestern forests averaged in the hundreds of acres per state, despite wildfires that might grow thousands of acres in a day (McCarthy 2004). Throughout the last decade the average treatments cost has been \$500–\$1,000 per acre in the Southwest. Funding is allocated to the forest or district level, and a 500-acre treatment at a cost of \$250,000–500,000 might be all a unit can afford in a given year. The Collaborative Forest Landscape Restoration Program (CFLRP), authorized in 2009, provides up to \$4 million year for selected large landscape projects, can finance treatments of thousands of acres and was enacted to boost the scale of restoration that can be accomplished (Schultz and others 2012). However, the authorized appropriation for CFLRP is capped at \$40 million, which is sufficient to fund 20 large landscapes around the United States. Despite the CFLRP, scientists are increasingly recognizing that the policy and funding context is making it impossible to restore large areas of fire-prone forests at a scale that can make a difference in fire behavior. (Ecological Restoration Institute 2013; Stephens and others 2013)

## **WATER FUNDS AS A FOREST RESTORATION AND CLIMATE CHANGE RESILIENCY FUNDING TOOL**

Funding decreases for federal fuels reduction, coupled with the national recession, federal budget cuts, and declining state revenue prompted some to look at other possible funding mechanisms for forest restoration. Water funds are among the most successful funding mechanisms under the model of payments for ecosystem services, that is, mechanisms whereby payments are made for ecological benefits or services that are not captured in traditional market prices (Goldman-Benner and others 2013). The Nature Conservancy in Latin America established its first water

fund in 2000 in Quito, Ecuador. Today there are 12 established water funds in countries in Latin America, each providing a mechanism for water users to help pay for land management in headwaters that improves water quality and reliability.

Water storage and release is an important service provided by forests in the arid Southwest. A number of cities and towns in the Colorado, Utah, Arizona and New Mexico have created mechanisms that link the water forests provide to downstream users with the funding needed to restore forest health—arrangements that are payments for water services (Carpe Diem West 2011).

In Denver, Colorado, the 1997 Buffalo Creek and 2002 Hayman Fire caused damage to watersheds supply the city with water. Denver Water spent \$26 million on reservoir dredging, water treatment and watershed stabilization (U.S. Department of the Interior 2013). Subsequently, Denver Water entered into a partnership with the Forest Service, Rocky Mountain Region, to share the cost of reducing fuels on forests that are important water sources. Their Forest to Faucets Partnership represents a 5-year \$16.5 million commitment by both parties to invest in restoration on the Pike-San Isabel, Arapahoe and Roosevelt National Forests (Denver Water 2013).

In Flagstaff, Arizona, the 2010 Schultz fire was estimated to cost taxpayers between \$130 and \$147 million in fire suppression and related post-fire flooding damage. These costs and the threat of fire damage to municipal water sources prompted the City to take action with a \$10 million bond to restore two areas with critical water sources (Combrink and others 2013). The bond passed in 2012 with support from 73 percent of voters (Stempniewicz and others 2013).

Both Denver and Flagstaff demonstrate that community leaders are becoming aware of the connections between the security of their water sources and the condition of fire-prone forests that supply their water. Water utilities especially face extra costs for post-fire clean up, costs that may include reservoir dredging, pipe and other infrastructure replacement, clean-up of dirty water in treatment plans, and trucking water to communities whose water supplies are disrupted. Given that forest conditions have deteriorated to the point that federal appropriations for Hazardous Fuels Reduction are insufficient to meet the need in fire-prone forests, community leaders are increasingly seeking to play a role in leveraging solutions.

In New Mexico, wildfire damage to water sources is prompting deeper community engagement. New Mexico is currently experiencing significant drought, higher temperatures and increases in wildfire intensity and severity (Williams and others 2012). With 9.4 million acres (3.8 million ha) of National Forest System lands (Western States Data 2007) in New Mexico, accounting for the majority of mid- and high-elevation forests, water managers have strong incentive to partner with forest managers on proactive solutions. The following two case studies describe the development of water funds as a tool for municipal water source protection in the fire-prone interior West. The first example is a water fund in Santa Fe, New Mexico established in 2009. The second example is a new water fund in development for the Rio Grande and Rio Chama watersheds in New Mexico to protect water sources for Albuquerque, Rio Rancho, Los Alamos, Santa Fe, Espanola, several Pueblos and numerous rural towns and villages. Both examples are based on the model of Latin America water funds, using the manual written by Nature Conservancy staff as a guide to design, creation and operation of water funds (Nature Conservancy 2012).

## CASE STUDIES

### *Santa Fe Water Source Protection Fund*

#### Situation

The Cerro Grande Fire of 2000 had direct effects on Los Alamos, New Mexico, which lost 280 homes (Gabbert 2010) and was without municipal water delivery for 4 months while fire-damaged pipes were repaired. One year after the fire, reservoir sedimentation was 140 times higher than the previous 57 years and remained significantly elevated for at least five-years (Lavine and others 2005)

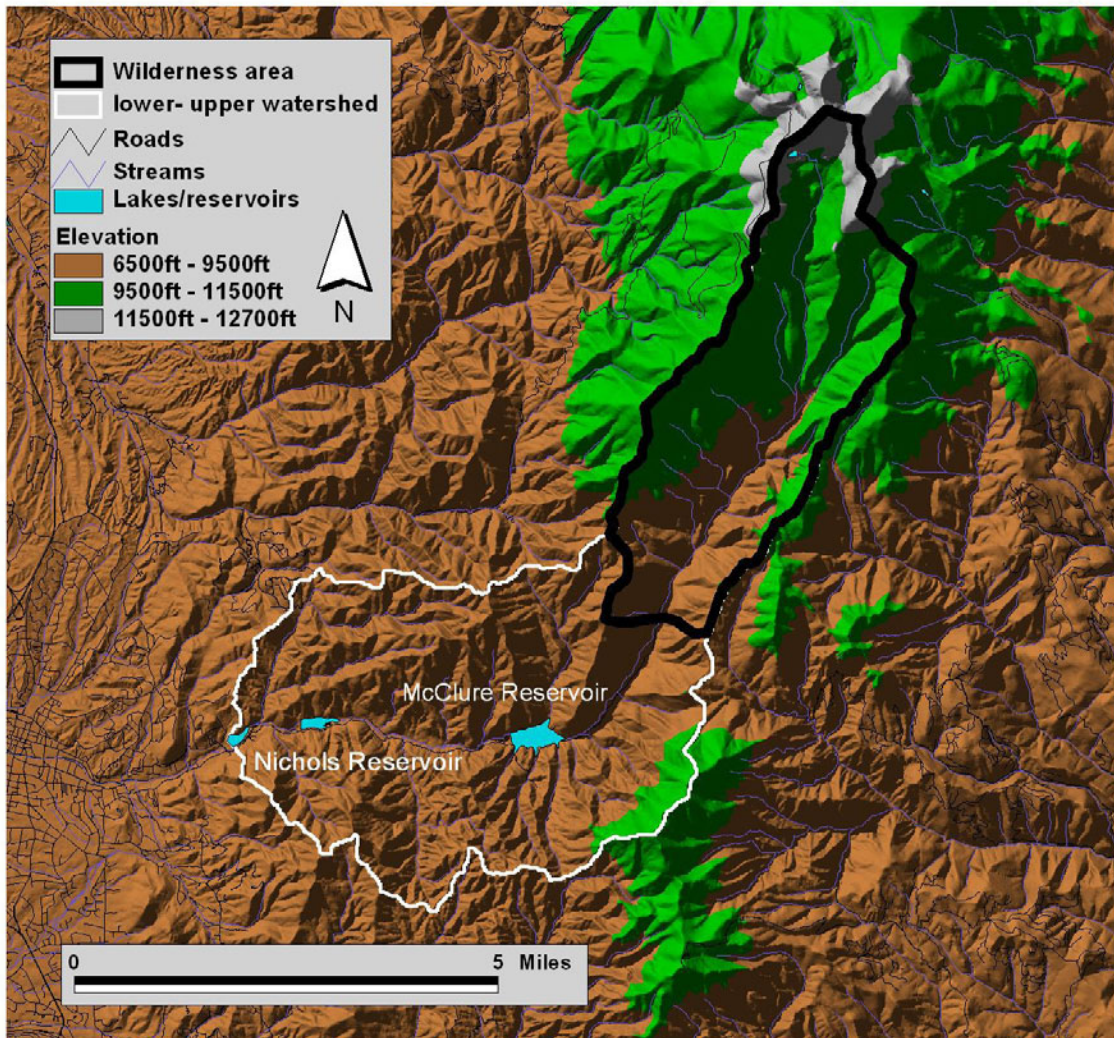
In nearby Santa Fe, the City considered the risk of a similarly damaging wildfire, should one ignite in their 17,000 acre (6,900 ha) municipal watershed, contained entirely within the Santa Fe National Forest. Even though the City sustained no direct costs from Cerro Grande fire, the threat of wildfire to their two reservoirs, supplying 30 percent of municipal water, was of serious concern. Local scientists noted similarities between the overgrown forest conditions in Santa Fe's watershed and the area where the Cerro Grande fire burned, and considered it only a matter of time before Santa Fe experienced a large fire of its own. A few months after Cerro Grande was extinguished, community leaders in Santa Fe launched a concerted effort to proactively cut and remove the overgrown brush and trees, replicating historical forest conditions and reducing the amount of vegetation that could act as fuels in future wildfires.

An Environmental Impact Statement for treatments was approved in 2003 and over the next four years more than \$7 million of Congressionally earmarked funding was appropriated to thin 7,000 acres (2,830 ha) of forests in the lower watersheds that are critical to supply Santa Fe's water (Figure 1). Controversy over the forest treatments was high at first, with local and national environmental groups expressing concern about tree cutting. Concerns diminished after dozens of public meetings, several science forums, and establishment of a multi-party monitoring process to ensure community oversight.

#### Making the Case

Historically, fire burned in the Santa Fe watershed every 15 years (Derr and others 2009), prompting forest and water managers to plan for maintenance of the thinned forest with controlled burning. The Nature Conservancy offered the "water fund" model as potential vehicle to pay for maintenance with controlled burning and other treatments. In 2008 the City of Santa Fe Water Division formed a partnership with the Santa Fe National Forest, Santa Fe Watershed Association and The Nature Conservancy to seek water user funding for long-term management of Santa Fe's critical water sources in the National Forest.

Data about the full economic costs of wildfire was limited in 2008, so the Nature Conservancy developed cost estimates based on the few actual costs available from other communities. Based on this, an estimate of \$22 million cost to the City of Santa Fe and Forest Service was projected from a 10,000 acre (4,050 ha) wildfire in the watershed (Derr and others 2009). These cost estimates were important to make the case for investment in preventative treatments.



**Figure 1.** Shaded relief digital elevation map of the upper Santa Fe Watershed, NM. The area delineated in white was the focus of initial fuels reduction and maintenance with controlled burning. The area delineated in black is designated Wilderness. Adapted from Derr and others 2009.

Public opinion research conducted in 2011 as part of the Santa Fe program found overwhelming voter support for the establishment of a fund to protect Santa Fe’s water supply from forest fires. In a poll conducted by telephone, voters were presented with a description of the threat that a major forest fire poses to the city’s water supply; steps the U.S. Forest Service currently takes to manage this threat; and the need for a stable source of funding to help prevent fires on lands that surround the City’s water supply (Metz and others 2011). The poll found that by a nearly four-to-one margin, voters voiced support for this concept. Voters were also asked how much they would be willing to pay for a Santa Fe Water Source Protection Fund, which would protect water sources and reservoirs from damaging wildfire. More than 80 percent of voters indicated they would be willing to pay, on average, an additional 65 cents per month on their water bill to go towards the Santa Fe Water Source Protection Fund. Voters also were asked whether they would support an average fee of one dollar, one dollar and fifty cents, and two dollars. Even at the highest potential price point—two dollars per month—nearly two-thirds of voters who were surveyed said they would be willing to pay the fee (Metz and others 2011).

### Into Action

The Santa Fe Water Source Protection Fund was approved by the City Council in 2011 as a program of watershed investment. In the final agreement, the City approved a Watershed Management Plan for sharing up to 50 percent of costs with the Forest Service for 20 years to maintain the current conditions in restored forest areas through burning, add new fuels breaks and restoration of some additional lands. The commitment also included funding for monitoring of water quality and restoration treatment effects, and for community outreach and watershed education programs for Santa Fe youth. The approved Watershed Management Plan describes the expected management needs over 20 years and includes a financial plan that outlines the cost-sharing agreement between the City and the Forest Service (Derr and others 2009).

The financial arrangement is for the City of Santa Fe to pay just over \$3 million over 20 years to the Forest Service to ensure protection of its water sources. The watershed treatment costs are split 50-50 between the City and Forest Service (Derr and others 2009). Considering the additional education, water quality and monitoring costs, the expenses are shared as follows: 62 percent City, 36 percent Forest Service, and 2 percent Santa Fe Watershed Association. The initial years of funding for the City and Santa Fe Watershed Association were provided by a \$1.4 million grant from the New Mexico Water Trust Board, funded by New Mexico gross receipts tax. The Water Trust Board funding enabled the City to finish paying for another water infrastructure project before using revenue from the Water Division budget to pay their half of the water source protection (Lyons 2013).

The Santa Fe case study predates Denver, and was the first application of the water fund model to U.S. public lands forests. Testing the water fund model on a small watershed with a few partners made it possible to prove the concept in just a few years. The key lessons from Santa Fe are to keep the funding mechanism simple and to develop a good monitoring and feedback mechanism to keep water fund investors up to date.

### ***Rio Grande Water Fund***

#### Situation

Historically, Albuquerque's political leadership, business community and water utility have put significant effort into planning for a sustainable water future. The Albuquerque Bernalillo County Water Utility Authority's (Water Authority) long-range water supply plan, completed in 2007, outlined the use of water imported from the Colorado River Basin to replenish groundwater and recharge Albuquerque's aquifer as a drought reserve and to establish surface water as the City's primary supply (Albuquerque 2007). Incentives were provided for municipal and industrial conservation, and as a result per capita use of water has dropped from over 250 gallons per person per day in the 1990s to 150 gallons per person per day today (Albuquerque 2013).

About half of Albuquerque's water today comes from the Colorado River Basin via a trans-mountain diversion known as the San Juan-Chama project. Planning for the importation of this water from the Colorado River Basin to New Mexico began in the 1950s, at a time of growth for Albuquerque and in the middle of a ten-year drought cycle. The San Juan-Chama Project is a system of diversion structures and tunnels that moves water from the Navajo River in the San Juan River Basin to the Rio Grande Basin where it flows into the Chama River, a series of



reservoirs, and then the Rio Grande. About 110,000 acre-feet of water are authorized for diversion, and most New Mexico cities have purchased rights to this water. Albuquerque owns the biggest share of San Juan-Chama Project water, but Santa Fe, Los Alamos, and other towns own San Juan-Chama water, as well as the Jicarilla Apache Tribe and the Middle Rio Grande Conservancy District, which uses the water for irrigated agriculture (Reclamation 2013).

The 2011 Las Conchas Fire and 2000 Cerro Grande fire both had a large impact on municipal water sources. The Las Conchas fire occurred in New Mexico's Jemez Mountains, within 30 miles of roughly half of the state's population living in Albuquerque, Rio Rancho, Los Alamos, and Santa Fe, and numerous Pueblos and small towns. The fire was notable for the extent of moderate and high severity burn, which affected 42 percent of the area (Tillery and others 2011). The severely burned areas in Las Conchas left nothing but ash and occasional standing dead trees and boulders. Monsoon rains about six weeks after the fire started created heavy debris flows in four canyons draining directly to the Rio Grande. For example, rainfall of 1.5 inches on August 21<sup>st</sup> and 22<sup>nd</sup> of 2011 caused debris flows in Bland and Cochiti Canyons. The debris flows flooded the popular Dixon Apple Orchard, deposited tons of debris into the U.S. Army Corps of Engineers' Cochiti Reservoir, and lowered dissolved oxygen content of the Rio Grande well past the point where fish and other aquatic species could survive (Dahm and others 2013). Utility operators in Albuquerque and Santa Fe decided the water was unfit for treatment and shut down their surface water use for 40 and 20 days, respectively, switching to groundwater wells at a time of peak summer usage.

### **Making the Case**

The Nature Conservancy began exploring the idea of a water fund focused on protecting water sources from damage by wildfire and post-fire flooding in the Rio Grande valley in 2012 with funding from Lowe's Charitable and Educational Foundation (Nature Conservancy 2014). Unlike Santa Fe, Albuquerque had not yet considered the possibility of wildfire and post-fire debris flow threatening their surface water or contaminating their San Juan-Chama water. However, the Las Conchas fire provided a tangible demonstration of the problem, and city and business leaders were soon convinced that a solution must be found. The Nature Conservancy's initial presentation to the water and energy subcommittee of the Greater Albuquerque Chamber of Commerce was met with a surprisingly high level of support. Additional outreach led to endorsements of the need to find a solution for this problem from other business groups, including the New Mexico Association of Commerce and Industry, which functions like a statewide chamber of commerce, and the New Mexico Water Business Task Force, a group initially formed to advocate for the San Juan-Chama Project.

The underlying problem of dense forests and high severity wildfire adjacent to important water supplies was relatively easy to establish; the more difficult task was to build support and establish funding for a large-landscape program of forest and watershed treatments to improve resiliency to climate change and wildfire. The Nature Conservancy convened a Rio and Forest Advisory Board in April 2013 for the specific purpose of establishing a water source protection fund for the Middle Rio Grande and Forested Watersheds. The Advisory Board is made up of leaders from federal and state forest and water management agencies, business community leaders, university experts, and a diverse cross-section of interest groups from traditional agriculture and recreation to the wood products industry. As the convener and facilitator, the Nature Conservancy has organized the Advisory Board into a set of task-oriented working groups.

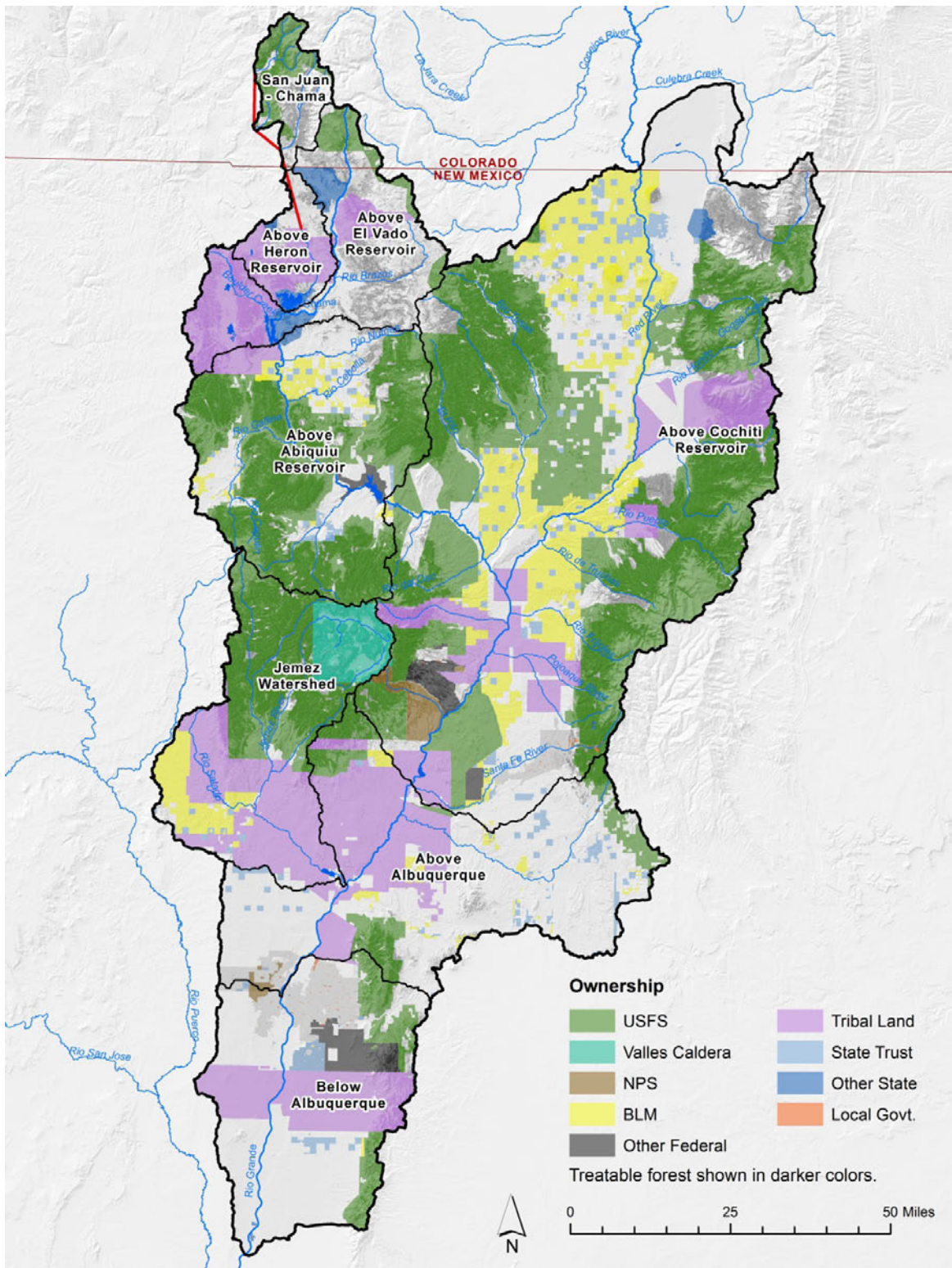
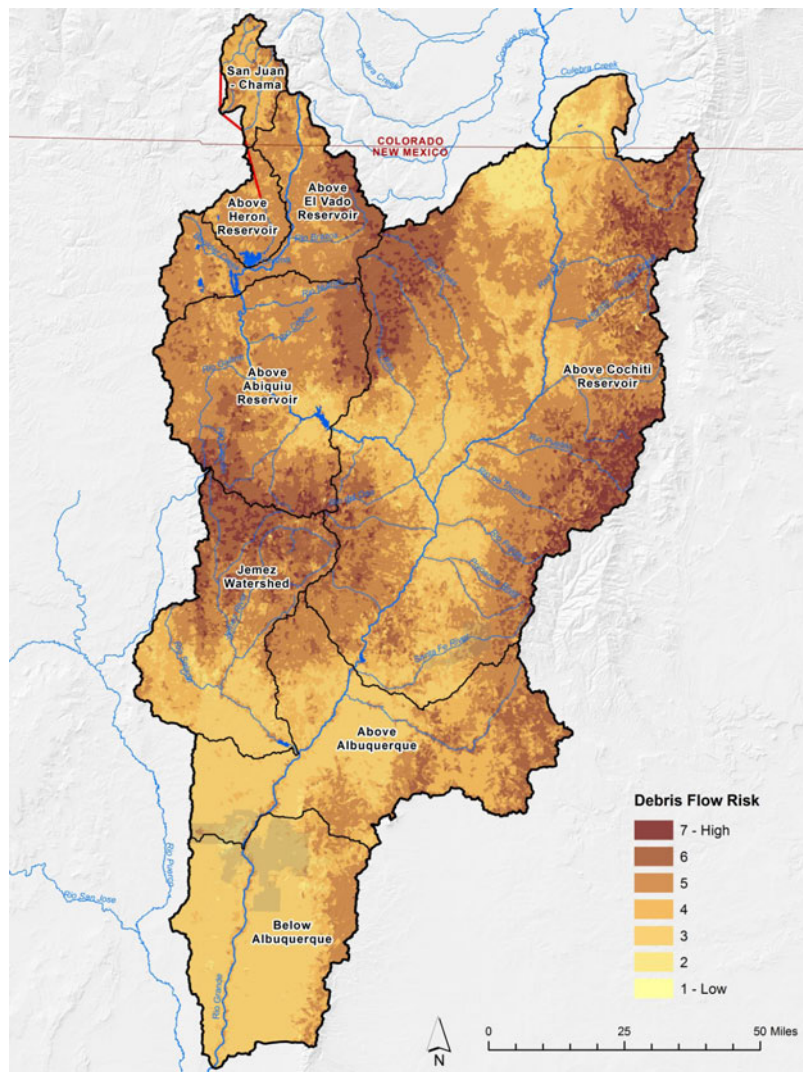


Figure 2. Proposed area for the Rio Grande water source protection fund.

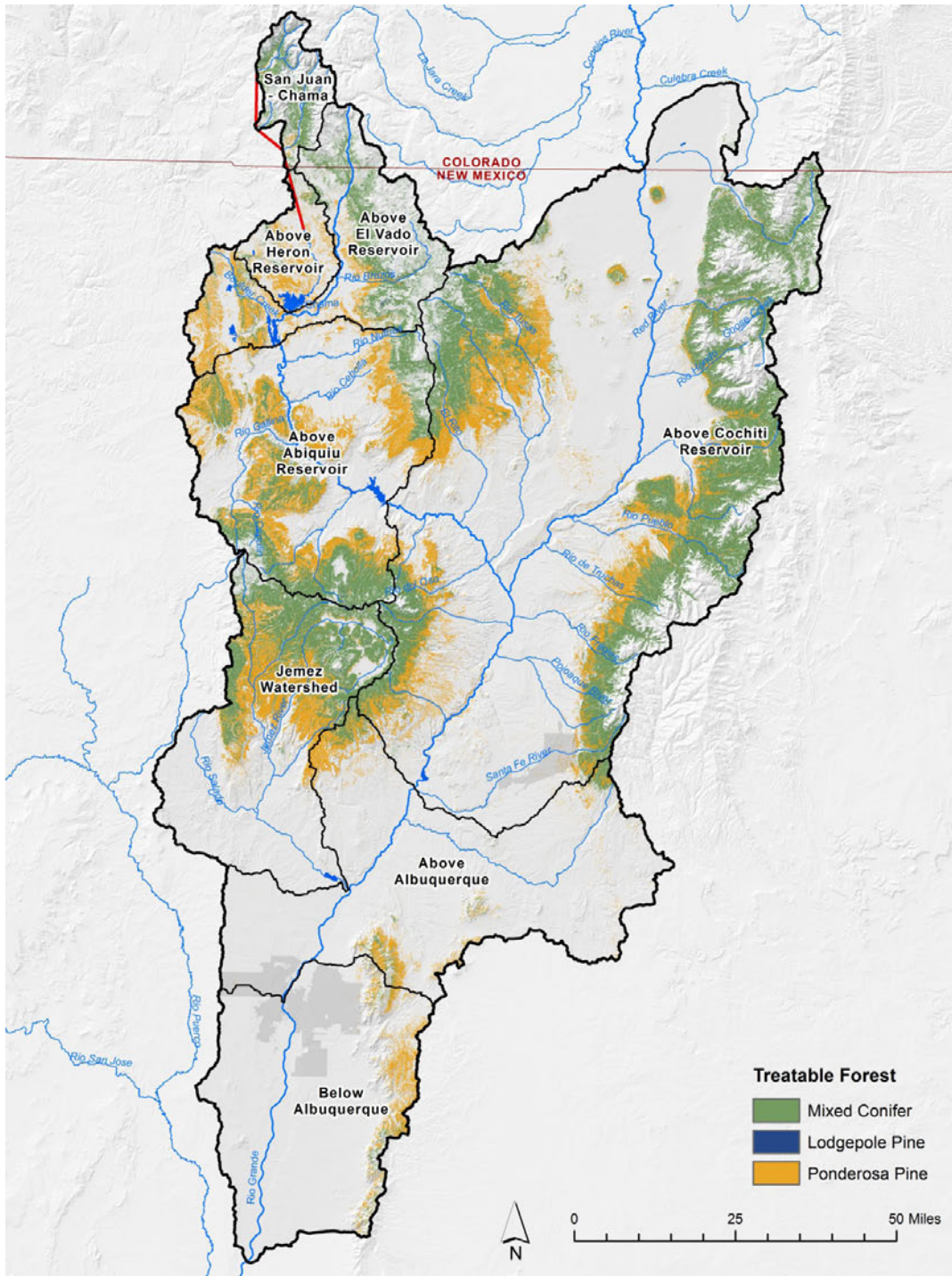
The Conservancy's efforts are focused on creating a dedicated funding mechanism for large-scale investment in forest and watershed treatments from Albuquerque north to the Colorado border (Figure 2). The Rio Grande Water Fund area includes all of the forested watersheds and tributaries to the Rio Grande and Rio Chama, as well as the headwaters of the San Juan-Chama water just over the state line in Colorado.

Studies are underway to establish a clear case for a water source protection fund for the Rio Grande. The studies are necessary to guide development of the water fund. The studies are to:

- Identify the watersheds that are most vulnerable to high-severity wildfire and post-fire to set priorities for water fund expenditures (Figures 3 and 4);
- Estimate water yield that may result from the forest treatments, including water increases that may sustain forests (Grant and others 2013) or streamflow;
- Assess the full economic costs of the Las Conchas wildfire to inform a cost-benefit analysis; and
- Survey municipal water users and agricultural users to determine their understanding of the threats to water security and willingness to pay for restoration treatments of at-risk forests.



**Figure 3.** Probability of Wildfire and Post-fire Debris flow in the proposed Rio Grande water source protection fund area.



**Figure 4.** Areas of ponderosa pine and mixed conifer forest in the proposed Rio Grande water source protection fund area.

The outcome of these studies and engagement of the Advisory Board and working groups will be to produce a comprehensive water security plan for the Rio Grande from Albuquerque north to the Colorado border. A draft of the plan is forthcoming and will be available at [www.nature.org/riogrande](http://www.nature.org/riogrande). The plan will include a prioritized list and map of restoration treatments for forests and riparian areas; estimated costs and capital needs to implement the plan, including NEPA assessment for federal lands, wood product utilization and investment needs in infrastructure; and a detailed plan for water fund structure, governance and revenue.

Early estimates by the Nature Conservancy are that the Rio Grande and forested watersheds in the area from Albuquerque north to the Colorado border includes 1.7 million acres (688,000 ha) of ponderosa pine and mixed conifer forests (Nature Conservancy 2014). Historically, these forests experienced frequent low-severity fire. Mechanical thinning and controlled burning recommended by scientists and land managers are effective treatments to reduce fuel loads. The Nature Conservancy's estimate assumes that 40 percent of the 1.7 million acres (688,000 ha) of eligible forests would actually be treated, with a preliminary goal to treat 700,000 acres (283,300 ha) in 10-30 years, depending on how quickly the rate of treatment can be accelerated. Current treatment levels in this area is estimated at roughly 3,000 acres (1,215 ha) annually, so a tenfold increase would be 30,000 acres (12,140 ha) per year, and it would take roughly 23 years to reach the goal. At a cost of \$500 per acre, about \$7-15 million revenue would be needed annually, assuming current markets for low-value wood and assuming federal appropriations at current levels are available as matching funds.

Raising \$7-15 million non-federal funds each year for 30 years for forest and watershed restoration will not be easy. The water fund needs to be structured in a way to receive funding from a variety of sources, including payments by municipal water users and irrigation district members, homeowner's insurance premium taxes, and corporate and voluntary donations. These options are under study now. After the investment period needed to reduce fuels substantially, a program of controlled burning and mechanical thinning with commercial by-products will need to be sustained in the long-term. The annual costs to maintain forest and watershed resiliency after the initial treatments should be far less and is estimated at \$1-3 million.

### Into Action

The Rio Grande Water Fund will be launched in July 2014. Strong support of political leaders and business interests is propelling the water fund idea into the political arena, where there is some possibility of having the fund established by the New Mexico Legislature in their 2015 session. In this scenario, the water fund would probably need to be statewide, with a provision for establishing priority areas that would likely include protection of the San Juan-Chama water.

## **CONCLUSION**

The evolution of water funds in New Mexico has progressed from a small-scale, proof of concept in Santa Fe to a large and complex Rio Grande Water Fund that includes many diverse partners and a complex landscape. The Rio Grande Water Fund is framing the issue as water security, and is gaining far more traction for forest restoration than was achieved when the issue was framed as wildfire protection. All aspects of New Mexico life are touched by water availability and reliability. The Cerro Grande and Las Conchas fires, and subsequent flooding and

debris flows, provided water managers, water users and politicians with a first-hand view of the consequences of inaction. Forests in New Mexico function much like water towers do in wetter parts of the United States. State leaders are starting to understand the risk of waiting to take large scale action to restore forests. New Mexico water managers and political leaders are realizing they will bear the costs of cleaning up water that is degraded by post-fire flooding and replacing water sources that sustain long-term fire damage. The water fund model from Latin America provides a structure for customized local solutions to water security problems in places like the Southwest where climate change is causing large-scale changes to forests. Both the Santa Fe and Rio Grande Water Funds are, in essence, climate change adaptation strategies, focused on garnering long-term funding to maintain resiliency in large, forested watersheds. It remains to be seen if a project as large in scale as the proposed Rio Grande Water Fund for treatments across 1.7 million acres (688,000 ha) of forest can be achieved. The concept, however, is gaining serious traction and its success or failure may be assessed within a few years.

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# Measuring Resilience to Climate Change: The Benefits of Forest Conservation in the Floodplain

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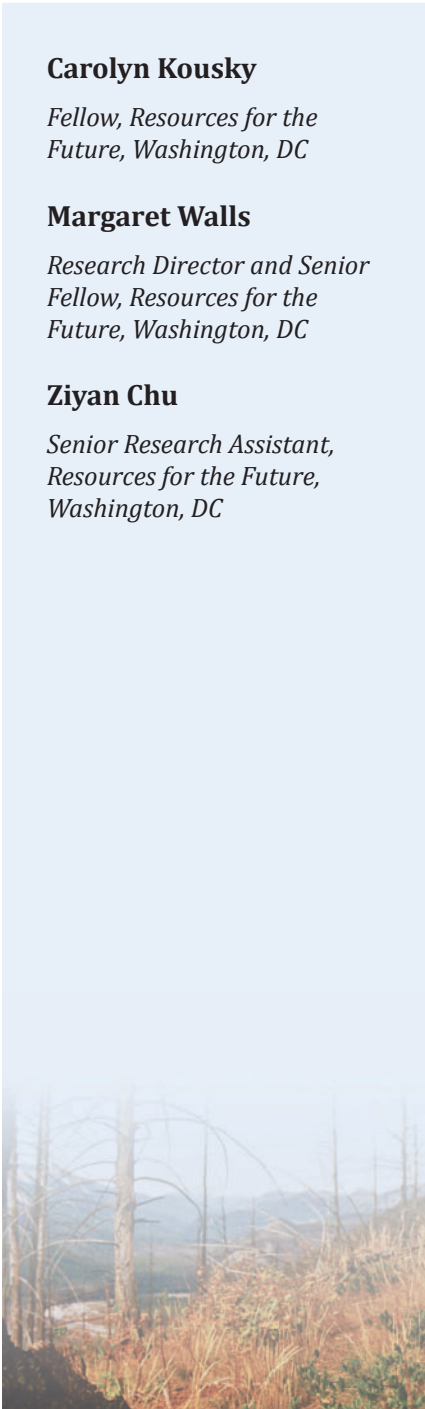
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## **INTRODUCTION**

The economic costs of flooding have increased in the United States over the last several decades, largely as a result of more people and property, and more valuable property, located in harm's way (Pielke and Downton 2000). In addition, climate models predict increases in the intensity of precipitation events in many locations (Wuebbles and Hayhoe 2004; IPCC 2012). How such precipitation changes will alter flood risks is not well understood, but could lead to greater flood damages in the future. Given these findings, various stakeholder groups have suggested it is time to think more seriously about relocating people out of harm's way or preventing development of the riskiest areas. This has been suggested for certain coastal areas in the wake of Hurricane Sandy, but inland floodplains are also a focus of conservation efforts. Conservation lands in floodplains and other hazardous areas not only can reduce exposure and thus bring down disaster costs but may provide an array of other ecosystem services.

Despite this growing interest, very little economic analysis has been conducted on the costs and benefits of conservation to lower future damages attributable to climate change. Can the benefits of reduced future damage from extreme events justify conservation investments today? When coupled with the other benefits that natural areas provide, would consideration of the reduced damages from future extreme events alter land acquisition strategies? If so, which investments provide the greatest "bang for the buck?" Communities are searching for "no regrets," or "low regrets," options that can (1) provide protection under a range of outcomes, (2) offer other ancillary benefits, and (3) come at a reasonable cost (Kousky and others 2012). Thus, sound quantitative analysis of the costs and benefits of the land conservation approach is critical.



We take a step toward such an analysis here by estimating the additional benefits that would be provided by floodplain conservation lands if flooding were to worsen in the future as a result of climate change. Our case study is the Meramec Greenway, a collection of roughly 28,000 acres (11,330 ha) of conservation lands along the Meramec River in southern Missouri. Approximately 9,000 of those acres lie in St. Louis County, which is the focus of our study. The Greenway includes two state parks, many local parks, and a system of trails and river access points. The lands consist primarily of hardwood forests and a small amount of open recreational spaces. In a recent study, we estimated the benefits of the Greenway in terms of avoided flood damages and non-market benefits such as aesthetics and recreational access that are capitalized in property values; we also compared these benefits to an estimate of the opportunity costs of preserving the lands from development (Kousky and Walls 2013). We did not consider the impacts of climate change, however. In this paper, we assess how increased flooding as a result of climate change would alter our estimates of the avoided flood damages from the Greenway. In other words, how much more is the Greenway worth in a world with more extreme flooding events? Does consideration of future changes suggest changes to the on-going land acquisition strategies in the region?

Climate projections at a local level are notoriously uncertain. Given that uncertainty, we look at several plausible future scenarios of flood risk based loosely on findings in the literature to provide some bounds on how potential changes in flood risk could translate into economic damages. These scenarios are not meant to represent any particular future reality, but instead are used to generate order-of-magnitude estimates of the climate resilience benefits of floodplain conservation. We look at scenarios in which the discharge of a given flood event is increased and scenarios in which the probabilities of floods of various magnitudes increase. Our methodology calculates the benefits from reduced exposure to flooding, i.e., the benefits from keeping developed properties out of harm's way. It does not calculate the additional hazard mitigation benefits that might be provided by forest cover in terms of altering the hydrology of the riverine environment. Forests can intercept rainfall before it reaches the ground, and the soils can store water and reduce the flow to nearby streams and rivers. In our particular setting, such benefits are likely to be small: surrounding land uses do not include a lot of development at the present time and the residential lots that do exist are quite large. Furthermore, the Mississippi, into which the Meramec flows, is a highly managed river with a system of levees and dams that control flooding, thus changes in flows from the Meramec are likely to have little impact downstream. In other settings, these additional benefits of natural systems may be important to quantify.

We find that the Greenway lands provide substantial benefits in the form of reduced flood damages even without climate change. Slightly more than \$13 million per year of flood damages are avoided, on average, by keeping the protected lands in the 500-year floodplain of the Greenway undeveloped. This is about a 38 percent reduction from average damages in a hypothetical scenario without the Greenway. On a per-acre basis, this amounts to about \$6,000 per acre of floodplain protected lands. In Kousky and Walls (2013), we estimate that in combination with the recreational and aesthetic benefits of the lands, the Greenway passes a simple benefit-cost test, yielding benefits for the region in excess of the opportunity costs of keeping the land out of development.

Increases in flood risk make the Greenway lands even more valuable. For scenarios in which we increase peak discharges either 30 or 50 percent, the annual avoided flood damages of the Greenway increase by \$3.8 million and \$6.6 million, respectively. Thus, climate change

reinforces the rationale for keeping the Greenway lands protected. The size of the flooded area increases in these scenarios—the 100-year floodplain grows by approximately 10 percent and 15 percent, respectively, in the two scenarios. This may justify additional expansions in conservation acreage. Increases in the frequency of flood events also raises the benefits of the Greenway lands. Doubling the probabilities of each individual flood event, from the 5-year flood up to the 500-year flood, doubles the annual avoided damages (from \$13 million to \$26 million). Some experts have suggested that the largest flood events are the ones that will worsen with climate change. We find that doubling the frequency of only the worst events (the 100-year, 250-year, and 500-year floods), leaving the frequencies of the smaller floods the same, has a relatively minor effect on avoided damages: annual avoided losses total \$14.3 million instead of \$13 million. Climate change will manifest itself gradually over the decades to come. We make no attempt in our analysis to discount future losses to the present or address other important dynamic concerns. We do include a discussion of these important issues, however, in the penultimate section of the paper. We also discuss other dynamic issues such as the irreversibility of development and certain kinds of “gray” infrastructure investments.

## **REVIEW OF THE LITERATURE ON CLIMATE-INDUCED CHANGES IN FLOOD DAMAGES**

Over the twentieth century, floods accounted for more lives lost and more property damage in the United States than any other natural disaster (Perry 2000). Most climate models predict these problems will worsen in the future; in fact, in a comprehensive overview of the likely effects of a changing climate on the nation, flooding is almost unique as an impact that will be felt nationwide, affecting coastal and inland communities, and rural and urban areas (National Research Council 2010). While the models vary widely in assumptions and results, they tend to find that warming will lead to greater moisture loads in the atmosphere, accelerating the hydrologic cycle and increasing the frequency, intensity, and/or duration of storm events.

Regional climate models specific to the Midwest have also generally concluded that an increase in the frequency and intensity of heavy precipitation events is expected in the region under likely future climate scenarios (Easterling and Karl 2001; Wuebbles and Hayhoe 2004). These model predictions are supported by some studies of the historical record; using historical data from the Midwest, Angel and Huff (1997) and Groisman and others (2004) have identified an increase in heavy precipitation events. Kunkel and others (1999) found that the frequency of extreme precipitation events occurring on average once per year—that is, “one-year” flood events—has increased 3 percent per decade nationally in the United States since the early part of the century; five-year floods have increased by 4 percent per decade nationally in the United States (Note: A 1-year flood in this context refers to an extreme precipitation event that has a recurrence interval of 1 year. This classification can be extended to a 5- or 100-year flood based on the severity and probability of its occurring.) An increase in extreme precipitation is expected by many flood experts to exacerbate flood risk. A study for the Upper Mississippi Basin that coupled a hydrology model to downscaled and bias-corrected climate projections found that by the end of the century, winter, spring, and summer peak flows will increase, as will the flashiness of the hydrograph, particularly in the spring (Wuebbles and others 2009). A global analysis found initial evidence that large floods (those exceeding 100-year levels) have increased in large river basins over the twentieth century (Milly and others

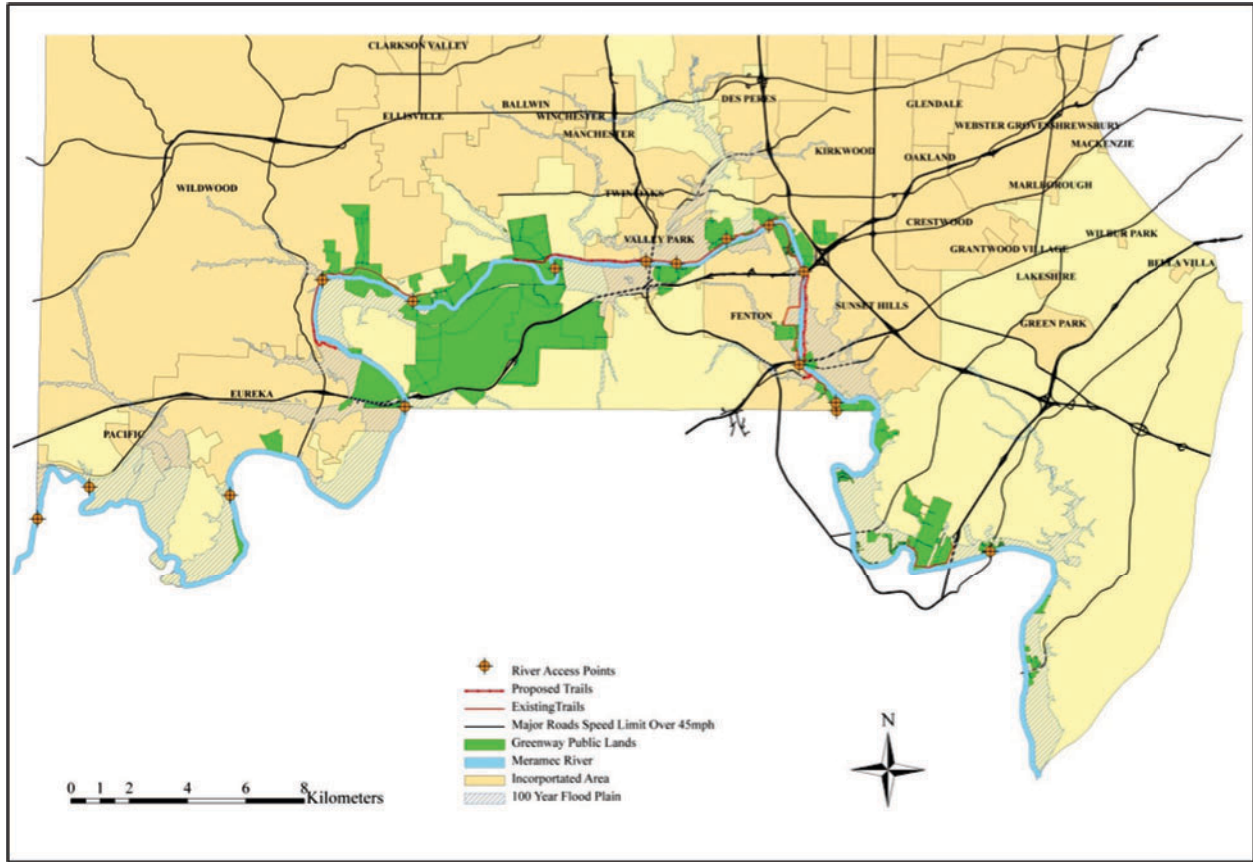
2002). A recent national level analysis, undertaken for FEMA, estimates how the discharge associated with the 100-year flood may change through 2100 based on climate and population scenarios (Kollat and others 2012). This study finds that the 100-year discharge could increase substantially, particularly in the Pacific Northwest, the Northeast, and in very urban areas. The authors estimate that these areas could see increases in the 100-year discharge of 30-40 percent by midcentury, and by more at century's end. The study did not examine sea level rise or storm surge but focused on riverine flooding.

There is, however, some disagreement between those researchers who run climate models and those who look at the historical record of flood stages. Despite the modeling predictions, there is only mixed observational evidence of increasing flood stages. Part of the issue is that flood stages are related to precipitation in a complex way (this is even more true for flood damages). It is difficult to tease apart the competing forces of climate change, land use, dam operation, levee construction, and other structural flood control measures. Pinter and others (2008) have looked at these issues on the Mississippi River but such studies are rare. Further, flood events depend not just on precipitation but also on antecedent soil moisture and changes in frozen ground cover, both of which may also be influenced by climate change (Hirsch 2011). And finally, all researchers agree that climate impacts have yet to materialize in full, creating a disconnect between the historical record and future projections.

## **BACKGROUND ON THE MERAMEC GREENWAY**

The Meramec River joins the Mississippi River at the southern edge of St. Louis County. Much of the Missouri and Mississippi Rivers in the county are lined with levees, but the Meramec River is largely devoid of any structural protection. The river has long been used for recreation and when dams have been suggested for the river, public sentiment has generally been opposed. As a result, the river has remained mostly in a natural state. Flooding along the Meramec in St. Louis County can occur when large floods on the Mississippi back up into the Meramec or when heavy spring and summer precipitation lead to seasonal flooding; in areas along the river with steep slopes and thin soil cover, flash flooding is common (Winston and Criss 2003). In 2000, for example, flash flooding along the Meramec River damaged structures, roads, and bridges, and led to two deaths (Winston and Criss 2003).

The Meramec Greenway runs from the confluence of the river with the Mississippi back 108 miles into the Ozark Uplands. It was initially created in 1975 and encompasses the lands around the river in the floodplain, the surrounding bluffs within sight of the river, upland areas deserving special protection, and publicly owned lands connected to the river valley (St. Louis County Department of Planning 2003). Much of the land remains in private hands, but the Greenway currently includes over 28,000 acres (11,330 ha) of parks and conservation lands, 9,000 of those acres in St. Louis County. This is roughly 15 percent of the 500-year floodplain of the Meramec and its tributaries that lie within the County. FEMA funded buyouts of frequently flooded properties in 1982 and again in 1993. St. Louis County adopted a Concept Plan for the Greenway in 2003 with multiple stated goals, including flood damage reduction, as well as water quality improvements and expanded recreational opportunities (St. Louis County Department of Planning 2003). A map of currently protected lands in the St. Louis County portion of the Greenway is shown in Figure 1.



**Figure 1.** Meramec Greenway in St. Louis County, Missouri

Table 1 shows the percentage of the Greenway protected lands in various land cover classes, as well as the percentage for the unprotected portion of the Greenway. Using 2006 land cover data from USGS, we identified that deciduous forests make up 73.3 percent of the land cover of the Greenway protected lands in St. Louis County; mixed and evergreen forests are not common in the area, comprising only 0.4 percent of the Greenway protected lands and none of the unprotected acreage. Developed open space is the next largest land cover class, making up slightly less than 11 percent of protected lands. These are open areas such as ball fields, other parkland, and subdivision open space that are covered mainly in recreational grasses. The lands in the Greenway that are unprotected have a quite different distribution of land covers. These are lands that remain mostly in private ownership but may be targets for future protection. The most common land cover, at roughly 27 percent is agriculture. Another 23 percent of these lands are deciduous forest. Almost 20 percent of Greenway lands not currently in a protected status are developed.

Figure 2 shows a map of land cover for the entire Greenway. Most of the farmland is in the western portion of the Greenway. The large area of deciduous forest in the center of the map, in green, covers two state parks and county parkland, as well as a private reserve. Forest cover exists in smaller patches throughout the Greenway. The purple areas are the developed open space; in the case of protected lands, much of this is in local parks. Development is concentrated in a few parts of the unprotected areas of Greenway, as shown on the map.

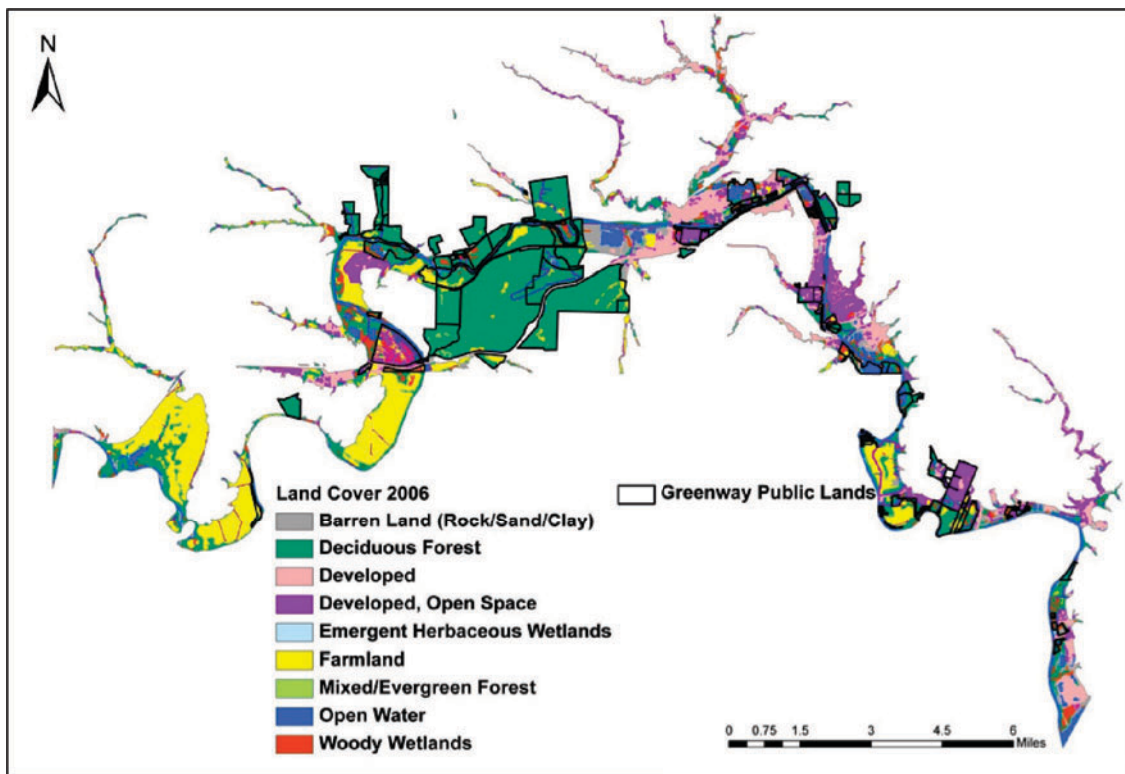
**Table 1.** Percentage of Meramec Greenway Lands in St. Louis County in Various Land Cover Classes.

	Protected Lands	Unprotected Lands
Deciduous Forest	73.3	23.0
Evergreen Forest	0.3	0.0
Mixed Forest	0.1	0.0
Developed Open Space	10.9	15.2
Emergent Herbaceous Wetlands	0.1	0.1
Woody Wetlands	4.1	5.1
Farmland <sup>a</sup>	4.5	26.8
Developed Uses <sup>b</sup>	2.1	19.5
Barren Land	0.7	4.6
Open Water	3.8	5.7

<sup>a</sup> Farmland includes pasture/hay, herbaceous vegetation and grasslands, and cropland.

<sup>b</sup> Development consists mainly of low intensity residential and commercial development.

Source: USGS 2006 National Land Cover Dataset and St. Louis County GIS Service Center, <http://www.stlouisco.com/OnlineServices/MappingandData>.



**Figure 2.** Land Cover for Meramec Greenway Lands

## METHODS

To evaluate the avoided flood damage benefits of the Greenway, we need to make an assumption about what would have occurred on these lands had they not been protected from development. We then compare the estimated damages under various flood events in this hypothetical scenario with the damages under current conditions. The difference is a measure of the benefits from the Greenway. To assess the benefits in a world with climate change, we undertake the same exercise but make assumptions about heightened levels of discharges and/or changes in the frequency of flood events. We do not consider any changes in population or economic growth over time, but rather simply compare and contrast alternative flood scenarios. In addition, we do not account for additional adaptation measures that households and businesses might adopt in the event of climate change.

To estimate flood damages, we use the Hazus-MH model, a national, GIS-based model developed for FEMA by the National Institute of Building Sciences. Hazus-MH couples a flood hazard analysis, which estimates the depth of flooding, with an analysis of economic losses. To implement the flood hazard module, Hazus relies on a digital elevation model (DEM) to delineate the stream network for a region. We upgrade our analysis to a finer resolution DEM (1/3 arc-second) from the National Elevation Dataset maintained by the U.S. Geological Survey (USGS). We estimate our stream network with a resolution of 0.5 square miles. Once the stream network is created, Hazus invokes a hydrology and hydraulics model to generate a flood surface elevation layer for the study region. For a given return period or discharge volume, this estimates the depth of the flood from a depth-frequency curve. For more detail on the flood hazard module, see Scawthorn, Blais and others (2006).

The default settings for Hazus-MH estimate economic damages at a Census block level. For a small-scale analysis, such as ours, this can introduce large errors. Hence, we undertake a parcel level analysis using the User Defined Facility tool in Hazus-MH and drawing on parcel level data we obtained from the St. Louis County Planning Department and the St. Louis County Revenue Department. To do this, we create a database of the structures in the Meramec floodplain for inputting into Hazus-MH. Depending on the type of structure, Hazus-MH then uses depth-damage curves to relate depth of flooding to building and contents damages for each property. Much of the developed land in unprotected areas of the 500-year floodplain of the Meramec and its tributaries is single-family residential development. Therefore, in our hypothetical counter-factual scenario, we assume that the Greenway-protected lands in the 500-year floodplain would have been developed as single-family residential properties in the absence of protection.<sup>1</sup> Lot sizes and property types and values are based on surrounding developed properties. For each protected parcel that is below the 90<sup>th</sup> percentile of lot size for existing single-family residential parcels in the floodplains, which is 1.05 acres, we assume one home would have been on the parcel in our hypothetical case. We assume larger parcels would have had more homes—that is, they would have developed as multiple lots. For these parcels, we use an average lot size of 1.05 acres and place as many houses as will fit on the parcel. For more detail, see Kousky and Walls (2013).

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<sup>1</sup> Our flood damage modeling includes return periods up to the 500-year flood. Since we do not model greater flood events, there is no need to put hypothetical development on lands outside the 500-year floodplain—even though the Greenway does include protected areas outside the 500-year floodplain—as they would never flood in our analysis.



Hazus will estimate flood depths and damages for various return intervals. We estimate building and content damage to our properties for 5-year, 10-year, 50-year, 100-year, 250-year, and 500-year flood events. We then use these estimates to calculate an annual expected loss from flooding for each property. This expected value is referred to as the average annual loss, or AAL; it is the sum of the probabilities that floods of each magnitude will occur, multiplied by the damages if they do (FEMA year unknown). To estimate the AAL, we assume damages are constant in the intervals between return periods and equal to the average of damages at each end point. For example, for the return interval 5-10 years, we add the damages for the 10-year flood to those for the 5-year flood and divide by 2. Since the x-year flood gives the probability of that flood or greater occurring ( $1-F(x)$  where  $F(x)$  is the cumulative probability distribution), the probability of a flood occurring in the interval between a x-year flood and a y-year flood (for  $y>x$ ) is equivalent to  $1/x$  minus  $1/y$ . We do this for each interval and then calculate the total average damage across all “bins.” We then sum the AAL for all properties for each scenario: current development and our hypothetical development absent the Greenway. It is important to keep in mind that this is an approximation to the true expected value as we are not estimating the entire distribution of damages, just the damages for particular discrete flood events (Farrow and Scott 2013). Using the AAL rather than just the losses from a single event, such as the 100-year flood, allows for a more comprehensive assessment of likely flood damages in a given year.

For the climate change scenarios, we estimate flood damages assuming (1) peak discharges are 30 percent greater than under current conditions, (2) peak discharges are 50 percent greater than under current conditions, (3) the probabilities of the 100-year, 250-year, and 500-year flood events are doubled, and (4) the probabilities of all flood events are doubled. In scenarios (1) and (2), flood events occur with the same frequency as under current conditions but peak discharge increases change the level of damages. In scenarios (3) and (4), the discharges stay the same, but flood events occur more often; in these cases, the estimated losses from a particular flood event stay the same, but because the probabilities are higher, the expected losses from flooding in a given year are higher. As stated above, we assume nothing about adaptation activities. We also do not assume there is any permanent change in location of households as a result of climate change.

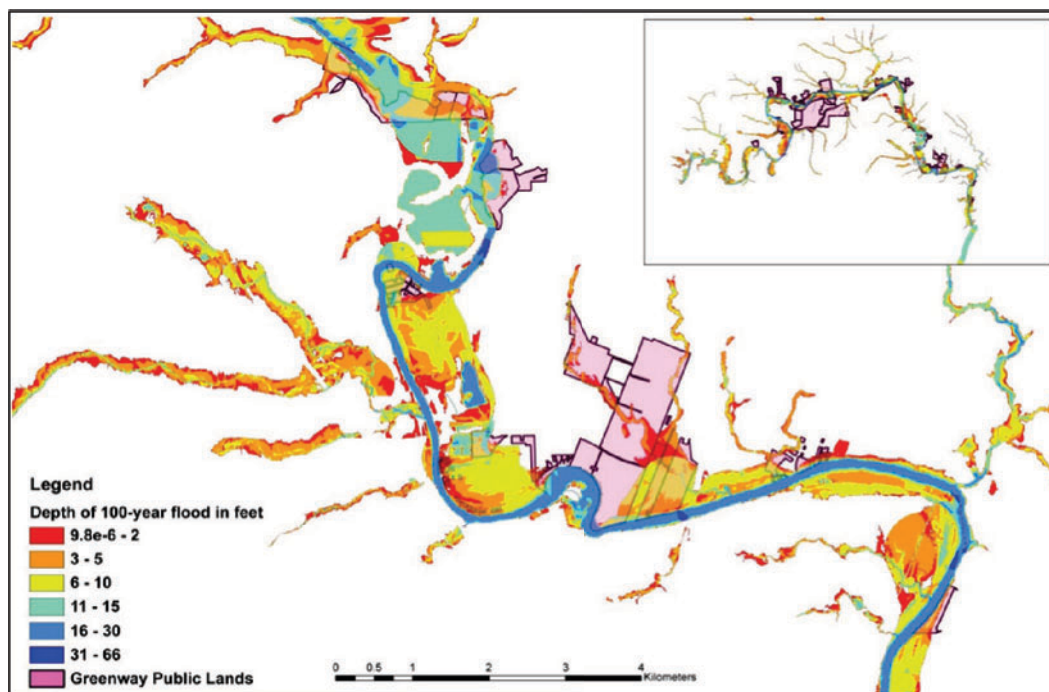
Our changes in peak discharge are based on findings, some referenced in the previous section, that climate change could increase discharge values, although estimates are highly uncertain given the uncertainties in changes to temperature and precipitation, among other variables (e.g., Jha and others 2006). The Kollat and others study (2012), which the authors stress should not be used for very local estimates, suggests a median 40 percent increase in the 100-year discharge in the region of our study area for the combined effects of population and climate by the end of the 21<sup>st</sup> century, and somewhere around 30 percent for just the influence of climate. A roughly similar increase in discharge, but using different methods, was found for a river basin in Maryland (Gilroy and McCuen 2012). There is not much in the literature on how discharges for other return periods may change going forward. We thus estimate two scenarios, one below and one above the order-of-magnitude Kollat and others (2012) estimate. Our second scenario of a 50 percent increase should be taken as an upper bound and is used to see how sensitive results are to various discharge magnitudes. The justification of our third scenario is that a greater share of precipitation could come in the form of heavy downpours. A report on climate impacts in the Midwest estimates that heavy downpours are now twice as frequent as they were 100 years ago and are expected to increase by more than 40 percent over the next several decades (Union of

Concerned Scientists 2009). Our fourth scenario simply takes this increased frequency a step further by assuming that all flood events are more common.

## RESULTS BASELINE, CURRENT CONDITIONS

Figure 3 shows the flood depths for the 100-year flood from our Hazus-MH modeling results, along with the public lands in the Greenway. The figure is a close-up of a portion of the Meramec River, while the box in the Figure shows the entire river. As seen in the figure, there can be quite deep flooding immediately adjacent to the river, while farther back and along the tributaries, flooding is shallower. The figure also shows that flood depths can vary greatly depending on whether the property is along the main stem or a tributary, how far from the water the property is located, and the elevation of the land between the river and the property. This spatial variability can be important for targeting conservation investments in a cost-effective way; not all parcels yield the same benefit, thus it makes sense to consider this when evaluating investments in public lands.<sup>2</sup> The total property damages (building and contents) for the 100-year flood under current conditions is \$165 million. To put this number into perspective, the total appraised value of all structures in the 500-year floodplain of the Meramec and its tributaries was approximately \$541 million in 2012. The losses from a 100-year flood are, therefore, roughly 30 percent of total property values. In our hypothetical development scenario, we have 2,170 additional single-family homes on roughly 2,180 currently protected acres. The estimated damages for the 100-year flood in our hypothetical scenario rise to \$264 million, a 60 percent increase over the losses under current conditions.

<sup>2</sup> In a study in the Lower Fox River Watershed in Wisconsin, we addressed this issue of spatial targeting in floodplains more carefully (Kousky and others 2012). Other economics studies that have focused on targeting conservation investments include Ando and others (1998) and Ferraro (2003).



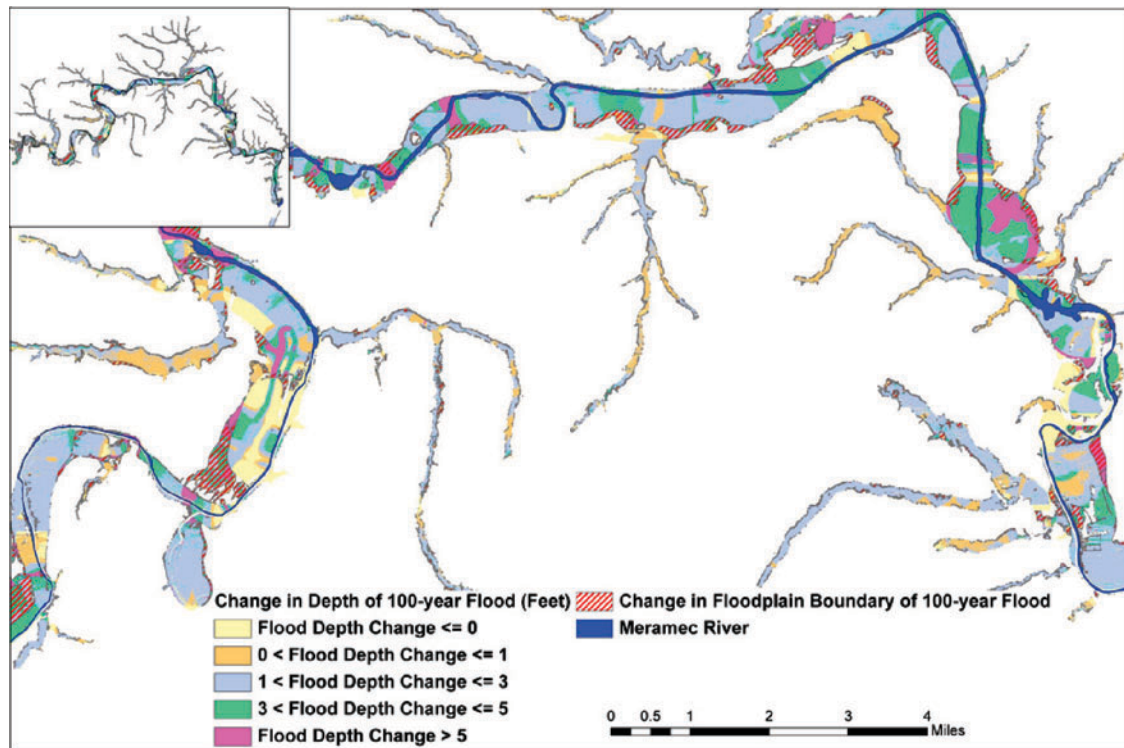
**Figure 3.** Flood Depths in the Meramec Greenway, for the 100-year Flood  
Note: Large map is a section of the Greenway, enlarged to show the flood depths more clearly; insert box shows the entire Greenway.

Combining these losses from the 100-year flood with losses for the 5-year, 10-year, 50-year, 250-year, and 500-year flood events, we solve for the AALs for both the current conditions and the hypothetical scenario. The AAL for current conditions is \$21.7 million; for the hypothetical it is \$34.8 million. Thus, average losses for any type of flooding in a given year are approximately 38 percent lower than they otherwise would be if the Greenway protected lands were developed. This means that the protected lands are yielding an average annual benefit in the form of avoided flood damages in St. Louis County of \$13.1 million—just over \$6,000 per acre of floodplain lands protected. In Kousky and Walls (2013), we find that in combination with the co-benefits from aesthetics and recreation, the benefits of the Greenway outweigh the opportunity costs of keeping the land out of development.

**Climate Change Scenarios: Increasing Peak Discharge**

As we described above, most scientists believe that precipitation in the Midwest will increase with climate change. Some studies have further concluded that this increase will come in the form of an increase in peak discharges. In line with those results presented earlier, we run the Hazus-MH model for both a 30 percent increase and, as an upper bound, a 50 percent increase.

These increases in peak discharges increase the extent of the floodplain for all flood events. For example, the Meramec River floodplain in St. Louis County for the 100-year flood is 31.4 square miles under current conditions; this increases 9.8 percent with the 30 percent increase in peak discharges (to 34.5 square miles), and 15.3 percent with the 50 percent increase in discharges (to 36.2 square miles). Flood depths increase as well. Figure 4 shows the change in the floodplain



**Figure 4.** Changes in Flood Depths in the 100-Year Flood with a 50 Percent Increase in Peak Discharges  
 Note: Large map is a section of the Greenway, enlarged to show the flood depth changes more clearly; insert box shows the entire Greenway.

**Table 2.** Average Annualized Losses (AALs) and Avoided Flood Damages from the Meramec Greenway, Baseline Case and Climate Scenarios with Increased Peak Discharges (in millions).

	Baseline	30% increase in peak discharge	50% increase in peak discharge
Current AAL	\$21.7	\$27.5	\$32.4
Hypothetical AAL	\$34.8	\$44.3	\$52.1
Annual Avoided Damages	\$13.1	\$16.9	\$19.7

and flood depths for the 100-year flood with a 50 percent peak discharge increase. The cross-hatched areas show the additional areas that are part of the 100-year floodplain when discharges are higher. The colors denote the increase in flood depths. In the 50 percent discharge increase scenario, approximately 25 percent of the floodplain sees an increase of 1 foot or less in the 100-year flood (the yellow and orange areas in the figure); 51 percent sees depth increases between 1 and 3 feet (the pale blue areas); 17 percent between 3 and 5 feet (green areas); and just over 6 percent has more than a 5-foot depth increase (pink areas). Most of the areas with flood depth increases of less than 5 feet are along the tributaries, with larger increases along the river itself.

Table 2 shows the AALs for the current conditions and under the hypothetical development case, for the two climate change scenarios, and for the baseline. The annual avoided flood losses from having the protected lands in the Greenway are shown in the last row. The benefits of the Greenway lands are greater in a world with climate change: the annual avoided flood damages rise by \$3.8 million with a 30 percent discharge increase and by \$6.6 million with a 50 percent increase; these losses are 29 and 50.4 percent greater, respectively, than those in the baseline case with no climate change.

### ***Climate Change Scenarios: Increasing Flood Probabilities***

It is possible that climate change will manifest itself as an increase in the frequency of flooding rather than an increase in discharges. In this case, the losses from the individual flood events stay the same as under current conditions, but the AALs increase because the probabilities that the events will occur increase. We look at two possibilities, one in which the probability of each flood event that we model in Hazus-MH doubles and a second in which only the probability of the three worst events—the 100-year flood, the 250-year flood, and the 500-year flood—doubles but the probability of all other events stays the same.<sup>3</sup> Table 3 shows the results.

Clearly, the doubling of all events will double the AALs and this is shown in the numbers in the table. As a result, the annual benefits from the Greenway also double—from \$13.1 million to \$26.3 million. If only the worst floods become more common, the benefits of the Greenway increase by a much smaller amount, \$1.2 million (the AAL rises from \$13.1 million to \$14.3 million). This is only a 9.2 percent increase and yet the worst flood events occur twice as often in this scenario. These large flood events are relatively uncommon—even if they occur twice as often, they are still very infrequent. Therefore, the expected annual flood damages are not that much different than in the baseline case. This is an important result to keep in mind. More

<sup>3</sup> The choice of terminology for flooding becomes unfortunate here because the “100-year flood” is no longer the flood that occurs with probability 0.01 in any given year; it now occurs with probability 0.02, which is technically a “50-year flood.” However, for our purposes, this nomenclature is irrelevant; we have simply altered the flood distribution and recalculated the AAL.

**Table 3.** Average Annualized Losses (AALs) and Avoided Flood Damages from the Meramec Greenway, Baseline Case and Climate Scenarios with Increased Flood Probabilities (in millions)

	Baseline	Doubling of all flood events	Doubling of 100-year, 250-year, and 500-year events
Current AAL	\$21.7	\$43.4	\$23.5
Hypothetical AAL	\$34.8	\$69.6	\$37.8
Annual Avoided Damages	\$13.1	\$26.3	\$14.3

critical may be keeping additional future development out of harm’s way so as not to exacerbate the losses.

## DISCUSSION

As a conservation investment, the Meramec Greenway is yielding sizeable benefits in the form of avoided flood damages. We estimate that if the Greenway protected lands in the floodplain were developed, the region’s average annual losses from flooding would be about 38 percent higher than they are today. Per acre of protected land, the annual avoided damages are about \$6,000. These benefits increase if flooding becomes more frequent or more severe with climate change, but the size of the extra benefit is not large relative to the benefits the lands already provide. With or without climate change, an open question is whether these avoided damages are true “benefits” as in theory, private property owners should take flood risks into account. The empirical literature suggests that properties in the floodplain are discounted relative to non-floodplain lands but the risk is likely not fully capitalized and the discount has been shown to vary over time depending on whether a recent disaster has made the risks salient (Bin and Polasky 2004; Bin, Kruse, and Landry 2008; Kousky 2010). In addition, private property owners are in most cases not bearing the full cost of flood risk due to disaster aid, discounted insurance, and/or other government funding. And finally, communities invest heavily in flood mitigation measures of all kinds—dams and levees as well as land conservation—thus knowing the payoff from any of these investments is important.

Moreover, the value of the ecosystem services from the lands is likely to swamp these climate-related flood protection benefits. In Kousky and Walls (2013), we estimate that the benefits captured in hedonic property values total \$25 million per year, well in excess of the avoided flood damages, with or without climate change. These hedonics are capturing aesthetic and recreational benefits to households that live near the Greenway but are likely an underestimate of the full recreational benefits, as they do not account for those who travel from farther away to recreate in the Greenway, and also do not fully capture water quality benefits that the lands provide, particularly as the river is a source of drinking water. In our view, the real story of the Greenway is the wide range of benefits these natural lands provide under current conditions and not the additional, and highly uncertain, benefits with climate change.

The climate scenarios could be useful for another purpose, however, and one that we did not investigate: how to target additional forest conservation investments along the Meramec River. As we explained in Section 3, much of the lands identified as part of the Greenway remain

unprotected. Local governments and conservation agencies in the region looking to purchase more acreage in the future will need to know which investments will yield the greatest return. Even within the floodplain, flood depths and damages vary greatly, as Figure 1 showed, thus not all investments will yield the same payoff. Consideration of areas that may see disproportionately higher changes in flood depths under multiple climate scenarios might be given greater weight in setting acquisition priorities. Our analysis excludes dynamic issues, which are pervasive in the area of climate change, and are important in this context, as well. If the additional benefits of the Greenway lands are reaped decades in the future when climate change manifests itself, then it is not clear exactly how to evaluate them vis-à-vis investments made today. Here, we estimated the climate benefits provided by lands that are already protected. But for additional conservation investments, the discounting of future benefits will be important. This brings up a contentious issue in climate policy, the appropriate discount rate to use when discounting future benefits and costs (Williams and Goulder 2012; Cropper 2013). Our benefit estimate of \$6.6 million with 50 percent higher peak discharges is reduced to only \$1.5 million if those benefits are reaped 50 years in the future and discounted at a (mere) 3 percent annual rate. While changes in risk levels will begin to be seen in advance of 50 years and will continue past 50 years, the difficulty comes in identifying such changes, given the infrequent nature of flooding. It takes a long record of weather events over time for changes in risk to be observed. These issues are complex and lead to difficult climate adaptation and mitigation policy decisions.

While we have focused on the extra avoided damages due to increased flood risks, another important benefit of floodplain conservation in the context of climate change is the robustness of this approach to reducing flood damages. Changes to flood risk and the timing of the changes are inherently uncertain. Given this, some scholars have suggested that instead of identifying optimal investments, it is more appropriate to search out robust investments—those that provide benefits under a range of future climate scenarios (RAND 2013). In some cases, strategic conservation may be a more robust approach than traditional hard infrastructure approaches to flood risk. This is a topic worthy of further study. We also have not analyzed the possibility of a combination of “gray” and “green” approaches. In the context of the Meramec River, which is currently undammed and is used recreationally in its natural state, our view is that the combined approach may come at a significant cost. However, in many locations, this is an issue worthy of study.

Other dynamic concerns relate to the irreversibility of some investments. Generally, once land is developed, it is very difficult to reverse those investments and return the land to open space. Combined with the uncertainty associated with climate change, this may increase the rationale for protecting the Greenway. This possibility of development to lock-in a suboptimal future would need to be explored in future work.

## **CONCLUSION**

Climate change forecasts are fraught with uncertainty and forecasts of flood risks are no exception. This makes evaluation of alternative approaches to adaptation difficult. Few studies have thus far attempted to combine expected biophysical outcomes from climate change with an economic assessment of costs and benefits. We have taken some first steps in this paper in an evaluation of a forest conservation investment in the floodplain. Using the Meramec Greenway in St. Louis County, Missouri, as a case study, we asked two important questions: (1) what are

the flood mitigation benefits this investment is already providing and (2) how might those benefits change in the future with more extreme weather events?

Our findings suggest that the Greenway is yielding sizeable benefits in the form of reduced average annual flood damages. This return would be higher in a world with climate change, but in our view, the current benefits are the real story. When combined with the recreational and ecosystem services benefits of the lands, the Meramec Greenway is providing value to the region. To focus on the added benefits in the form of climate resilience may be the “tail wagging the dog.” In this paper, we have not discussed the opportunity costs of the Greenway as our focus is on the climate resilience issue, but in an earlier study, we found that the benefits outweighed these costs, without consideration of climate change (Kousky and Walls 2013). In that study, we estimate the opportunity costs as the value of the land in residential development, as that is the dominant land use in the study area.

In targeting future additions to the Greenway protected lands, however, local officials may want to consider climate change. While the climate resilience benefits are unlikely to justify, on their own, additional land acquisition, they should be included in the suite of benefits that such lands provide—the recreational benefits, water quality and other ecosystem services, and protection against today’s flood risks.

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# A Community Based Approach to Improving Resilience of Forests and Water Resources: A Local and Regional Climate Adaptation Methodology

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***Abstract:** Forest-based ecosystem services are at risk from human-caused stressors, including climate change. Improving governance and management of forests to reduce impacts and increase community resilience to all stressors is the objective of forest-related climate change adaptation. The Model Forest Policy Program (MFPP) has applied one method designed to meet this objective since 2010. MFPP's program, "Climate Solutions University: Forest and Water Strategies," delivers a climate change adaptation process based on the 2007 publication by the Climate Impacts Group at the University of Washington, "Preparing for Climate Change: A Guidebook for Local, Regional, and State Governments." MFPP enrolls up to six communities each year in Climate Solutions University, and guides them through a four step process: engagement of a community based climate planning team; assessment of resource and economic risks and adaptation opportunities; prioritization and development of an adaptation plan; and implementation with a range of governance, education, and land use management tools. This paper discusses some of the findings and lessons learned, that include: (1) People are the single most crucial success factor, both individual leaders with dedication to plan implementation and a supportive network of people in the community representing a range of interests. Outsiders cannot make it happen. (2) Using local values as the framework for communicating and avoiding fear of catastrophic change and scientific jargon is the best way to build public trust. (3) Even a modest adaptation plan can have a positive impact with targeted actions. (4) Plan stewards can be of any type (local government, resource agency, non-governmental organization (NGO)) if diverse and affected stakeholders are engaged, but local governments or agencies are more likely to have sufficient resources and established networks, as well as a background in policy. Ongoing commitment and allocation of positions (FTEs) are the most important "resources" needed for successful adaptation. Increased budget support for personnel dedicated to climate adaptation in local communities by federal and state governments would help.*

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## INTRODUCTION

Climate Solutions University—a program of the Model Forest Policy Program and the Cumberland River Compact—is a distance-learning program to increase forest, water, and economic resilience in rural underserved communities. We believe that addressing climate change impacts will require a sustained commitment to integrating climate information into the day-to-day governance and management of infrastructure, programs, and services that may be affected by climate change (Binder 2010). Through a lead entity such as county government, conservation district, or nongovernmental organization (NGO) working on science, education, and/or advocacy, communities enroll in a ten-month course of assessment and planning with the objective of producing a climate change adaptation plan to implement in following years.

This paper summarizes the purpose, content, outcomes, and lessons learned by the Climate Solutions University (CSU) experience after working with two dozen communities around the United States during a five-year period from 2008-2013. First, we briefly place the program in the context of the rapidly developing field of climate adaptation science and policy. We describe the program elements and what has been learned through practice, and synthesize a list of challenges and recommendations for communities. We conclude with specific suggestions offered to both improve effectiveness as well as scale up local adaptation actions promoting forest, water and economic resilience.

## PURPOSE

### ***Global Resource Crises***

Climate changes are being driven by increased retention of solar irradiance (“global warming”) caused by fossil fuel combustion and other emissions of atmospheric greenhouse gases (GHGs). Climate change is but one part of a series of resource management problems. These problems include continued growth of human population, economic activity based on energy resources that emit GHGs, impending “peak” of finite resources such as petroleum, natural gas, and phosphorus, and increasing human appropriation of net primary productivity of the biosphere to the detriment of long-term sustainability of ecosystem services required by human society (Haberl and others 2007; Heinberg 2010; Hall and Klitgaard 2012; Kates and others 2010). In sum, “Humans now dominate Earth, changing it in ways that threaten its ability to sustain us and other species. ... [A] global-scale state shift is highly plausible [in the near future] if it has not already been initiated” (Barnosky and others 2012). Forests are a significant resource affected by and affecting ecology and economy across multiple scales from the local to the global. The importance of forests for water supply, habitat, carbon sequestration and other ecosystem values is well documented, as are the potential impacts of climate change on those values (National Research Council 2008; National Climate Assessment and Development Advisory Committee 2013).

### ***Governance, Resource Management, and Climate Resilience***

Changes in fundamental social structures appear to be necessary to successfully adapt to climate change, including major changes in global governance systems (Biermann and others 2012). Governance means the process of decision-making and the process by which those decisions are implemented. In this respect, governance is much broader than government as it includes the

full range of political, social, economic and administrative actors that regulate development and management of decisions (Rogers and Hall 2003). In rural forested communities, these actors include land and resource owners (public, private, and tribal), regulatory and taxation governments and agencies, a broad range of NGOs, and recognized community leaders.

The latter—community leaders—are the most underappreciated factor in governance. As stresses become more acute and current governance less functional (multiplicity of overlapping crises, shortage of funding, political polarization and gridlock), authority at the local level is enriched. Our work supports the assertion from Lusiani (2013) that claims in an increasingly interdependent and multi-polar world, which has witnessed a fragmentation in responsibilities in recent years, it is more important than ever that the voices of ordinary people be heard and adhered to in the design, implementation and monitoring of sustainable development policies.

It is primarily at the local level of governance that specific adaptation actions and management choices are being made, or not (Moser 2010). Local governance actions continue apace whether or not they are planned with sustainability and resilience in mind. Thus empowerment at the local level is most important in natural resource dependent rural communities; local communities are the space where public policy and landowner decisions concerning land and resource use affecting climate change resilience come together. Fortunately, the opportunities to bring sustainability to local decision-making are ample if they can be catalyzed with good decision-making and implementation processes developed by the CSU program to drive “good governance.”

## **CLIMATE SOLUTIONS UNIVERSITY IN ACTION**

### ***Basis for the Program***

The Model Forest Policy Program (MFPP) based the Climate Solutions University (CSU) program on a 2007 publication by the Climate Impacts Group at the University of Washington<sup>1</sup>, ICLEI<sup>2</sup>, and King County, Washington:

The purpose of *Preparing for Climate Change: A Guidebook for Local, Regional, and State Governments* is to help ... decision-maker[s] in a local, regional, or state government prepare for climate change by recommending a detailed, easy-to-understand process for climate change preparedness based on familiar resources and tools. The content of this guidebook was developed from reviews of scientific literature, the Climate Impacts Group’s experience working with U.S. Pacific Northwest decision-makers on preparing for climate change, and King County, Washington’s experience developing and implementing a climate change preparedness plan (Snover and others 2007).

Since the publication of Snover and others (2007), others have confirmed the importance of local level governance to achieve successful adaptive action (Perkins and others 2007; Binder and others 2010; Measham and others 2011).

The motivation for initiating the Climate Solutions University program in 2008 was a keen awareness that climate change was moving beyond mitigation (prevention) and that forest and

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<sup>1</sup> <http://cses.washington.edu/cig/>

<sup>2</sup> <http://www.icleiusa.org>

water resources would be experiencing serious consequences with wide-ranging impacts to rural communities and downstream urban areas. At the same time, climate resilience efforts were heavily weighted to energy and transportation and the natural resources of rural areas were being underserved in science, program offerings, and funding (c.f. USDA Forest Service 2010, Forest Service 2000). Methods to bring climate resilience to rural communities was still a largely unknown art.

The Model Forest Policy Program's Climate Solutions University seeks to be a catalyst for sustainable forest and water governance choices. The program focuses on locally specific climate risk in rural areas, where most U.S. forest and water resources are located, providing close-to-the-source effective planning and implementation of adaptation strategies. In addition, as the need for payment for ecosystem services becomes clearer, CSU helps communities connect to downstream and other communities that benefit from the rural communities forests and water resources.

Before the formal launch of CSU in 2010, MFPP engaged with two communities as pilots to explore two possible approaches to climate adaptation at the local level: Bonner County, Idaho, in the Northwest and the City of Cookeville, Tennessee in the Southeast. In Bonner County, the effort focused on improving riparian resource conservation when property was developed. That effort did result in significant improvements to the county's lacustrine and riparian buffer requirements in the zoning code. In Cookeville, the need to adapt to climate change was included in the newest iteration of the city's comprehensive plan. The plan states that to adapt to predicted climate changes, measures such as committing to the reduction of green house gas emissions, promoting and implementing sustainable building practices, and protecting and enhancing our forests and green infrastructure should be implemented. These two processes demonstrated the ability to bring climate planning and policy to fruition, even in conservative states, the first of its kind in both Idaho and Tennessee at the time. Out of the experience with these two pilot communities, and building on Snover and others (2007), MFPP and the Cumberland River Compact developed the CSU curriculum.

### ***Overview of the Program***

Following the guidance of Snover and others (2007) and others, CSU addresses climate impacts together with other stressors, such as development pressures. The program has four basic steps in two programs. The first program, *Plan Development*, is a 10-month curriculum that guides rural communities in the first year to: 1) build and engage a strong, diverse stakeholder team; 2) assess climate risks and opportunities related to climate, forest, water, and economic conditions; and 3) formulate a climate adaptation plan that prioritizes water and forest restoration and protection measures. The second program, *Implementation*, in years two and beyond, guides communities toward concrete actions with measurable outcomes such as policy changes and restoration practices to improve land use, protect water quality and quantity, and support stable economies (more information can be found here: [http://www.mfpp.org/csu/our\\_programs/implementation\\_program/](http://www.mfpp.org/csu/our_programs/implementation_program/)).

CSU provides training and technical expertise to enrolled communities through a variety of interactive methods. The *Plan Development* program includes eight learning modules supported by an online classroom, step-by-step worksheets and checklists for resource assessments and

planning process, extensive resources and references, webinars every other week, coaching calls weekly, and editorial review of adaptation plans as written and finalized.

The *Implementation* program focuses on providing customized programming to meet the specific needs of participating communities to implement their particular adaptation strategies. Webinars are offered monthly by noted experts on wide-ranging topics requested by community leaders or that analysis indicates would be beneficial. Webinar topics have included climate communications, ecosystem services, engaging in agency land use policy, and outreach to conservative audiences among others. In order to better achieve program objectives, we review the success of each community's planning effort at the end of each year, and conduct extensive interviews to determine how to improve the CSU program.

From 2010-2013, five or six communities were enrolled each year in the *Plan Development* program. Communities with resources and commitment continued in the *Implementation* program in following years. Community participation in Climate Solutions University since inception is indicated in Figure 1, and the governance categories of planning lead entities are shown in Table 1.

**Table 1.** Climate Solutions University, Curriculum Outline 2013

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**Module 1: Orientation**

- #1 Introductions
- #2 Program Overview

**Module 2: Climate**

- #1 Climate Overview & Framing the Issue
- #2 Global / Regional / State Perspectives

**Module 3: Team Engagement**

- Stakeholder Engagement & Team Facilitation

**Module 4: Forest**

- #1 Assessing Risks and Vulnerabilities
- #2 Assessing Opportunities and Solutions
- #3 Assessment Status and Planning Narrative

**Module 5: Water**

- #1 Assessing Risks and Vulnerabilities
- #2 Assessing Opportunities and Solutions
- #3 Assessment Status and Planning Narrative

**Module 6: Economics**

- Assessing Conditions, Risks and Solutions
- Integrating Economics into Forest and Water Assessments

**Module 7: Analysis**

- #1 Risk Analysis
- #2 Risk Prioritization
- #3 Setting Adaptation Goals

**Module 8: Adaptation Planning**

- #1 Setting Objectives
- #2 Gap Analysis and Strategies
- #3 Detailing an Action Plan for Implementation

**Module 9: Adaptation Plan Review Sessions**

- #1-5 Five Individual Draft Plan Review Sessions and Editing
  - Climate Adaptation Plans Completed
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**Table 2.** Governance Categories of Climate Solutions University Lead Entities

Class Year->	2009		2010					2011						
	Bonner County ID	City of Cookeville TN	Whatcom County/ Nooksack WA	Keene/ Ashuelot NH	Sumner County TN	Grand County UT	La Plata County CO	Town of Taos NM	Trinity County CA	Nez Perce Tribe ID	Alger County MI	Greene County TN	Chau-tauqua County NY	Bath ME
Category of Plan Development/ Implementation Leader														
Local government municipality														
Local government special purpose														
Tribal government														
NGO youth education														
NGO science/research														
NGO conservation/restoration														
NGO advocacy														

Class Year->	2012			2013					
	Mattole CA	Shasta County CA	Delta County MI	Rockingham County NC	Upper Delaware NJ/NY/ PA	Marquette County MI	Santa Fe NM	Rogue OR	Norton Bay AK
Category of Plan Development/ Implementation Leader									
Local government municipality									
Local government special purpose									
Tribal government									
NGO youth education									
NGO science/research									
NGO conservation/restoration									
NGO advocacy									

## ***Plan Development***

The first substantive step in the CSU curriculum is to orient the communities to the current state of climate science, including the location of resources needed to conduct assessments in each geographical area represented (e.g., NCADAC 2013; Vose and others 2012; National Research Council 2008). Next is the most important practical step, to develop a team within the community. This is done to ensure that sufficient resources are available to conduct the resource assessments and to prepare a plan that reflects the interests of as many constituencies as possible (cf. USDA Forest Service 2000).

In each of the two key resource assessments—forests and water—both past and ongoing stressors are evaluated, with the addition of the likely impacts of future climate change. Of great importance is for the communities to understand the limits of the existing data, and the implications of the uncertainties inherent in projections of future resource conditions and impacts, especially with respect to climate change (Peterson and others 2011). While downscaling (increasing the resolution) of resource data and climate change impacts has improved, it is still true that the smaller the geographic scope of the assessment, the more uncertainty there is (Sunyer and others 2012; Hawkins and Sutton 2009; Wilbanks and Kates 1999).

The curriculum increasingly works to incorporate economic impacts and solutions in the forests and water assessments. Economic solutions such as payments for ecosystem services (PES) are inextricably linked with the assessments of risks to and solutions promoting resilience of forest and water resources. Economic measures are often significant justifications for other plan elements, for example cost avoidance by taking specific actions to prevent or reduce fire-fighting costs by prohibiting subdivisions in Wildland Urban Interface (WUI) zones. Economic measures also include direct expenditures to increase resilience, such as planting trees in riparian areas to reduce erosion and flood damage, purchase of in-stream water rights to conserve riparian resource values, and transfer of value from benefitting urban areas by means of payment for ecosystem services.

Finally, the communities and their teams are guided through a synthesis and planning exercise. Strengths and weaknesses, opportunities and threats are evaluated (“SWOT” analysis), a prioritization of risks and opportunities is prepared, and specific plan elements are developed along with a first draft of an implementation plan (Kazmierczak and Carter 2010). Focused goals, objectives and strategies are carefully crafted using SMART criteria (specific, measurable, attainable, relevant, and time-bound) (c.f. Niemeijer and de Groot 2008; Bell 2012). A year-one implementation timeline is laid out that clearly outlines who will do what by when, using practical actions over short, medium and long-term timeframes.

## ***Implementation***

The *Implementation* program is designed to ensure plans are put into action to the fullest extent allowed by available time and resources. In some cases, plan element implementation occurs concurrently with plan development. For example, in Sumner County, TN, a comprehensive plan update was in process at the same time the County was preparing its climate change adaptation plan. The forest resource assessment prepared by the county planner for the CSU program became the basis for the natural resources section of the County’s adopted, wholly revised comprehensive plan.



In most cases, plan implementation occurs in the years after the CSU's Plan Development program curriculum year ends. Communities that choose to participate in the *Implementation* program enjoy the benefits of an active network of climate adaptation practitioners. This provides communities with shared experiences and information through peer implementation learning opportunities.

As the long-term focus of the CSU program is to generate plan implementation, MFPP also works with communities to expand their capacity by means of geographic clusters; it is easier for an adjacent county to replicate a successful planning effort than to create a plan in a community in an entirely new area. Other support to expand capacity include direct policy assistance, collaborative outreach, and fundraising support. Special projects that have been provided through the CSU Implementation program have included webinars on dealing with conservative constituencies, using storytelling to convey the need to adapt, and how to develop tools to implement PES (payment for ecosystem services).

## **OUTCOMES—COMMUNITY PLANNING AND ACTION**

Drawing on a few examples from the 24 communities in the program to date, we highlight a few outcomes of the CSU program.

### ***Bonner County, ID – 2009***

The first pilot community for testing the CSU adaptation process was Bonner County in northern Idaho, home base of the executive director of the Model Forest Policy Program (MFPP). Bonner County fits the rural, forested community profile the program was seeking to assist with climate resilience. The MFPP director led the project through an intense 18-month process of climate data collection, analysis and risk assessment, local leader education, and policy research and advocacy. The planning team organized itself into three subcommittees—education, policy, and politics—according to the passions and skills of its members.

Taking advantage of a window of opportunity, the climate planning overlapped with the county's land use codes revision process. The climate risk findings for the county included increasing forest tree mortality, extreme spring floods, warmer lake temperatures, severe milfoil invasion in the lake, and inadequate policies to protect the riparian zones of streams and shorelines. The climate team advocated for a "watershed overlay" in the county's land use codes, with a special focus on riparian zone protections, largely unregulated at the time.

The outcomes for the Bonner project included:

- Community leaders were well educated on climate change and acknowledged its importance to the natural resources of the county;
- A new county commissioner was elected who favored addressing climate risks; and
- New riparian zone protection requirements were adopted by the Bonner County Board of Commissioners.

As with many communities, the political winds shifted again with the next election two years later and little further progress has been made on the policy front. However, the new riparian zone protections are in place benefiting the water quality and health of the lake over time.

This community example illustrates the importance of outcomes related to: education of both leaders and key stakeholders, employing policy solutions, and engaging elected officials. It also illustrates that persistence and longevity is critical to maintaining progress. The climate education and leadership must continue indefinitely in order to keep resilience progress in place. While the code changes are having ongoing beneficial effects, further adaptation actions have yet to be taken in Bonner County due to the lack of local organizational capacity to persist with education and advocacy activities around climate resilience, as well as hostile to uninterested political leadership.

### ***Sumner County, TN – 2010***

In 2010, the first full year of the CSU program, the county planner for Sumner County, TN, led the adaptation planning process for this rural, but urbanizing, county in Middle Tennessee immediately northeast of Davidson County (Nashville). Sumner County was motivated to participate by two factors: 1) the nearby Cookeville community had completed the process as the Southeast pilot community; and 2) Sumner County was in the midst of a new 25-year comprehensive planning process and the climate assessment would benefit that plan by prioritizing future land actions in the most conservation and resilience promoting locations. The climate planning team also served as the natural resource subcommittee for the comprehensive plan.

During the planning year, middle Tennessee experienced a catastrophic 1000-year flood on the Cumberland River,<sup>3</sup> severely impacting Sumner County and highlighting the extreme weather patterns already occurring in the region. The flood reinforced the assessment risk findings, including precipitation extremes (floods and drought); population growth coupled with unsustainable growth patterns threatening critical habitats, and public health impacts.

Public polling as part of the comprehensive planning process showed broad support for natural resources conservation and preserving rural characteristics in the county. The goals of the climate plan were incorporated in the county's adopted 2035 Comprehensive Plan, calling for increasing the tree canopy county wide, protecting headwater streams and forests with new steep slope ordinances, and low impact development patterns.

While Sumner County has moved toward sustainable development by improving the stormwater regulations, other progress has been slow largely as a result of a change in planning staff, budget cuts, and changing priorities.

### ***La Plata County, CO – 2010***

In the San Juan Mountains of southwest Colorado, the Mountain Studies Institute (MSI), a science-based conservation organization, recognized the climate change impacts to the alpine ecosystems and communities. MSI led the climate adaptation planning process with a team including public land agencies, universities, and NGOs. The Colorado team conducted a rigorous assessment: southwest Colorado has warmed about 2° F since 1977. Climate zones will migrate to higher elevations and warmer temperatures will lead to drier soils and changes in precipitation patterns, including reduced snowpack, earlier timing of snow melt and shifting streamflow peaks leading to shortages for agricultural irrigation. Snowmelt has already shifted two weeks earlier from 1978 to 2004. The results for the forests of the region will

<sup>3</sup> <http://www.state.tn.us/tsla/exhibits/disasters/floods2.htm>

include increased risks for pests and disease, forest fires, and upslope shifts for forest species ranges. These changes are being exacerbated by increasingly intense wildland-urban interface pressures.

A plan was developed with a focus on mitigation of catastrophic wildfire risks on both private and public lands and management of scarce water resources. Initial outreach to private landowners at the wildland-urban interface received intense opposition from anti-Agenda 21 activists following a local election that put their sympathizers in office. A fire education grant to the local government for work by MSI was returned to the funder. To adapt to the changing political winds, MSI shifted focus to fire mitigation on public lands and the productive relationships they already had in place with the U.S. Forest Service and the Bureau of Land Management (BLM). Building upon existing public-private collaborations, MSI is actively engaged in public lands work along with hosting climate conferences, restoration projects, and field research. However, due to resource limitations and the political climate, no governance changes called for by the plan have been implemented.

### ***Rockingham County, NC – 2010***

The Dan River Basin Association (DRBA) is a nonprofit watershed organization in the mostly rural, forested hills of the southern Appalachian Mountains. DRBA’s mission is to safeguard the watershed and promote the history, natural resources, and unique cultural features of the Dan River valley region.

The CSU planning project was led by Jenny Edwards and focused on the portion of the basin in Rockingham County, North Carolina. A major factor in a successful planning effort was the active involvement of the Piedmont Triad Regional Council, a regional planning organization with GIS expertise that recognized the value of adaptation goals and supported the assessment and plan development process. DRBA chose to focus on natural resources and a “no regrets” approach to conservation without focusing on “climate change” terminology, which helped avoid unnecessary conflicts in a conservative community.

Risks to the Piedmont forest include high rates of loss and fragmentation of prime forest and farm land to development; drought with hotter, drier summers; tree stress of invasive pests and species; and increasing rates of extreme storm events. The beautiful rivers and streams of the region are at risk from increasing flood events coupled with an infrastructure of high-risk coal ash ponds in the flood plains and hundreds of aging Depression Era small farm pond dams with degrading structural integrity. After this paper was drafted, one of the coal ash ponds discharged a large quantity of toxic waste to the Dan River (Sholchet 2014); the climate adaptation plan prepared the DRBA to respond rapidly to the crisis. DRBA has been able to maintain continuity of personnel working on plan implementation, leading to a growing network of collaborators working toward resilience in the county.

## **OUTCOMES—LESSONS LEARNED**

### ***Community Selection, Team Membership***

Community selection has been based primarily on “readiness” factors including significant forest and water resources at risk, the perceived organizational capacity of the lead entity to complete

the project, demonstrated local government leadership or support, and project leader skills. The geographic distribution of the communities over time was coast to coast with a preference for areas where regional clusters of communities could develop over time. The rural nature of the selected communities tended to result in a predominance of politically conservative leadership in elected officials and agency leadership. The organizations serving in the project lead role varied considerably including watershed NGOs (10), local governments (3), conservation districts (3), forest NGOs (3), Tribal governments (2), science NGO (1), youth education (1), local elected official (1), and university extension service (1). The numbers are higher than the 24 communities due to co-leader positions with a number of communities. In fact, the co-leader situation proved to be a strong model for effective project management.

A major criterion for outreach and community selection is to build regional networks. Communities near each other tend to have similar resource issues and impacts as well as overlapping governance entities (e.g., same state government); building clusters of planning communities enables them to learn from each other in a synergistic way that is not possible solely with distance learning from MFPP staff. The four largest CSU community clusters to date are in Upper Michigan and around the Great Lakes, those in the Four Corners region of the Southwest, in Northern California and Southern Oregon, and in the Southeast in Tennessee and North Carolina.

### ***Climate Risks Assessed***

The assessment process completed by the communities identified risks to forest, water and economic resources related to existing non-climate stressors, current climate impacts, and projected future climate impacts for each community. While each community had different local conditions, they tended to be consistent with the corresponding regional climate risks reported in national climate assessments. In spite of the wide geographic distribution, the key climate risks identified shared many commonalities across nearly all the communities including changes in forest composition, invasive species, changes in the hydrologic cycle, degradation of water quality and quantity, and weather extremes.

The forest risk assessments had similar results within geographic regions. In the West, fire is a major concern almost everywhere (except for the wettest community, Whatcom County/Nooksack Watershed in Washington). In the Great Lakes, Northeast, and Southeast, increasing severity of precipitation and related flooding and changing species composition are the major concerns. A few communities containing or close to urban areas also have significant conversion and land use change issues increasing wildland-urban interface lands. Some are isolated enough that they are not growing in population, although resource extraction is expanding (e.g., Upper Peninsula, Michigan).

Assessed water risks are closely related to forest risks, and include land-use changes and urbanization patterns that exacerbate climate impacts. Changing hydrology and the impacts of changes in the forest are the major concerns. Hydrological changes, together with increasing demand for water for municipal and agricultural uses stresses both water quality and quantity. Sea level rise and coastal erosion was a factor in coastal communities. In nearly every case, these impacts were already occurring in measurable ways with projections for increasing severity in coming years.

Economic Risks were correlated closely with the loss of natural-resource-dependent livelihoods and included degraded tourism and outdoor recreation opportunities, higher costs for at-risk ecosystem services of water supply from forested watersheds, and higher costs for insurance, risk management, and damages to infrastructure.

### ***Adaptation Strategies and Solutions***

The range of solutions fell into three major categories: education and outreach, policy and governance, and on-the-ground restoration or conservation. In addition, monitoring and adaptive management was an important element for the long-range effectiveness of the communities' adaptation plans (c.f. Hawkins 2009).

Education and outreach plays a key role in every stage of planning and implementation. Education focuses heavily on the planning teams themselves early during the CSU curriculum, then it extends out into stakeholder education and engagement as part of plan development and implementation. A third level of outreach is required to the broader community and specific stakeholders in order to successfully enact many plan elements, especially when considering policy changes to land use planning and zoning or local codes and ordinances. Education of private landowners to motivate voluntary conservation practices is also necessary, especially in areas where the majority of forestland is owned by private landowners (northeast, southeast, Great Lakes).

Policy solutions require the most political will and the longest time horizon to accomplish. The goal of policy changes is conservation of forest cover and source water areas to protect ecosystem services and avoid the harm caused by inappropriate development such as in floodplains and wildland-urban interface areas. It is also a frequent policy goal to integrate climate risk strategies into all community planning process, such as comprehensive plans, habitat conservation plans, drought and flood plans, watershed management plans, and public agency plans (Binder and others 2010; Cohen 2011; USDA Forest Service 2010).

On-the-ground conservation activities is an element in each adaptation plan. Recommendations include wildfire management practices for forests, riparian and shoreline restoration projects, wetlands restoration, and invasive species monitoring and control measures. There is also significant call for infrastructure projects to better withstand extremes of floods, drought, and storms with improved stormwater management and upgraded culverts, pipes, bridges and roads. Collaborative projects with land management agencies or community-based forestry is a goal in several plans (cf. Cheng 2011).

### ***Organizational Capacity and Planning Process***

There are two basic outcome categories: "process and organization" and "forest and water resilience." The main lesson MFPP has learned regarding process and organization is that it is difficult to predict whether any particular lead entity will be able to successfully put together a broad stakeholder team and follow through with plan development, let alone implementation. In some cases, local agencies have unexpectedly not been able to allocate sufficient staff time to the effort. On the other hand, two other community efforts were led by very small NGOs, but due to the good relationships between the organization and the local power centers, good work

was accomplished and continues in the larger community (cf. Danks 2009; Danks and Jungwirth 2008).

On the substantive side, the main predictor of what kind of adaptation elements will be in the plan and implemented is the type of organization in the lead. Local governments (including tribes) tend to be more focused on policy, so they are likely to work for incorporation of climate adaptation into various plans, with a higher chance of follow through into substantive policy changes. NGOs tend toward less regulatory measures, such as education, monitoring, and restoration. Over all, conservation districts have been the single best performers in both assessment and implementation, perhaps because they are a hybrid type with capabilities in both policy and on-the-ground conservation efforts. Watershed groups have the closest mission affinity for working at the landscape level and skills in effective education and outreach coupled with restoration activities.

### ***Difficulties Obtaining Outcomes***

Continuity of staffing dedicated to implementing and breathing life into an adaptation plan over time is the most certain predictor of completion of a plan with community buy-in and long-term implementation follow through. The single most common cause of poor plan implementation is lack of allocation of sufficient human and financial resources. This can often be traced to inadequate organizational capacity and lack of institutionalization of the adaptation goals into the lead entity's core mission and budget.

Monitoring and evaluation (M&E) is another key element of adaptation that is very difficult to achieve. There are both qualitative and quantitative measures of successful improvement in resilience: examples include more sustainable forest practices, miles of stream bank planted with trees, wetlands restored, acres of forest under conservation easement, stable instream flow, species biodiversity, etc. However, it takes significant resources to conduct appropriate monitoring, and it is rarely done outside of large public or private landowners. The CSU program continues to work to obtain long-term commitments by communities to monitor the impact of their adaptation activities and funding to support those activities.

Our conclusions concerning barriers to climate adaptation are consistent with those found throughout the governance and climate adaptation literature (Moser and Ekstrom 2010; Smit and Wandel 2000).

### ***Factors for Success and Future Potential***

As the community examples above illustrate, participating communities have achieved some significant successes in adaptation implementation but all also have great unfulfilled potential in their long-term commitment to climate resilience activities. Plan leads included entities across the governance spectrum, from county and city governments, to conservation districts, to NGOs. Some government leads have been successful in obtaining quick governance changes, but continuity of effort has been stronger in the conservation districts and some NGOs.

The community successes vary in type and distribution. Education, at the soft end of the solution spectrum (with land use and related regulations at the other end), has had a fairly consistent result. Numerous people in the lead entities and on the planning teams reported having learned

a great deal about climate change, the impacts likely to occur in their communities, the costs of those impacts, and the range of actions that can be taken to deal with the impacts and their costs. In communities with significant National Forest System land, collaborative participation by the Forest Service, and even joint management efforts such as community forestry, have been furthered by the CSU planning process. As new national forest planning regulations—including climate change as an explicit element—are implemented, the success of CSU communities to build upon relationships developed in the planning process will be put to the test.

Obtaining explicit recognition of the need to address climate change in local comprehensive and resource planning processes has occurred in most CSU communities that take up the question. Moving from that recognition into regulatory measures is far more difficult, with rural communities often being particularly resistant to change. In many rural communities, the path of education and working on collaborative relationships with public and private stakeholders holds greater promise than strong direct advocacy of policy changes that is difficult to obtain without first building good working relationships. Linkage with mandatory policy change, such as those associated with EPA's stormwater permitting regulations or California's climate planning requirements, offers more powerful methods for adaptation measures to be incorporated into policy change by simultaneously providing negative feedback for failure to comply with higher level governance dictates, and positive feedback such as planning grants, reduced infrastructure and disaster management costs, and potential for PES from nearby urban communities.

On-the-ground activities such as tree planting in riparian buffers are relatively easy to accomplish politically, but require long-term organizational continuity and dedication, as well as significant funding resources. In order to be most effective, these activities should be conducted on the basis of careful evaluation of where the greatest benefit can be obtained per unit of effort, i.e., assessment and prioritization. Furthermore, riparian restoration should be designed in association with a full assessment of the upstream watershed and its anticipated hydrologic shifts so that subsequent floods or droughts don't negate the riparian restoration benefits in future years. Assessing risks and prioritizing restoration activities has been easier than avoiding harm by changing flood plain land use policies.

A number of specific governance measures show great promise of providing significant resilience capacity through the CSU program. MFPP staff are particularly excited by the synergy of an expanding network of adaptation practitioners with experience and expertise in forested rural communities all around the country. Substantive governance measures we will be working on over the near term are implementing PES, inclusion of forest and water resilience in all applicable plans and decision-making processes, collaborative or community-based forestry on public lands, and use of fiscal and management tools available to rural communities to increase the knowledge and practice of sustainable forestry (Binder and others 2010; Danks and Jungwirth 2009).

Finally, the single most obvious factor determining whether or not a community will implement a climate adaptation plan is the continuity of dedicated staff time. Communities have little problem learning how to obtain scientific information to support resource risk assessments; the federal government has been funding research and top-level educational and coordination efforts at consistent and fairly high levels—\$2.5 billion per annum (OMB 2013). Adaptation activities are funded at fairly low levels—\$100 million per annum—and few of those dollars appear to be

supporting personnel in rural communities to prepare and implement climate adaptation plans. This weakness in the funding structure supporting climate adaptation in local communities is confirmed by the work of Fran Sussman and others (Sussman and others 2013, 2014).

## CONCLUSIONS

Adapting to climate change is an essential public and private governance activity in order to increase community resilience to inevitable impacts, as well as promote sustainable use and conservation of natural resources. Uncertainty about future climate changes and impacts of those changes are great, but adaptation, and adaptive management, are specifically designed to increase resilience in the face of uncertainties. It is relatively easy to assess the range of likely impacts from climate change, and it is becoming easier with advances in our understanding of the climate system and monitoring data over time. It is also relatively easy to identify the needed policy changes to respond to the identified threats. The more difficult task is to overcome inertia in our governance systems to actually implement adaptive actions.

Climate Solutions University endeavors to achieve adaptation with risk assessment and community planning processes developed by numerous practitioners in the field over a period of years. Working with rural forested communities around the country, we guide them through an intense program of resource and risk assessment, prioritization and planning, leading toward on-the-ground actions to increase resilience. In the course of this work over more than four years, we have learned a number of lessons about what works and what doesn't work.

First, people and relationships are primary. Without people who are willing to do the hard work of assessing the status and trends of resources in their community *at the same time* as they develop a network of supporters, successful implementation over time is not likely. Building public trust is essential, and this is best done by using local values as the framework for communicating, and by avoiding alarmist fear of catastrophic change and by not using scientific jargon. The plan leaders that have been most successful in the CSU program are those that already have the necessary relationships and sense of trust within their community.

Second, the relevance and appropriateness of chosen adaptation objectives to the community is a key factor. The types of adaptation actions that are likely to emerge at the end of the planning process are in good part related to the type of entity in the lead role. Local governments, either general purpose like counties or special purpose like conservation districts, are much more comfortable with policy or regulatory actions than NGOs. The ideal scenario entails collaborative ownership of plan implementation with each organizational type being engaged in the adaptation effort and playing to their strength, whether it is policy, education, or restoration.

Third, incremental implementation is better than no implementation. Almost every plan includes significant provision for education and outreach. Even if no "hard" governance changes are likely in the short term, a message that is spread by members of the community—as opposed to by outsiders—lays the foundation for locally empowered adaptive actions. This foundational work is particularly important in communities with a significant presence by landowners from outside, such as the U.S. Forest Service and industrial forestland owners. The collaborative relationships developed in the process become a positive outcome in themselves. These relationships lead to



a strengthening of democratic governance at the local level that Americans should be proud of and promote as a key component of climate adaptation (Moser 2009; Oyono and others 2006).

Finally, there are no short-term or easy paths to resolve many of the natural resource stresses currently being experienced around the world. Governance institutions have a great deal of inertia, even in the face of overwhelming impacts. Adaptation practitioners must be dedicated to a long-term commitment in their community to develop the trust and build a base to enable governance shifts when opportunities arise, whether in the form of regular county or national forest planning cycles, or crises like a thousand-year flood or loss of an important tree species. The required dedication does not exist in a vacuum; both monetary and human resources must be allocated to local efforts over time, by the local communities themselves, and by state and national agencies and NGOs in the best position to provide it. One action that would help the effort is for the federal and state governments to provide more direct support to local communities with budget support for personnel over time dedicated to adaptation planning and action. The grace period has passed, the climate impacts are already happening, and the time to act is now.

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# Climate Change Effects on Forests, Water Resources, and Communities of the Delaware River Basin

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**Abstract:** *The Delaware River provides drinking water to 5 percent of the United States, or approximately 16.2 million people living in 4 states, 42 counties, and over 800 municipalities. The more than 1.5 billion gallons withdrawn or diverted daily for drinking water is delivered by more than 140 purveyors, yet constitutes less than 20 percent of the average daily withdrawals. Approximately 64 percent of the water withdrawal is used for thermoelectric cooling, a primarily non-consumptive use. The main stem of the Delaware River is free-flowing, such that permitted water withdrawal and discharge depends on weather-related flow conditions. Low flows can limit power generation based on in-stream temperature limits, and can also result in the salt line reaching water intakes in the 133 mile tidally-influenced portion of the river. High flows can damage facilities and cause exceedance of drinking water standards. Source water areas of the Delaware River Basin (DRB) are primarily forested (>75 percent), accounting for the relatively high existing water quality, and contributing to attenuation and reduction of flows. These areas are predominantly in private ownership, and in recent years have been among the areas of the Basin experiencing the fastest population growth. Development of private lands and associated changes in forest cover, impervious surface and floodplain encroachment are of concern. Modeled climate-related changes in timing, type, and intensity of precipitation are also concerns. The diversity in types of water use within the DRB corresponds with a variety of types of risk imposed by changes in climate and land cover. Common Waters, a partnership of close to fifty organizations is piloting strategies to avoid and adapt to changes affecting forests and water resources that are predicted to occur with climate change. This paper discusses predicted climate changes for the Delaware River Basin and what they imply for the importance of forests and water resources, and presents two case studies: a source water protection program for landowners and a climate adaptation plan for the Upper Delaware River Basin. These efforts in the Delaware River Basin could be models for watersheds with highly diverse types of use and complex regulatory systems.*

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## INTRODUCTION

The mainstem Delaware is the longest undammed river east of the Mississippi, flowing freely for 330 miles from

southern New York (2,362 square miles or 18.5 percent of the basin's total land area), through eastern Pennsylvania (6,422 square miles or 50.3 percent), New Jersey (2,969 square miles, or 23.3 percent), and Delaware (1,004 square miles, or 7.9 percent) to the Atlantic Ocean. The Delaware River's 13,539 square mile watershed drains only about 0.4 percent of the United States land area yet supplies drinking water to 5 percent of the U.S. population—some 16 million people in four states. The Basin also supports the largest freshwater port in the world within the 782 square mile Delaware Bay. Three reaches of the Delaware River, about three-quarters of the non-tidal River, are included in the National Wild and Scenic Rivers System (Kauffman 2011).

In 2010, over 8.2 million residents lived in the basin including 654,000 people in Delaware, 2,300 in Maryland, 1,964,000 in New Jersey, 131,000 in New York, and 5,469,000 in Pennsylvania. An additional 8 million people in New York City and northern New Jersey receive their drinking water through interbasin transfers from Upper Delaware River reservoirs. Between 2000 and 2010, the population in the Delaware Basin increased by 6.1 percent. Over the last decade, a number of counties in the basin showed double-digit population increases and Philadelphia gained population for the first time in centuries (Kauffman 2011).

## **WATER USE AND MANAGEMENT IN THE DELAWARE RIVER BASIN**

In the Delaware River Basin, as in many river systems around the world, water is put to an astounding number of uses. In some ways the mainstem Delaware River is unique for its size in that it is the longest free-flowing river east of the Mississippi. Flows from upper tributaries are partially controlled by dams, holding back 238 billion gallons in two reservoirs supplying the city of New York, for an average daily detention and diversion of 665 million gallons. The remaining 90 percent (land area) of the watershed downstream of the NYC reservoirs is controlled by the weather, and serves the needs of another 7 million people.

Approximately 64 percent of the 8.6 billion gallons withdrawn daily from the Delaware River is used for thermoelectric cooling. Typically less than 5 percent of cooling water is actually consumed; the rest is discharged back into the basin. Less than 20 percent is used for drinking water—an average approximately 665 million gallons allowed for diversions to the city of New York and New Jersey and the rest (860 million gallons per day) for residents throughout the region, many of whom live outside the basin's boundaries.

In recent years per capita water consumption has declined with increased efficiency in all sectors, and declining productivity associated with the economic downturn. Declines in water consumption are offset to some extent by increased deployment of closed-cycle cooling (CCC) for electricity generation. This type of cooling reduces total water withdrawn, but increases water consumption as more water is lost from closed cycle systems. Despite improved efficiency, a projected increase in population within the Delaware River Basin is predicted to result in a gradual increase in total water consumption for drinking water, industrial processes, and energy generation (DRBC 2012).

A recent study estimates the annual regional economic value of water supply at \$25 billion (Kauffman 2011). Estimates in this study do not include the embodied water content and energy in and goods and services exported to the world from the New York, Philadelphia, and

Wilmington corridor—a region containing the 1<sup>st</sup> and 6<sup>th</sup> most populous metropolitan areas in the United States.

That the entire main stem of the river is free-flowing and is principally managed by the storage and release of water in the very upper reaches of the watershed, with implications for the annual water availability to New York, makes the system vulnerable to weather extremes. Periods of low flow can have several interrelated effects. Drought conditions became the first test of the federal compact between New York, New Jersey, Delaware, and Pennsylvania and resulted in a 1978 “Good Faith Agreement” developed and implemented by the Delaware River Basin Commission, and designed to protect aquatic life by maintaining minimum flows through reservoir releases (DRBC 2013; Albert 1987). Drought conditions and extended periods of low flow pose many other problems for water use in the basin, not the least of which is allocation for drinking water and energy generation. Energy generation—the largest category of water withdrawal—is limited by temperature requirements set for the river downstream of facilities. The Schyukill Restoration Fund in the Schyukill River watershed (a major river flowing into the Delaware River) was created through an agreement that also includes augmentation of “pass-by flows” for a nuclear generation station, which had at times exceeded temperature limits.

Perhaps one of the biggest problems posed by low flows is the upstream movement of the “salt-line.” The Delaware River has the largest freshwater tidal prism in the world, as the Delaware Bay’s depth and “cone-shaped geometry” allows for more than 100 miles of tidal exchange upriver. Freshwater flows normally impede tidal advance. However, low flows can allow high chloride levels (>250 ppm) to reach drinking water and cooling intakes within the tidally influenced portion. Floods are also a concern in the Delaware River Basin, especially the potential for lower basin flooding resulting from a combination of coastal storm surge and floodwaters from upstream—a scenario that was narrowly missed during Hurricane Sandy in 2012, which still devastated lower portions of the basin. Prior serious flooding in 2004 and 2006 led to the development of a Flexible Flow Management Program (FFMP) which balances drinking water needs for New York and the rest of the basin, energy generation, ecological requirements, and upstream movement of the salt-line (Gong 2010).

### ***Climate changes affecting water quality and quantity in the Delaware River Basin***

Changing climatic conditions are already being felt in the Upper Delaware region. Both annual mean temperature and annual mean precipitation in the upper basin have increased significantly over the past 100 years. The trend over the past 30 years for temperature and precipitation is more than 3 and 5 times the 100-year trend, respectively. The number of days per year with heavy precipitation shows a significant upward trend. Future projections generally show the basin getting progressively warmer and wetter throughout the 21<sup>st</sup> century (Najjar and others 2012). Higher average temperatures, increased magnitude and frequency of heavy precipitation events, a longer growing season, warmer winters with more precipitation falling as rain, and changing hydrologic conditions all put multiple sectors at risk, including forests, water resources, agriculture and human health.

Information on how these projected trends could affect *water quality* and *quantity* of the Delaware River is only beginning to emerge as global climate change models are downscaled to the region, and interpreted for the watershed. As described above global models predict that

the region encompassing the DRB will experience more precipitation, and greater variability and intensity of events (Najjar and others 2012; McCabe and Ayers 1989). The magnitude of changes in streamflow is less clear. Milly and others (2005) have modeled the relative change in runoff over the next century under a number of scenarios, generating an “ensemble mean” of percentage increase in streamflow, which for portions of the northern Mid-Atlantic and New England constituting the DRB is projected to increase between 5 and 10 percent above 1900-1970 levels (Milly and others 2005). Considering storage capacity in the upper basin this alone may not be a problem were it predictable from season to season and year to year. However, increased unpredictability of seasonal storms and the difficulty of predicting the pathway of large single events can cause problems. Some models also suggest that the net increase could be accompanied by more severe droughts, earlier snowmelt, and more intense precipitation events in late fall through spring—an increase in droughts and floods (Najjar and others 2012). Similarly, the differences in projections for streamflow generated by the Hadley and CCC scenarios for the neighboring Susquehanna River Basin illustrate the challenges in understanding just how to prepare for climate change. Both show increasing and earlier streamflow in the late fall and early winter, but differ in their predictions for the spring (24 percent increase for Hadley, and 4 percent decrease for CCC) (Neff and others 2000).

Other model results more explicitly include the effect of increasing temperatures on forests, which shifts the story to some extent, and perhaps adds to the “dampening effect” that forests can have on floods. Huntington (2003) shows that for 38 forested watersheds in the east, forests are an important determinant of predicted streamflow based on temperature-related changes in evapotranspiration (ET). For every 1°C increase in mean annual temperature (MAT), ET increased 2.85cm, suggesting that with a predicted 3°C increase in MAT over this century; the annual *reduction* in streamflow in a New England forested watershed could reach 11-13 percent (Huntington 2003). Their results are annual averages, reflecting longer growing seasons, less snowmelt during spring green-up, and other seasonal dynamics. In the Western United States vegetative water demand is also predicted to further decrease water availability (Westerling and others 2002).

A suite of water quality changes will also likely occur due to climate change, and will vary depending on conditions. Predicted increases in precipitation could expand stream networks and the volume of shallow subsurface flow in forested areas of the watershed, mobilizing more nutrients, and delivering them along with increased sediment to stream channels (Murdoch and others 2000). In urban and exurban areas the increase in volume would mean more non-point source pollutants. At the same time warming temperatures would increase microbial processing of nitrogen in forest soils, and accelerate metabolic processes in-stream, resulting in reduced nitrate loading in source water, and dilution and increased assimilative capacity of inputs from all sources (Murdoch and others 2000; Murdoch 1991). The other possibilities for potential water quality impacts are too numerous to describe, and many are speculative and depend on what happens in forests, along streams, and in developed parts of the watershed.

How modeled trends balance out in the DRB has not been determined. Longer growing seasons extending into later months with more rain could result in more, less, or similar amounts of runoff depending on the role of ET. Less forest cover would increase the runoff—the combined result of less ET and infiltration—increasing the possibility of flooding, especially during hurricane season. Warmer summers with less rain and increased vegetative water stress in upper

portions of the basin surely seem a recipe for more severe droughts. Water quality will be tightly correlated with the flow regime—how, when, and where nutrients and sediments are delivered to the system. The magnitude of all of these changes is uncertain.

Calling these “...amplified water-related extremes,” Kundewicz and others (2002) reviewed the causes of major floods and droughts around the world stating that “. . .Mechanisms of climate change and variability are intimately interwoven with more direct anthropogenic pressures.” They go on to emphasize that global increases in the intensity of flood events are confounded, and often exacerbated, by changes that have already occurred in river basins.

### ***Considering combined climatic and anthropogenic effects on forests***

What happens to forests will influence how a changing climate affects water quality and quantity. Coined the “forest water controversy” scientists and politicians have debated how forests influence water quantity and quality since the emergence of hydrology and forestry as fields of study (Andriessen 2004). The debate is not entirely settled in that studies still reveal conditions in which different forest types, physiographic characteristics, and weather patterns produce unexpected outcomes. To some extent much of what has been learned in particular watersheds now changes, especially for watersheds managed on models using historical conditions.

Across the country changes in temperature and precipitation will variously affect forest ecosystems. For example, forests of the Southwestern United States are predicted to be increasingly subject to water stress due to decreases in precipitation, leading to extensive mortality and a wholesale change in vegetation types (Grant 2013; Westerling 2002). Increased drought is also expected in some parts of the U.S. Southeast—and similar to the West, introduces the possibility of changes in forest ecosystems that are driven by water stress (Sun and others 2008). In the DRB region the effect of longer growing seasons, warmer temperatures, and seasonal changes in precipitation must be considered along with concurrent anthropogenic forces that will also affect forest ecosystems. For example will streamside hemlocks that shade headwater streams throughout the basin be overcome by drought stress during the summer, and finally succumb to the forest pest hemlock wooly adelgid now undeterred by winter? How soon will more southern forest types come to dominate the landscape? What other changes and shifts in species may occur, and will the process take decades during which greater senescence and decay mobilizes more nutrients in the system (Murdoch and others 2007)? How will the inexorable loss and fragmentation of forests to development—and associated increases in impervious cover—exacerbate changes in water quality and quantity?

Along with climatic changes, forests of the DRB are being lost at a rate of 100 acres (40 ha) each week. Forests of the region were largely denuded for agricultural and industrial uses during the 1700s and 1800s, leading to extreme floods. With regrowth through the second half of the 20<sup>th</sup> century, small watersheds (HUC12) in the upper portions of the DRB were more than 75 percent forested in 2006, but this is predicted to change. There are also indicators of long-term forest unsustainability; forests are generally even-aged, maturing, dominated by larger, saw timber-sized trees, lacking in diversity, not fully stocked and predominantly privately owned by an aging demographic. Additional non-climate forest stressors include parcelization and fragmentation driven by population increases and changes in land ownership and land use. An array of diseases, insects and invasive species are present in forests throughout the region. Regeneration



is negatively impacted by white-tailed deer populations and harvesting practices such as “high-grading” and diameter-limit cuts (PA DCNR 2010; NY DEC 2010; NJ DEP 2010).

Non-climate stressors on water resources include population growth and associated land use and impervious cover changes, competing demands for water and flow management practices that result in flow fluctuations, thermal stress to fish and other ecological impacts. Natural gas drilling, not currently a factor in the Upper Delaware region due to a moratorium on drilling while the Delaware River Basin Commission develops regulations to address potential risks, could become a stressor to both water quality and quantity in the near future.

As described by Kundewicz (2002), the effects of climate change are critically dependent on how anthropogenic pressures shape future conditions. In some cases, ongoing reductions in forest cover coupled with engineered storage (e.g., urbanized watersheds) may alleviate water scarcity in the face of increased droughtlines. The tradeoff is that with fewer forests the quality of the water declines, timing is more episodic, and flows are more responsive to precipitation events. In other settings (e.g., moist temperate forests of the Pacific Northwest) forest loss would reduce fog interception by trees, which can account for up to 30 percent of the annual water budget (Harr 1982). For regions in which climate change poses risks related to the increasing intensity and frequency of storms, it is conceivable that the dampening effect provided by increased infiltration in forests soils and ET later into wet seasons are perhaps one of the greatest services of forests can offer. Forests in the Delaware River basin, as in many temperate systems, are the top consumptive use of water in the basin (Sloto and Buxton 2005), and therefore a major factor in managing flows. The impact of climate change on the Delaware River Basin’s forests will regulate the change in evapotranspiration and rates of infiltration, and as a consequence the severity of floods and droughts.

### ***Managing watersheds in the face of climate change***

To date there has been no attempt to assess the combined influence of forest loss, ecosystem change, and climate change on water resources in the DRB. More troubling is that models developed for managing water allocation, determining permitted uses, and understanding flood probability have not yet accounted for significant land use and climate change effects. Additionally, most studies of climate change and water availability have not taken into account the effects of competition, response and adaptation to changes, factors which are critical in a basin like the DRB with its numerous and diverse forms of use. Hurd and others (2004) used Water Allocation and Impact Models (Water-AIM) to “simulate the effects of modeled runoff changes under various climate scenarios.” Their models allow for analysis of changes in pricing, patterns of water use, and reservoir storage and associated economic welfare, based on changes in supply driven by different climate change scenarios. Overall, their modeling predicts that negative economic impacts are mostly borne by non-consumptive water uses that are dependent on instream flow (e.g., thermoelectric) and agricultural users. For the Delaware River Basin these types of uses would also include ski areas, golf courses, and other amenities that are critical to the economy of more rural portions of the basin.

Given the certainty of changes in climate and forest cover, but the uncertainty of the magnitude of the difference this will make for water quality and quantity, a pre-cautionary and conservative approach is perhaps the best watershed management strategy. Such a strategy

should include conservation of forests that based on available data are most important for preserving water quality and affecting flows. A pre-cautionary approach should also include climate adaptation planning that promotes conservation of forests and ecosystem resiliency, while preparing communities that will be affected by changes in quality and quantity of water resources. Two cases studies illustrate efforts in the DRB to pursue these two strategies. One, the Common Waters Fund, seeks to engage downstream water users in the protection and maintenance of forests that are most important for water quality and regulating flows, before they are lost or degraded. Another case study is the development of a climate adaptation plan for the upper basin region, which provides a roadmap for taking multiple actions that reduce the impacts and vulnerability of upstream and downstream communities and the forests and the river on which they depend.

## **CASE STUDY ONE: THE COMMON WATERS FUND**

The Common Waters Fund (CWF) is one of more than 70 source water protection funds or payment programs established around the country to maintain the quality and quantity of water resources on behalf of downstream beneficiaries (Bennett and others 2013). The programs differ by origin and structure, many of which were launched by cities such as New York, Denver, and Seattle—all of which are investing in forest conservation. For example the New York City program, which also involves the DRB, emerged as an alternative to installation of additional filtration capacity by instead investing in forestland acquisition, easements and *stewardship*—or the development and implementation of conservation-minded forest management plans (Pires 2004). Few of the models around the country have attempted to create a water fund/program in which the upstream protection priorities are predominately privately-owned and span multiple political jurisdictions (i.e., states, counties, and municipalities). Fewer still have attempted to engage as many different kinds of downstream beneficiaries. However, many of the large watersheds of the eastern United States face similar challenges.

CWF was developed by public agencies, conservation groups, and individuals that had formed a partnership called “Common Waters,” with the support of private foundations, the U.S. Department of Agriculture (USDA) Forest Service, USDA Natural Resource Conservation Service (NRCS), and the U.S. National Park Service. As a pilot the CWF initiative seeks to protect source water through investments by downstream users (e.g., water purveyors, electricity generators, and water-intensive manufacturing) to manage future water resource risks. As an alternative, investments could also be mobilized through policies enacted on behalf of all stakeholders. The CWF demonstrates approaches that can help meet the challenge of managing risks and protecting water resources at the watershed scale: (1) developing an integrated program with the buy-in and capacity to work across a large geography with multiple political jurisdictions; (2) incorporating all readily available peer-reviewed scientific information to set consensus watershed protection priorities; (3) engaging a diversity of water users who share a common resource.

The partnership that created the CWF formed as a collaborative for sharing information and pursuing joint initiatives that would help protect the Delaware River and forests of the region, which are considered essential to the economy and quality of life for a three million acre area encompassing portions of New Jersey, New York, and Pennsylvania. It was modeled after the *Chicago Wilderness*, and eventually developed a formal mission and voluntary

self-governance structure that permitted the active engagement of a broad spectrum of interests (Helford 2000). Members included public land management agencies at the state and federal level, whose participation in the development in the CWF program for landowners helped ensure it would meet federal and state requirements (i.e., state stewardship and tax incentive programs for NJ, NY, and PA; and participation requirements for the USDA NRCS Environmental Quality Incentives Program). Meeting these requirements meant that watershed protection projects involving stewardship planning and conservation practices could be implemented anywhere in the watershed, and would be familiar to partners working with landowners. Members also included land trusts engaged in working with landowners on the donation and sale of conservation easements. These organizations helped design CWF program requirements for permanent protection projects in priority areas, for which CWF paid transaction expenses. The collective capacity and expertise represented by the partnership was essential to the pace and scale of implementation of CWF, which at the end of the pilot period had enrolled approximately 50,000 acres (20,200 ha).

A pre-cautionary approach implies that areas most important for maintenance of water quality and quantity are protected using the best information and means possible. For the CWF, this meant: (a) offering protection options amenable to private landowners at the time of enrollment (e.g. permanent easements, ten-year watershed stewardship plans, and/or conservation practices), and (b) establishing priorities throughout the upper portion of the DRB based on the best available peer-reviewed science. Priorities were established by creating water resource *priority tiers* (0 to 4) that combined several datasets developed by Common Waters partners. These included the Natural Land Trust's *SmartConservation<sup>TM</sup>* dataset (Cheetham and others 2003); The Nature Conservancy's *priority conservation blocks*; the USDA Forest Service's *Index of Forest Importance to Surface Drinking Water* (Weidner and Todd 2011); and datasets associated with the *Delaware River Basin Conservation Areas and Recommended Strategies report* (2012). In some cases CWF represented the first attempt to use these priorities for land protection. The use of combined datasets not only ensured that the highest priorities were targeted, but that there was broader agreement that CWF projects addressed goals held by participating organizations.

Concurrent with creating the CWF program and initial investment in protection projects, Common Waters engaged different types of water users, mostly located in the lower portion of the basin where the majority of the electricity and drinking water demand is located. Delaware River surface water is delivered to more than 16 million people by more than 100 water purveyors, whose water withdrawal is regulated by the Delaware River Basin Commission (DRBC). As described above, more than one-half (65 percent) of the average daily withdrawal (8,650MGD) is non-consumptive use for cooling in energy generation—whose withdrawal and discharge is also regulated by the DRBC. Drinking water purveyors include public (municipal) utilities, and publicly and privately-held corporations. Electricity generators are mainly publicly-held corporations. There are also major beverage producers and bottling facilities, pharmaceutical companies, and manufacturers with headquarters and/or facilities located in the DRB. All are dependent on DRB surface waters, or in some way face risks posed by changes in quality, floods, and droughts. Of these different kinds of water users Common Waters met with the largest consumptive users and representatives of each kind of use/industry, for a total of 26 organizations. The purpose of the meetings was to learn how users perceive their own business risks related to water resources, assess readiness to consider investing in source water

protection, and determine the information that would be necessary to justify investments. As of 2013, two companies have made some investment in CWF, in support of science activities that would help better predict and assign economic value to changes in the water quality and water quantity. Better information linking climate change and forest loss with hydrology and chemical quality will be essential for identifying and valuing the proportional benefits of source water protection in the DRB.

## **CASE STUDY TWO—CLIMATE ADAPTATION STRATEGIES FOR THE UPPER DELAWARE RIVER BASIN**

Common Waters joined with the Model Forest Policy Program (<http://www.mfpp.org/>) and a network of rural forested communities working collaboratively across the nation to develop a climate adaptation plan specific to the tri-state Upper Delaware region. The plan examines how environmental changes associated with climate could affect forests, waters, people and economies of the region, and recommends strategies for adapting to these changes. The planning area included portions of Monroe, Pike, and Wayne counties in Pennsylvania; Sussex and Warren counties in New Jersey; and Delaware and Sullivan counties in New York (Beecher 2013).

To assess the potential impacts of climate change on the Upper Delaware Region and identify strategies by which communities might adapt and prepare, the planning group conducted an assessment and risk analysis for each sector—forests, water resources and economics. A master list of current and potential climate risks was developed and consequences associated with those risks were ranked. The probability of each risk occurring and the ability of communities to respond were also part of the overall risk value assigned.

The broad goals identified to address key risks are summarized below.

### ***Education***

Generating dialogue and information exchange about climate risks was identified as a top priority for the Upper Delaware region—both to reduce risks and build support for implementing solutions. While many of the region’s residents have a general understanding of climate change as a future global problem, they might not make the connection with impacts happening in their communities now or, if they do, don’t know what can be done about it. Raising the awareness level about climate risks in the region will have the added benefit of building understanding about what it will take to reduce greenhouse gas emissions (mitigation). This is important since the ability to adapt will likely be limited if the pace of climate change continues on its present course.

### ***Local Government Policy and Planning***

In considering the findings of the risk assessments, analysis and prioritization, it is clear that risks to the region could be reduced significantly through implementing land use policies that maintain existing forest cover, reduce forest fragmentation, maintain impervious cover at reasonable levels (e.g., < 10 percent), and take full advantage of the ecosystem services provided by floodplains and riparian corridors. Local governments have primary responsibility for the

land use decisions that can ultimately make communities less vulnerable and more economically resilient to environmental changes. Although it is a challenge to coordinate land use policy in a region that includes three states, seven counties and hundreds of municipalities, it has great potential for far-reaching climate resiliency benefits.

Local governments also have responsibility for the health, safety and welfare of the people in their communities and for managing the impacts associated with flooding and heavy precipitation, extreme heat and drought and the municipal budgets that fund emergency response. To prepare for these changes, local governments can develop floodplain management policies that reduce flood risks and the substantial costs of emergency response, infrastructure damages and property losses. Local governments can also incorporate what they know about climate change into updates of emergency plans, hazard mitigation plans, transportation plans, stormwater management plans, comprehensive plans and other local planning efforts. Culvert sizing and bridge design standards should be examined and updated to account for changing precipitation patterns. Funding mechanisms should be identified to address the backlog of high hazard dam maintenance and repairs as these structures are vulnerable to increases in precipitation intensity and present a safety threat to downstream people and properties.

### ***Forest Landowner Support***

Management practices that improve the health and diversity of forests in the region are important to reducing forest and water stressors. With so many of the forests in the Upper Delaware region under private ownership, landowners and the professional foresters that work with them are essential to enhancing forest resilience during an expected long period of climate change. Land trusts and a network of hunting and fishing clubs are also key partners in forest health initiatives, such as managing insects and invasive plants or supporting science-based deer population management that balances populations with sustainable forests and quality timber management. Collaborating with these groups and identifying funding to support management practice implementation are key strategies. Tax assessment policies that incorporate the value of ecosystem services provided by forest lands are another important tool to help landowners keep forests as forests.

### ***Financial Investment***

Forests in the Upper Delaware River watershed are essential to maintaining the extraordinary water quality of the Delaware River. Forests that keep water clean for the residents of the New York City metropolitan area, who draw their water directly from reservoirs in the headwaters, are maintained by the NYC Department of Environmental Protection, a public, tax-dollar funded authority. But the millions of people who live downstream and also depend on Delaware River water (Philadelphia, Easton, Trenton) have no such centralized oversight of the forests on which their water quality depends. The Common Waters Fund discussed above aims to fill this gap, by funding stewardship and conservation by the private forest landowners in the Upper Delaware region on whose forests the water quality of all downstream users depends. A permanent funding stream would include contributions from downstream users who enjoy the extraordinary water quality of the Delaware River and are willing to invest in its protection.

## ***Support and Mitigate Impacts to Businesses***

Strategies that address climate change by conserving forest and water resources are also crucial to the region's economic vitality, quality of life, and natural and cultural heritage. Sustainable development does not represent a trade-off between business and the environment but rather an opportunity to strengthen the synergies between them. The Plan recognizes the significant economic importance to the region of entrepreneurship, agriculture, tourism and outdoor recreation and the risks to these sectors, and to small businesses in general, of climate-driven extreme weather, hydrologic changes and seasonal disruptions. Strategies that help manage impacts while identifying and capitalizing on new economic opportunities presented by a changing climate will be important to businesses in the region now and in the future.

## ***Flow Management***

There are many entities vying for Upper Delaware region water resources and few regional stakeholders directly involved in decisions about how that water gets allocated and managed. Given the hydrologic changes associated with increasing temperatures and the finite storage capacity in upper basin reservoirs, it is essential that flow management policies factor in climate change to ensure sufficient water quantity for both human and ecological needs.

There is much at risk with both non-climate and climate-related stressors, but the Upper Delaware region has the natural assets that can help reduce those risks: a high percentage of forest cover; private landowners with a stewardship ethic; clean water and healthy ecosystems; and institutional and organizational frameworks in place that could facilitate regional adaptation strategies. Translating the Climate Adaptation Plan to action represents an opportunity for the people and governing bodies of the region to prepare for a “new normal” set of environmental conditions while maintaining the health of the natural systems that sustain the quality of life and support the region's economic base.

## **CONCLUSION**

Predicted changes in climate combined with anthropogenic pressures have implications for forests, water resources and regional economies in the Delaware River Basin. Common Waters partnership has piloted approaches to avoid and adapt to these changes. The two case studies presented here—a source water protection program for landowners and a climate adaptation plan for the Upper Delaware River Basin—represent strategies that could be models for watersheds elsewhere with highly diverse types of use and complex regulatory systems.

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# Cumulative Effects: Managing Natural Resources for Resilience in the Urban Context

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***Abstract:** Cities throughout the United States have started developing policies and plans that prioritize the installation of green infrastructure for the reduction of stormwater runoff. The installation of green infrastructure as a managed asset involves relying on natural resources to provide a predictable ecosystem service, stormwater retention. The placement of green infrastructure in urban areas may result in additional ecosystem services, such as climate change resilience. While climate change mitigation may not be the goal for the installation, green infrastructure may provide the value-added benefit of reducing local temperatures, reducing flooding associated with frequent severe storms, carbon dioxide sequestration, and reducing energy needs. While the benefits of installing green infrastructure may be significant, installing and managing natural resources in urban areas is not without its challenges. In the urban environment, it can be hard to find physical opportunities for installation and complicated to get permission due to conflicting ideas about how an area should be used. A lack of understanding about how plants will survive in harsh environments can make designing green infrastructure difficult and can increase the long-term maintenance costs. Cities are often learning as they go and experimenting to discover what works best. The science of green infrastructure is developing alongside practice; therefore, research is not always informing the decisions that are made in terms of design, installation, management, and outreach. Supporting local efforts to increase green infrastructure may require assistance not just with the development of national policy and local policy, but also through the development of research to support and guide design and decision-making, capacity-building around community engagement, and methods for equitably distributing resources.*

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## INTRODUCTION

This article provides an overview of the natural resource challenges facing cities, and the green infrastructure solution that many cities are implementing from a practical to policy level. Green infrastructure may provide ecosystem services that have the potential to reduce local temperatures, reduce flooding associated with severe storms, reduce carbon dioxide emissions, and reduce energy

needs. This article describes the challenges associated with implementing green infrastructure policies and plans in urban areas, including lack of space for installation, underestimated maintenance needs, potential exposure to contaminated soil, and conflicting land uses. Working in urban areas also means addressing the human dynamics associated with densely populated and sometimes impoverished and underserved communities. As practitioners work towards greener, more sustainable and livable cities, researchers have an opportunity to help inform the decisions that are made in terms of design, installation, management, and outreach.

## **USING NATURAL RESOURCES TO ADDRESS COMBINED SEWER OVERFLOWS**

City governments are charged with providing clean water, sanitation, and other services that allow residents to live in densely populated areas safely. Managing these water and sanitation services often involves addressing stormwater runoff and flooding. While increasing the capacity of water and wastewater systems is an option for handling increased volume associated with stormwater runoff and reducing flooding, many cities are poorly equipped financially to replace and expand their gray infrastructure. As a result, cities throughout the United States are increasingly constructing green stormwater infrastructure, such as rain gardens, bioswales, green roofs, and constructed wetlands, as a cost-effective management tool to address increased stormwater volume.

In some cities, sewer water and stormwater are conveyed together to a sewage treatment plant. This kind of system is referred to as a Combined Sewer System. When these systems experience high stormwater volume, the pipes exceed capacity and sewage exits the pipe and goes into streams, streets, and basements. These events are referred to as Combined Sewer Overflows (CSOs). As development pressures increase and lead to additional impervious surfaces, stormwater volumes increase, placing additional pressure on wastewater infrastructure. Cities are not only burdened by the high expense of repairing old infrastructure, but are also responsible for handling flow from neighboring communities. Since cities are often located near major waterways at downstream points in a watershed, they are at the receiving end of stormwater runoff produced by neighboring communities.

CSOs can be a threat to public health when the overflows result in untreated wastewater in city streets and in basements. While there is insufficient research on actual health incidences associated with CSOs, wastewater is associated with several pathogens that pose a health risk, including *Escherichia coli*, which causes gastrointestinal distress. Additionally, bacteria associated with wastewater, and therefore with CSOs, can cause pneumonia, bronchitis, and swimmer's ear (EPA 2004). A number of viruses and other pathogens are associated with wastewater and can lead to additional health issues. These potential health risks could be significantly acute in some places, for example in Camden, N.J., regularly occurring 1-inch rainstorms can lead to sewage entering the basements of homes (Andy Kricun 2013, personal communication). While some of this flooding is due to stormwater runoff in neighboring communities, some of this flooding is due to old, malfunctioning infrastructure, which is costly to repair. While these regular events are rarely covered in news media, they are nonetheless significant and drive changes in local policy.

CSOs in urban areas may disproportionately impact vulnerable populations. Both Philadelphia, P.A., and Camden, N.J., have high poverty levels compared to their respective States. Any impact associated with CSOs in these cities may impact people who do not have the financial means to move elsewhere. According to the 2010 U.S. Census (U.S. Census Bureau 2010), 25.6 percent of the population in Philadelphia lives below the poverty level, compared to 12.6 percent in Pennsylvania. In Camden, 38.4 percent of the population lives below the poverty level, compared to 9.4 percent in New Jersey. Since these CSO events bring with them a potential for health issues, they also represent a potential environmental injustice issue.

### ***Green Infrastructure Policy***

The shift towards the installation of green stormwater infrastructure marks an opportunity to increase access to the benefits associated with natural resources. The Environmental Protection Agency (EPA) refers to green infrastructure as the use of “vegetation, soils, and natural processes to manage water and create healthier urban environments” (EPA 2004). The management of stormwater through green infrastructure has led to policies and planning efforts like *Green City, Clean Waters* (Philadelphia Water Department 2011) in Philadelphia or the *Camden SMART Initiative* (Camden SMART Team 2011) in Camden New Jersey, which aim to reduce the volume of stormwater entering the sewer system.

Much of the push towards green infrastructure is driven by the need to better manage stormwater despite funding constraints. The Philadelphia Water Department developed the *Green Cities, Clean Waters* Plan (Philadelphia Water Department 2011) to communicate a vision for the city that integrates vegetation into every part of the city. This plan was developed to use “green stormwater infrastructure” to manage stormwater and reduce the impact of Combined Sewer Overflows. Green roofs, rain gardens, tree trenches, constructed wetlands, and a variety of other natural tools were used to reduce the amount of rainwater entering the sewer system. The *Green City, Clean Waters* Program includes several focus areas: Green Streets, Green Schools, Green Parks, Green Parking, Green Homes, and Clean Streams.

The City of Philadelphia has a formal agreement with the U.S. Environmental Protection Agency that allows for the use of “greened acres” to meet permitting requirements. As part of that agreement, the Philadelphia Water Department developed “The Implementation and Adaptive Management Plan”, which states that Philadelphia will add 9,564 greened acres (3,870 ha). A greened acre is defined as an acre of impervious cover that is retrofitted to utilize Green Stormwater Infrastructure (GSI) which manages stormwater using source controls such as infiltration, evaporation, transpiration, decentralized storage, alternative stormwater routing, reuse and others (Philadelphia Water Department 2011). That definition does not address the benefit of protecting existing green spaces, but does provide an opportunity to increase the amount of green space and its associated benefits in Philadelphia. In practice, it is not unusual for a constructed green stormwater infrastructure site to be less than one acre and oftentimes less than a half-acre. To get to 9,564 greened acres may require working with thousands of residents and property owners throughout the City of Philadelphia.

Similarly, Camden, New Jersey has been working towards developing a green stormwater infrastructure program, called Camden SMART (Camden SMART Team 2010). This program is intended to use green stormwater infrastructure to reduce the impact of CSOs on residents.

Through this program, 26 rain gardens (as of summer 2013) have been built to capture about 2 million gallons of stormwater per year (Kricun 2013, personal communication). While a reduction of 2 million gallons of stormwater is significant, a storm event can input 40 million gallons of stormwater into the City's sewer system, which is 4 times the amount found during dry weather flow (Kricun 2013, personal communication). Managing the volume of stormwater entering the system using green stormwater infrastructure would result in a significant increase in green space. As is discussed more later, these sites are designed to function as parks or gardens as well as stormwater management facilities; thus, offering the potential to increase the ecosystem services provided by the green infrastructure and improving the quality of life in this underserved and impoverished urban area, in other words, potentially transforming the city.

### ***Ecosystem Services of Green Infrastructure***

Replacing impervious surfaces with vegetation reduces stormwater runoff and decreases temperatures, ultimately reducing the amount of stormwater entering the sewer system. With that in mind, broadening the focus of green infrastructure to include trees and intact forested areas within the urban landscape can present new opportunities to better address issues associated with stormwater, severe storms, and climate change.

According to the 2010 U.S. Census, over 80 percent of the U.S. population (U.S. Census Bureau 2010) lives in urban areas. With such a large percent of the country's population living in urban areas, green infrastructure provides an opportunity to integrate nature and green space into the urban environment and provide green space benefits to many people. While the priority for installing green infrastructure, or green stormwater infrastructure, is stormwater management, there are added benefits associated with trees and open space that accompany these installations.

Some work has been done to better understand how cities benefit from trees, which are a type of green infrastructure. Trees can increase carbon sequestration and storage in cities (Nowak and others 2013). Trees and green spaces can reduce air temperatures (Gill and others 2007). Trees in cities can reduce energy needs (Heisler 1986). During storm events, trees intercept stormwater and can reduce runoff (Xiao and others 1998; McPherson 1998; Calder 1996). Increasing tree canopy can effectively reduce both volume and timing of stormwater runoff (Sanders 1986) suggesting that increased tree canopy could have a measurable effect on the total volume of stormwater runoff entering a sewer system.

Research also supports the idea that trees can improve health for city residents. For instance, trees have been associated with reducing mortality caused by cardiovascular and lower respiratory tract illnesses (Donovan and others 2013). Views of nature have been associated with reducing hospital stays and reducing the use of pain medicine for patients after surgery (Ulrich 1984). Additionally, there has been some work illustrating a strong relationship between trees and higher house values. For example, the presence of a street tree canopy may reduce the time that houses are on the market (Donovan and Butry 2010).

Aesthetically, green infrastructure that is maintained can improve the look of a site. In South Camden, where residents are surrounded by impervious surfaces, industrial facilities, and very little open space, a rain garden was installed at a vacant lot and was designed to function as a small pocket park with a small path, benches, and trees. While no research has been done to

document the impact that this particular rain garden and associated green infrastructure has had on residents' quality of life, the average passerby would be able to see a site that has been transformed from a vacant lot to a park. Being able to quantify the benefits associated with this site would help bring a better understanding of the cumulative impact of converting more impervious spaces into green space.

A study in the Netherlands found that residents perceive that they are healthier when they live near green spaces (Maas 2006), and a follow-up study found that anxiety disorders and depression were lower near green space (Maas 2009). Whether this is the case at this site in Camden is uncertain, but the possibility of improving health and well-being while solving stormwater and flooding problems simultaneously is worth pursuing.

The benefits associated with trees are well documented and continue to be supported by new research. Knowing that trees are just one piece of the green infrastructure tool kit, the next questions may be: do these benefits extend to all green infrastructure? Can the cumulative effects of all of the green infrastructure in a city, including trees, forested areas, constructed green stormwater infrastructure, mitigate the impacts of climate change in urban areas and thereby, improve the quality of life for a large majority of the U.S. population?

### ***The challenges to managing green infrastructure in an urban area***

Implementing a policy and vision such as *Green City, Clean Waters* has challenges as design and construction are met with real world challenges, such as lack of space, lack of community buy-in, maintenance issues, and the emerging nature of the science. First, urban areas are often densely populated areas (U.S. Census Bureau 2010), which can mean less available space for green infrastructure. Parking lots, homes, apartments, commercial areas, and industrial areas often dominate the urban landscape leaving little opportunity to install plants or retain water without changing the landscape. Selecting sites for installed green infrastructure facilities, which may include trees, can be complicated by existing land use or different ideas about how the land should be used in the future. Baseball diamonds, soccer fields, lawns, and picnic areas can be seen from some perspectives as perfect places to install green infrastructure or at least plant trees, because these open spaces represent large amounts of publicly owned open space. The conversion of athletic fields to forest patches and other green infrastructure may be poorly received by city residents who use those amenities for recreation. City managers may be reluctant to try to change the land use in this situation due to the lack of acceptance by the community and the potential for negative backlash. This eliminates or limits some of the easier places to install green infrastructure or plant trees. Private property, existing forested areas, and right of ways offer alternative opportunities for trees and other green infrastructure.

Second, community outreach is a critical variable for successful green infrastructure implementation. For example, according to a recent Urban Tree Canopy Assessment completed by the University of Vermont Spatial Analytics Lab, there are 20,821 acres (8,426 ha) of impervious surfaces in Philadelphia (Dunne-O'Neill 2011). Some of those impervious areas are vacant lots. In Philadelphia, an estimated 40,000 lots are vacant (Redevelopment Authority of the City of Philadelphia and Philadelphia Association of Community Development Corporations 2010), which could be an opportunity for green infrastructure. However, many of those lots are located between existing homes and are privately owned or intended for development. In addition,

apprehension exists about potential crime associated with overgrown vegetated vacant lots (e.g., drugs and guns can be hidden in trees and overgrown areas). With the average project being less than an acre (.4 ha) in a city like Philadelphia, a considerable amount of time may be required to do an adequate amount of outreach, but a successful project needs community acceptance, and therefore requires an investment in time and energy to have a dialogue with communities.

Third, dealing with private property can be a challenge for green infrastructure implementation. It is difficult for a government agency at any level to spend money on investments located on private properties, so incentives to get private property owners to participate may be necessary. In Philadelphia, a parcel-based billing system has been created to capture the costs associated with stormwater runoff by charging property owners with a separate stormwater fee based on the amount of impervious surfaces on their property (Philadelphia Code Section 14-704 Online). This program offers a cost savings to owners who reduce their stormwater runoff by decreasing impervious surfaces, installing green infrastructure, or installing gray infrastructure designed to store runoff.

Vegetation is another challenge to green infrastructure success. Successful use of green infrastructure for stormwater reduction requires plants to survive, but plants do not function with the same predictability as a steel pipe. The factors influencing survival need to be taken into consideration when expecting green infrastructure to provide these ecosystem services. Since some plant species survive and thrive better than others and site conditions can be different from one facility to the next, an understanding of individual plant requirements is critical to designing functional systems. Expectations for plant performance need to be realistic, so that mortality can be considered and accommodated in design. If we broaden the objective of green stormwater infrastructure to include addressing climate change, then we to expand our understanding of plants beyond just knowing how plants respond to existing conditions in urban environments, but also how plants will be affected by future conditions.

When stormwater basins started being planted in the late 1990s, obligate wetland plants were often selected for the bottom of the basin. These plants often did not survive because for most of the year the basins were dry. Over the years, it became clear that the plants that were installed at the bottom of a stormwater basin needed to be both flood tolerant and drought tolerant. Many constructed green stormwater infrastructure sites require the same thing, plants that are flood and drought tolerant.

In the urban environment, plants also need to be pollution tolerant. Stormwater that includes road runoff can include sediment, organic carbon, nutrients and metals at levels double the national mean for stormwater (Claytor and Shueler 1996). Information about how different species of plants tolerate the pollution associated with stormwater runoff may still be needed. A challenge in understanding the pollution tolerance of plants is that each species needs to be evaluated individually to determine its ability to survive exposure to common road pollution, which may contain salt, heavy metals, oil and grit, and trash associated with road runoff.

Plant survival in installed green stormwater infrastructure also depends on the history of the individual plants used. Prior to being installed at a site, a plant has already had experiences that influence its survival at the green infrastructure facility. A number of factors influence the plant during its time at the nursery: the kind of media the plant is grown in, the way the plant roots

have been handled prior to and during transplanting, how frequently the plant has been watered, and where the seed or plug came from originally. Therefore, poor nursery practices can contribute to low survival. For instance, plants started in plugs need to be moved into larger containers as soon as their roots start to fill the capacity of the container, but sometimes nurseries wait to move plants up a size based on other factors, like time constraints and work schedules. When plants stay in a small container too long their roots can encircle the inside of the container which if left unfixed can cause the plant to be girdled by its own roots increasing the likelihood of mortality (NeSmith and Duval 1998).

Finally, cities are faced with the challenge of how to most efficiently and effectively maintain green infrastructure after installation. Unlike a steel pipe, once construction is completed, green infrastructure cannot be left without attention. During establishment, newly planted plants need to be watered, protected from vandalism, and protected from invasive weed competition. Installed green infrastructure sites may need to be treated like a garden with regular maintenance. People conducting the maintenance need to identify the difference between installed plants and undesirable weeds. In addition, many constructed green infrastructure sites also include some mechanical components that require an understanding of plumbing. As a result of the nuances of maintenance, how well maintenance workers are trained can impact the success of the project in terms of both plant survival and community buy-in.

### ***An emerging science***

Using plants as infrastructure means understanding the engineering of the system, the biology and ecology of plants and natural systems, the associated benefits of green spaces, and the implications of design and site selection on the quality of life of residents and the aesthetics of communities. An interdisciplinary approach is necessary to develop this understanding. While there is science that addresses some elements of green infrastructure, there is still much to learn.

The installation of designed green infrastructure is not necessarily done with the goal of climate change mitigation in mind, but if climate change does in fact result in an increased number of storms and an increase in the intensity of storms, then urban areas may need to consider stormwater management as part of a climate change mitigation strategy. In addition, if temperatures increase, the use of plants for green stormwater infrastructure may become an important component for reducing temperatures.

To maximize the benefits of green infrastructure, whether naturally occurring or constructed, many questions remain to be answered. How will climate change impact plants in urban areas? What is the role of plants in climate change mitigation? Knowing that green infrastructure could lead to compounding benefits to a community, how do we allocate resources in a way that is equitable? Can the cumulative effects of increasing the green infrastructure in a city have a measurable impact on reducing the consequences of climate change in urban areas?

## **CONCLUSION**

As development has continued and physical infrastructure has aged, the need to manage water resources has become imperative. Meanwhile, cities are facing the consequences of climate change and are trying to find ways to make cities resilient in light of anticipated challenges.



The use of green infrastructure, whether constructed or natural, is not just a stormwater issue, but also part of a larger natural resource management issue addressing the question of how to manage and restore natural resources in a way that makes cities more resilient in the face of change. The policies and plans guiding the increase in green infrastructure in cities should not only refer to constructed stormwater management facilities like rain gardens, green roofs, constructed wetlands, but should also include forested areas within urban landscapes that provide ecosystem services. Incentives could be created not only for the installation of green stormwater infrastructure, but also for the protection and restoration of existing green spaces and trees. There is a great opportunity to direct research towards work that helps guide practice. Returning nature to cities through the construction of installed green infrastructure and the protection and restoration of urban forests in cities throughout the Eastern United States will lead to a reduction in stormwater runoff and its associated problems, but may also lead to reducing the impact of climate change, and improving the quality of life of residents.

Pieces of the climate change puzzle have been addressed, but understanding how all of the pieces, for instance, temperature, precipitation, storm frequency and severity, will come together over longer temporal scales is unclear. Furthermore, how the changes in the physical environment will influence quality of life is unknown. Decisions made now about the location of constructed green infrastructure, the protection of forested areas, or the amount of investment made to incorporate plants in the urban environment, could have a direct impact on how climate change will be felt by city residents. While individual green infrastructure facilities and green spaces in urban areas tend to be small, collectively their value may be much higher. As research advances to better understand how different kinds of green infrastructure contribute to decreasing local temperatures, reducing greenhouse gases, and improving quality of life, there will be an opportunity to understand the cumulative impact of green infrastructure, installed and natural, through spatial analysis and modeling. Looking at green infrastructure from a landscape perspective can help practitioners make decisions that lead to greater outcomes. Green infrastructure may be an opportunity to distribute the ecosystem services of green infrastructure more equitably than has been done in the past. Without understanding how some of these questions might be answered, opportunities to maximize impact may not be realized.

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# Considerations for Forest Adaptation to Climate Change in Sustainable Production of Wood/Fiber/Biomass and Ecosystem Services

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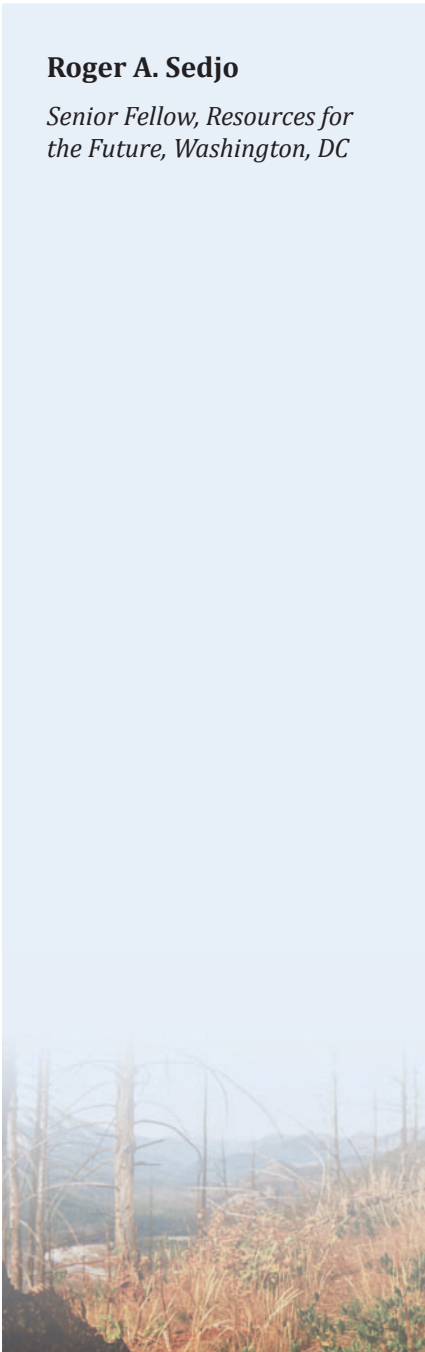
***Abstract:** Climate change is expected to affect forests into the future. Although forests have an inherent resiliency that allows them to adapt to various disturbances, including past climate change, concerns are expressed that the rate of change of current and future climate may be more rapid than the ability of many forests to adapt. This paper examines the background of forest challenges to natural disturbances. Recent research on the ability of forests to adapt is cited, as are their general projections. This paper notes that most research suggests that while some areas are likely to experience dieback, other forests may flourish. Various tools available for humans to assist the adaptation process are discussed, with the management options for both timber-production and non-production forests discussed.*

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## BACKGROUND

Throughout most of human history, forests were largely a gift of nature, and human management was absent or modest at best. Wild forests are resilient, so they have persisted despite the numerous disturbances and threats. They have been adapting to modest climate changes since the last ice age (Shugart and others 2003). In much of the world, it is only in the past several decades that forest management has become important.

Today, forestry involves two types of forests: natural wild forests, and planted and intensively managed forests. The first type provides a host of environmental services, e.g., water values, wildlife habitat and carbon sequestration, while the latter tends to focus on the commodity timber production, as well as providing many environmental services. Forestry has changed a great deal since the mid 20<sup>th</sup> century. Humans now have a better understanding of forests' inherent resiliency and their ability to adjust and adapt to changing conditions. We also have learned a lot about managing forests. However, forests



face tremendous pressures. Although they are a source fiber, fuel, and fodder, forests were often viewed as a hindrance to economic development. In the United States, forestland was converted to agriculture, and the land was converted to living space for expanding populations. Although some may view this conversion as unsustainable, and indeed it was, economists would view this movement as an adjustment from one equilibrium to another. This was true worldwide, but especially in New World and the United States.

As early as the 1870s Secretary Schurz raised concerns about the long-term viability of the U.S. forests to continue to provide water and timber, and throughout most of the 20th century, forecasts regularly predicted a coming “timber famine” (see Clawson 1979). However, even long-term trends rarely last forever. In the early 20th century, the forest area of the United States stabilized, and the forest stock started to expand as most of the land conversion was complete, agriculture in some areas declined as it lost its competitive position, e.g., New England. Many logged-over forests on sub-marginal agricultural lands experienced natural regeneration, e.g., part of the Lake States. Since 1952, the USDA Forest Service has undertaken systematic timber inventories, through what is now known as the Forest Inventory and Analysis (FIA) program. They found that for each inventory, the forest stock was greater than in the previous inventory. Forest stock cannot expand forever, but according to FIA it has not yet reached its biological peak in forest biomass on currently forested lands. This trend has been encouraged by the advent of forest management and particularly tree planting and planted forests.

Before the 1950s, little commercial tree planting was done, although the “make work” projects during the Great Depression did begin the tree-planting process. However, the 1950s saw the advent of the “soil bank” program, which evolved into the modern Conservation Reserve Program, with its emphasis on tree planting. In the following decades, the greater ability to control wildfire made commercial planted forest a less risky investment. Once managers began to incur the costs of planting trees, it made sense to strive to identify and develop superior trees (Sedjo 1983). During the latter decades of the 20th century, the era of plantation forestry emerged broadly across much of the globe. In the United States, most years between 1970 and 2000 saw tree-planting levels exceeding 2 million acres (Moulton and Hernandez 2000).

The ability to plant and manage forests effectively offers promise of aiding humans in their ability to address major crises including forest regeneration, and perhaps, future forest dieback that may be associated with climate change. Today we rarely, if ever, hear concerns expressed over a “timber famine.” Some have characterized the situation at the beginning of the 21st century as facing a “wall of wood.” Although the harvest within the National Forest System has declined dramatically as a result of political considerations, from about 12 billion board feet (BBF) in the late 1980s to 2 BBF annually since the early 1990s, no shortage of industrial wood has occurred. Concerns with the national forests now focus on ecosystem values and wildfire control, with relatively little attention given to timber production.

In summary, while forests may be subject to many pressures, historically they have proved to be extremely resilient systems. However, they are now believed to be threatened by a new foe—human-induced rapid climate change. But humans need not rely solely on the ability of natural systems to address forest challenges. Human activities can assist in confronting the challenges of climatic change facing wild forests and also provide for the production of industrial wood from planted and intensively managed forests during these challenging times.

## FORESTS UNDER CLIMATE CHANGE: SOME PROJECTIONS

The current focus of concern is increasingly on the effects of climate change on forests. Will a warmer world threaten global forests? Clearly, trees have demonstrated that they can prosper in many environments. From the tropics to the tundra, from seashores to mountaintops, trees flourish.

As the climate changes, forests must find ways to adapt, and adaptations have been tracked in earlier periods (Shugart and others 2003; Smith and Shugart 1993). Forests can adapt to climate changes by migrating to areas with a more favorable climate either through natural seed dispersal or human intervention. For example, forecasters predict that the most dramatic increases in temperatures will occur in high latitudes. Thus boreal forests of the northern latitudes may migrate to the north and occupy large areas that were previously tundra. As they depart from the warming temperatures at the southern edge of their range, temperate forests of the middle latitudes may expand into the lands formerly occupied by boreal forests.

A host of studies have systematically questioned the implications of climate change, specifically warming and corresponding precipitation changes on vegetation and forests (e.g., Haxeltine and Prentice 1996; King and Neilson 1992; Neilson and Marks 1994; VEMAP Members 1995). These studies have generally found that many future climates are likely to be conducive to forests. Studies generally agree that a warmer (and wetter) globe, as anticipated for many parts of the globe, is likely to be as accepting of forests as the global climates of recent decades. However, these studies also project warmer and drier areas where forests are unlikely to flourish. Studies suggest that brush and grasses are likely to replace forests in some warmer and drier climate (van Mantgem and others 2009; Bowes and Sedjo 1993). In fact, many studies suggest that forests overall may flourish and perhaps expand in a warmer and wetter world (e.g., see Haxeltine, unpublished dissertation; Haxeltine and Prentice 1996; VEMAP Members 1995).

Projecting these changes on a regional basis, however, may be difficult. Regional climate change projections are usually done using general circulation models (GCMs) that focus on regional climate change. However, for many regions, the different models project different climate outcomes (Watson and others 1998; VEMAP Members 1995). As noted above, temperature is important, but so is precipitation. A warmer and wetter climate will support a very different forest than a warmer and drier one (e.g., Bowes and Sedjo 1993). Although GCMs often generate similar regional temperature projections, their variability regarding precipitation projections is much greater.

For the continuation of the forest, the challenge likely will be to get the right species in the right locations. As the climate changes, forests must find a way to adapt. Although forests have demonstrated mobility, researchers have often estimated range shift to be relatively quite slow (e.g., Davis and Shaw 2001). However, this issue is not wholly resolved (Clark 1998), and it appears that migration rate varies with tree type and species, as well as the severity of climatic change. Of course, no one is quite sure how rapidly climate change will occur either. We can conceive of climate change outrunning the mobility of forests (Solomon and others 1996), but most researchers now believe a moonscape outcome is unlikely. Not all plant and tree species demonstrate the same degree of mobility, however, so many of the resulting forests will likely experience changes in composition, thereby changing the broad forest ecosystem (Shugart and others 2003).

We humans believe, in principle, that we can limit the extent of climate change by controlling greenhouse gas emissions. Otherwise, why would we bother with a climate policy? But the jury is still out—and is likely to be out for most of this century—as to how effective human mitigation of climate change will be and thus how much global climate change will subsequently occur.

Beyond the question of future forests is that of the potential of these forests—wild and managed—to provide industrial wood to society. Based on the various projections of forest changes, numerous studies have examined the implications of these changes on global forest area and particularly on future industrial wood production potential (Joyce and others 1995; Perez-Garcia and others 2002; Kirilenko and Sedjo 2007; McCarl and others 1999; Sohngen and others 2001). Generally, the results have been encouraging for global wood production and for meeting the world's wood consumption requirements.

## **WHERE ARE WE TODAY?**

Our generation has inherited a global forest of about 4 billion hectares (FAO 2012a). These forests provide a host of ecosystem services, as well as industrial wood, of which the world consumes about 2 billion cubic meters annually (FAO 2012b). That computes to about 0.5 cubic meters per hectare per year. Achieving an average growth rate equivalent to this rate of consumption does not appear to be too daunting a task. There are many places in the world where a managed forest can yield an average of 10 cubic meters per hectare per year. At this growth rate, which assumes appropriate climatic conditions, it would require only 200 million hectares of sustainability managed forests—5 percent of the existing forest area—to produce this volume indefinitely (Sedjo and Botkin 1997). Thus, in facing a world of climate change, humans have been dealt an apparently strong hand with respect to industrial wood production.

Although the world is still harvesting from natural forests, the portion harvested from planted or managed forests today is about 50 percent, and this is projected to rise to 75 percent by 2050 (Sohngen 2007). Importantly, the fact that we can produce most of the world's industrial wood on a small fraction of the world's forested area provides opportunities in addition to presenting challenges. Having these large forested areas allows for many opportunities for forests to adapt to changing climate, both through natural processes and with human assistance.

## **FOREST MANAGEMENT AND ADAPTATIONS**

Forest managers now have a significant ability to control the production and location of much of the industrial wood supply, and a variety of management activities can be used to help forests adapt to a changing climate (Seppala and others 2009; Sohngen 2007). When trees are planted, as they are now for nearly half of the world's industrial wood (Sohngen 2007), managers can choose seedling types based on the expected future climate conditions of the site. Furthermore, shorter rotations enhance the forest manager's flexibility and ability to adapt to unforeseen changes. Humans can assist this inherent adaptive ability through activities such as providing vegetative corridors and aerial seeding.

Additionally, as in agriculture, biological breeding can customize tree genetics to make a species more tolerant to the conditions it is expected to face (Sedjo 2004). Genetic modifications can make a tree more resistant to climate-related challenges such as drought or higher or lower

temperatures, and genes can also be modified for greater growth rates. Planting, as opposed to natural regeneration, allows for the customization of tree species and genetics to the particular site, as well as to current and expected future climatic conditions.

Carbon dioxide (CO<sub>2</sub>) itself will likely assist forests in adapting to climate change. Higher levels of CO<sub>2</sub> will generate a “fertilization effect” that is expected to accelerate the growth of trees (Norby and others 2005; Shugart and others 2003). Evidence shows that this effect may already be occurring (Boisvenue and Running 2006).

## **A STRATEGY FOR FOREST MANAGEMENT IN AN UNCERTAIN WORLD**

Forestry, like agriculture, has always been plagued with a high degree of uncertainty and risk due to droughts, storms, diseases, infestations, and other threats. For forests, wildfire can be added to the list. Nevertheless, humans can anticipate changing climate conditions and begin to undertake mitigating activities.

If we view the world’s forest as consisting of two groups—natural, largely wild forests and managed planted forests—the climate strategy for each might be different. Where management and planting are common, harvest of existing forests can be followed by planting trees expected to be appropriate to the newly emerging climate (Sedjo 2010). Adaptations can be achieved via using different provenances, different species, or trees bred to deal specifically with the anticipated environment. Even without climate change, planting, although expensive, commonly makes economic sense for commercial plantations in many regions. When facing predicted climate change, managers can make judicious choices as to planting stock to anticipate that change.

More broadly, for largely planted forests, management has a variety of tools (see Seppala and others 2009; Sohngen 2007). Managers can control the choice of site, species, and genetics of what is planted. They also can control the timing of planting and harvests and can vary the rotation period as desired. If managers have confidence as to the nature of the future regional climate, they can adjust species, planting, management, and harvesting cycles accordingly.

In regions where the future climate is viewed as quite uncertain, managers may stress flexibility recognizing that their best analytical speculations may be incorrect in some aspects. For example, if uncertainty exists as to the speed or direction of climate change, the manager might adapt by reducing the harvest rotation period or by modifying a planned sawtimber rotation to a pulpwood or fuelwood rotation. This approach, while not satisfactory for all situations, might be appropriate for many climate change situations, particularly for planted forest.

For existing wild forests, other approaches may be more judicious. Many plants, including trees, have a natural mobility, but this mobility can be inhibited by various barriers, such as intervening cropping modes, industrial developments, or roads. Humans can act to keep mobility channels open for trees and other indigenous plants in much the same way that channels for wildlife mobility are maintained. Additionally, other human interventions can be undertaken. For example, aerial seeding is a fairly inexpensive method that can be used to assist nature in enhancing forest mobility.



Finally, wildfire is an especially important component of the threats and uncertainties facing forests. For example, although fire suppression is useful in allowing new types of more suitable stands to become established during a transition to the new climate, fire can also be useful in facilitating the species transition in natural forests by creating openings in previously well established older forests (Sedjo 1991).

## SUMMARY AND CONCLUSIONS

In summary, climate change is likely to have a substantial effect on forests. Although some individual trees and species will likely experience decline and dieback, many forest types may flourish in modified forms in the anticipated modified global climate.

However, a huge amount of adaptation will be necessary as forests adjust to a rapidly changing climate. Wild forests will see migration and dieback of many of their tree species, and the broader forest ecosystems will change as tree types migrate into and out of various regions as the local climates change. The fate of individual forests will depend on the interaction of several variables, including temperature, precipitation and moisture, changes in natural disturbances such as fires and infestations, and importantly, the type of human interventions. Humans can play a role in aiding wild forest transitions by reducing barriers to tree migration and perhaps establishing plant corridors, aerial seeding, and other facilitating activities.

The global industrial wood industry is probably relatively well-positioned to address climate change, although not without costs. Highly managed and planted forests are providing increasing portions of the industrial wood supply. Forest managers have a number of tools they can use to adapt industrial wood production to a changing climate, including choice of species, genetically modified stock, selection of location, timing of planting and harvest, and various other silvicultural practices. Although it is generally believed that humans can predict warming with some confidence, predicting regional precipitation is more problematic but no less important to forest success. In the absence of highly confident outcomes, flexibility in the timing and application of management tools is probably the key to industrial forest management success.

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This paper received peer technical review. The content of the paper reflects the views of the authors, who are responsible for the facts and accuracy of the information herein.

# Section V:

## Evolving Institutional and Policy Frameworks to Support Timely Implementation of Adaptation Strategies

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# National Wildlife Refuges: Portals to Conservation

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***Abstract:** Scientific uncertainty regarding the potential effects of climate change on natural ecosystems will make it increasingly challenging for the National Wildlife Refuge System to fulfill its mission to conserve wildlife and fish habitat across the diverse ecosystems of the United States. This is especially true in the contiguous 48 states, where 70 percent of the land and water resources are in private ownership. One answer is to employ science-driven landscape planning and design, establish refuge boundaries defined by those of major watersheds or ecological regions, and then use our presence in communities to encourage and deliver land conservation and habitat improvement on both private and public lands. Refuges thereby become a portal to conservation for private landowners who can really make the biggest difference in the long-term sustainability of wildlife and their habitats. This paper summarizes results from using this approach in the Connecticut River watershed, and its potential value in supporting public-private habitat conservation strategies adapted to a changing climate.*

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## INTRODUCTION

The National Wildlife Refuge System (Refuge System) is among the largest, most diverse collection of lands and waters in the United States, dedicated primarily to the conservation of fish, wildlife and their habitats (USFWS 2011). The Refuge System had its beginnings at Pelican Island in Florida, when in 1903 President Theodore Roosevelt set aside a 5-acre mangrove swamp for breeding pelicans. Since then, the Refuge System has grown to encompass more than 560 units, totaling over 150 million acres, in every state and territory of the Nation. The Refuge System protects wildlife habitats from the Arctic to the Florida Keys, and from Maine's coastal islands to the desert Southwest. Considerable investments continue to be made in the prairie pothole region, which produces millions of ducks each year and where energy exploration and high commodity prices threaten dwindling grasslands and wetlands. Threatened and endangered species like the manatee, piping plover, whooping crane and nearly 300 other species facing potential extinction can be found on national wildlife refuges. The Refuge System provides habitat to more than 700 species of birds, 220 mammals,

250 reptiles and amphibians, and more than 1,000 fish species (USFWS 2011). Nonetheless, the Refuge System alone cannot conserve the habitat necessary to sustain fish and wildlife populations of the United States. In fact, because many refuges have unprotected land within their acquisition boundaries it would take another 100 years just to fill out existing refuge boundaries, given the rate of land acquisition over the last decade (USFWS unpublished data).

The total area protected by refuges in the lower 48 states is about 18 million acres. This represents less than 1% of the total area of lands and waters in the contiguous United States. Since 70% of these total lands and waters are in private ownership (USDA 2002), private landowners are key to successfully sustaining fish and wildlife populations.

Adding to this the impacts of climate change it becomes clear that new strategies must be employed if the Refuge System is to meet its 1997 mandate from Congress “to contribute to the conservation of the ecosystems of the United States” through the National Wildlife Refuge System Improvement Act (U.S. Congress 1997, P.L. 105-57). In response, the U.S. Fish and Wildlife Service (FWS) developed several collaborative approaches to conserve fish and wildlife habitat at a landscape scale: employing the concept of Strategic Habitat Conservation (SHC), encouraging development of Landscape Conservation Cooperatives, and working within communities to encourage local involvement and action. This paper provides brief summaries of these strategies and uses the Silvio O. Conte National Fish and Wildlife Refuge to demonstrate the success that is possible by working with communities within large refuge boundaries.

## **STRATEGIC HABITAT CONSERVATION**

The SHC model begins with science-driven landscape assessments, planning and design, incorporating predicted changes in land use, human population growth, climate and other factors that impact fish and wildlife populations over time. The scale of landscapes used for planning and design purposes vary, but typically reflect the combination of abiotic and biotic factors that create similarities in habitats and corresponding wildlife use. Landscape design begins by identifying conservation features (such as priority habitats and species), and targets for these features, which may also help define the geographic scope of the project area. Once conservation objectives are established, such as species population objectives, limiting factors are analyzed including stressors from predicted climate change. Models and maps are developed around the conservation targets, prioritizing areas and actions needed based on life history analyses and incorporating uncertainty. Implementation is done through collaboration with partners including migratory bird joint ventures, state natural resources agencies, other federal agencies, tribes, non-profit organizations, hunters, anglers and landowners to develop strategies to address the limiting factors. These collaborative actions necessitate standardized protocols for inventorying and monitoring the effects on populations and habitats, and are essential to document success and failure, and to develop research needed to fill information gaps, and further refine techniques. The answers found through rigorous analysis of these actions in turn refine landscape design, and the process continues.

## **THE EVOLUTION OF COLLABORATIVE PARTNERSHIPS**

A fundamental tenet of modern conservation practice is that collaboration is essential to achieve success in conserving natural resources. There are many local, regional and national examples of

partnerships that have achieved great success in protecting, managing, enhancing and restoring lands and waters to benefit fish and wildlife. It is important to keep innovating and expanding our collaborative efforts, particularly considering climate change. Climate change requires us to reconsider concepts such as managing for “historic conditions,” an approach espoused by many land management agencies, and by FWS as recently as 2001. FWS policy on “biological integrity, diversity, and environmental health” of the Refuge System (2001) defines “historic conditions” as “composition, structure, and functioning of ecosystems resulting from natural processes that we believe, based on sound professional judgment, were present prior to substantial human related changes to the landscape.” Though the policy is still in effect, it is widely recognized that revisions are necessary to acknowledge that achieving habitat conditions present before the industrial revolution will not be possible as a changing climate influences many ecological processes for which we have no definitive solutions. There is no precedent for what we are experiencing, making innovation, experimentation and collaboration more critical now than ever before.

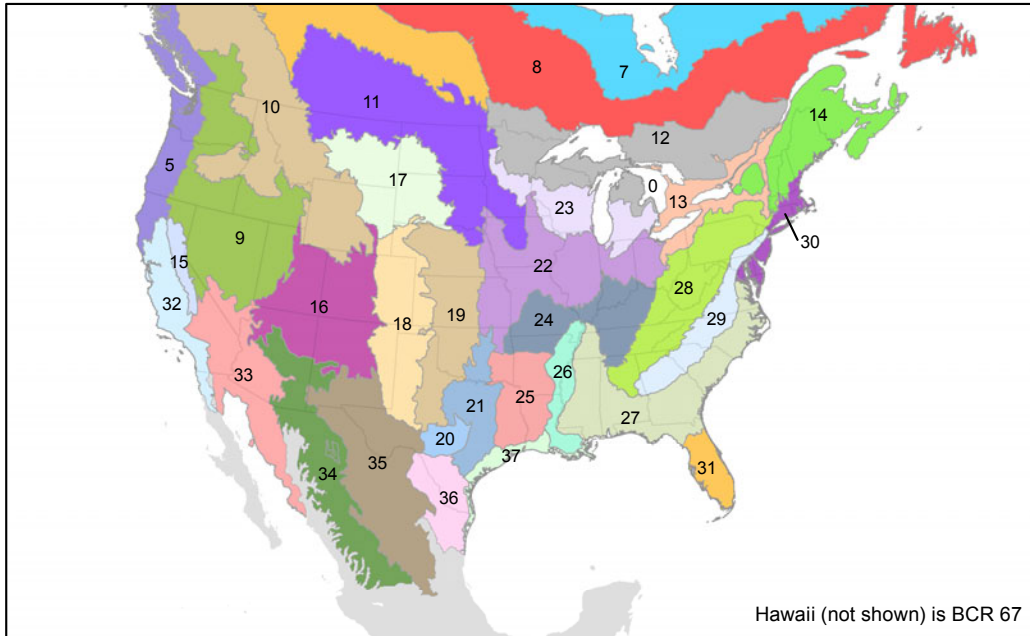
**Joint Ventures**—One of the best examples of collaborative landscape conservation is the North American Waterfowl Management Plan (NAWMP). For decades the NAWMP has promoted Joint Ventures, self-directed partnerships that worked within specific geographic boundaries to implement the plan by conserving habitat for waterfowl. The success of this model prompted the evolution of joint ventures that incorporated the full suite of bird species into their conservation partnerships. The North American Bird Conservation Initiative (NABCI) was formed in 1998, and established in Bird Conservation Regions (BCR) that spanned North America, with ecologically based geographic boundaries.

**Landscape Conservation Cooperatives**—Joint ventures were cutting edge in the 1990s, using modeling and GIS technology effectively to design and plan conservation actions at the landscape scale. The efforts of the joint ventures did not go unnoticed by leadership within the FWS. The late Sam Hamilton, then Director of the FWS, was prominent among those who recognized the joint venture model—using self-directed partners and current technology, and science-driven methodologies, to develop decision support tools—was the wave of the future. The Bird Conservation Regions, with their underlying, ecologically based geographic framework, helped provide the basis for what came next: addressing all species and incorporating climate change impacts through establishment of 22 Landscape Conservation Cooperatives (LCC) across the United States and adjacent parts of Canada and Mexico, based on an amalgamation and modification of BCR boundaries (see figure 1).

As described in the FWS’s publication, *Rising to the Urgent Challenge: Strategic Plan for Responding to Accelerating Climate Change* (2010), LCCs are “formal partnerships between Federal and State agencies, Tribes, non-government organizations, universities and others to share conservation science capacity (including staff) to address landscape scale stressors, including habitat fragmentation, genetic isolation, spread of invasive species, and water scarcity, all of which are accelerated by climate change. LCCs are envisioned as the centerpiece of the Service’s and the Department of the Interior’s (via Secretarial Order 3289) informed management response to climate change impacts on natural resources.” These 22 LCCs are developing collaboratively and starting to deliver landscape conservation science to guide conservation decisions, including landscape designs to prioritize refuge acquisitions.

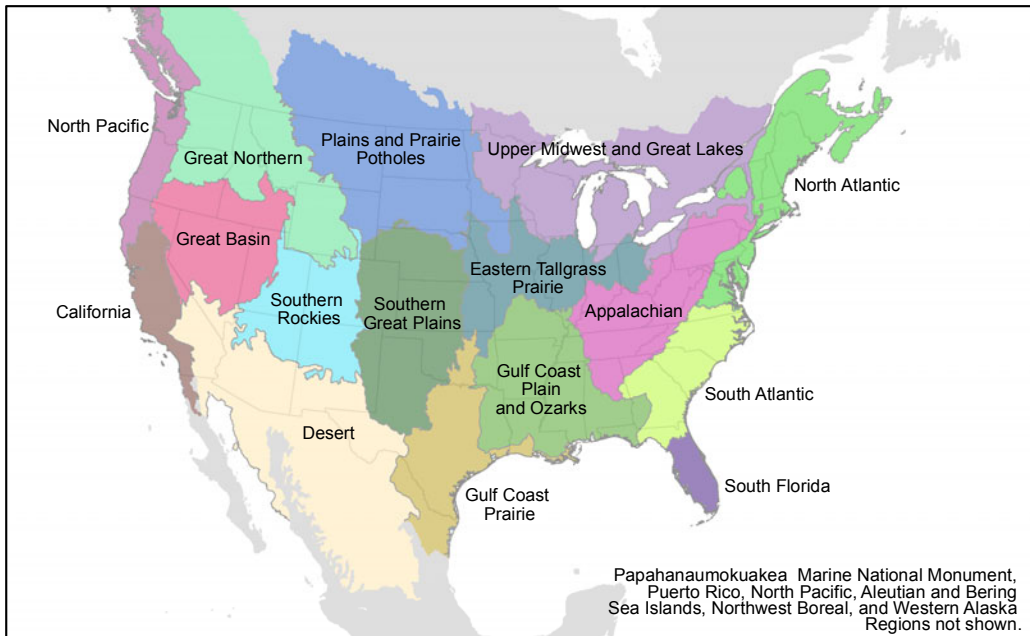


## Bird Conservation Regions and Landscape Conservation Cooperative Boundaries



Hawaii (not shown) is BCR 67

Bird Conservation Regions



USFWS Landscape Conservation Cooperatives

**Figure 1.** Bird Conservation Regions and Landscape Conservation Cooperatives (LCC) across the United States

## BRINGING IT TO GROUND TO SAVE DIRT

This historical perspective is important to understand the major changes occurring within the National Wildlife Refuge System. The development of the SHC model and LCCs will provide decision support tools for conservation at multiple scales. This will allow refuge managers to look beyond their boundaries and make decisions on land protection and management that will make the greatest contributions to conservation in the landscapes. This has not always been the case, and only with the recent approaches and technological advances have managers had the information necessary to understand refuges' role within their larger landscapes.

The real revolution however, is the way in which refuge boundaries are being created and the extended reach refuges can have within communities inside and adjacent to refuge boundaries. In the past, refuge boundaries were typically drawn around concise areas that were identified by the FWS and conservation partners, as having particular value in achieving the mission of the Service and Refuge System. Boundaries were carefully drawn to exclude developed areas or other areas that did not contain important wildlife habitat. The FWS then worked with willing sellers, as land acquisition budgets allowed, to protect all the lands and waters within the boundary. This model served the NWRS well for 100 years, protecting habitats for breeding, migrating, and wintering birds, threatened and endangered species, and big game. Advances in landscape ecology and conservation biology, coupled with advances in remote sensing and other technologies, eventually began to shape the way that the FWS established refuge boundaries. A refuge that epitomizes the new landscape approach to refuge boundary establishment in the FWS Northeast Region is the Silvio O. Conte National Fish and Wildlife Refuge in Connecticut, Massachusetts, Vermont and New Hampshire.

**Silvio O. Conte National Fish and Wildlife Refuge**—The Conte refuge was established in 1997. Like all refuges, it was not considered to be “established” until the first tract of land was acquired. The idea of the Conte refuge originated much earlier, when in 1991, Congress passed Public Law 102-212, the Conte Refuge Act, in honor of the late Congressman Silvio O. Conte of Massachusetts. Rep. Conte introduced the bill before his death in 1991 and envisioned a Connecticut River restored to its former stature, with clean water, abundant fish and wildlife populations, and a resource for all to enjoy, and from which to derive sustainable economic benefits. The goals of the Conte Refuge Act were as follows:

- Conserve, protect and enhance the Connecticut River watershed populations of Atlantic salmon, American shad, river herring, shortnose sturgeon, bald eagles, peregrine falcons, osprey, black ducks, and other native species of plants, fish and wildlife;
- Conserve, protect and enhance the natural diversity and abundance of plant, fish and wildlife species and the ecosystems upon which these species depend within the refuge;
- Protect species listed as endangered or threatened, or identified as candidates for listing, pursuant to the Endangered Species Act of 1973, as amended;
- Restore and maintain the chemical, physical and biological integrity of wetlands and other waters within the refuge;
- Fulfill the international treaty obligations of the United States relating to fish and wildlife and wetlands; and

- Provide opportunities for scientific research, environmental education, and fish and wildlife-oriented recreation and access to the extent compatible with the other purposes stated in this section.

The Connecticut River runs 400 miles, from the Canadian border to Long Island Sound. Its watershed encompasses 7.2 million acres. The planners charged with putting Rep. Conte's vision into practice faced some significant challenges: never before had the FWS attempted to positively influence conservation across an entire watershed of the magnitude of the Connecticut River, involving four states, and hundreds of municipalities.

They began by talking to people. Beginning in 1993, the FWS held more than 130 meetings across the watershed, including 27 public meetings. Workbooks were distributed to solicit ideas, opinions and concerns on important topics such as agriculture and forestry, biological resources, local economies, environmental education, public use and access, and water use and water quality. The information gained was incorporated into a Draft Environmental Impact Statement (EIS), which was issued for public review and comment in May of 1995. The FWS' proposed action centered around 4 major themes:

- land protection (public and private);
- working with private landowners on voluntary conservation projects;
- increasing environmental education efforts and programs; and
- developing and maintaining partnerships to achieve mutual conservation goals.

Another extensive outreach effort then occurred during the public comment period, with more formal and informal meetings and sessions held in 16 communities across all four states. The Final EIS and Action Plan was completed in October 1995, and on October 3, 1997, the refuge was formally established with the donation of a 3.8-acre island by the Connecticut River Watershed Council. It is fitting that an island, surrounded by the waters of the Connecticut, was the refuge's first acquisition, and even more so that it was donated by a watershed organization, for the Northeast Region's first watershed refuge.

For its 110-year history, the Refuge System has been a land-based network. To be established as a national wildlife refuge, there had to be an interest in land, which could include fee title, conservation easement, or lease. There are currently no virtual refuges, where the FWS has a presence, promoting and demonstrating conservation, but no land interest. That concept may be changing, as the FWS implements the recommendations of, *Conserving the Future*, the 2011 vision document for the Refuge System. It calls for the FWS to make the Refuge System and its message of conservation more relevant to diverse cultures and ethnicities, with a focus on urban areas. This may result in the presence of refuge themes within urban partnerships that do not require FWS land ownership. Three of the five alternatives evaluated in the Conte refuge's EIS did not include land protection by the FWS. The alternative selected did include FWS land protection, but not in a traditional way.

*Land protection*—The 7.2 million-acre boundary of the Conte refuge differs from a traditional refuge acquisition boundary in that it authorizes FWS land acquisition only within designated areas of the watershed. In the final EIS, the FWS identified 48 Special Focus Areas plus smaller

sites that contain “important, scarce and vulnerable wetlands and scattered rare species sites” (USFWS 1995). It is within these areas that the FWS is authorized to negotiate with willing sellers to purchase interests in land, including conservation easements, and accept donations of land. Even within the Special Focus Areas, the FWS’s authority is limited. The area encompassed by the Special Focus Areas is approximately 180,000 acres. The FWS has established its authority to protect up to 97,510 acres, with the expectation that partners will protect additional land within the Special Focus Areas. As of September 30, 2012, the FWS had protected 35,525 acres as part of the Conte refuge.

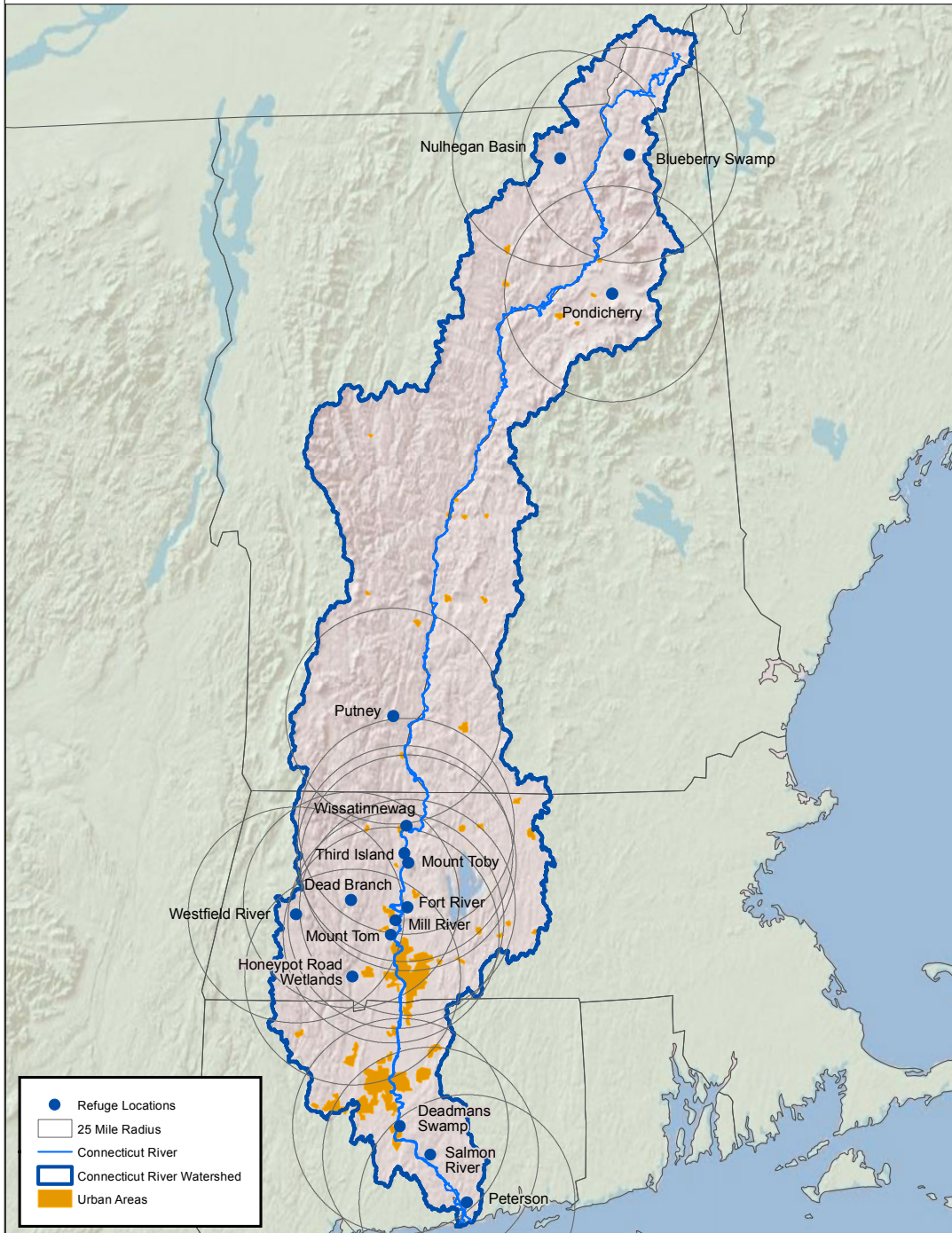
The criteria for inclusion as a Special Focus Area included the following:

- Habitat for federally listed (endangered, threatened or candidate) species;
- Habitat for a number of rare species and/or rare or exemplary natural communities;
- Important fisheries habitat;
- Important wetlands;
- Habitat for waterbirds (waterfowl, herons, rails);
- The potential to protect a substantial area of contiguous habitat for declining area-sensitive species;
- Large blocks of unusual habitat type; and
- Landbird breeding and migratory stopover habitat.

Today we have more information and better decision support tools to identify priority areas for protection, but in 1995 these criteria represented our best effort to insure that Federal funds were applied to the most critical areas. Even if the FWS reached its target of protecting 97,510 acres within the Special Focus Areas, it is unlikely that would be sufficient to achieve the vision that Silvio Conte had for the Connecticut River. However, direct land protection by the FWS was only one of the four major themes included in the Final Conte Refuge EIS. The other three centered around working with private landowners on conservation projects, environmental education and partnerships. The successful implementation of all four themes will provide the greatest chance for a healthy and sustainable watershed. Land protection however, is essential and is the cornerstone that leads to communication and collaboration.

*Working outside the boundary*—Figure 2 shows the focus areas where the Conte refuge’s land holdings occur. The circles around the properties represent a 25-mile radius from those lands, incorporating the area where the refuge has the most direct presence and influence on conservation. When the FWS obtains an interest in land and assumes stewardship responsibilities for that land, it becomes a stakeholder in that community. That requires the FWS to look around at adjoining lands and land uses to understand how to best protect the conservation investment that has been made. It could involve discussions with landowners about their willingness to sell additional lands to the FWS, because larger amalgamations of land holdings facilitate conservation and management, but landowners are often equally protective of their investments. The focus areas FWS has identified contain not only important wildlife habitats but also some of the most beautiful and high-value recreational areas. Lands adjacent to water, wetlands and large forested blocks are attractive to wildlife and people. It is therefore understandable that an adjoining landowner may not be interested in selling, and this interests presents opportunities.

U.S. Fish and Wildlife Service  
 Silvio O. Conte National Fish and Wildlife Refuge



**Figure 2.** U.S. Fish and Wildlife Service Silvio O. Conte National Fish and Wildlife Refuge.

People who value their land are often interested in knowing more about it and how they can make it more attractive to wildlife. They may appreciate technical advice on invasive species control, or information on plants that may provide food or cover for wildlife. For more intensive projects, like restoring a drained wetland, they may seek financial assistance in the form of a grant where the costs of the project are shared by those with mutual interests. There are incentive programs for landowners from the FWS, including the Partners for Fish and Wildlife program and the many coastal program offices. In addition, the FWS works closely with United States Department of Agriculture (USDA) in all four states of the Connecticut River Watershed to help implement cost sharing programs, such as Forest Legacy and the many programs offered by the Natural Resources Conservation Service (NRCS). The Conte refuge has memoranda of understanding with NRCS in each of the four states to share resources toward achieving mutual objectives in working with private landowners.

The process for applying and navigating various requirements can be daunting for many people. The NRCS has staff to assist landowners, but like all federal agencies, they are stretched thin. The Conte refuge recognized that personal contacts with landowners can mean the difference between an idea or desire for a conservation project and actually accomplishing it. In October 2011, the refuge combined resources with NRCS to hire a biologist on a term appointment to work directly with private landowners and partners to coordinate what can be complex processes.

One current project being coordinated by the refuge involves working with NRCS, the U.S. Department of Transportation, Federal Emergency Management Agency, Trout Unlimited (TU),

The Nature Conservancy, and American Rivers to inventory road crossing culverts and dams on public and private lands that may be negatively impacting fish passage or stream health. Many culverts are improperly sized or perched above the streambed, causing erosion and inaccessibility to spawning grounds. Obsolete dams are another obvious impediment to fish passage.

On the Kinne River in Chester, Massachusetts, the refuge coordinated with NRCS, TU and the State to assist a private landowner in removing a six-foot concrete dam. Problems with this dam became apparent during Hurricane Irene, as did many other issues involving small streams in New England. The refuge helped coordinate permitting requirements, funding and contracting for the dam removal, providing the extra effort that made the project a reality. Phase two of this project will involve replacing two improperly sized culverts to open up more than five miles of stream to native brook trout.

Another example of a successful program started by the refuge with an eye toward private lands is its “Adopt-a-Habitat” initiative. The program is intended to establish long-term relationships that will spur schools, organizations and individuals (adults and youth) to adopt and manage local areas within the watershed. Program participants will manage public and private land in order to promote healthy habitat for plants, wildlife and people. The Adopt-a-Habitat initiative offers an opportunity to accomplish more for wildlife and habitat on lands not governed by FWS. In the process, relationships are established and a commitment to wildlife and habitat is fostered, making the FWS and the refuge more relevant to the public.

*Environmental education and the WOW Express*—The outreach and offers of collaboration from the Conte refuge extend far beyond adjoining landowners. The Connecticut River watershed is

home to approximately 2.4 million people, from urban dwellers to corporate interests that control tens of thousands of forested acres. Maintenance of watershed health and vitality is a long-term process and commitment. As promised during establishment of the refuge, environmental education remains an important aspect of the refuge's work in the nearly 400 communities that exist within the watershed. In his book, *Last Child in the Woods* (2005), Richard Louv investigates the relationship between children and nature, past and present, and highlights the potential negative health effects that result from the separation of young people from their natural environments. There are also implications for the future of land conservation as the youth of today become the decision-makers of tomorrow.

The Conte refuge has specific goals to provide opportunities for teachers, students and others to explore and learn about wildlife and their habitats, both on and off the refuge. On-refuge, they have built fully accessible interpretive trails with site-specific information about habitats and related wildlife use and conservation. These and other sites also serve as wildlife observation trails, platforms for nature photography, access for hunting and fishing, and sites for structured environmental education. The refuge has also created an innovative tool to help educate and inform people of all ages about the concepts of conservation, ecology and ecosystem services across the entirety of the watershed.

The Watershed on Wheels, or WOW Express, is a traveling exhibit designed to engage children of all ages in the beauty and wonder of the Conte refuge. It includes three engaging components: a walk-through immersion exhibit featuring the diverse sights and sounds of plants and animals from habitats found in the Connecticut River watershed; a watershed table showing how rivers form and change; and seven interactive kiosks exploring the cultural, economic and environmental significance of the watershed the Conte refuge seeks to conserve. The WOW Express travels to schools and natural resource-related fairs, festivals, and conferences throughout the four states of the watershed.

From April 2012 to July 2013, the WOW Express visited more than 70 communities. The more structured environmental education visits touched nearly 4,000 students and 377 teachers from 30 schools in the four states. Including visits to summer camps and more than 50 special events, the WOW Express reached more than 18,500 people across the watershed in the most recent 11-month period when it was most active. Most staffed refuges in the Refuge System offer opportunities for environmental education and interpretation, but few can match the reach of the Conte refuge both in terms of geography and population.

*Partnerships*—Developing partnerships to achieve mutual objectives is now ubiquitous in the NWRS and almost every staffed refuge in the System can point to a successful partnership that they help facilitate. The breadth and depth of partnerships that the Conte refuge has inspired in a short time is stunning.

Some partners, such as the Connecticut River Watershed Council, predate the Conte refuge in their efforts to promote conservation at the watershed scale. However, even these more advanced initiatives benefit from the elevation of the area to national status via inclusion within the Refuge System. What is most impressive is that partners with a diversity of interests have found common ground within the watershed and coalesced around the refuge. The Friends of Silvio O. Conte National Fish and Wildlife Refuge is a coalition of more than 40 groups, representing

Audubon chapters, local, regional and national land trusts, fisheries interests, outdoor recreationists, museums, farming interests and all levels of government. Each member has gravitated to the refuge as a galvanizing force for watershed conservation, each seeing their own interests being advanced by joining forces with others, under the mantle of a national wildlife refuge. In October 2013, the refuge Friends group was awarded the FWS National Land Protection Award at the Land Trust Alliance rally for their efforts.

## LOOKING TO THE FUTURE

The Conte refuge provides not only an example of the evolution and innovation of the National Wildlife Refuge System, but also shows where the Refuge System is heading. The refuge's Comprehensive Conservation Plan is nearing completion, with an expected final plan due in 2014. Among the issues being addressed in the plan are a re-examination of land protection goals and a re-emphasis on other major themes of cooperatively working with private and other public landowners, focusing on environmental education and maintaining and expanding partnerships. These efforts are augmented by projects from the North Atlantic Landscape Conservation Cooperative (NALCC).

The NALCC is in the second phase of a project entitled *Designing Sustainable Landscapes*. This project is designed to support the overall goals of the NALCC, which are as follows:

- (1) Assess the current capability of habitats in the NALCC to support sustainable populations of wildlife;
- (2) Predict the impacts of landscape-level changes (e.g., from urban growth, conservation programs, climate change, etc.) on the future capability of these habitats to support wildlife populations;
- (3) Target conservation programs to effectively and efficiently achieve objectives in State Wildlife Action Plans and other conservation plans and evaluate progress under these plans; and
- (4) Enhance coordination among partners during the planning, implementation and evaluation of habitat conservation through conservation design.

This modeling framework will ultimately allow LCC partners to assess landscape change, analyze changes in ecological integrity and habitat capability for representative species, and identify priorities for land protection and conservation priorities for existing conservation lands. This effort is being piloted in three places in the Northeast Region, including the Connecticut River Watershed and will be available across the region by July, 2014. The LCC is also working to deliver the information and tools from this and other projects to partners at regional, state and local levels. National wildlife refuges can play a key role by working with partners to utilize this conservation planning information in their landscapes.

While much of the work of the LCCs will help inform refuge managers, land protection planners, state partners, and other organizations, it will also provide important tools to inform conscientious private landowners. As the skepticism about the reality and potential impacts of climate change diminishes with continued evidence, landowners will want more information. They need to know whether to expect drought or deluge, about which plants will persist on their properties, and how rising sea levels and more intense storms will affect shorelines. Through LCCs



and other cooperative entities, this information will be widely disseminated, but where we have national wildlife refuges, the information has a better chance of being used to benefit fish and wildlife and their habitats.

New national policies developed by the FWS will directly affect the way that land protection occurs within the National Wildlife Refuge System. A new Strategic Growth Policy (in draft at this time) proposes to sharpen the focus of future refuge land acquisitions on three primary conservation targets: declining migratory birds, threatened and endangered species, and waterfowl. New land protection planning policies are also under development that would require landscape conservation designs to be produced before any new refuge establishment or major expansion. The landscape designs now being developed by the NALCC through their *Designing Sustainable Landscapes* initiative, that incorporate climate change impacts and other predicted stressors of wildlife and the environment, are examples of what the FWS is promoting nationwide. A new prioritization tool is under development to help allocate annual funding for refuge acquisitions. What all these initiatives have in common is that they employ the SHC principles at a landscape scale and the realization that we must focus our limited resources in the most strategic way to sustain vulnerable wildlife, and remain relevant to the American people in the Anthropocene.

## CONCLUSION

Over its 110-year history, the Refuge System has adapted and responded to wildlife exploitation, the Dust Bowl, pending extinctions, disease, and other environmental catastrophes. Compared to climate change, these stressors were obvious and measureable over a relatively short time span. Fortunately, improvements in our understanding of landscape ecology and conservation biology, combined with incredible advances in technology and advanced modeling capability, provide hope for the future. FWS policies are catching up and provide blueprints for success. Of the last 10 national wildlife refuges established, five have boundaries of more than 700,000 acres. The Conte refuge demonstrates what is possible: working with partners to identify and protect the best habitat, connecting with people to help them help wildlife, inspiring the next generation of decision-makers, and doing it in manner that fosters communication and collaboration.

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This paper received peer technical review. The content of the paper reflects the views of the authors, who are responsible for the facts and accuracy of the information herein.



# Policy Challenges for Wildlife Management in a Changing Climate

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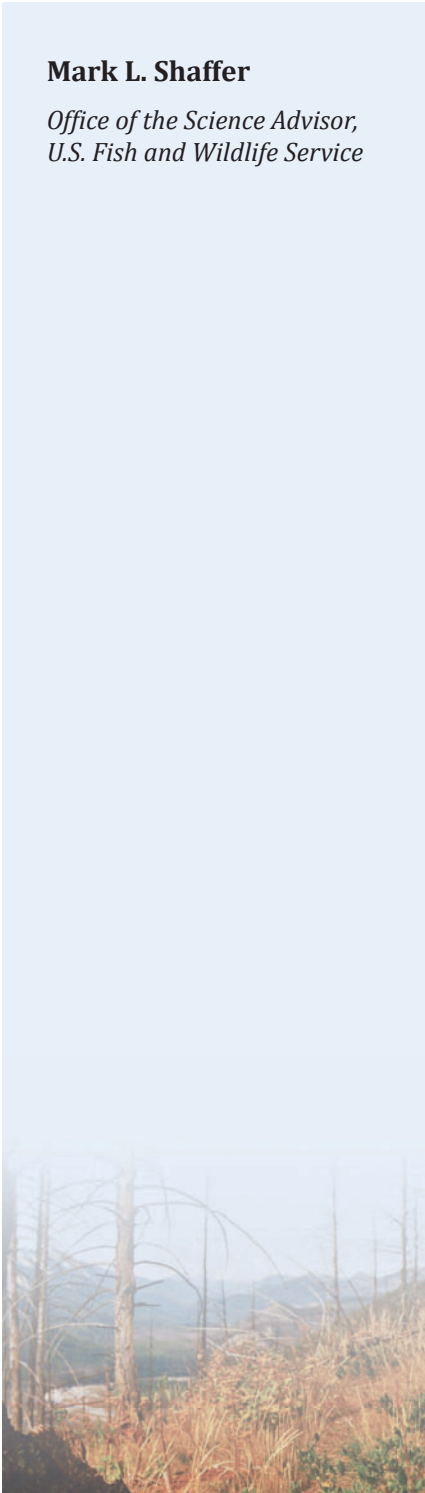
***Abstract:** Try as it might, wildlife management cannot make wild living things adapt to climate change. Management can, however, make adaptation more or less likely. Given that policy is a rule set for action, policy will play a critical role in society's efforts to help wildlife cope with the challenge of climate change. To be effective, policy must provide clear goals and be based on a clear understanding of the problem it seeks to affect. The "National Fish, Wildlife, and Plants Climate Adaptation Strategy" provides seven major goals and numerous policy related actions for wildlife management in a period of climate change. The underlying themes of these recommendations and the major challenges to their achievement are identified and discussed.*

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## INTRODUCTION

As one of the major biome types on Earth, forests are of fundamental importance to wildlife. (Note: the term "wildlife" when used alone is meant as short hand for all species living in an undomesticated state: both plant and animal.) From the standpoint of species diversity, the most diverse terrestrial habitats on Earth are the great tropical rainforests. From the standpoint of sheer standing biomass, the great temperate rainforest of the Pacific Northwest may be unequalled. In terms of charismatic megafauna, which for most people are the face of wildlife, many signature North American species (e.g., deer, bear, elk, wolf, moose, cougar) are principally forest species. A large fraction of the lands American society has chosen to devote to conservation are forested lands.

Reflecting their importance, American society has developed a substantial institutional and policy framework for the management of its forests and for wildlife (the U.S. Forest Service and the National Forest Management Act, the U.S. Fish and Wildlife Service and the Endangered Species Act, state forestry and wildlife agencies and laws, etc.). This institutional and policy framework was developed in a period of relative biological stasis. The question now is whether this existing framework is



adequate during a period of great biological change and, if not, what adjustments might be in order.

## THE PROBLEM

Climate is fundamental to biological systems. It is the interaction of temperature and precipitation that is the major determinant of the distribution of biomes (e.g., forest, grassland, desert, etc.) that in turn controls the distribution of species dependent on those systems. Drastic changes in climate are thought to have been proximal, if not an ultimate drivers, of past mass extinction events such as those that occurred at the end of the Cretaceous and Permian epochs (Twitchett 2006; Feulner 2009).

The earth is again entering a period of rapid climate change. According to the last National Climate Assessment (USGCRP 2009), measurements and observations show that, among other things: average air and ocean temperatures are increasing globally, rain falling in the heaviest storms is increasing, extreme events such as heat waves and drought are becoming more frequent and intense, sea level is rising, and Arctic sea ice is shrinking.

Not surprisingly, many species are showing signs of changes in their distribution and the timing of major life history events (e.g., migration, nesting, emerging, blooming, etc.) consistent with a warming climate (Parmesan 2006). Some of these observed changes are signaling that additional climate change is likely to affect the ability of some of our conservation institutions and/or laws to achieve their stated objectives. For example, the namesake species of Joshua Tree National Monument may no longer grow in that area in the coming decades (Cole and others 2011). Moose, one of the signature species of Minnesota's North Woods—and a prime game species—are in a sharp decline that is thought to be related to increasing temperatures (Cusick 2012). The great Western forest fires of the last half decade or so—fueled in part by temperature mediated insect infestations—may, in some cases, result in a change from forest to shrubland and grassland ecosystems (Williams and others 2010).

## COMING TO GRIPS

Recognizing the emerging challenges of climate change for our wildlife resources, Congress in 2009 requested that the Council on Environmental Quality (CEQ) and the Department of the Interior (DOI) develop a national strategy to "...assist fish, wildlife, plants, and related ecological processes in becoming more resilient, adapting to, and surviving the impacts of climate change" (CEQ/USDOJ 2009). As DOI's wildlife bureau, the U.S. Fish and Wildlife Service (FWS or Service) took the lead in structuring a process to fulfill this request. Because of the complementary nature of U.S. wildlife law, the Service invited the National Oceanic and Atmospheric Administration (NOAA) and state wildlife agencies to co-lead the effort. Ultimately, a Steering Committee of representatives from 15 federal agencies, five state fish and wildlife agency directors, and leaders of two inter-tribal natural resource commissions oversaw development of the *National Fish, Wildlife, and Plants Climate Adaptation Strategy* (NFWPCAS 2012).

The NFWPCAS is an unprecedented effort by all levels of government that have authority or responsibility for wildlife in the United States to work together collaboratively to identify what needs be done in a period of rapid climate change. It was developed by teams of managers,

**Table 1.** Goals of the NFWPCAS.

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<b>Goal 1</b>	Conserve habitat to support healthy fish, wildlife, and plant populations and ecosystem functions in a changing climate.
<b>Goal 2</b>	Manage species and habitats to protect ecosystem functions and provide sustainable cultural, subsistence, recreational, and commercial use in a changing climate.
<b>Goal 3</b>	Enhance capacity for effective management in a changing climate.
<b>Goal 4</b>	Support adaptive management in a changing climate through integrated observation and monitoring and use of decision support tools.
<b>Goal 5</b>	Increase knowledge and information on impacts and responses of fish, wildlife, and plants in a changing climate.
<b>Goal 6</b>	Increase awareness and motivate action to safeguard fish, wildlife, and plants in a changing climate.
<b>Goal 7</b>	Reduce non-climate stressors to help fish, wildlife, plants, and ecosystems adapt to a changing climate.

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researchers, and policy experts drawn from federal, state, and tribal agencies organized around major ecosystem types. The Strategy identifies seven major goals that must be achieved to give wildlife the best chance of surviving the projected impacts of current and anticipated future climate change (Table 1). Numerous strategies (23) and actions (100+) are identified that are essential for achieving these goals.

All of the seven major goals identified in the NFWPCAS are things that the wildlife management community already does (e.g., conserve habitat, manage species and habitats, enhance management capacity, etc.). What will be new, and what the NFWPCAS tries to illustrate is that these things will need to be done in new ways, or in new places, or at new times, or in new combinations for conservation to be effective. In other words, conservation in a period of climate change will be equipped with the same types of tools, but they may need to be used in new ways. In some cases, such as policy, the existing tools themselves may need modification or even replacement.

## **POLICY RECOMMENDATIONS OF THE NFWPCAS**

The NFWPCAS includes one recommended strategy and seven actions that are policy focused (Appendix 1). The major policy focused strategy (3.3) is to: *“Review existing federal, state, and tribal legal, regulatory and policy frameworks that provide the jurisdictional framework for conservation of fish, wildlife, and plants to identify opportunities to improve, where appropriate, their usefulness to address climate change impacts.”* This recommended strategy is further broken down into seven specific actions that focus on: (1) incorporating the value of ecosystem services into habitat protection and restoration; (2) developing or enhancing market-based incentives to support restoration of habitats and ecosystem services; (3) improving compensatory mitigation requirements; (4) improving floodplain mapping, flood insurance, and flood mitigation; (5) identifying existing legal, regulatory or policy provisions that provide climate change adaptation benefits; (6) provide appropriate flexibility under the ESA to address climate change impacts on listed species; and (7) addressing sea level rise. Many other strategies and actions (see Appendix 1), although not focused specifically on policy, raise policy issues. For example, Action 2.1.8 is to: *“Utilize the principles of ecosystem based management and green infrastructure.”* Depending on the specific context for utilizing these principles, new policy might be required.

As it stands, the NFWPCAS is a very long to-do list of the many things the wildlife management community needs to undertake to fully come to grips with the challenge of climate change to its mission and the resources for which it has authority and responsibility. Rather than rehash this extensive list, it may prove more informative to look for the underlying themes in the Strategy and to identify a few of the major challenges for wildlife conservation policy going forward.

## UNDERLYING THEMES OF THE STRATEGY

Prior to the formal launch of the NFWPCAS development process, FWS held several Conservation Leadership Forums to convene representatives from other agencies, other levels of government, and the academic and non-governmental communities to consider the climate change challenge and to develop appropriate response. From those meetings emerged nine guiding principles that were used in development of the NFWPCAS (Table 2).

These guiding principles are reflected in so many of the NFWPCAS goals, strategies and actions that they suggest four broad themes for wildlife adaptation efforts.

**Be Inclusive and Collaborative.** Climate change is so pervasive, and its impacts potentially so far-reaching, that no single agency, no single level of government, indeed no single sector will be able to mount an effective response on its own. All affected agencies and interests need to be at the table working collaboratively to be effective.

**Think, Plan, and Act at the Right Scale.** The days are over of believing that a single set of best management practices universally applied will automatically lead to a biologically functional landscape. Different agencies and organizations work at different scales. Entities that operate at the local scale need to do so in the context of the broader physical, biological, and institutional landscape of which they are a part. And entities that operate at the national or regional scale need to be mindful of the needs, realities, and differences of the many landscapes in which they operate.

**Integrate Across Sectors.** A corollary of being inclusive within the conservation sector is also to be inclusive of other sectors. Much of what governs the fate of wildlife is not the actions or inactions of the wildlife management community, but actions by other sectors that affect the natural world (e.g., agriculture, transportation, energy development, construction, etc.).

**Table 2.** Guiding Principles of the NFWPCAS.

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- Build a national framework for cooperative response.
  - Foster communication and collaboration across government and non-government entities.
  - Engage the public.
  - Adopt a landscape/seascape based approach that integrates best available science and adaptive management.
  - Integrate strategies for natural resources adaptation with those of other sectors.
  - Focus attention and investment on natural resources of the United States and its Territories.
  - Identify critical scientific and management needs.
  - Identify opportunities to integrate climate adaptation and mitigation efforts.
  - Act now.
-

Starting an adaptation planning process by including everyone and everything may be too large a burden for any sector to bear, but once each sector has a working understanding of its needs relative to adaptation, it needs to reach out to the other sectors relevant to its interests to identify commonalities, synergies, conflicts and resolutions.

**Engage, Communicate, and Act.** The effects of climate change on species are beginning to be readily apparent. Because projections of future conditions and impacts come with great uncertainty it is tempting to wait until more is known, the models are better; there is less uncertainty before we act. Unfortunately, like many large systems, Earth's climate has great inertia, and once change is entrained it will not be quickly or easily restrained. There is unequivocal evidence that the climate is changing, that the underlying cause is the growing accumulation of greenhouse gases (GHGs) in the atmosphere resulting from human activity, and that there is no plausible institutional or policy framework in place to restrain additional GHG emissions which will increase the impacts on wildlife. Species are already responding; it's time for the wildlife management community to engage, communicate, and act on what we do know, even if the rates and patterns of change and the future status of species and communities remain uncertain.

## MAJOR POLICY CHALLENGES GOING FORWARD

Achieving the goals of the NFWPCAS will in many instances require having the right policies. As noted above, the NFWPCAS has one major strategy and a number of actions focused on or related to having the correct conservation policies. Whether existing or new, these policies will need to be developed and employed in the face of several emerging realities about wildlife conservation in a period of climate change.

**No Precedent.** Depending on how it is defined, wildlife management is a few hundred to a few thousand years old. The best global circulation models are now projecting that if GHGs continue to accumulate at current rates, average global temperatures will by 2100 reach levels that have not occurred for millions of years (Houghton and others 2001). Wildlife management, either as primitive practice or modern profession, has not seen such a period of change in its history. There is no precedent, no body of knowledge derived from experience to underpin wildlife conservation policy for a period of rapid climate change. Nor can we replicate the Earth to take an experimental approach to discover the best way forward.

*Policy can be defined as a rule for decision-making. Many of the decisions the conservation community will have to make in the coming decades will have to be made in unprecedented circumstances. It will be a time of trial and error and wildlife conservation policies will need to be cast in flexible terms to acknowledge and adjust to that uncomfortable reality.*

**Unknown Destination.** CO<sub>2</sub> is the principal GHG. In the range of atmospheric concentrations of CO<sub>2</sub> explored with current climate models, global average temperature appears to increase proportionate to CO<sub>2</sub> concentration; the more CO<sub>2</sub>, the more temperature will increase. At present, CO<sub>2</sub> concentrations appear to be increasing at least linearly, perhaps even accelerating (IPCC 2013). Under current patterns of usage of fossil fuels, the burning of which is the principal source of the CO<sub>2</sub> increase, there is no plateau in sight for CO<sub>2</sub> concentrations and, therefore, temperature. If global climate effects are also proportionately sensitive to



temperature, then the climate of a +1°C world will be different, both from that of the current world and from the climate of a +2°C world. Thus, the world is not moving from the current climate to a new climate, it is leaving the current climate, with no fixed destination. Novel climates will emerge presenting species with new combinations of temperature and precipitation that they may not have experienced before in their individual evolutionary histories (Williams and Jackson 2007). This makes adaptation planning and policy formulation even more challenging. Plans and policies need target conditions around which to be formulated. Even if the effects of each 1°C increase are modest by themselves, their impacts will likely prove ecologically cumulative. Having multiple degrees of temperature increase means having multiple or at least iterative plans and policies that are, perhaps, very different. *Wildlife conservation plans and policies will need to be re-visited regularly in light of the emerging trends in GHG accumulation and the resulting level of projected climate change.*

**Species Shift, Communities Change.** There are many unknowns with regard to the response of living systems to climate change. One thing that is known with some certainty is that in past periods of climate change species responded individually and not as tightly integrated communities. In other words, each species shifted its range in its own way at its own rate and, therefore, the co-occurring assemblages of species that are recognized as natural communities changed in composition (Hunter and others 1988). This has profound implications for wildlife conservation planning and policy in an era of rapid climate change.

Many of our existing conservation plans use natural communities as coarse filters for conserving wildlife diversity (i.e., as proxies for habitat). The logic is that by identifying the range of communities and then conserving some of each, their constituent species will be maintained (Hunter and others 1988). This coarse filter approach is often complemented by the use of a fine filter that is focused on the needs of certain individual species that may be of particular importance for one or more reasons (i.e., ecological, economic, social, cultural, etc.).

The individualistic response of species to climate change is already becoming apparent. Some species ranges are beginning to shift (e.g., the Joshua Tree example). If natural communities are defined as all the species in a given area interacting together, then is the North Woods without moose still the North Woods? The potential replacement of forests with shrublands and grasslands after the recent major fires in the American Southwest is perhaps an extreme example of community change. The larger message for the wildlife conservation and management community is that we are entering an era when effective conservation will hinge more than ever on understanding the needs of individual species. With more than 1500 native taxa already listed as Threatened or Endangered in the United States and likely many more to come due to the impacts of climate change, this will be a major challenge. Even without considering climate change, a major study of the conservation status of U.S. species (Stein and others 2000) suggested that up to a third of our native species in major taxonomic groups (e.g., vertebrates, flowering plants, etc.) are at risk of extinction in the coming decades due to existing threats. A subsequent global analysis suggested that up to 35 percent of species could be at risk due to climate change (Thomas and others 2004). Although no cross-comparison of the two studies seems to have been done, the conservative conclusion at the moment is that anywhere from 33-68 percent of native species could be at risk. That is perhaps an order of magnitude more species than the 1500 currently listed in the United States.

*Wildlife conservation policies will need to recognize the essential independence of species in terms of their response to climate change. The sheer magnitude of species that may need to be managed suggests that conservation policies will also have to try and differentiate the relative importance of species for a variety of considerations (environmental, ecological, utilitarian, etc.)*

**Speed Kills.** Perhaps the most challenging feature of the current period of climate change from an evolutionary perspective is its projected speed. The range of estimates from the last National Climate Assessment (USGCRP 2009) is that, at current rates of CO<sub>2</sub> emissions, average annual temperature in the United States could increase by 3–6°C by 2100. Although the world has experienced this level of temperature increase and more in past periods (Stager, this volume), those past increases played out over time frames of 10,000's to 100,000's of years—100 to 1,000 times slower than what is currently anticipated over the next century. The adaptive capacity of species is currently one of the great unknowns in projecting the future of wildlife in a changing climate. Some species may prove to have greater adaptive capacity than is currently anticipated nevertheless, the fossil record suggests that evolution is a relatively slow process even in geologic terms. Relying on a slow process in a period of rapid change may leave many species unable to keep up.

There are four basic responses of species to climate change: acclimation, relocation, adaptation (in the evolutionary sense), or extinction. Acclimation is a function of a species phenotypic plasticity and genetic variation to address short-term changes at any point in time. Although an assessment of the genetic diversity of a species may provide some insight into both its ability to acclimate in the short-run and to adapt in the long run, it is no guarantee of success in novel circumstances. Relocation is a function of both behavior and selection pressure. For relocation to be a successful survival strategy, a species needs suitable habitat to which it might relocate, and the ability to reach that habitat.

Given the speed at which climate is projected to change, both short-term acclimation and relocation are likely to be the principal mechanisms by which current species might endure this period of change over the short-term. Thus, the most promising interventions for maximizing the retention of species diversity will be to provide a range of habitats and some level of biological connectivity across the landscape. Given the importance of population size to both demographic survival and genetic diversity, the amount of each habitat type conserved will also prove important. The modern landscape is so fragmented from a biological standpoint that the managed relocation of species may prove necessary as a component of “functional connectivity” going forward. Determining what all of this means in operational terms will prove to be the heart of wildlife management's challenge for the next century. *Wildlife conservation policies need to emphasize the retention of significant amounts of the variety of habitats across the landscape and their functional connectivity, including the possibility of managed relocation.*

**Friend or Foe.** Invasive species are one of the major challenges to wildlife conservation. As of 2000, they were ranked number two as a cause of species listings under the U.S. Endangered Species Act (Stein and others 2000) and their impact may have grown since that time. The conservation community is predisposed to see a species new to an area as a threat and to move to contain or eliminate it. With relocation as one of the principal responses of species to a changing climate, more and more species will be showing up in areas they have not previously inhabited. Will they be invasive? Should they be viewed as exotic? Or, are they the climate pioneers?

Current policies on invasive species were not formulated with this situation in mind. A blind reaction to something new as a threat might actually work against one of the principal means by which species will attempt to adjust to climate change. *Wildlife conservation policies will need to develop criteria by which to differentiate climate change pioneers from invasive species.*

**Climate Change is Only One of the Problems.** There are few, if any, natural communities that have not been impacted to some degree by non-climate stressors. Habitat loss, fragmentation, and degradation have already taken a toll on the status of many U.S. species (Stein and others 2000). As mentioned earlier, the impacts of invasive species have also been substantial for many native species. Pollution, especially in the form of pesticides and chemicals that disrupt the endocrine systems of vertebrates are also a problem in some cases (Colborn and others 1996). It is expected that climate change will not only be a threat in its own right through direct challenges to the thermal and moisture tolerances of species, but also by exacerbating these existing stressors. Consequently, one of the major goals of the NFWPCAS is reducing these existing stressors, the theory being that species will then be better able to cope with the additional pressures of climate change. This recommendation is a common theme in the wildlife adaptation literature (Mawdsley 2009; Heller and Zavaletta 2009). *Wildlife conservation policies will need to be based on an inclusive and integrated consideration of species vulnerabilities and not simply their climate related vulnerabilities.*

**Realism.** Wildlife management is, in some sense, a misnomer. It is really about managing human behavior that affects wildlife rather than managing wildlife itself. The human activity of harvesting is managed so as to leave wild populations that can replenish themselves. Management, however, cannot make a species reproduce. Human activities that can alter land use are foregone in some circumstances to retain the conditions that support a species. But management cannot make a species use a certain habitat or stay in a certain area. So it is with adaptation to climate change. Management cannot make a species adapt to climate change, but it can influence the human activities that will make such adaptation more or less likely.

Human activity with regard to the use of fossil fuels has now reached a level that is entraining a directional shift in Earth's climate and wildlife is responding. As a primary driver of biological systems, climate will always trump management. Management, at best, will be a tugboat that can only nudge a much larger ship in a hopefully useful direction. *Going forward, wildlife conservation policies will need to be based on a clear-eyed assessment of their potential leverage to reach a desired outcome.*

## CONCLUSION

A large fraction of species studied in the context of climate change are showing changes in their distributions or the timing of life history events that are consistent with a warming world (Parmesan 2006). Some natural disturbance regimes like floods and fires seem to be occurring outside historical bounds, in some cases forcing a switch from one biome type to another. Additional warming is anticipated, as are effects on precipitation and other climate variables; hence further biological response seems inevitable.

The NFWPCAS was a Congressionally mandated, collaboratively executed attempt by the U.S. wildlife management community to begin to come to grips with the challenge of climate change.

It identifies seven major goals and numerous strategies and actions that need to be pursued to give wildlife the best chance of coping with the increasing impacts of climate change. Many of its recommendations are focused on, or are related to the need to review current wildlife conservation policies in light of climate change. As the community begins that work in earnest, it confronts serious challenges related to the unique aspects of climate change, including: (1) its uniqueness in human history; (2) the individuality of species responses in periods of change; (3) the speed of the changes projected to come; (4) the challenge of differentiating between invasive species and climate change pioneers; (5) the interaction of climate change with existing stressors; and (6) perhaps most importantly, the disparity in the power of management interventions in the face of the scope and scale of climate's inertia and its impact on living things. The later point serves to underscore the fundamental point that ultimately, climate change adaptation efforts cannot succeed without the curtailment of CO<sub>2</sub> emissions at some level. *In other words, in the long run, there will be no adaptation without mitigation.*

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## Appendix I: Policy-related Strategies & Actions

Strategy	Action
<b>Goal 1: Conserve habitat to support healthy fish, wildlife, and plant populations and ecosystem functions in a changing climate.</b>	
Strategy 1.1: Identify areas for an ecologically-connected network of terrestrial, freshwater, coastal, and marine conservation areas that are likely to be resilient to climate change and to support a broad range of fish, wildlife, and plants under changed conditions.	1.1.5: Re-prioritize conservation targets of existing land and water conservation programs in light of areas identified in 1.1.1 and listed in 1.1.4 and 1.4.2.
Strategy 1.2: Secure appropriate conservation status on areas identified in Action 1.1.1 to complete an ecologically connected network of public and private conservation areas that will be resilient to climate change and support a broad range of species under changed conditions.	1.2.1: Conserve areas identified in Action 1.1.1 that provide high priority habitats under current climate conditions and are likely to be resilient to climate change and/or support a broad array of species in the future. 1.2.2: Conserve areas representing the range of geophysical settings, including various bedrock geology, soils, topography, and projected climate, in order to maximize future biodiversity.
Strategy 1.3: Restore habitat features where necessary and practicable to maintain ecosystem function and resiliency to climate change.	1.3.6: Develop market-based incentives that encourage habitat restoration where appropriate.
Strategy 1.4: Conserve, restore, and as appropriate and practicable, establish new ecological connections among conservation areas to facilitate fish, wildlife, and plant migration, range shifts, and other transitions caused by climate change.	1.4.3: Conserve corridors and transitional habitats between ecosystem types through both traditional and non-traditional (e.g., land exchanges, rolling easements) approaches. 1.4.5: Assess existing physical barriers or structures that impede movement and dispersal within and among habitats to increase natural ecosystem resilience to climate change, and where necessary, consider the redesign or mitigation of these structures. 1.4.6: Provide landowners and stakeholder groups with incentives for conservation and restoration of key corridor habitats through conservation programs such as those under the conservation title of the Farm Bill and landowner tools under the ESA as well as other mechanisms such as conservation easement tax incentive programs designed to protect private lands of high connectivity value under climate change.

<b>Goal 2: Manage species and habitats to protect ecosystem functions and provide sustainable cultural, subsistence, recreational, and commercial use in a changing climate.</b>	
Strategy 2.1: Update current or develop new species, habitat, and land and water management plans, programs and practices to consider climate change and support adaptation.	<p>2.1.1: Incorporate climate change considerations into new and future revisions of species and area management plans (e.g., North American Waterfowl Management Plan, National Forest Plans, State Wildlife Action Plans, and agency-specific climate change adaptation plans such as federal agency adaptation plans required by E.O. 13514) using the best available science regarding projected climate changes and trends, vulnerability and risk assessments, scenario planning, and other appropriate tools as necessary.</p> <p>2.1.3: Identify species and habitats particularly vulnerable to transition under climate change (e.g., wetlands, cool-water to warm-water fisheries, or cool season to warm season grasslands) and develop management strategies and approaches for adaptation.</p>
	<p>2.1.5: Review and revise as necessary existing species and habitat impact avoidance, minimization, mitigation, and compensation standards and develop new standards as necessary to address impacts in a manner that incorporates climate change considerations.</p> <p>2.1.6: Review permitting intervals in light of the scope and pace of climate change impacts.</p> <p>2.1.8: Utilize the principles of ecosystem based management and green infrastructure.</p> <p>2.1.9: Develop strategic protection, retreat, and abandonment plans for areas currently experiencing rapid climate change impacts (e.g., coastline of Alaska and low-lying islands).</p>
Strategy 2.2: Develop and apply species-specific management approaches to address critical climate change impacts where necessary.	2.2.2: Develop criteria and guidelines that foster the appropriate use, and discourage inappropriate use of translocation, assisted relocation, and captive breeding as climate adaptation strategies.
Strategy 2.3: Conserve genetic diversity by protecting diverse populations and genetic material across the full range of species occurrences.	2.3.4: Seed bank, develop, and deploy as appropriate plant materials for restoration that will be resilient in response to climate change.

<b>Goal 3: Enhance capacity for effective management in a changing climate.</b>	
<p>Strategy 3.2: Facilitate a coordinated response to climate change at landscape, regional, national, and international scales across state, federal, and tribal natural resource agencies and private conservation organizations.</p>	<p>3.2.1: Use regional venues, such as LCCs, to collaborate across jurisdictions and develop conservation goals and landscape/ seascape scale plans capable of sustaining fish, wildlife, and plants.</p> <p>3.2.2: Identify and address conflicting management objectives within and among federal, state, and tribal conservation agencies and private landowners, and seek to align policies and approaches wherever possible.</p> <p>3.2.3: Integrate individual agency and state climate change adaptation programs and State Wildlife Action Plans with other regional conservation efforts, such as LCCs, to foster collaboration.</p> <p>3.2.4: Collaborate with tribal governments and native peoples to integrate traditional ecological knowledge and principles into climate adaptation plans and decision-making.</p>
<p>Strategy 3.3: Review existing federal, state and tribal legal, regulatory and policy frameworks that provide the jurisdictional framework for conservation of fish, wildlife, and plants to identify opportunities to improve, where appropriate, their usefulness to address climate change impacts.</p>	<p>3.3.1: Review existing legal, regulatory and policy frameworks that govern protection and restoration of habitats and identify opportunities to incorporate the value of ecosystem services and improve, where appropriate, the utility of these frameworks to address climate change impacts.</p> <p>3.3.2: Review existing legal, regulatory and policy frameworks and identify opportunities to develop or enhance, where appropriate, market-based incentives to support restoration of habitats and ecosystem services impacted by climate change. Identify opportunities to eliminate disincentives to conservation and adaptation.</p> <p>3.3.3: Review existing legal, regulatory and policy frameworks and identify opportunities to improve, where appropriate, compensatory mitigation requirements to account for climate change.</p> <p>3.3.4: Review existing legal, regulatory and policy frameworks that govern floodplain mapping, flood insurance, and flood mitigation and identify opportunities to improve their usefulness to reduce risks and increase adaptation of natural resources and communities in a changing climate.</p> <p>3.3.5: Review existing legal, regulatory and policy tools that provide the jurisdictional framework for conservation of fish, wildlife, and plants to identify existing provisions that provide climate change adaptation benefits.</p> <p>3.3.6: Continue the ongoing work of the Joint State-Federal Task Force on Endangered Species Act Policy to ensure that policies guiding implementation of the ESA provide appropriate flexibility to address climate change impacts on listed fish, wildlife, and plants and to integrate the efforts of federal, state, and tribal agencies to conserve listed species.</p> <p>3.3.7: Initiate a dialogue among all affected interests about opportunities to improve the usefulness of existing legal, regulatory, and policy frameworks to address impacts of sea level rise on coastal habitats.</p>



<p>Strategy 3.4: Optimize use of existing fish, wildlife, and plant conservation funding sources to design, deliver, and evaluate climate adaptation programs.</p>	<p>3.4.1: Prioritize funding for land and water protection programs that incorporate climate change considerations.  3.4.2: Review existing federal, state, and tribal grant programs and revise as necessary to support funding of climate change adaptation and include climate change considerations in the evaluation and ranking process of grant selection and awards.  3.4.3: Collaborate with state and tribal agencies and private conservation partners to sustain authorization and appropriations for the State and Tribal Wildlife Grants Program and include climate change criteria in grant review process.  3.4.4: Collaborate with agricultural interests and businesses to identify potential impacts of climate change on crop production and identify conservation strategies that will maintain or improve ecosystem services through programs under the conservation title of the Farm Bill or other vehicles.  3.4.5: Review existing conservation related federal grants to tribal agencies and revise as necessary to provide funding for tribal climate adaptation activities.  3.4.6: Develop a web-based clearinghouse of funding opportunities available to support climate adaptation efforts.</p>
<p><b>Goal 4: Support adaptive management in a changing climate through integrated observation and monitoring and use of decision support tools.</b></p>	
<p>Strategy 4.1: Support, coordinate, and where necessary develop distributed but integrated inventory, monitoring, observation, and information systems at multiple scales to detect and describe climate impacts on fish, wildlife, plants, and ecosystems.</p>	<p>4.1.4: Expand and develop as necessary a network of sentinel sites (e.g., tribal lands, National Estuarine Research Reserves, and National Wildlife Refuges) for integrated climate change inventory, monitoring, research, and education.  4.1.8: Promote a collaborative approach to acquire, process, archive, and disseminate essential geospatial and satellite-based remote sensing data products (e.g., snow cover, green-up, surface water, wetlands) needed for regional-scale monitoring and land management.</p>

<b>Goal 7: Reduce non-climate stressors to help fish, wildlife, plants, and ecosystems adapt to a changing climate.</b>	
Strategy 7.1: Slow and reverse habitat loss and fragmentation.	<p>7.1.3: Provide landowners with appropriate incentives for conservation and restoration of key habitats, such as conservation easement tax incentive programs, designed to protect private lands of high habitat connectivity value under climate change.</p> <p>7.1.6: Consider application of offsite habitat banking linked to climate change habitat priorities as a tool to compensate for unavoidable onsite impacts and to promote habitat conservation or restoration in desirable locations.</p> <p>7.1.7: Consider market-based incentives that encourage conservation and restoration of ecosystems for the full range of ecosystem services including carbon storage.</p> <p>7.1.8: Minimize impacts from alternative energy development by focusing siting options on already disturbed or degraded areas.</p>
Strategy 7.2: Slow, mitigate, and reverse where feasible ecosystem degradation from anthropogenic sources through land/ocean- use planning, water resource planning, pollution abatement, and the implementation of best management practices.	<p>7.2.1: Work with local and regional land-use, water resource, and coastal and marine spatial planners to identify potentially conflicting needs and opportunities to minimize ecosystem degradation resulting from development and land and water use.</p> <p>7.2.8: Reduce ground and surface water withdrawals in areas experiencing drought and/or increased evapotranspiration.</p> <p>7.2.9: Promote water conservation, reduce water use, and promote increased water quality via proper waste disposal.</p> <p>7.2.11: Incorporate the recommendations and actions from the <i>National Action Plan for Managing Freshwater Resources in a Changing Climate</i> into water resource planning.</p>
Strategy 7.4: Reduce destructive capture practices (e.g., fisheries bycatch, destructive fishing gear), over-harvesting and illegal trade to help increase fish, wildlife, and plant adaptation.	7.4.5: Increase efforts to monitor and reduce illegal species trade in the United States.

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This paper received peer technical review. The content of the paper reflects the views of the authors, who are responsible for the facts and accuracy of the information herein.



# Evolving Institutional and Policy Frameworks to Support Adaptation Strategies

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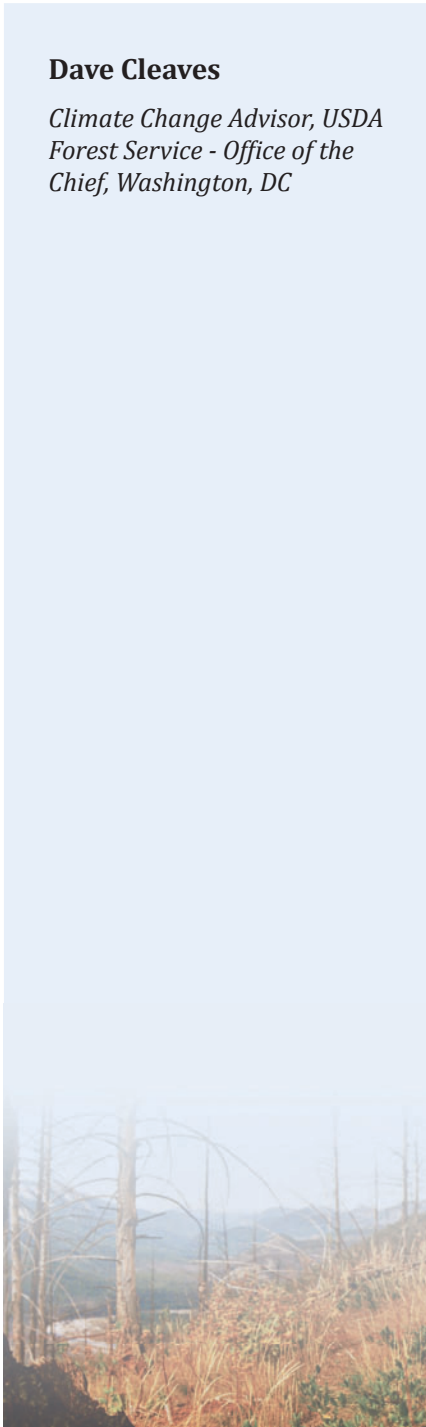
***Abstract:** Given the consequences and opportunities of the Anthropocene, what is our underlying theory or vision of successful adaptation? This essay discusses the building blocks of this theory, and how will we translate this theory into guiding principles for management and policy.*

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## INTRODUCTION

Gifford Pinchot in 1911 defined conservation as “the application of common sense to the common problems for the common good”. To reach this ideal in the future, we will have to adapt approaches we take in resource management. The new normal is that there is no normal. The challenge will be more about how we go about the adaptation process than about particular adaptation measures or adjustments. Finding common sense, defining common problems and the common good will become an intense and dynamic engagement.

As systems change and human influences become even more pervasive, the roles of leadership in aligning policies and institutions and helping change human behavior will become more critical. Without some guiding framework, we will be always in motion, like the mythical ghost ship Flying Dutchman doomed to sail forever, never able to make port. We need a working theory as a shared framework for learning as we gain experience and scientific discovery. Without such a framework, we can fail to recognize events as lessons. A working theory should embody notions of success—how we should characterize and measure progress, set goals, and reshape pathways of change. It should also promote flexibility and itself be adaptable, not a source of new dogma. It should help to codify the advances that are occurring as managers and landowners experiment and struggle with changes already impacting them. It should include the seeds of its own adjustments, allowing the working theory to catch



up with practice and innovation as well as scientific advances, or we risk defaulting to a passive or reactive model of adaptation, defining uncertainties always as downside risks and scrambling to minimize losses without seeing opportunities and lessons that change sends our way.

## **DIMENSIONS OF A WORKING THEORY FOR ADAPTATION**

The building blocks of such a theory include (1) climate-smart decision making, (2) active management and adjustment, (3) public engagement and expectations discovery, and (4) landscape-scale conservation.

### ***Climate-smart decision making***

We have few actual “climate change” decisions to make. We have thousands of land management decisions that influence and are influenced by the changing climate. Our decision processes can be made more adaptive to climatic and other changes. The Forest Service uses the following principles of climate “smartness” to refine its decision processes:

- match analysis detail to the level of climate-sensitivity;
- test expected outcomes of alternatives in multiple, plausible futures (scenarios);
- use information about relative vulnerability to stressors (climate and non-climate together) in designing and choosing alternatives and ranking actions;
- challenge traditional assumptions about future change;
- build in flexibility and adaptive responses; and
- consider carbon and GHG implications; compare and display the nature and levels of uncertainties.

### ***Active management and adjustment***

In a world put in motion all around us by human/ecosystem interactions, can we really steer anything if we are not actively involved? Hope is a necessary but insufficient component of proactive adaptation. We cannot just pause for an adaptation break with a sign—“Do Not Disturb: The System is Adapting”. Human elements are already at work. We have to understand them and try to work with them in all systems in the Anthropocene. Trying to keep human activity out of systems in the name of resilience won’t work. Building human activity into the concept of resilience, as a necessary function rather than an external force to turn up or down, can contribute to the resilience of whole system. The concept of sustainability is often perceived as the triple bottom line—what we want out of systems in ecological, economic, and social terms. But the concept can also be used to visualize these dimensions as three components of every adaptive adjustment.

Coupled human/natural systems comprise a mosaic of adaptation opportunities. The nation’s forests for example offer gradations from rural to urban, from “working” to “protected”, and all in various frames of response to climate impacts. Our working theory should call for more deliberate approach to human actions, favoring those that (1) avoid waiting for “complete” science that never arrives, (2) boost learning by blending science and experience, (3) create “controlled”

disturbances to reduce irreversible costs and losses of inevitable disturbance episodes, (4) respond to stressor complexes—climate and non-climate rather than single hazards, and (5) buy lead time and reduce panic responses.

### ***Public expectations***

Our theory must guide us in helping prepare citizens to deal with change and to share in adaptation. This will involve defining resilience of the human/system interface and the role of citizens, integrating the science of human behavior and social systems, communicating transitional issues, and recovering from more frequent and intense events. We may have to work with citizens to more strongly infuse dynamics into the concept of sustainability, and institute terms such as “desired futures” to replace the notion of a single desired future condition.

We may have to revisit and rewrite social contracts to better wrestle with new realities of change. We must confront the public’s underlying expectations of institutions and policies to provide surety in an increasingly uncertain world. These expectations are embedded in our policies in words that derive from the Latin “se-cure” or “without care”. For example:

- Assure—remove doubt or anxiety, create confidence
- Ensure—guarantee an event or condition will happen, implement and create reliability
- Insure—compensate for liability, create recourse
- Secure—take possession, create ownership

The cumulative effect of so many policies, prohibitions, and checks in the name of assuring some particular condition should be a major topic of policy analysis. How does it influence our ability to try different approaches or adjust to changes? We cannot yet say.

### ***Landscape-scale conservation***

Landscape scale conservation as an overarching approach to adaptation begs to be defined, refined, and pressed into service. It has a solid ecological background, but is less well codified or appreciated as a business and social change approach to place-based adaptation. Landscape-scale conservation relies on concepts and skills of collaboration, sustainable resource management, climate adaptation, and risk management. It means using the scalability of the landscape itself to employ a range of risk management mechanisms that include, but not necessarily limited to: spreading out exposures to moderate systemic risks; balancing diversity with the scales of operations needed for economic activity, regeneration success, habitat connectivity, and others; planned redundancy and preservation of multiple adaptive options; reserves from which to cushion shocks, restart regeneration, resist invasion; and building cushions for experimentation with emerging novel systems.

Our working theory will have to fully integrate landscape conservation as an orchestration mechanism to deploy collaboration, analysis, and social engineering to manage multiple, interacting hazards. In landscape scale approaches to adaptation, the social, economic, and institutional elements can become parts of the “baseline” and the system’s adaptive capacity. Different institutional arrangements in landscape scale collaborations influence important abilities to think, innovate, predict, anticipate, collaborate, and self-regulate.

## CHANGING THE POLICY “FABRIC” IN THE ANTHROPOCENE

A wide variety of policies—environmental, land use, economic and taxation, estate, and others at federal, state, local, and organizational levels all interact to influence the decisions of land owners and managers. As a body, they shape problem frames, goals, information availability, options, analysis requirements, risk postures, and other elements of adaptation decision processes. They also introduce their own sources of uncertainty and barriers to the processes of adaptation. These various policies may not be aligned to support adaptation, sending mixed or conflicting signals to land managers. They may be aligned all too well in the wrong direction, limiting flexibility for adaptive responses, presenting structural barriers and imposing transaction costs that discourage responses to new information or experience. There is no magic policy pill, but can we adapt our policy mix to encourage adaptive behavior? What blend of existing and new policies could best support a future of adaptive challenge and response?

Sorely needed is a cohesive policy package and framework organized around active management. It should integrate climate change mitigation goals (management of the forest carbon) with adaptive responses to climate impacts. Active forest conservation, restoration and management are critical interventions in preserving and improving the ability of forests to uptake carbon, adapt to a changing climate, and provide associated ecosystem services such as water, wood products, wildlife habitat, biodiversity, and recreational opportunities.

A policy framework to support proactive adaption in forest systems could be built on three archetypal actions—*retention*, *restoration*, and *reforestation*. Retention involves keeping forest as forests in face of disturbance and land use pressures. Restoration involves repair and recovery of health to key system functions. Reforestation includes bringing new or returning forest systems to unforested land or forests degraded by abuse or disturbance.

Policies and initiatives to support these actions should focus on developing *markets* for ecosystem services, wood products, and carbon sequestration; facilitating public/private *partnerships*, establishing *principles* (rather than rules) for adaptive response, and setting *priorities* for treatment based on science-based observation and analysis.

Markets enable action through economic activity by provide better information and assistance, reduce transaction costs and gridlock, and reallocate cost and risk-bearing. Partnerships tap into new sources of investment and human resources and assure diversity of perspective. Policies should support a diverse array of different types of partnerships, including research/management, public/private, interagency, landscape coalition, and supply chain partnerships.

Changes to the policy mix should be formed more around principles rather than around new rules, which tend to become rigid and expensive to monitor and enforce. These principles would reduce the influence of the “precautionary principle” and its “if in doubt, don’t” interpretation in favor of a more realistic “cautionary action” principle. The focus would be on monitoring and analysis at appropriate scales across a wide range of actions.

In an age in which all systems are being influenced by humans through the changing climate, the “no-action” option should not be the universal standard. At a large enough spatial and temporal scale and under the ubiquitous influence of humans, there is really no such thing as “no-action”.

We should reframe problems to allow collaborative retreat from the old battlegrounds of “action vs. no-action”. We need instead to create policies to give future decision makers the capacity to adapt across a range of interventions. These policies should promote neither “no-action” nor “action-for-action’s sake”. We must focus precious energy on how to wisely implement pro-active management, create incentives for looking ahead, and wrestle with surprise and unintended consequence.

Some of the best thinking on policy and institutional change has been captured in the Resources for the Future report series “ Reforming Institutions and Managing Extremes—U.S. Policy Approaches for Adapting to a Changing Climate (Morris et al. 2011). The authors described how effectiveness for the future could be enhanced with the following:

- Provide specific guidance for federal rulemaking.
- Create connections and synergy with other policy areas.
- Address inefficiencies in current federal legislative and regulatory policy.
- Supply information and data to enable policy makes to better understand risk and uncertainty.
- Embed flexibility and responsiveness into management structures.
- Address equity and social justice concerns.

I cannot begin to address the policy needs at the level presented in this and other scholarly and penetrating investigations. However, we can start to develop a list of preparations for adaptation policy.

### ***Aligning Institutions to Support and Build Adaptive Capacity***

Do institutions have resilience? Do they create resilience? Are some institutions too resilient or perhaps too rigid for the good of the systems they were designed to shepherd? Resilience is the ability of a social-ecological system to reorganize and retain necessary functions in the face of change and disturbance. Adaptive capacity is the ability of an individual, organization, or social-ecological system to adjust to changes, to moderate potential damages, to take advantage of opportunities, and to cope with consequences. In other words, adaptive capacity is the ability to manage or influence resilience. Institutional resiliency is the ability to self-organize and adjust not only to *uncertainty*, but also to other manifestations of a changing climate—increased *complexity and conflict*.

Adaptive capacity derives from assets and resources (such as knowledge, networks, human capital) and governance mechanisms that enable the mobilization of resources to transform and adapt. Intangible attributes and behaviors are also critical capacities, including learning to live with change and uncertainty, nurturing diversity for resilience, combining different types of knowledge for learning, creating opportunity for self-organization towards sustainability, and alertness to patterns of change, especially those that challenge the underlying assumptions that drive current strategies and programs (Berkes et al. 2003).

It may be useful, if perhaps painful, to reflect on elements of our institutional approaches and structure and how they are performing as the demands for adaption grow. Authoritarian approaches are giving way to more self-organized arrangements that tap into local leadership and



attachments to places. The newer institutional arrangements are more like evolving institutional ecosystems, and the roles of government agencies in these evolving structures are changing from authority and intervention to providing services and enabling self-organized solutions. It may be helpful in this period of institutional readjustment to consider what Elinor Ostrom (1993) and other social scientists have referred to as principles of institutional design. Ostrom's list of principles are organized around user participation in setting boundaries for use, equalizing costs and benefits, making collective choices about operating policies, monitoring and enforcement through graduated sanctions, resolving conflicts, and nesting work efforts. These insights might help us better deliver government services to support self-organized adaptation and resilience building.

New institutional forms include (1) large scale, place-based, citizen-led collaborations, (2) forms of ownership and management such as land trusts, community forests, non-governmental owners, private timber investment and management and real estate investment trusts (TIMO's and REIT's), and (3) government configurations focusing on delivering actionable science such as USGS's Climate Science Centers, USDA's climate adaptation and mitigation hubs, NOAA's Regional Integrated Science and Assessment Centers (RISA's); or convening stakeholders and science providers toward adaptation action, the most prominent being DOI-Fish and Wildlife Service's Landscape Conservation Cooperative (LCC) system. These new players are nestling into regional and landscape level adaptation efforts, interacting with traditional institutional players. Existing institutions can be part of this evolution by removing lingering barriers to collaborative adaptation efforts. Areas of improvement are discussed below.

### **Coordination**

Adapting to change is energy-intensive. Land owners and managers cannot afford to waste energy sorting through confusing arrays of information, programs, and processes. More information, well-intentioned as it is, can still create high transaction costs for people making adaptive adjustments. Organizations that provide adaptation services—information, technical, financial, and others—need to work toward “one-stop shopping” by organizing their multiple programs into packages that can be easily used and customized to local needs. This is the aim of the 7 new USDA Climate Change Hubs—virtual networks of USDA agencies to coordinate regional delivery of risk management information and services.

### **Boundary management**

The limitations of “silo” functional structures are becoming more evident. Not only do dwindling financial resources make it less feasible to maintain internal “empires”, the inefficiencies of communicating across boundaries and the needs for rapid integration and flexibility by managers are combining to pressure organizations to dissolve functional boundaries.

One of the most pernicious boundary-based barriers to adaptation is found in budget structures. The ability to blend different sources of funds to accomplish adaptation objectives is becoming more critical, despite pressures to account for every dollar in its narrow program category. Adaptation-friendly budget structures include the Forest Service's new Integrated Resource Restoration (IRR) fund that combines 7 separate program budget lines, and the Collaborative Forest Restoration Program (CFLRP) which funds large scale projects with multiple budget codes.

## **Risk management**

Adaptation involves the need to deliberately consider multiple risks, develop options for managing them, and wrestle with the difficult decisions of who should pay. Institutions need to develop skill sets for diagnosing patterns of risk and intervening in the most cost-effective ways. Many individual stressors are actually linked through system functions and processes as well as their common ties to the changing climate, so it is becoming more important to understand and manage systemic or connected risks. Tradeoffs and costs to be incurred at the scale of these risk complexes may demand different decision skills and tools than we have relied on to independently manage each stressor. It may also require institutional adjustments that support more sophisticated and explicit ways to approach complex risks.

Risk behavior is already woven into our institutional fabric. Many government and private sector institutions are founded to transfer risk-bearing from one party to another. But how do these institutional arrangements act as a barrier to adaption by shielding us from the consequences of our actions? How long will these institutions (e.g., subsidized insurance) hold up under the changing patterns of intense events? Risk-based thinking should drive us to reconsider our own behavior in the face of a changing risk context.

## **Knowledge management**

Approaches and technologies for creating, sharing, and applying knowledge are being transformed. New social and institutional structures for exchanging information have so rapidly developed, that institutional assumptions about how people access and use information to make adaptation decisions may be outdated. Communities of practice, such as The Nature Conservancy's fire learning network, may become the knowledge management institutions of the future. More scientific organizations are using "crowd-sourcing" methods that expand their reach to diverse investigations and that may involve citizens in providing data. These represent new sources of knowledge that are less dependent on "go-to" agencies and "official information", and more oriented to blending knowledge of different types, sources, and vintages. They combine collaborative learning with the powers of social media to give place-based meaning to information as it emerges. We may have to find new ways to nourish these networks with actionable science and lessons gleaned from adaptive management.

Our worries about the effectiveness of technology transfer and the health of the science/management interface are now part of a bigger question of how institutions participate in the relationships and networks that manage knowledge. Can the research community provide tools and platforms with which managers can investigate their own hunches, and blend their tacit knowledge with broader scientific findings? How can we better involve practitioners and citizens in the development of the science base? These and other new questions have emerged in the Anthropocene.

## **Performance management**

Adaptive actions and programs will be increasingly scrutinized for effectiveness and efficiency. They will have to compete rigorously with other uses of public and private capital. Measures of resilience and adaptive capacity are now being brought into some agency budget discussions, a good start. We must be able to articulate, quantify, and realize returns on investment. Adaptation

investments must (1) frame both future positioning and ecosystem outcomes as returns on investment, (2) distinguish among inputs, outputs, outcomes, and range of future options in “value chains”, (3) estimate the true costs of conservation practices, including the benefits and costs of collaboration, and (4) establish performance measures that are meaningful to the individuals and organizations who would work together to make the adaptation successful.

The challenges of measurement and program evaluation will no doubt stimulate a lot a creative thinking about the business of adaptation in the new few years. How do we incorporate attributes of adaptive capacity such as flexibility, social license, preservation of options, learning, and scalability along with measures of ecosystem outcomes into measures and program goals? How do we track the cycle of moving science into action and back, or the cycle of learning from field experience to adjustments in practice? Measuring only parts of the science application and learning cycles fails to provide the whole performance story.

The U.S. Forest Service has since 2011 been using a balanced scorecard approach to measure progress in incorporating climate change into sustainable forest management programs and practices. The FS Climate Change Scorecard is comprised of performance hurdles and guidance in four dimensions: (1) organizational capacity; (2) partnerships, engagement and education; (3) adaptation; and (4) mitigation and sustainable consumption. Each of the 155 National Forests and 20 National Grasslands complete the scorecard report annually. A national network of 130 collateral duty climate change coordinators evaluate the utility and the insights provided and exchange lessons learned to improve the state of climate response practice. Three years of measurement and narrative reports are providing a clearer and more useful picture of what is needed to make adaptation to climate successful.

### **Leadership in the Anthropocene**

As waves of baby boomer retirements and agency downsizing meet, organizations are undergoing important changes in their workforce—capacity reductions, losses in experience, and rapid repopulation of leadership ranks. This is a great opportunity to adjust leadership development and rewards to support adaptive decision making. We need transformational leadership that can help an increasingly diverse citizenry through ill-structured problems and uncertainty, and to take actions that improve learning. This leadership will help people confront their own expectations and wrestle with situations where the changing climate and their own responses can lead to unexpected losses and gains. It is a form of leadership ideally as a ubiquitous quality of the workforce and partners themselves, as practiced by all employees, not an exclusive set of titular leaders in hierarchical structures. What knowledge, skills, and attitudes should we promote in this new “gene pool” of leadership?

### **Managing change**

Leaders of adaptation will have to be experts in managing organizational and social change. They will have to turn big ships (institutions) more sharply than they were designed to turn, and challenge organizational, political, and others barriers to flexibility. Communication and engagement skills will become more critical in helping stakeholders become partners, wrestle with issues of risk transfer, and adopt new behaviors for living “up close and personal” with extreme events. Communication will need to evolve beyond media talking points into true engagement,

and toward better understanding of how people respond to risk and how to avoid “pseudo-certainty” in a rapidly changing world.

Leaders of the future will have to understand the science of decision making, as well as the science of ecosystems. They must deal with human judgment in the myriad functions and decision processes of land management, and be able to adjust decision process to improve learning and respond to new information. We are the benefactors of major advances in behavioral economics and decision science and an evolution in decision practices in many fields. New models are emerging that involve clear shifts in decision processes: choosing robust rather than optimal solutions; from single decision maker to consensus choices; from reliance on published science to wider varieties of evidence; from solving problems to coping with conditions; from information-starvation to information overload; from averages to extremes.

### **Risk-based thinking and dealing with extreme events**

Extreme events can create social and organizational chaos, divert resources (e.g., witness the wildfire issue) and attract political scrutiny and reputational risk. These events are no longer rare. Our landscapes are being shaped by both climate and human-driven disturbance and it seems that we should learn how to recover from or use the disturbance to create more resilient conditions rather than just be “clean up” the damage. We can continue to view extreme events as “natural” disasters even though we know that damages emanate from exposure caused by human choices. But we can also view them as punctuation marks in the bigger narrative of unrelenting change. They can be teachable moments and political opportunities to nudge the process of organizational learning and change.

Leadership will do well to emphasize opportunism, flexibility, and recovery after these events. Can we use these “unscheduled” disturbances to guide larger scale adaptive transitions? How nimble are we in jumping expected cycles of ecological succession into new ecosystem states? We may have to rethink our translations of management “control” theory from business and the factory floor to the management of increasingly dynamic ecosystems. We need new landscape scale science, as well as new theories of management under turbulence, to guide our quest for resilience.

### **Foresight skills—dealing with alternative futures**

Theodore Roosevelt said, “In utilizing and conserving the natural resources of the Nation, the one characteristic more essential than any other is foresight ...”.

Adaptive capacity includes developing foresight to understand key uncertainties and identify emerging issues, deal better with surprise, anticipate unintended consequences, decrease reaction time to rapid change, clarify multiple external perspectives about trends and plausible futures, and shape preferred futures and future pathways (Bengston et al. 2012).

Leaders must create the organizational space and appreciation for exploring alternative futures. This includes insight from projections, models, scenarios, futuring exercises, and expert judgment, while maintaining balance between these sources of information and history, experimentation, and other forms of evidence. Foresight does not mean obsessing over forecasts. The

current yearning for finer resolution climate model projections is understandable, but must be tempered lest it grow into illusions of precision, excuses for inaction, or anchoring choices to individual forecasts. A keen understanding of the craft of foresight development and the caveats of using forecast information and managing cognitive biases must be built into our leadership skill bank.

### Leading inquiry about the roots of resilience

We search for new implications and recommendations in each new study or report from the field. Our emphasis on uncertainty, new discoveries, and new tools may at times divert us from fully using what we already know about systems and their adaptive mechanisms. It may be time to relearn from some of the “old” science in light of the adaptation challenges ahead. There may be fewer secrets to be found than there are principles and basic understanding to be applied to new situations. Are there roots of resiliency hiding in plain sight in these classic studies and science findings? We may have to reinterpret what we think we know with an adaptative “going forward” perspective. Leadership can sanction and direct this reflection with appropriate questions. What problems were the scientists who created this knowledge responding to? What did they observe about climate-forest interactions that could guide our expectations about possible futures? What about this information might be relevant to vulnerability and resilience issues being surfaced today?

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# Climate Change: Wilderness's Greatest Challenge

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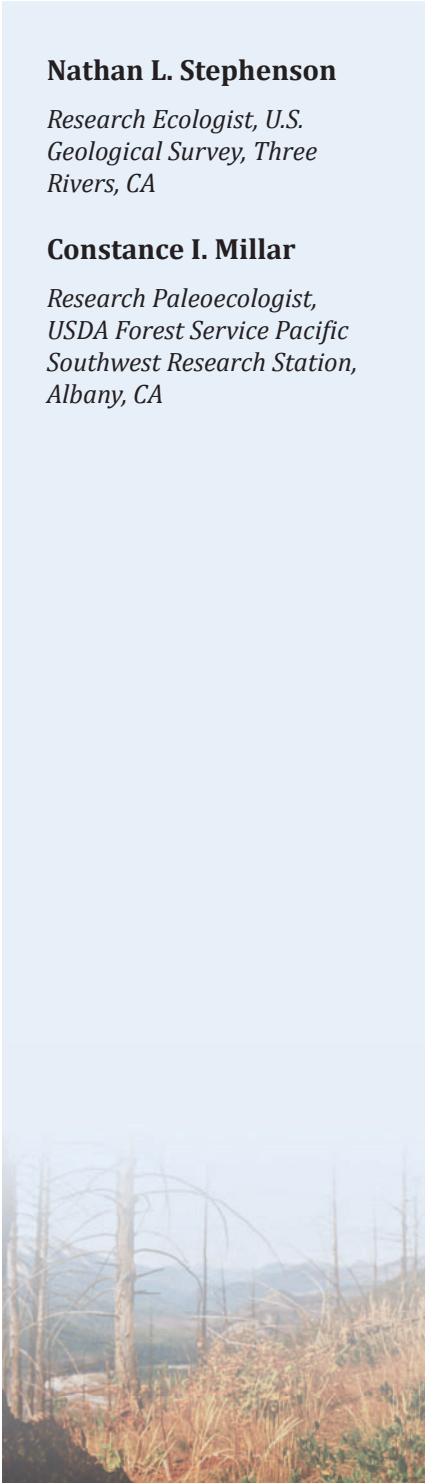
***Abstract:** Anthropogenic climatic change can no longer be considered an abstract possibility. It is here, its effects are already evident, and changes are expected to accelerate in coming decades, profoundly altering wilderness ecosystems. At the most fundamental level, wilderness stewards will increasingly be confronted with a trade-off between untrammelled wilderness character and primeval, natural conditions, accompanied by increasing impetus for management intervention. Possible strategic responses to climatic change fall into four broad classes: restraint (do nothing), resilience, resistance (near-term ways of buying time), and realignment (long-term adaptation). Planning responses will be made challenging by the unprecedented and unpredictable nature of future changes; fortunately, robust planning approaches, like scenario planning, are available.*

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## **INTRODUCTION**

Some 20,000 years ago, the area that we now know as the Marjory Stoneman Douglas Wilderness in Everglades National Park (Florida) was not graced by the sprawling “river of grass,” dense mangrove forests, and the rich waters of the Florida Bay. With a sizable amount of Earth’s water locked up in continental ice caps, the present bay was high and dry, the nearest ocean shore was miles away, and the land supported pine woodlands and scrub. On the other side of the continent, the parched salt flats of today’s Death Valley Wilderness (California) were drowned under a 600-foot-deep (183 m) lake. The Yosemite Wilderness’s (California) stately forests, lush meadows, and high mountain lakes were buried under hundreds of feet of ice.

What a difference a few degrees can make! The dramatic changes described in the preceding paragraph accompanied a Pleistocene-to-the-present global warming of about 4° to 7°C (Jansen and others 2007). Yet Earth is now poised to undergo another round of warming of comparable magnitude. Current projections indicate that a further 4° to 6°C global warming could be reached by as early as the end of this century (IPCC 2007), when



global temperatures could exceed any reached in the last several million years. Earth has already gained about 0.6°C since 1975, and the pace of warming is expected to accelerate. Even the relatively modest warming so far has affected hydrology, fire regimes, and biota in national parks and wildernesses (Gonzalez 2011). The message is clear: In the coming decades wilderness seems certain to face its greatest stewardship challenge yet, in the form of profound climatic and other global changes.

Wilderness stewards must determine how best to respond to this greatest of challenges, and the goal of this article is to help them by offering relevant ideas and provoking discussion. First, we briefly reexamine the Wilderness Act in the light of rapid climatic changes, and conclude that stewards will be forced to confront trade-offs that were not anticipated by the act's authors—trade-offs that will be accompanied by increasing impetus for management intervention in wilderness. Next, we briefly outline four broad classes of management actions (or inaction) that wilderness stewards might consider in their efforts to adapt to a rapidly changing climate. Finally, we highlight some considerations for planning in the face of rapid climatic changes.

## THE WILDERNESS ACT IN THE ERA OF RAPID CLIMATIC CHANGES

The Wilderness Act of 1964 famously defines the idealized concept of wilderness as an area where Earth and its community of life are “untrammeled by man,” with “untrammeled” meaning unrestrained, self-willed, and allowed to run free (Landres and others 2008). However, the authors' careful choice of the term “untrammeled” was underlain by a critical assumption: that for generations to come Earth's environment would be inherently stable within its historically observed bounds of variation. The dominant thinking of the era had not yet awakened to the onset of rapid, human-induced, boundary-transcending global changes. The term “untrammeled” in the act thus primarily referred to an absence of *intentional* human influences, as was neatly encapsulated by one of the authors' pleas that humans act as “guardians not gardeners” of wilderness (Zahniser 1963).

If untrammeled was meant to refer to an absence of intentional human influences, what are we to make of pervasive *unintentional* human influences, like anthropogenic climatic change? Imagine the following scenario—the sort of scenario that seems likely to play out with increasing frequency in the future:

With rising temperatures and earlier snowmelt, a forested wilderness experiences a massive crown fire well outside of the range of historical fire behavior. Most of the local seed sources are killed, and subsequent rains cause extensive erosion. Rising temperatures and soil loss preclude the reestablishment of continuous forest cover, and the wilderness is colonized by shrubs and an array of nonnative invasive grasses and forbs adapted to disturbed sites.

This wilderness remains untrammeled in the sense that its new condition is not a consequence of intentional human influences. But does it remain untrammeled simply because the massive changes ultimately were the consequence of unintentional human influences (anthropogenic climatic changes and introductions of nonnative invasive species)? If, in an alternative scenario, wilderness managers had intentionally thinned the forest, enabling it to survive the fire relatively intact, would the resulting forest have less wilderness character than the eroded shrubland of the first scenario?

These sorts of questions are not new (e.g., Sydoriak and others 2000), and we will never know how the framers of the Wilderness Act would have addressed them. But hints are embedded in the second sentence of the act's definition of wilderness, which was intended to provide a more pragmatic definition of wilderness areas (Scott 2002): areas that retain their "primeval character and influence" and that are "protected and managed so as to preserve [their] natural conditions." The terms "primeval" and "natural" usually carry a sense of historical fidelity—conditions that fall within the bounds that occurred in the centuries preceding the influences of modern technological society. At the time of the act's passage it would have been normal to assume that a protected (untrammelled) landscape would necessarily express a high degree of historical fidelity, so the two ideas usually were conflated. We now know this assumption is false, and we must explicitly consider the relationship between untrammelled quality and historical fidelity (e.g., Aplet and Cole 2010).

In the future, trade-offs between these two strongly defining characteristics of wilderness—untrammelled quality and historical fidelity (primeval and natural character—will be inevitable. Climatic and other global changes will increasingly act to erode historical fidelity, as in the forest scenario presented above. But any efforts to maintain critical and sometimes legally protected aspects of historical fidelity—such as native biodiversity and key ecosystem functions like hydrologic regulation—will require increasing management intervention (trammeling). When this trade-off is assessed in light of rapidly accelerating global changes, it seems inevitable that reasons to intervene in wilderness will increase through time.

### ***Classes of actions to consider***

Appropriate management actions in anticipation of (or in response to) rapid climatic changes will vary widely among wilderness areas, and in many cases will need to be founded on careful, site-specific thought and research, well beyond the scope of this article. However, it is useful to think of the spectrum of possible management actions as falling into four broad classes that include the more familiar "three Rs"—resilience, resistance, and realignment (Millar and others 2007)—plus a "fourth R" that is particularly relevant to wilderness—restraint. We begin with restraint.

#### ***Restraint (leave some places alone)***

For reasons well articulated by Landres (2010) and others, wilderness stewards usually should be (and usually are) very wary about intervening in wilderness. Yet for other well-articulated reasons, management interventions do occur in wilderness (Sydoriak and others 2000; Cole and others 2008), and expected climatic changes seem sure to increase the impetus to intervene. Yet even if managers decide they have good reason to intervene in a particular wilderness, the realities of limited staffing, funds, and access will usually mean that interventions can occur only in relatively small, strategically chosen parts of a wilderness landscape, focused on resources of particularly high value and vulnerability (such as a popular grove of giant sequoias or an endangered species). Thus, by default, large parts of the landscape will remain untrammelled, in the strict sense of lacking intentional human influences. In those rare cases when managers might have the ability to affect every part of a wilderness landscape, strong consideration should be given to restraint—selecting certain areas in which no interventions will occur (Landres 2010). The remaining "three Rs," described below, therefore will



usually apply only to limited, high-value parts of a wilderness that are strategically selected for intervention. The first two classes of actions, resilience and resistance, are perhaps best considered as near-term actions.

### **Resilience (enhance ecosystem resilience)**

Resilience is an ecosystem's ability to absorb a stress without flipping into an entirely new state, such as from forest to eroded shrubland. Of all possible near-term actions wilderness stewards can take, maintaining or increasing resilience is one of the most important. Resilience should not be viewed as an end in itself. Rather, it is a means of buying time while (1) wilderness stewards, policymakers, and the public more carefully assess the policy and management implications of climatic changes for wilderness, and (2) wilderness stewards and researchers develop and test possible long-term adaptive responses. Actions that maintain or increase resilience might include, for example, strategically controlling selected nonnative invasive species and thinning forests.

### **Resistance (resist changes)**

Resistance can be a property of an ecosystem itself, but here we use it to refer to management actions designed to resist change (e.g., Millar and others 2007). Like enhancing ecosystem resilience, in the near term resistance can provide a critical means of buying time. Resistance might include intensive actions taken to protect an endangered species, such as creating fuel breaks to diminish the probability of severe wildfire, controlling a tree-killing beetle outbreak, or keeping an endangered plant population healthy by drip irrigation.

In the long term, climatic changes are likely to be so large that most strategies focusing only on resilience and resistance eventually will fail, perhaps catastrophically. But the value of a near-term focus on resilience and resistance is that it can buy us valuable time while we seek long-term strategies for the final R, realignment.

### **Realignment (facilitate changes)**

In the long term, maintenance of native biodiversity and key ecosystem functions into the future may be most successful if wilderness stewards actively facilitate change. A few examples illustrate facilitation. If a species is unable to migrate fast enough to keep up with geographic shifts in suitable habitat, physically moving the species—assisted migration—might sometimes be appropriate, especially if the alternative is losing the species entirely. Following a major disturbance, it may be appropriate to plant an area with species better adapted to warmer conditions. Finally, adaptive potential of some species might be increased by purposefully mixing genotypes from other regions. Of course, any one of these actions would demand deep forethought and extreme caution, and depending on site-specific context might be rejected as undesirable.

### ***Planning considerations***

Implementation of any of these classes of strategic management actions must be preceded by careful planning, but planning for a changing climate presents some unique challenges. We offer the following ideas for consideration.

### *The past may no longer provide a useful target for the future*

The profound Pleistocene-to-the-present landscape transitions described earlier give us a feel for the magnitude of changes wilderness could face by the end of this century. Wilderness will also be affected by an array of other novel anthropogenic global changes, such as pollution, altered disturbance regimes, habitat fragmentation, and nonnative invasive species. Collectively, these changes mean that our world has entered an era in which keystone environmental drivers—those that define the possible range of characteristics of a wilderness area—simply have no analog in the past, no matter how distantly we look (Saxon and others 2005; Stephenson and others 2010). An important consequence is that historical wilderness conditions will no longer automatically provide a useful target for restoring or maintaining wilderness ecosystems (Millar and others 2007; Stephenson and others 2010). While wilderness stewards will almost certainly want to maintain certain broad aspects of historical fidelity (such as native biodiversity and key ecosystem functions), attempts to maintain precise historical fidelity will almost certainly need to be abandoned.

### *Familiar planning approaches may become ineffective*

At the scales, accuracy, and precision most useful to wilderness stewards, the future promises to be not only unprecedented but also unpredictable. Model projections can help us envision the possible nature and magnitude of future landscape changes, but such projections carry large uncertainties and therefore cannot be used as precise predictions (Stephenson and others 2010). A corollary is that surprises are inevitable. A critically important class of surprises is threshold events, in which gradual environmental changes eventually trigger sudden, dramatic, and sometimes irreversible changes in ecosystem conditions (Scheffer and Carpenter 2003); for example, in parts of western North America gradual warming has contributed to sudden and extensive outbreaks of bark beetles, killing large swaths of forest. A consequence of uncertainty is that familiar planning approaches, which usually assume we either know the future or can accurately predict it, are likely to become ineffective (Weeks and others 2011).

### *Use planning approaches that consider a broad array of possible futures*

In the face of such uncertainty, the most useful planning approaches may be those that seek to identify management actions that are likely to succeed under a broad array of possible future conditions. Such approaches include scenario planning and its relatives (Nydick and Sydoriak 2011; Weeks and others 2011). All planning efforts will likely benefit from considering scenarios that include abrupt threshold changes.

### *Define undesired future conditions*

Another consequence of the unprecedented and unpredictable future is that the familiar planning approach of defining relatively precise desired future conditions is likely to become less effective. Instead, planning efforts might benefit from including explicit definitions of undesired future conditions—conditions to be avoided. For example, undesired future conditions might include loss of native biodiversity or critical ecosystem functions. A broad array of future wilderness conditions might be deemed acceptable as long as they do not fall within the undesired future conditions.

### *Plan appropriate responses before abrupt changes occur*

Sudden threshold changes can effectively denude large portions of a wilderness landscape in a matter of a few years, months, or in the case of fire, days or hours. While we cannot predict exactly how or when such transformations will occur, we can predict with high confidence that their frequency and severity will increase in the future. Possible management responses—such as erosion control or planting native species that are better adapted to a warmer future—usually will be most effective in the months immediately following the event. Yet planning for management intervention in wilderness, along with necessary legal compliance, can take years to accomplish, meaning that the opportunity to effectively intervene after a major disturbance often will be lost. While most wilderness stewards already carry a full load of planning responsibilities, it seems wise to seek opportunities—perhaps beginning as case studies in a few wilderness areas—to complete plans that anticipate sudden, broad-scale disturbances before those disturbances occur, so that responses are more likely to be well planned, timely, and deliberate.

### *Hedge your bets*

Another corollary of our inability to precisely predict the future is that it may be best to plan a variety of different management interventions. For example, in many regions the magnitude and direction of future changes in precipitation are unknown. If the decision is made to restore a landscape denuded by wildfire by planting species adapted to a warmer future, some areas could be planted with species adapted to a warmer, wetter future, some to a warmer, drier future, and some with a mix of both. Each treatment could be repeated in widely dispersed locations, reducing vulnerability by creating redundancy. Similarly, implementing a mixture of restraint, resilience, resistance, and realignment strategies is a means of hedging bets.

### *Broaden the geographic scope of planning*

More than any other threat, climatic change highlights the importance of planning across administrative boundaries. While challenging in itself, regional planning can make certain decisions and actions easier. For example, if climatic changes are driving a species to extinction within a particular wilderness, an initial reaction may be to take expensive, heroic actions to slow the species' decline. But viewed in a regional context, the species might simply be migrating into wildlands farther north. Regional planning could forge agreements ahead of time to allow or facilitate migrations across administrative boundaries as a means of maintaining native biodiversity.

## **CONCLUSION**

The era of rapid climatic changes is here, and seems sure to bring the greatest challenge wilderness stewards have yet faced. Efforts to plan for and respond to the challenge are still in their infancy, and solutions are unlikely to come easily or quickly. In addition to the considerations we have presented, planning will require a broader engagement of wilderness stewards, policymakers, and the public to assess the implications of climatic changes for wilderness values and policy, a topic well beyond the scope of this article. We hope, however, that we have presented some ideas to help move the process forward; the time for engagement is now.

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# Evolving the Policy Framework: Budget Strategies, Legislative Authorities, and Management Strategies to Facilitate Federal Forest Adaptation and Collaborative Partnerships

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***Abstract:** Some of the greatest challenges to the management of federal forests in the United States result from inadequate public and private investment in proactive forest restoration projects. This situation has been exacerbated by the growing fiscal and logistical demands of wildfire suppression activities, which currently consume at least 40 percent of the U.S. Forest Service's total budget. This paper presents some near-term policy, funding and collaborative management options that would enhance the ability of citizens and agencies to increase the pace and scale of beneficial forest treatments, resulting in healthier, more resilient forests and communities.*

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## **INTRODUCTION**

This paper offers some near-term policy options, which would have beneficial impacts on the ability of federal forests, and associated non-federal forests and communities, to become more resilient, especially to wildfire. Twelve years ago the Congress, the Administration and the states established a National Fire Plan through which they increased actions to reduce wildfire risks to communities, improve efficiencies in wildfire response, and restore more resilient forest conditions (USDA Forest Service and USDOJ 2001).

The recent release of the Final Phase in the Development of the National Cohesive Wildland Fire Management Strategy provides some updated and coordinated strategies for action at all levels of government (USDA Forest Service and USDOJ 2014). There are a myriad of possibilities for water utilities, recreation and tourism sectors, forest-based businesses and other private interests to also contribute to the management and sustainability of forests from which all sectors derive significant benefits. Policy options discussed below can effectively support



both essential emergency wildfire preparedness and response and the proactive fuels reduction and forest restoration that are needed to reduce the demand for emergency expenditures in the future. Our current approach to wildland fire and forest management in the U.S. creates a false choice, pitting the viability of one against the other. During this time of tight federal budgets and pressing forest restoration needs, limited resources should be invested both strategically and proactively in order to maximize the benefit for people, water and wildlife, while also reducing the costs for future generations.

## **BACKGROUND**

Forests are vital for America. Our forests cover more than a third of our nation and they store and filter half our nation's water supply. They are a significant source of employment, providing jobs to nearly a million forest product workers. Likewise, they generate more than \$13 billion in recreation and other related economic activity on Forest Service lands alone. Moreover, important considerations in the Anthropocene is that they absorb 13 percent of our nation's fossil fuel carbon emissions and provide habitat to thousands of wildlife and plant species.

However, the societal, environmental and fiscal costs of wildfire in our nation's forests continue their precipitous climb. During the 2012 wildfire season, alone, a relatively small 68,000 fires burned across nearly 10 million acres (4.05 million ha) and resulted in a \$1.9 billion bill for federal wildfire suppression (on top of the nearly \$1.5 billion required to staff the federal fire programs) (National Interagency Fire Center 2013). The real economic and social impacts of uncharacteristic wildfires are not fully known, but we do know that the annual cost of fire suppression alone is at least \$4.7 billion (\$2.5 billion for federal agencies, \$1.2 billion for State agencies and about \$1 billion for local governments) (International Association of Fire Chiefs 2013). The cost of wildfire management currently consumes more than 40 percent of the U.S. Forest Service budget, leaving an ever smaller pool of funds to support hazardous fuels reduction, timber management, wildlife habitat improvement, recreational access, watershed protection and the wide variety of other important services that the American people value and expect (Tidwell 2013).

We also know that the cost of fire suppression is only a small part of the direct cost of fires. Recent analysis of 6 wildfires showed that fire suppression expenditures were as little as 3 percent or 5 percent of the direct financial impact of the fire (Western Forestry Leadership Coalition 2010). More research is needed to help us understand and plan for the true costs of fire. Currently, much of the federal fire funding policy and decision space has focused only on costs of fire suppression and not all of the other fiscal and societal impacts. As Scott Stephens and colleagues recently wrote in *Science*: "Policy focused on fire suppression only delays the inevitable" (Stephens and others 2013).

Climate change is exacerbating the fire problem, as our forests are becoming warmer, dryer and subject to both more extreme weather events and longer fire seasons. 2012 was the third biggest fire year since 1960, with 9.3 million acres (3.76 million ha) burned. The Forest Service itself expects severe fires to double by 2050 (Finley 2013). We are already seeing these impacts: the Four Corners region has documented temperature increases of 1.5-2 degrees Fahrenheit over the last 60 years (Robles and Enquist 2010).

The recent comprehensive climate science synthesis for the U.S. forest sector suggests that, whereas currently forests sequester fully 13 percent of the nation's fossil fuel carbon emissions, trends in forest cover loss due to fire, urbanization and other impacts will make forests a net emitter of carbon by the end of the century (Vose and others 2012). Besides all the historic and substantial benefits of forests mentioned above, maintaining forest cover is probably one of the most cost effective ways to mitigate climate change, simply by helping forests adapt and become more resilient.

## **THE NATURE CONSERVANCY APPROACH TO FOREST RESTORATION**

The Nature Conservancy strongly supports the goal of accelerating restoration in our Nation's forests as described in the February 2012 report, *Increasing the Pace of Restoration and Job Creation on Our National Forests* (USDA Forest Service 2012a). In this report, the agency acknowledges that the pace and scale of restoration must dramatically increase if we are going to get ahead of the growing threats facing our forest ecosystems, watersheds and forest-dependent communities. The Conservancy's work across North America is guided by an ambitious vision that involves developing nature-based solutions to some of humanity's most pressing global challenges. Among our primary North American priorities is our *Restoring America's Forests* program, which aims to foster a dramatic increase in the proactive, science-based, collaborative restoration of our nation's federal forests, thereby reducing the tremendous human and environmental costs associated with unnaturally large and damaging megafires (The Nature Conservancy 2013a).

In short, we are convinced that science-based collaboration and open, public processes can foster community and economic conditions that create the social license allowing more forest treatments to be done, with locally based goals and benefits to local communities, water, and wildlife. Creating a new method of funding emergency fire suppression, could ensure funds are available to meet those needs without continuing to jeopardize the important restoration, fire risk reduction and other vital conservation projects that are essential for sustaining our forests and communities into the future. It may also set the stage for encouraging other sectors of society to invest in and share the benefits of proactive forest management and community preparedness.

## **KEY RECOMMENDATIONS**

The Nature Conservancy has been working on a broad policy platform to enhance forest resilience. Much of the Conservancy's proposed policy framework is focused on wildfire issues, since fires are having such a huge impact on forests, communities and especially on funding available for conservation action. The summary paper by Sample and Topik (Sample and Topik, this volume) goes into more detail explaining the policy ramifications and summarizes some of the science behind these recommendations. Additional details of these recommendations were presented in recent Congressional testimony (Topik 2013a; Topik 2013b; Topik 2013c).

### ***Budgetary Policy Strategies***

Budgetary policy suggestions that could be considered include: (1) increased federal funding for hazardous fuels reduction, (2) Support for Collaborative Forest Landscape Restoration projects, (3) associated proactive federal land management operations and science, and (4) creating and



funding a new federal fire suppression funding mechanism. Each will be discussed in more detail below.

(1) There are a variety of tools available, including controlled burns and mechanical treatments, to help managers proactively reduce hazardous fuels while also enhancing natural ecosystem processes and overall forest resistance and resilience to disturbance if additional funds were available to do so. The post-fire assessment of Arizona's record-setting 2011 Wallow Fire is a typical example that clearly demonstrated that homes and forest were saved in and around the town of Alpine by management treatments applied in tandem with FireSafe practices near structures. A detailed reconnaissance flight over the entire Wallow Fire burn, courtesy of Project Lighthawk in 2012, clearly showed a complicated and complex burn pattern over the half a million acre (202, 340 ha) site (Topik personal observation 2012). It was clear that the extensive tree thinning treatments around the town of Alpine caused the fire to reduce in intensity so that firefighters, including the Conservancy's own Southern Rockies Wildland Fire Module, could protect extensive infrastructure.

(2) The CFLR Program has been a valuable vehicle for prioritizing and testing a variety of collaborative, science-based approaches to forest restoration that both reduce wildfire risks and contribute to local jobs and economic opportunities. In just three short years since its inception, the CFLR Program has provided support to 20 projects in 14 states, with an additional 3 high priority restoration projects receiving support from non-CFLR funds (CFLR Steering Committee 2012). Many CFLRPs, especially in the West, are engaging with thinning and prescribed fire to achieve landscape-scale forest restoration. Hazardous fuels reduction near communities has become a high priority for many collaboratives, reducing the potential for mega-fire near outlying residential areas (Bixler 2014). It is a very promising new legal and institutional tool that could be monitored, emulated, and expanded in the future.

The current and recent budgetary stresses to Forest Service management have taken a real toll as evidenced by the substantial reduction in the agency's overall staffing for non-fire personnel (cite?). One attempt to enhance efficiency is the (3) Integrated Resource Restoration (IRR) strategy that attempts to increase budgetary efficiency and flexibility by blending funding sources for a variety of forest, watershed and wildlife habitat programs. The IRR is being employed in three regions on a pilot basis (Northern, Southwest and Intermountain). These pilots are encouraging but there is little evidence available yet to determine if the IRR approach actually increases efficiency and produces meaningful outcomes on the ground. Continuing this approach on a pilot basis, with careful monitoring by both the agency and external partners, could be considered.

Another significant policy option to consider is to (4) create and fund a new federal fire suppression funding mechanism to free up resources for proactive management. During the past decade there have been repeated instances during which emergency wildfire suppression costs have far exceeded the available funding, so the Forest Service and the Department of the Interior have had to transfer non-fire funds to support immediate emergency needs. This fire borrowing has had effects on the ability of land managers to plan and execute a normal program of work. Even the threat of fire borrowing has made normal contracting and staff planning difficult (cite?). Furthermore, the need to use discretionary operation funds to support emergency activities has been a drain on the ability of federal funds to support basic land management. At a time when we could be investing in up-front forest restoration to reduce the intensity and impacts of wildfire

we find the opposite happening. This new proposed mechanism could be modeled on the way other disasters have budget caps.

One potential option lies in establishing a new, separate federal funding source that ensures vital fire suppression activities are funded distinct from existing land management requirements. Legislation, named the “Wildfire Disaster Funding Act, has been proposed very recently on a bi-partisan basis in both the US Senate (Senate Bill S. 1875) and U.S. House of Representatives (H.R. 3992). Such legislation or other approaches could help ensure that emergency wildfire suppression needs are supported while also allowing for investments in forest treatments that enhance forest resilience and reduce wildfire risk.

Another opportunity, currently being pursued in Congress, lies in increasing the ability of the Federal Emergency Management Agency (FEMA) to provide states impacted by wildfire with additional resources for fuel hazard mitigation. As discussed in item 1 above, broadening and diversifying the investments in proactive management and mitigation activities may be more cost-effective than continuing to focus tremendous resources on emergency response.

### ***Legislative Authority Strategies***

A recent legislative effort was the permanent authorization of stewardship contracting. Stewardship contracting is a tool that allows the U.S. Forest Service and Bureau of Land Management to implement projects that restore and maintain healthy forest ecosystems, foster collaboration and provide business opportunities and local employment (Pinchot Institute for Conservation 2013). Stewardship contracts are the only administrative tool that can ensure up to 10-year supplies of timber, a level of certainty that encourages job creation and long-term industry investment. Permanent authority for stewardship contracting and agreements was provided in the Agricultural Act of 2014 (February 7, 2014, Public Law 113-79). This authority provides stability and flexibility to accomplish a wide range of forest and habitat improvements. Land managers and stakeholders can now work together to ensure that the authority is effectively and appropriately applied in a variety of landscapes.

However, more could be done in terms of working with local communities. Forest management and preparation for fire may require close coordination with state and local governments, and with communities, for long-term success. There are a variety of existing state and federal programs aimed at establishing and increasing state and local fire management and planning capacity, but clearly this is an area where additional attention could be focused. There are many good examples of positive work in community and social science, including the efforts of the Fire Learning Network and the Fire Adapted Communities education coalition. The Nature Conservancy has partnered with the Forest Service, Department of the Interior, and scores of other governmental, non-profit and community entities to help communities better understand fire and its role in local forest management. Additional information is available (USDA Forest Service 2013a; The Nature Conservancy 2013b). The Fire Adapted Communities coalition (see [www.fireadapted.org](http://www.fireadapted.org)) brings a wide range of partners together along with specialized education skills to help communities and various industries improve their ability to live with fire. An additional new partnership, the Fire Adapted Communities Learning Network (The Nature Conservancy 2013c) is testing innovative ways of working with communities to enhance their ability to live with fire.

Additionally, increased research on economic, social and ecological impacts of forest investment will be necessary if we desire to evaluate the return on investment of these actions. The forest and wildfire management issues and arena involve billions of dollars of expenses every year yet there is comparatively small investment in basic and applied science and monitoring to develop better methods and encourage innovation. Given the new frontiers in fire operations, fire ecology and social science, small investments could bring large benefits to society.

### ***Management Strategies***

Several management strategies can support the accelerated forest restoration that is needed. In order to facilitate this accelerated rate of treatment, we must make effective use of all available management tools and explore opportunities to increase the efficiency of planning and implementation processes. These suggestions include: (1) improving the NEPA process, (2) increasing commitment by state and local governments, (4) increasing multi-sectorial participation, and (5) increasing use of fire as a management tool.

Policy adjustments that foster innovation and improvement in (1) NEPA implementation could be sought, thereby increasing the scale and quality of resulting projects and plans. The principles of public engagement and environmental review embodied in the National Environmental Policy Act (NEPA) facilitate open and informed federal decision making. The Nature Conservancy believes that the full public participation and transparency of federal decision making based on science and public discourse, as required by NEPA, results in better management decisions that in the long run are more effective and efficient. There may be opportunities to increase the efficiency of these processes through targeted adjustments in policy and implementation.

(2) State and local governments can play vital roles in helping communities, as well as public and private landowners, adjust their planning and land management strategies to be more compatible with the changing environment that forests in the United States face in future decades. Authoritative assessments for the US Forest Sector (Vose et al 2012; USDA Forest Service 2012b) indicate just how much change is likely under most climate and economic development scenarios. Greater public participation in planning and local collaboration concerning both the structural conditions of communities and the conditions of wildlands in and around communities may be needed.

Ultimately the conditions of our forests have tremendous impact on a myriad of ecosystem services that are vital for society as a whole. This is why (3) enhanced participation of additional sectors of society, such as water and power utilities, recreation and tourism, public health, and industrial users of clean water, in forest restoration could be beneficial. Diverse and sustainable sources of non-governmental funding could provide an effective complement to federal, state and local land management resources, thereby facilitating an overall increase in landscape-scale forest restoration on American forests. A broad coalition of citizen and commercial sectors and interests in various forest restoration issues would need to be developed and expanded. This effort would recognize the enhanced value and services to the public and nature that could accrue from a new restoration oriented economy. Several models already exist, such as water funds, and there is opportunity for innovative solutions that could guide more sectors to unite for common forest improvement purposes. Several options are summarized elsewhere in this volume (Sample and Topik).

Finally, (4) there could be enhanced use of fire as a management tool. Much of North America includes forests that have evolved with fire as a common and important ecosystem process (Nelson and others 2013), however, much of the current sub-optimal forest condition in the United States is partially the result of overly aggressive fire suppression that has not allowed fire to function as a normal and natural ecological disturbance. Prescribed fires and controlled burns are efficient, cost-effective and ecologically beneficial tools to reestablish healthy forests, as is the managed use of wildfire for resource benefit. The U.S. fire community has a constantly changing view of this issue, and even the terminology changes frequently. What was called ‘wildland fire use’ and limited to natural fire events (USDA Forest Service and USDOJ 2004) is now called ‘manage wildfire for resource objectives’ and is being encouraged as a way to manage fire-adapted ecosystems and achieve fire-resilient landscapes (USDA Forest Service and USDOJ 2013). Increasing the safe and effective use of both controlled burns and managed wildland fire may require operational improvements by firefighters as well as improvements in community involvement and education on risk acceptance.

## CONCLUSION

The 2013 wildfire season, punctuated by devastating losses of life and property, brought into sharp focus the costs of damaging wildfire. Finding a way to effectively support both essential emergency wildfire preparedness and response, and the proactive fuels reduction and forest restoration that are needed to reduce the demand for emergency expenditures in the future is challenging. Our current approach to wildland fire and forest management creates a false choice, pitting the viability of one against the other. In reality, we must do both. Science-based, cost-effective and meaningful options exist for changing our nation’s approach to forests and wildfire. The policy approaches described above, if enacted, could set us on a positive course toward realizing a more sustainable and resilient future.

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# Summary and Synthesis

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***Abstract:** America's forests are undergoing changes unlike any seen before in human history. The concept of the Anthropocene Era, a new geologic epoch characterized by anthropogenic dominance over the Earth's systems, has become an important framework for thinking about the processes and consequences of worldwide environmental change, particularly global climate change, widespread species extinctions, mega-forest fires, and the erosion of the Earth's life support systems. If humanity is now in an epoch where large-scale ecological functions and relationships are outside the historic range of variability, then new and interdisciplinary approaches to forest conservation are required. The people and organizations charged with the conservation and sustainable management of the world's forests and their associated renewable natural resources are at the forefront of efforts to understand and address these challenges. This summary and synthesis is from presentations and discussion at the conference on Forest Conservation in the Anthropocene, convened by the Pinchot Institute for Conservation in Washington, DC, September 17-18, 2013.*

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## **INTRODUCTION**

As the distinguished authors in the preceding chapters have shown, America's forests are undergoing changes unlike any seen before in human history. With each passing year, new precedents are being set for the extent and impacts of wildfires. Record areas of forests stand dead or dying, not just from exotic insects and diseases, but also from species that have been native to these forests for eons. More subtle but potentially more profound changes are taking place each day as native plant and animal species quietly disappear from their historic home ranges, perhaps to reappear at the frontiers of some other more poleward ecosystem. Scientists and forest managers puzzle over new arrivals, trying to decide whether to define them as invasive species to be eradicated, or as climate change refugees that should be nurtured as they continue their exodus toward destinations unknown even to them.

In the midst of this time of unprecedented change and new uncertainties, the stewards of America's forests, both public and private, must decide how they will act differently if they are to sustain the forests themselves





and the array of economic, environmental, and societal values and services forests provide—water, wildlife, biodiversity, wood, renewable energy, carbon sequestration. Side by side with some of the best climate and resource scientists, forest resource managers are striving to understand, prepare for, and adapt to the effects of climate change. As they do their best to anticipate a ‘no analog future’ in which the lessons of the past can offer little guidance, they must assess the risks associated with several alternative courses of action, and then manage those risks through intensified monitoring and continuous readjustments aimed at preserving as many options as possible for future resource managers.

A sort of triage has developed for forest resource managers and the ecological communities themselves. One can try to *resist* the effects of climate change, taking advantage of niches here and there where survival may be possible. One can try to be more *resilient* to the impacts of new patterns of disturbance, with strategies to survive the periodic and perhaps intensifying shocks and still have the ability to recover afterwards. Or one can accept that the magnitude of the changes is just too large and the momentum too great for either of these approaches to work, and that the only practical strategy is to *readjust* one’s future expectations, continuously monitor the changes taking place on the ground, and modify management actions in order to simply sustain key values or ecosystem services.

## **WILDLIFE AND BIODIVERSITY CONSERVATION**

Traditional wildlife and biodiversity conservation strategies have relied heavily on the establishment of reserves and other protected areas to conserve habitat, but as climate changes, optimal habitat zones shift to different places on the landscape as well. So a basic question that has arisen for conservation biologists is whether protected areas that are fixed and static on the landscape can still play a useful role in protecting plant and animal species that are in the process of relocating. What is developing in biodiversity conservation is a portfolio approach that still relies upon protected areas, but within a larger and more dynamic context, and utilizes all three of the resistance, resilience, and readjustment approaches to climate change adaptation.

As Gary Tabor and his co-authors describe, landscape-scale habitat conservation strategies originally developed to address the issue of habitat fragmentation are now being pressed into service as climate adaptation strategies. Corridors and linkages that can connect habitat across several degrees of latitude are becoming critically important to facilitate the emigration of some plant and animal species and the immigration of others. Schmitz and Trainor point out that, because some species within a given ecological community are more mobile than others, some are able to migrate and others are left behind, disassembling existing communities of interdependent species. At the same time, a region will experience the immigration of mobile species from elsewhere, developing species assemblages that may never have existed before. How to regard these “novel ecosystems” is a topic of considerable ongoing debate among conservation biologists. From one perspective, many of these novel ecosystems are highly biologically productive and may also exhibit a high level of species diversity, so they may represent a significant biodiversity resource in themselves. In any case, they are inevitable and will develop with or without biologists’ consent. From another perspective, this tendency increases the importance of large protected areas with well-buffered interior regions that are more resistant to immigration by species from distant locales.

This still leaves the question of whether something can be done to minimize the emigration of species from such reserves, and the dismantling of the existing ecological community. Anderson and Johnson describe characteristics that can help scientists define both biological and geological characteristics that allow the identification of ‘resilient sites’ that tend to resist the influence of climate change and hold their ecological communities intact. These sites tend to have certain characteristics of geology, soils, and topography. Identifying, mapping, and then protecting a sufficient number of these resilient sites across large landscapes can be an important component in a comprehensive, portfolio approach to adapting biodiversity conservation to the effects of climate change.

There are significant additional challenges associated with actually implementing such a strategy on large landscapes predominantly characterized by private ownership and comprised of many small tracts. These tracts are typically managed for objectives as diverse as the private owners themselves, who may or may not understand or share a commitment to biodiversity conservation. Once again, large landscape conservation strategies originally developed for other purposes can be repurposed to help achieve biodiversity conservation objectives in regions characterized by mixed public-private or predominantly private ownerships.

McCauley describes an innovative approach successfully pioneered by the U.S. Fish & Wildlife Service (FWS) on the Silvio O. Conte National Fish and Wildlife Refuge following its designation by special legislation in 1991. Unlike traditional wildlife refuges at the time, the Silvio Conte encompassed large areas of land that were not directly owned or managed by the FWS—in fact, the entire 7.1 million (2.87 million ha) in the Connecticut River watershed, across four states. The model was motivated by the understanding that the important wildlife and aquatic species in this watershed could never be adequately protected by the FWS working only on the agency’s small reserves. It was a model based on outreach to other landowners in the region, facilitating local meetings in which the FWS provided spatial information about key habitat that had mapped throughout the watershed, and about land management practices that could maintain or enhance these habitat values. Landowner actions were voluntary, not done as a matter of law or regulation, and a large number of landowners stepped forward to learn more about how they could protect habitat values that happened to occur on their land.

Wildlife refuges in other regions have now adopted this watershed-based large landscape conservation model, and the concept is at the heart of the FWS strategy for wildlife and fish habitat conservation in response to climate change. As climate adaptation strategies such as the identification and mapping of ‘resilient sites’ are developed, especially in eastern regions of the United States where forests are primarily in private ownership, outreach models such as that developed on the Silvio Conte Refuge could become critically important to translating the knowledge about where resilient sites are located to actually achieving their conservation and protection, through actions that can only be taken through communication, collaboration, and cooperation with the individuals who actually own the land.

## **WATER RESOURCE MANAGEMENT**

The relationship between climate change, water, and forests is complex, involving direct, indirect, and induced effects. Regions that experience prolonged drought and elevated temperatures will obviously face challenges resulting from lower precipitation and higher evapotranspiration,

and areas that depend upon high elevation snowpack to maintain late-season flows will more often find themselves in extreme water emergencies. This will be a major issue for aquatic habitat, especially when combined with higher water temperatures and lower dissolved oxygen levels. Cold-water species such as West Slope cutthroat trout and Dolly Varden (bull trout) may face particular environmental stress, and localized populations unable to migrate to more suitable habitat may die out.

Intact forests can mitigate all of these influences on water supply, quality, and temperature, but as forests themselves begin to show the effects of climate change their ability to do so will be sharply reduced. Forests are remarkably efficient at absorbing precipitation, storing it, and gradually releasing it as streamflow. Forests in higher elevations can be managed for optimal snow interception by maintaining crown cover that is open enough to not intercept too much snow, where it will sublimate back into the atmosphere, but closed enough to provide shade to the snow that does penetrate to the ground, slowing spring snowmelt and helping to maintain late-season flows. Climate-induced environmental stress that results in tree mortality from drought, insects, or disease diminishes each of these functions.

The most extreme effects are from wildfire, of course. Extensive crown fires in Colorado's Front Range in 1996 and 2002 caused major damage to the Strontia Springs and Cheesman Reservoirs, threatening the municipal water supply for Denver and communities up and down the Front Range. A decade later, local water authorities were still spending millions of dollars annually for additional water treatment and the removal of tons of sediment and debris from check dams installed upstream from these reservoirs after the fires. Unprecedented flash floods that caused millions of dollars in property damage in Colorado in the summer of 2013 were exacerbated by recent massive wildfires that left slopes barren of trees and other vegetation, and vulnerable to storms.

The decisive steps that Denver took to reduce the likelihood of wildfire damage to its other reservoirs provide a model that other cities and communities are taking up, especially as the changing climate is raising the stakes. Denver Water and several water authorities serving other Front Range communities sought and received permission to add a small surcharge to customers' regular water bills, creating a fund that was used to accomplish hazardous fuels treatments and forest health thinnings on forest lands upstream from municipal reservoirs. Most of these lands are National Forests, and Denver Water and the U.S. Forest Service subsequently entered a cooperative agreement in which each party would contribute more than \$16 million to accelerate treatments on thousands of acres of forest.

The lessons learned in Denver were not lost on other western communities, themselves surrounded by fire-prone forests which, should a wildfire occur, would cause substantial damage to the local water supply. Laura McCarthy's paper describes an analysis conducted by The Nature Conservancy for the city of Santa Fe, New Mexico estimated the economic losses should a major fire occur in the city's primary watershed on the Santa Fe National Forest. The study also demonstrated that the probability of such a fire could be significantly reduced through hazardous fuels treatments and forest health thinnings whose cost would be a fraction of the projected damages. The city council approved a modest surcharge on local water customers, and used this to create a water fund that is used to carry out the necessary forest management activities. The Nature Conservancy is currently working to create a similar water fund on the middle Rio

Grande, where cities like Albuquerque—seeing the results of recent New Mexico fires such as the Las Conchas and the Cochita—are becoming convinced that it is worth it to them to invest in fuels treatments in headwaters forests more than a hundred miles north.

In regions of the country where the changing climate is expected to bring higher levels of precipitation and more of it in the form of extreme storm events, intact forests are becoming a high-value asset. Hurricane Irene in 2011 dumped an extraordinary volume of rain on the Mid-Atlantic States and New England in a very short period, and satellite photos from a few days after the storm showed the Susquehanna River in full flood stage, choked with sediment and debris, which was flushing into the Chesapeake Bay and turning its northern portion an opaque brown. Municipal water supplies were interrupted in Harrisburg, Pennsylvania and other communities drawing their drinking water from the Susquehanna for nearly two weeks, and power plants drawing cooling water from the river were either shut down or operating at reduced output.

In the same satellite photo, the next major watershed to the east, the Delaware River, can be seen running clear and blue, sparkling in the sunlight. One major reason for this is the fact that the headwaters of the Delaware River are roughly 80 percent forested, whereas forest cover has been reduced to less than 40 percent in the headwaters of the Susquehanna. There is a major effort now under way to restore thousands of acres of riparian forest in the upper Susquehanna watershed—a valuable initiative but one that will take years to begin having a meaningful effect.

Meanwhile the upper Delaware River watershed continues to lose forest cover at an average of more than 100 acres (40 ha) a week. The Pennsylvania, New York, and New Jersey counties that come together in the upper Delaware are the fastest developing counties in their respective states. Will Price and Susan Beecher describe the effort to create the Common Waters Fund, an innovative mechanism developed to give private forestland owners a financial incentive to conserve their forest, and to manage it in ways that will enhance its watershed protection capabilities.

But most of the communities and businesses downstream on the Delaware have yet to be convinced that it is in their interest to invest in keeping the forested headwaters intact, rather than waiting for there to be a problem requiring emergency restoration actions such as on the Susquehanna. Water supply and water quality have been good recently, and many water users seem willing to take a chance that the continued loss of forest cover to development will not have any significant impact on them. The growing prospect of more extreme storm events like Hurricanes Irene and Sandy may be changing that benefit/cost ratio. The economic impacts of a severe flood event on the Delaware would be enormous, and the forested headwaters play an important role in flood mitigation and buffering the effects of extreme storm events. Unlike the Rio Grande or the Susquehanna, whose headwaters forests are in need of costly restoration, the headwaters forests of the Delaware simply need to be maintained as they are. Currently there are more private forestland owners in the upper Delaware waiting to participate than there is money in the Common Waters Fund to enlist them—and the development pressure continues. As the effects of climate change become more pronounced, it will be clear that what the headwaters forests provide in terms of water supply, water quality, flood mitigation, and buffering extreme storm events exceeds the modest investment needed to keep them intact.

## WOOD PRODUCTION

For the wood products industry, certain high value hardwood species are likely to become more susceptible to exotic pests and pathogens such as the emerald ash borer (*Agrilus planipennis*), Asian long-horned beetle (*Anoplophora glabripennis*), and Sudden Oak Death (*Phytophthora ramorum*). Hopefully this will not have the impacts that the chestnut blight (*Cryphonectria parasitica*) has had on the American chestnut (*Castanea dentata*) that once dominated the eastern hardwood forests, but it is not something that even the best scientists are able to predict with confidence.

In the dry conifer forests of the Southwest and central Rockies, native forests have already been fundamentally altered by widespread mortality from the mountain pine beetle (*Dendroctonus ponderosae*) and other naturally endemic species, the result of a ‘perfect storm’ in which warmer winters have fostered the survival of extraordinarily high populations of bark beetles and other agents, and drought stress has drastically reduced the ability of trees to resist and survive insect attacks. Even in fire-adapted forest types such as Ponderosa pine (*Pinus ponderosa*), the unnatural and all-consuming crown fires that often follow leave vast areas of forests with no means to regenerate and restore themselves. Many areas, especially in the American Southwest, will not return to forest within the foreseeable future and are even now in the process of converting from forest ecosystems to grassland or shrubland ecosystems. As noted by Craig Allen, Anthony Westerling, and others, this is profoundly changing water regimes, wildlife habitat, and biodiversity across immense areas of forests, challenging local communities as well as resource managers to quickly develop new strategies for resistance, resilience, or the readjustment of their future expectations in light of climate change.

In the intensively managed forests in regions such as the U.S. South and Pacific Northwest, there seems to be a sense that the short rotations typical of commercial plantation forests will allow forest managers to stay ahead of the accelerating pace of climate change. Research is producing more drought-resistant varieties of important commercial tree species, which presumably will replace existing forests as they are harvested. Genetic modification may offer opportunities to attune certain tree species to new and evolving climate characteristics, but the acceptance of widespread use of such techniques is far from certain. A strategy based simply on more frequent opportunities to replace existing trees may not fully account for other climate-related effects such as more intense storms, which as seen with Hurricanes Katrina and Hugo, can destroy millions of acres of forest very quickly. Prolonged drought and elevated temperatures also reduce resistance to pests such as bark beetles, which can still kill large expanses of forest in a relatively short time. All of these factors contribute to increases in wildfire activity, a trend that is already being documented even in the South (Vose and others 2012).

## FOREST MANAGEMENT ADAPTATION TO CLIMATE CHANGE AS PART OF A CARBON MITIGATION STRATEGY

There is an important duality in the relationship between forests and climate change, and this may become a central consideration in the development of forest management adaptation strategies. Forests both affect and are affected by climate change in major ways. Fortunately, the strategies and techniques that will enhance the role of forests in mitigating climate change,

through carbon sequestration and reducing net carbon emissions, are largely consistent with the techniques that can best support adaptation strategies.

As early as 2020, U.S. forests are projected to switch from being a key mechanism for storing carbon to being themselves a significant net source of greenhouse gas emissions. Today, U.S. forests store enough carbon to absorb roughly 14 percent of total U.S. greenhouse gas emissions. By 2020, this very significant carbon offset is expected to drop to zero. And by 2030, the nation's forests are expected to become significant net sources of carbon emissions themselves (USDA Forest Service 2012a). This is largely due to two factors: (1) the increasing size, frequency, and intensity of wildfires, as most of the western United States continues on a trend of elevated temperatures and extended drought, and (2) the continuing loss of private forests for development.

Conceivably, it is still possible to avoid or at least mitigate this projected future, but it will require decisive actions and a substantial strengthening of current conservation and sustainable forest management efforts to change the trajectory U.S. forests are now following. These actions include (Vose and others 2012):

1. Increase afforestation and decrease deforestation:

- Stem the conversion of forests to development and other land uses; the loss of forests and open space to development was recently estimated at approximately 6,000 acres (2,400 ha) per day—roughly 4 acres (1.6 ha) per minute.
- Increase the resistance and resilience of dry forests in the western United States to minimize the conversion to grassland ecosystems in the wake of major insect or disease outbreaks and wildfires.

2. Increase substitution of wood for fossil fuels in energy production, and for other building materials to maximize long-term carbon storage:

- Increased biomass energy from the current 2 percent of U.S. energy use to 10 percent would prevent the release of 130-190 million metric tons/year of carbon from fossil fuels (Perlack and others 2005; Zerbe 2006); commitment to conservation and reforestation of harvested sites is critically important to this net gain.
- Use of 1 metric ton of carbon in wood materials in construction in place of steel or concrete can result in 2 metric tons in lower carbon emissions, due to lower emissions associated with production processes (Sathre and O'Connor 2008; Schlamadinger and Marland 1996). Using wood from fast-growing forests can be more effective in lowering atmospheric carbon than storing carbon in the forest, where increased wood production is sustainable (Baral and Guha 2004; Marland and Marland 1992; Marland and others 1997).

3. Manage carbon stocks in existing forests:

- Increase forest carbon stocks through longer harvest intervals and protect forests with high biomass.
- Manage forest carbon with fuel treatments: carbon emissions from wildland fires in the coterminous United States have averaged 67 million metric tons/year since 1990 (USEPA 2009, 2010); stand treatments to reduce fire intensity, especially crown fires that result in near-total tree mortality, have the potential to significantly reduce carbon emissions.

## POLICY OPTIONS

A careful consideration of the foregoing information and insights from distinguished scientists and experienced natural resource managers, and from the vigorous discussions that took place among the diversity of interests represented at the conference, leads to several overarching conclusions:

1. A *better integrated approach* is needed to understand, prepare for, and adapt to the effects of climate change on natural resources. Scientists and natural resource specialists in wildlife habitat management, biodiversity conservation, water resource protection, and other disciplines are all working to develop effective climate change adaptation strategies, but there is still a strong tendency to focus within rather than across disciplines. Land and resource management requires an integrated approach of course, but there is an added concern that strategies developed independently to optimize one set of objectives, e.g., carbon management, may dictate management activities that run counter to strategies oriented to other objectives, such as biodiversity conservation.
2. *Wildfire management and policy is central* to adaptation strategies across all resources. There is much more to climate change adaptation than managing the increasingly damaging effects of wildfires, but how these risks are managed will have a profound influence on biodiversity, wildlife, water, carbon and virtually every other aspect of any climate change adaptation strategy. The development and *effective implementation* of policies to limit the ecological, economic, and social impacts of wildfires are not the only consideration, but they are an essential consideration.
3. A more *dynamic policy framework* is necessary to enable natural resource management that can adapt to climate change. To the extent that the existing institutional, legal, and policy framework for natural resource management is based on science, it must continue to evolve just as science itself evolves. The most important lesson is not that the existing policy framework should be replaced by a new one, but that policies themselves must be dynamic enough to accommodate rapidly changing environmental conditions. Statutes and regulations that provide a broad enabling framework may be more effective than prescriptive laws, and rules that reflect theories and approaches that are highly changeable can continue to evolve with new scientific knowledge.

To the extent that there currently is a strategy for forest management adaptation to climate change, it is more of an amalgam of several different strategies being developed largely independent of one another. As the papers in this volume demonstrate, considerable scientific research and management resources have been devoted to developing new adaptive strategies for biodiversity conservation, as geographic shifting of habitat zones raises questions about the long-term effectiveness of traditional protected-area approaches. The extraordinary increase in the size, frequency, and extent of wildfires in forest watersheds has prompted urgent development of strategies to protect municipal water supplies and water quality. This increase in the number of ‘megafires,’ and the immense volume of greenhouse gases emitted during both the fire event itself and the often lengthy recovery period afterwards, have become a new and significant factor in the nation’s climate change mitigation policy. Because of the impact that megafires have on

these and other resource values and environmental services from forests, wildfire policy itself is undergoing a thorough re-examination in light of the projected influences of climate change.

The downward trajectory in U.S. forest conditions is negatively affecting all of these resource areas, with environmental, economic, and societal impacts that are likely to increase in the absence of coherent, cohesive policies, and integrated, results-oriented strategies. To a large extent, the actions needed to prepare for and adapt to climate change effects on these resources are similar to one another, and a more explicitly integrated approach to climate change adaptation could increase the likelihood that these actions will be timely and effective.

Correcting this downward trajectory in forest conditions and reinforcing their resiliency to the effects of climate change is a daunting challenge, requiring ecosystem restoration on an estimated 152 million acres (61.5 millions ha) of federal, state, tribal, and private forest land in the United States (USDA Forest Service 2013b). Ecosystem restoration in this context is focused on restoring ecosystem functions and processes, and strengthening the capacity to recover from significant, large-scale natural disturbances. It is not about attempting to restore forests to some earlier evolutionary state, in climate conditions that are already quite different from those of today, and which are unlikely to return any time in the foreseeable future.

Substantial improvements may be needed to the current institutional, legal, and policy framework for the management of forests and their associated values and services, including at the federal level. Encouraging policies and practices increase community engagement and local involvement could develop common visions for forest management and facilitate the work being implemented. Nowhere is this truer than wildfire policy and management. Not only are there major direct impacts of wildfire on multiple resources discussed above; there are also important indirect effects, as well as the burgeoning costs of emergency wildfire suppression that have drained away much of the public funding available for the management and protection of other resources.

Climate change is exacerbating the wildfire problem, as forests are becoming warmer, dryer and subject to both more extreme weather events and longer fire seasons. Acres burned by wildfires during 2012 were the third most of any year since 1960, with 9.3 million acres (3.76 million ha) burned, and the Forest Service is estimating 20 million acres (80.9 million ha) will burn annually by 2050. The Forest Service itself expects severe fires to double by 2050 (Finley 2013). These impacts are already evident: the Four Corners region has documented temperature increases of 1.5-2.0 degrees Fahrenheit over the last 60 years (Robles and Enquist 2010).

The societal, environmental, and fiscal costs of fire in the nation's forests continue their precipitous climb. Federal expenditures for emergency wildland fire suppression during 2012 alone were \$1.9 billion, in addition to the nearly \$1.5 billion required to maintain, staff, and equip federal fire programs. The cost of wildfire management currently consumes more than 40 percent of the U.S. Forest Service budget, leaving an ever smaller pool of funds to support hazardous fuels reduction, timber management, wildlife habitat improvement, recreational access, watershed protection, and the wide variety of other important services that the American people value and expect.



The full economic and social impacts of this extraordinary increase in wildfires are far greater, but thus far have been difficult to quantify. A study by the International Association of Fire Chiefs (2013) estimated that direct public expenditures for emergency wildfire suppression are averaging around \$4.7 billion annually—\$2.5 billion from federal agencies, \$1.2 billion from state agencies, and about \$1 billion from local governments. But even this is only a fraction of the total economic and social costs of these wildfires. An analysis of six recent wildfires by the Western Forestry Leadership Coalition (2010) showed that fire suppression expenditures may be as little as 3-5 percent of the total economic impact of these fires. Current federal wildfire policy and funding priorities are focused on strategies to limit direct emergency wildfire suppression costs. A more comprehensive approach based on reducing the overall environmental, economic, and social impacts of wildfires may better inform federal wildfire policies to optimize spending on emergency wildfire suppression, versus wildfire prevention through forest restoration actions that reduce wildfire risks.

The following near-term policy recommendations are aimed at providing some practical methods that might be considered in order to enhance forest and fire management in the United States and create more resilient forests and forest-dependent communities.

***Recommendation 1. Strengthen the institutional framework for long-term investment in forest restoration and sustainable management***

*a. Hazardous fuels reduction*

Congress and the Administration could increase federal investments to reduce fire risk in a manner that make forests more resilient and resistant to fire and other stressors. This could be based on a broadly supported long-term strategy so that, with respect to the annual process by which federal budgets and appropriations are determined, steady progress can be made toward overarching goals for resource protection and long-term sustainability. Strategic, proactive hazardous fuels treatments have proven to be a safe and cost-effective way to reduce risks to communities and forests by removing overgrown brush and trees, leaving forests in a more natural condition resilient to wildfires. A recent meta-analysis of 32 fuels treatment effectiveness studies confirmed that when implemented strategically, fuels treatments make a crucial difference in the size, spread and severity of wildfires (Martinson and Omi 2013). These treatments can improve the safety and effectiveness of firefighters and provide protection for a community or essential watershed that might otherwise see extensive loss.

Federal investments in maintaining the capacity and skills for hazardous fuels treatments have been shown to improve firefighter safety and reduce property losses, while also providing jobs and other economic benefits to rural communities. There is a growing body of literature documenting the many instances in which hazardous fuels treatments have modified wildfire behavior, thereby allowing firefighters to safely engage in protecting infrastructure and landscapes (Ecological Restoration Institute 2013). A recent economic assessment of forest restoration in eastern Oregon by the Federal Forest Advisory Committee (2012) revealed “an investment in forest health restoration has the potential to save millions of dollars in state and federal funds by avoiding costs associated with fire suppression, social service programs and unemployment benefits.” It is estimated that for every \$1 million invested in hazardous fuels treatments, approximately 16 full-time equivalent jobs are created or maintained, representing more than a

half million dollars in wages and over \$2 million in overall economic activity (Nielsen-Incus and Moseley 2010). Nevertheless, recent federal budgets have cut funding the Hazardous Fuels Reduction programs at both the U.S. Forest Service and the Department of the Interior.

Strategic mechanical fuels reduction in wildlands, combined with controlled burning to reduce fuels across large areas, can significantly reduce the chance that megafires will adversely impact the water supply, utility infrastructure, recreational areas, and rural economic opportunities on which communities depend.

There has been an ongoing discussion of whether hazardous fuels projects should be done primarily to protect structures nearly to the exclusion of natural areas that support life and livelihood. Community protection buffer zones can limit the damage from wildfire. Fighting fires will remain costly until such buffers are in place and people feel safe. But shifting too much funding away from undeveloped forest areas where fires have been excluded for a century, and where conditions remain overly dense and susceptible to unnaturally damaging wildfire, will have a long-term negative impact on forest health and resiliency. A careful science-based evaluation system to inform a balanced allocation of funding between treatments in wildland and developed areas could be developed. Strategic mechanical fuels reduction in wildlands, combined with controlled burning to reduce fuels across large areas, can significantly reduce the chance that megafires will adversely impact the water supply, utility infrastructure, recreational areas, and rural economic opportunities on which communities depend.

*b. Strengthen results-based cooperation on forest restoration through initiatives such as the Collaborative Forest Landscape Restoration (CFLR) Program*

The active involvement of local communities and stakeholders plays an essential role in the management of public lands, but the challenges of forest restoration will likely require an unprecedented level of cooperation among federal land managers, stakeholders, and organizations that provide the local economic infrastructure for carrying out resource protection and restoration activities in the field. The Collaborative Forest Landscape Restoration (CFLR) Program is an new mechanism aimed at enhancing community involvement in forest restoration and management. It is being used to test a wide variety of approaches, bringing science and local needs together in forming collaborative visions for future forest management.

Through these projects, the CFLR Program is demonstrating that collaboratively-developed forest restoration plans can be implemented at a large scale with benefits for people and the forests. From fiscal year 2010 through fiscal year 2012, the cumulative outputs generated by the funded projects already total: 94.1 million cubic feet of timber; 7,949 jobs created or maintained; \$290 million in labor income; 383,000 acres (155,00 ha) of hazardous fuels reduction to protect communities; 229,000 acres (92,600 ha); and 6,000 miles of improved road conditions to reduce sediment in waterways (CFLR Steering Committee 2012).

The scale and complexity of the situation facing the nation's forests and communities means that we must find ways to forge agreement among diverse interests about the 'where, when, and how' of forest management and then focus resources on those landscapes that are poised for success. Collaboration once considered 'innovative' and 'new', has often become an essential tool to reduce wildfire risks, increase forest restoration, and contribute to the sustainability of

local economies. By bringing together county commissioners, local mill owners, water and utility managers, fire protection officials, conservation groups, scientists, and others, collaborative groups can identify mutually beneficial solutions to forest health challenges and, sometimes by enduring a few bumps and bruises, pave the way for smooth and successful projects on the ground. Equally important is the long-term commitment these projects have fostered to both community sustainability and forest resilience (Butler 2013). Various funding sources, and even the state of Oregon, are providing funds that support the community collaborative capacity to enhance implementation of the CFLR program.

The CFLR Program can be a test of administrative and operational processes, as well as the project planning and preparation activities that facilitate implementation success, if allowed to continue over the ten-year life span of the projects. Future expansion could be considered. Applying lessons learned through the CFLR Program may improve National Forest management throughout the system as collaborative, large-scale projects are created and new land management plans are developed under the new forest planning rule.

*c. Maintain capacity for multi-resource management and protection through increased administrative and budgetary efficiencies*

Given the scope of the wildfire management challenge on federal lands, it is likely that other resource programs will continue to be funded at levels below projected needs for resource protection and stewardship. One way of addressing this challenge may be to consider more efficient and better integrated approaches to budgeting and accomplishing multi-resource management on federal forests. Both the U.S. Forest Service and BLM have in the past considered budget reforms aimed at facilitating a more integrated approach to implementing land and resource management plans developed under the National Forest Management Act (P.L. 94-588; 16 U.S.C. §§ 1600-1614) and the Federal Land Management and Policy Act (P.L. 94-579; 43 USC 1701-2, 1711-23, 1732-37, 1740-42, 1744, 1746-48, 1751-53, 1761-71, 1781-82) (Sample 1990). These early pilot studies of consolidated budgeting, planning, and accomplishment reporting demonstrated significant cost savings, increased performance accomplishment, and improved accountability in many instances.

Finding budgetary and administrative efficiencies that allow the U.S. Forest Service and BLM to accomplish multi-resource management and protection priorities at lower funding levels will be an essential component in these agencies' strategies for wildfire management and broader adaptation to climate change. Among the key lessons learned from the earlier efforts at USFS and BLM budget reform is that Congressional and Administration support is essential. This more integrated approach to planning, budgeting, and accomplishment reporting may require significant modification to the existing budget structure. To the extent that these modifications result in changes to existing Congressional and Administration processes for budget development and appropriations, these efforts have met with resistance, particularly at the President's Office of Management and Budget (OMB), and among members of Congress with a strong personal or constituent interest in specific resource programs (Sample and Tipple 2001).

The increasing proportion of the U.S. Forest Service and BLM budgets being directed to emergency wildfire suppression, in addition to the more general budget reductions, means that other resource programs are struggling to accomplish management objectives with a smaller and

smaller piece of a steadily shrinking budgetary pie. The efficiencies discovered in previous attempts at budget reform suggest that it may be time to consider this once again, in ways that will be acceptable to Congress and OMB. The U.S. Forest Service is currently experimenting with Integrated Resource Restoration (IRR), a budgetary tool that attempts to increase efficiency by blending funding sources for a variety of forest, watershed, and wildlife habitat programs. The IRR is being employed in three regions on a pilot basis (Northern, Southwest, and Intermountain).

***Recommendation 2. Create and fund a new federal fire suppression funding mechanism to free up resources for proactive management referenced above***

Policy action may be needed to guarantee adequate resources for wildland fire first responders, but to do so in a way that allows needed investments in the up-front risk reduction programs discussed above. Even with a robust, proactive approach to land management, federal fire preparedness and suppression resources will still need to be maintained at an effective level to protect life, property, and natural resources. Emergency preparedness and response resources may need to be provided through a new mechanism that does not compromise the viability of the forest management activities that can actually serve to reduce risks to life and property and mitigate the demand for emergency response in the future. The current system of funding fire preparedness and suppression, at the expense of hazardous fuels and other key programs threatens to undermine the other management and conservation purposes for which the USDA Forest Service and Department of the Interior bureaus were established.

The dramatic increase in the number of homes near federal lands that are prone to frequent and unnaturally damaging fire has added significantly to the cost of fire suppression. In the past, paying for this tremendous cost often resulted in ‘borrowing’ of funding from other resource management and stewardship programs into fire suppression accounts. Fire borrowing, and the threat of fire borrowing, severely impacts even the most basic level of resource management planning, reducing non-fire related agency personnel, and undermines efforts to retain skilled contractors in local communities to carry out land management and stewardship activities. Studies by GAO have documented the tremendous adverse impacts of this fire borrowing (GAO 2004). Congress subsequently passed the Federal Land Assistance, Management, and Enhancement (FLAME) Act of 2009 (43 USC § 1748a) as part of a bipartisan effort to change the funding mechanism for wildfire suppression by establishing two emergency wildfire accounts funded above annual suppression. These FLAME reserve accounts are intended to serve as a safeguard against harmful fire borrowing and should have represented an important change in the funding mechanism for wildfire suppression.

Unfortunately, the implementation of the FLAME Act has not proceeded as intended. Due to several factors, during both 2012 and 2013 the Administration had to again transfer hundreds of millions of dollars from the agencies’ non-suppression programs into emergency response accounts (Taylor 2013).

A new, separate federal funding source could be established so vital fire suppression activities are funded distinct from ongoing land management requirements. One option is the establishment of a ‘Wildland Fire Suppression Disaster Prevention Fund’ that could be utilized to support federal fire suppression actions during emergencies, just as the Disaster Relief Fund is utilized to help communities recover after disasters. Fire suppression is different from other natural

disasters, since the federal response is needed most acutely during the actual event. Such support could complement prevention and risk reduction activities discussed earlier, and post-fire recovery and restoration actions. It may also be wise and appropriate to enhance state participation in such a fund. This wildland fire suppression disaster prevention fund could be established through the Congressional appropriations process and could be supported using declarations in subsequent annual appropriations bills. In addition, Congress could increase the ability of the Federal Emergency Management Agency to provide states impacted by wildfire with additional resources for fuel hazard mitigation. Broadening and diversifying the investments in proactive management and mitigation activities may be far more cost-effective than continuing to focus tremendous resources on emergency response.

### ***Recommendation 3. Accelerate implementation of cooperative stewardship authorities***

Stewardship contracts and agreements are among the most valuable effective tools the U.S. Forest Service and BLM have to carry out ecosystem restoration actions, including hazardous fuels treatments, on federal forests (Hausbeck 2007). This statutory authority was first granted by Congress on a pilot basis, to allow the U.S. Forest Service to carry out critically important land stewardship and resource protection activities, many of which had been carried out previously through National Forest timber sales. The success and effectiveness of these pilot studies led Congress to expand the program to authorize both the U.S. Forest Service and BLM to utilize stewardship contracts anywhere on the federal forests under their management (16 U.S.C. § 2104). The authorization was temporary, however, covering only a ten-year period in order to give Congress a chance to evaluate its effectiveness through multi-party monitoring (Pinchot Institute 2006). Permanent statutory authority for stewardship contracts and agreements was provided within the Agricultural Act of 2014 (Public Law 113-79; 2.7.14).

Over the past decade, stewardship contracting has proven to be an innovative and flexible tool that allows the U.S. Forest Service and Bureau of Land Management to implement projects that restore and maintain healthy forest ecosystems, foster collaboration, and provide local employment through sustainable community economic development (Pinchot Institute 2012). Stewardship contracts are the only administrative tool that can provide certainty to local contractors for up to ten years, a critically important consideration for small businesses in local communities securing financing to purchase equipment, expand facilities, or increase their skilled workforce to carry out the land management activities specified in the stewardship contract. Continued strong public and Congressional support may be needed to enable the U.S. Forest Service and DOI Bureau of Land Management (BLM) to move forward rapidly to expand forest restoration, forest management and fire risk reduction activities utilizing the new permanent authority for stewardship contracting and agreements provided in the Agricultural Act of 2014 (P. L. 113-79).

The following specific could be taken to achieve two objectives: (1) expedite agency-level policy direction on Stewardship Contracting to resource managers in the field at both the U.S. Forest Service and BLM, and (2) immediately initiate the agency-level process for enhancing the implementation of stewardship contracting in the field.

- Release updated guidance to agency field staff related to the permanent authorization of stewardship contracting, and how the authorities can be used to accelerate the pace and scale of

restoration of our federal lands. The Forest Service and BLM operate under different policy frameworks, but that should not prohibit interagency coordination. Agency and Department communications related to the Farm Bill should include consistent messaging and communications.

- Develop a forum or communications process for interested stakeholders to remain current. Provide guidebooks to help with industry, tribal and citizen outreach on the use of stewardship contracts and agreements.
- Evaluate opportunities to use the recently expanded Good Neighbor authority to work with stewardship contracts and agreements (Public Law 113-79).
- Expedite the release of an updated Forest Service stewardship contracting handbook.
- Consider the recommendations from the FY 2012 Stewardship Contracting Programmatic Monitoring report ([http://www.pinchot.org/gp/Stewardship\\_Contracting](http://www.pinchot.org/gp/Stewardship_Contracting)), and the recommendations from the Stewardship Contracting Roundtable and regional partners.

#### ***Recommendation 4. Increase capacity of states and communities to become fire adapted***

Programs such as State and Volunteer Fire Assistance and Forest Health Protection provide important resources to help states and local communities develop and sustain community wildfire protection capacity. These programs foster the development of fire-adapted communities. Policy makers could seek opportunities to allocate other federal resources in a way that rewards communities for proactive actions that collectively result in national benefit.

Relatively small federal and state investments in community capacity can have substantial results for lowering wildfire risk. Building local community capacity to learn to live with fire is the most cost-effective way of reducing harmful impacts to society, while also allowing for enhanced, safe, and controlled use of fire to restore wildlands as appropriate.

Given the potential for devastating increases in both values lost and public expense, a diverse range of agencies and organizations (including The Nature Conservancy) have begun promoting the concept of ‘fire-adapted communities.’ The U.S. Forest Service defines a fire-adapted community as a knowledgeable and engaged community in which the awareness and actions of residents regarding infrastructure, buildings, landscaping, and the surrounding ecosystem lessen the need for extensive protection actions and enables the community to safely accept fire as a part of the surrounding landscape.

The U.S. Forest Service and other members of the Fire Adapted Communities Coalition are working to get communities the information and resources they need to successfully live with fire. The web site [www.fireadapted.org](http://www.fireadapted.org) provides access to a wide variety of educational materials and tools in support of community wildfire protection planning and action. Coalition members are also working to develop local, grassroots leaders and partnerships. These partnerships are essential for engaging all relevant stakeholders to assess and continually mitigate a community’s wildfire risk.

***Recommendation 5. Seek policy adjustments that foster innovation and improvement in National Environmental Policy Act (NEPA) implementation, thereby increasing the scale and quality of resulting projects and plans***

The Administration has established a goal of increasing the pace of restoration and job creation on the National Forests (USDA Forest Service 2012b). The Forest Service acknowledges that the pace and scale of restoration must dramatically increase in order to get ahead of the growing threats facing America's forest ecosystems, watersheds, and forest-dependent communities. To facilitate this accelerated rate of treatment, effective use must be made of all available management tools and the Forest Service must explore opportunities to increase the efficiency of planning and implementation processes.

There is broad commitment to the principles of public engagement and environmental review embodied in NEPA. There may be opportunities to significantly increase the efficiency of these processes, while continuing this commitment, through targeted adjustments in policy and implementation. The U.S. Forest Service is currently testing and tracking a variety of innovative NEPA strategies that hold promise for broader application. Adaptive NEPA, for example, is a relatively new approach in which the official record of decision allows sufficient leeway for some variety of subsequent federal actions, thereby greatly streamlining the analysis, allowing for more efficient project implementation, and enabling land managers to more effectively incorporate emerging science. These innovative approaches to NEPA could be expanded and additional opportunities sought for streamlining policies and processes in a way that increases the pace and scale of implementation while holding true to the core values inherent in the Act.

Greater use of the categorical exclusion procedures allowed under NEPA may be possible without diminishing the intent of this key environmental law. Full public participation and transparency in federal decision making, based on science and public discourse, results in better management decisions that in the long run are more effective and efficient. The new National Forest System Land Management Planning Rule and draft Directives (Federal Register 2012) emphasize collaborative, science-based adaptive management. Application of this new framework will guide a new round of forest planning that is intended to be more meaningful *and* more efficient, and set the stage for timely implementation of projects that achieve multiple benefits on the ground. Clear guidance and support for the development and implementation of monitoring strategies will also be essential to the rule's success.

***Recommendation 6. Increase shared commitment to and support for forest restoration by states and local governments***

Federal agencies alone cannot prevent the loss of homes, infrastructure and other values in the wildland-urban interface (WUI). Individuals and communities living in the WUI must meaningfully invest in preparing for and reducing their own risk from fire. Post-fire studies repeatedly show that using fire resistant building materials and reducing flammable fuels in and around the home ignition zone are the most effective ways to reduce the likelihood that a home will burn (Graham and others 2012). Similarly, community investments in improved ingress and egress routes, clear evacuation strategies, strategic fuel breaks, and increased firefighting capacity can go a long way toward enabling the community to successfully weather a wildfire event.

Community commitment is also necessary to effectively shift the national approach to wildfire from a emphasis on disaster response to a proactive strategy with multiple benefits. Research increasingly shows that rising wildfire suppression costs are directly linked to the growing presence of homes and related infrastructure in the WUI (Stein and others 2013). A corresponding analysis by Headwaters Economics revealed that 84% of the WUI is still undeveloped, so there is tremendous potential for the costs associated with wildfire protection to exponentially increase (Rasker 2013). According to the same study, if just half of the WUI is developed in the future, annual firefighting costs could explode to between \$2.3 and \$4.3 billion. States and communities could examine the ramifications of their planning on the resulting wildfire environment, especially since future decades will no doubt bring more and more severe droughts and wildfire incidents.

Federal public lands and surrounding communities could also foster greater partnerships and multi-lateral cooperation and coordination. There are many opportunities for states and municipalities to directly participate and even help fund beneficial forest management activities on nearby federal forest lands. The Eastern Oregon study cited above (Oregon Department of Forestry 2012) demonstrates that state investments in federal land management can yield great savings to the state in reduced unemployment costs, reduced social services, and increased tax revenue. Elsewhere, such as in Flagstaff, Arizona, communities are contributing directly to restore forest conditions that reduce fire risk in order to protect existing watershed and recreation resources (Flagstaff Watershed Protection Project 2012). There may be additional opportunities for many states and communities to investigate a wide spectrum of innovative funding mechanisms that will support up-front investments that increase the livability of forest dependent communities and reduce fire risk.

***Recommendation 7. Enhance participation of additional sectors of society, such as water and power utilities, recreation and tourism, public health, and industrial users of clean water***

There are tremendous opportunities for diverse and sustainable sources of non-federal funding to provide an effective complement to federal land management resources, thereby facilitating an overall increase in landscape-scale forest restoration on federal lands. There are a number of efforts underway, including water funds, which produce revenue for upstream forest restoration that benefits downstream water users and water companies while enhancing the restoration and maintenance of federal forests. Other utility and industrial partnerships can be developed.

The Forest Service has been particularly active in Colorado. Since 2009 they have established partnerships with five water utilities (Denver Water, Aurora Water, Colorado Springs Utilities, Northern Water, and Pueblo Water), several major corporations (such as MillerCoors, Vail Resorts, and Coca-Cola), and several philanthropic entities (Brian Ferebee, USDA Forest Service, personal communication 2013). Such efforts, often spearheaded by the National Forest Foundation, are facilitating greater shared responsibility that can reduce wildfire risk while enhancing forest health and enhancing the values those companies and other entities rely on (see National Forest Foundation 2013).

There are additional, important partnerships with forest products industries. Forest products industry investments in new biomass and wood products development can play a substantial role



to facilitate the removal of overstocked trees, while enhancing the condition of the forest and streams following harvest.

The insurance and reinsurance industries are closely involved in wildland fire issues and are important partners in such efforts as the Fire Adapted Communities Coalition (see website [Fireadapted.org](http://Fireadapted.org)). There are important opportunities for greater engagement of these industries since they have such direct contact with citizens and they have such a direct involvement and desire to see fire risks reduced (Munich Reinsurance America, Inc. 2013). There may be additional opportunities to bring various compensatory mitigation funds for the support of forest restoration.

Wildfires and even controlled fires can have sizable impacts on public health due to smoke (Knowlton and others 2011; Kochi and others 2012). There is potential need to increase engagement with public health agencies and air agencies concerning impacts of smoke, and analyze the relative merits of massive, uncontrolled smoke events from severe wildfires versus controlled smoke episodes from prescribed burning accomplished to reduce severe wildfire risks.

***Recommendation 8. Increase the safe and effective use of wildland fire***

The beneficial use of fire as a tool for resource management is another area where greater forest restoration efficiency and effectiveness could be achieved. By increasing the use of both controlled burns and naturally ignited wildland fires to accomplish resource benefit, land managers can accomplish both ecological and community protection goals on a larger scale and at reduced cost. In fact, some states annually reduce fuels on more than 100,000 acres (40,400 ha) in wildlands with fire treatments. Both Congress and the Administration could make it clear that the safe and effective use of fire is a priority for land management agencies, and provide the necessary funding, training, and leadership support needed to foster increased fire use where appropriate.

Many communities across the nation are already deeply engaged in trying to proactively address their role within fire-driven forest ecosystems, but this engagement could be both sustained and increased. For more than 10 years, The Nature Conservancy has worked cooperatively with the U.S. Forest Service and the Department of the Interior to foster the Fire Learning Network (FLN) that brings communities together and helps them to build collaborative, science-based strategies that protect both people and ecosystems (The Nature Conservancy 2013). The FLN supports public-private landscape partnerships that engage in collaborative planning and implementation, and provides a means for sharing the tools and innovations that help them scale up. Locally, the FLN helps federal land managers to: convene collaborative planning efforts; build trust and understanding among stakeholders; improve community capacity to live with fire; access training that helps fire professionals work with local communities; and address climate change and other emerging threats.

***Recommendation 9. Increase research on economic, social, and ecological impacts of forest investment***

It is essential that the federal government and other sectors invest in monitoring, research, and accountability studies for fuels treatment, wildfire management strategies, and related efforts. This requires relatively small investments, when compared to the costs of fire suppression and

fire damage, but it is essential if scientists are to really learn what works and what does not. Furthermore, new technologies, including remote sensing, LIDAR, and focused social science studies can offer creative new perspectives to increase efficiency of action.

## CONCLUSION

The challenges of forest management adaptation to climate change are great, but the opportunities may be even greater. There is a higher level of interest and public concern over the state of the world's forests than at any time in recent history. Forest science is becoming more relevant than ever to sustaining the economic values and environmental services that forest ecosystems provide and that society needs—water resources protection, fiber, biodiversity, renewable energy, and carbon mitigation.

The Anthropocene, this new epoch in which *Homo sapiens* has become the predominant force in the global biosphere, is about more than just a changing climate. The climate has always been in a state of flux, and certain past episodes have been as drastic as what the world is witnessing today. Species and communities have in most instances found ways to adapt and survive, through migration, mutation, or other coping mechanisms. One thing that is different this time is the pace of the change. As Curt Stager notes, climate shifts that in past epochs have taken place over millennia are now happening in just a few decades (Stager 2011). Natural adaptation strategies of the past are of limited success in today's circumstances, heightening the risk of unprecedented ecological disruptions, with consequences no one can predict.

The other major difference this time around is the presence of 7 billion people, with extensive human infrastructure that often interdicts historic migratory pathways and corridors, and limits the ability of species to get where they need to be. Large landscape conservation initiatives like Yellowstone-to-Yukon that were developed to address habitat fragmentation have become essential tools for enabling species to migrate along continental-scale corridors that include roads, towns, and other manifestations of humanity's ubiquity. 'Assisted migration' or 'managed relocation' of species to areas to which they are climatically better suited, or will be in the near future, may be something that works well with a few commercially important tree species. But as suggested by the continuing controversy over these techniques within the conservation biology community, there is still a sense by many that the unintended consequences of humans inserting species into new ecosystems may still outweigh the purported benefits. Forest managers are increasingly seeking guidance as new species arrive on their own—is it an invasive species or an environmental refugee? Should it be killed or cared for? Wildlife managers and conservation biologists are hotly debating whether to emphasize traditional efforts to protect natural landscapes, or focus on more advanced techniques for working in explicitly human-dominated landscapes to sustain both the 'players' and the 'stage' in the evolving theater of life on Earth.

Forest managers with responsibilities for sustaining multiple ecosystem services without interruption or significant decline will be especially challenged. First they must develop the science and management practices to respond to continuously changing conditions. There are numerous valuable examples of scientists working side by side with forest managers to conduct vulnerability assessments and develop strategies that move very quickly from development to implementation on public forest lands. Helping private forestland owners understand how climate change is likely to affect their management objectives is the first step to assisting them in

taking actions that—because two-thirds of the nation’s forests are in private ownership—can collectively have a major impact on how well U.S. forests adapt to, and also mitigate, climate change. The information-based outreach model pioneered by the U.S. Fish and Wildlife Service on the Silvio Conte and other units of the wildlife refuge system is a one example of how knowledge can be quickly translated to action on the ground, even on very large landscapes in mixed public-private or predominantly private ownership.

The second and perhaps greater challenge is to develop the political will to make considerable public investments in sustaining forests and the essential services on which society depends. Ambitious goals have been set for forest restoration aimed at reducing risks and strengthening resilience—only to have these goals missed by wide margins as dedicated funding has been withdrawn and redirected to other purposes, year after year. Efforts could be focused on developing new and alternative budgeting methods for wildfire suppression and mitigation, in addition to making a clear and compelling economic case illustrating avoided costs by investing in proactive forest restoration treatments.

Similarly, public programs aimed at stemming the loss of private forest land to development or conversion are perpetually funded below to the level of interest among private forestland owners who want to utilize these programs for conservation easements and other forms of land protection. Creating and sustaining non-federal funding sources through water funds, biomass, and wood products development, and fire funds for mitigation and risk reduction is a potential complement to a funding portfolio that includes traditional sources of federal funding.

Efforts to increase the use of wood biomass to substitute for fossil fuels in renewable energy production are hampered by difficult economics and public concerns that biomass removal will result in long-term impacts on forest productivity, water regimes, biodiversity, and other values. The economic question could be addressed by a more comprehensive accounting of the benefits of risk reduction and forest restoration, which produce many of the wood biomass byproducts that go into renewable wood bioenergy, as well as the continuing contribution of these activities through job creation, small business development, and environmentally sustainable economic growth in rural communities.

For conservationists, this may be a defining era. Meeting human needs for food, shelter, energy, and especially water will continue to alter landscapes at an expanding scale, with direct, indirect, and induced effects that are far too complex for humans to predict or for other species to anticipate.

The knowledge and the tools to optimize the role of forests in strategies for both mitigating and adapting to climate change are close at hand. Uncertainties around the potential future effects of climate change on forests are high, but there already is enough knowledge to begin managing the risks and taking the first steps in a strategy that incorporates robust monitoring and continuous course corrections. To do so will require continuous improvement in collaborative efforts that expand learning networks and utilize the diversity of expertise and experience among forest managers, interest groups, and local communities.

Most importantly, through decisive actions taken now, there is an opportunity to change the future, and avoid the projected switch in U.S. forests from providing an important carbon sink to

becoming themselves a major net source of carbon emissions. Stemming the loss of private forests to development, restoring public forests to relieve climate-induced environmental stresses, reduce fire risks, and protect essential public values and ecosystem services—these all have substantial environmental, economic, and societal benefits in addition to reducing carbon emissions. Also, these are goals that are already well understood and widely supported by a broad consensus of Americans. The barriers to achieving these goals are eminently surmountable.

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