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.*

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-Texeira 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 instill 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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