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## WATER QUALITY MONITORING IMPROVEMENTS AT INDIANA DUNES

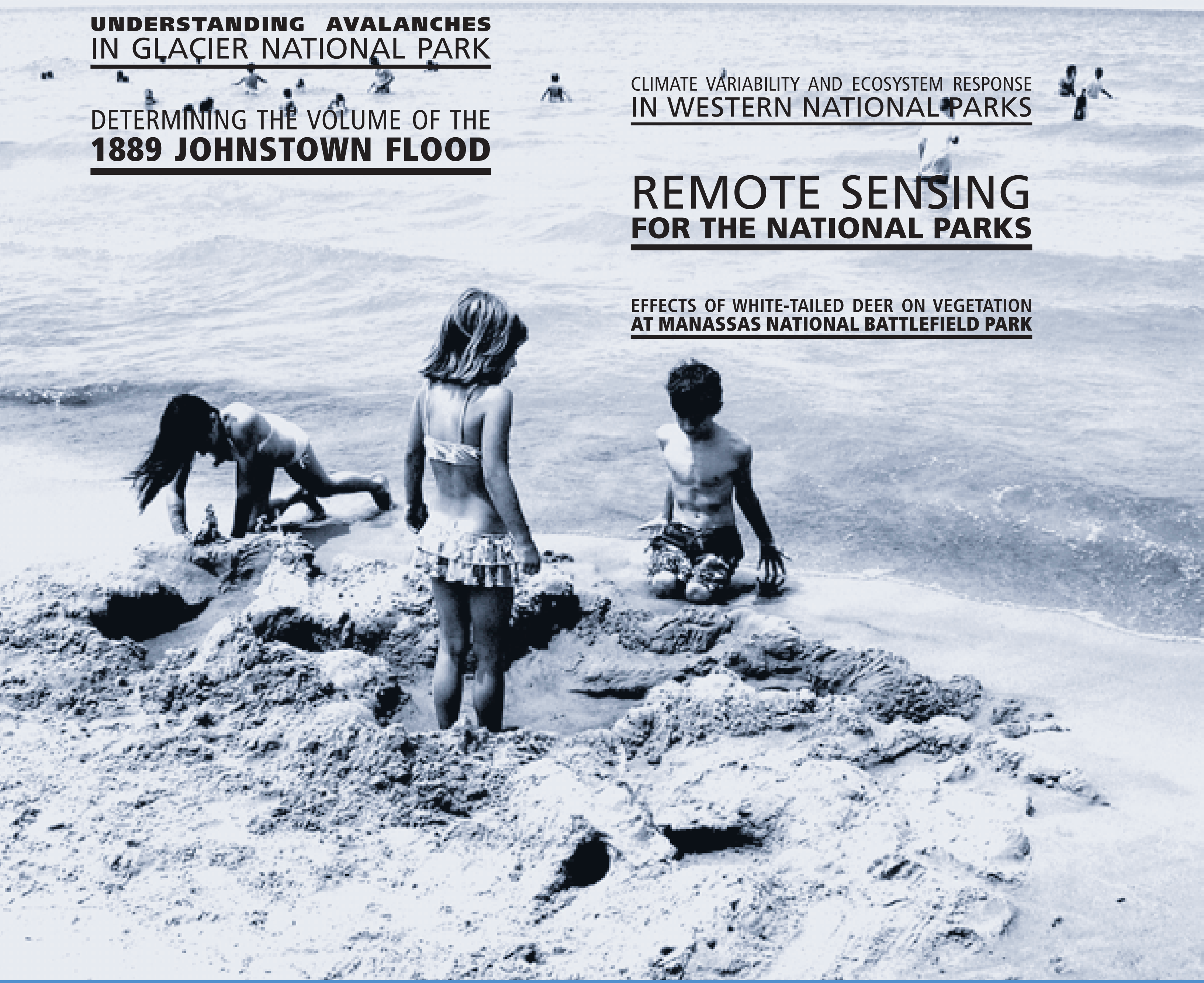
## UNDERSTANDING AVALANCHES IN GLACIER NATIONAL PARK

## DETERMINING THE VOLUME OF THE 1889 JOHNSTOWN FLOOD

## CLIMATE VARIABILITY AND ECOSYSTEM RESPONSE IN WESTERN NATIONAL PARKS

## REMOTE SENSING FOR THE NATIONAL PARKS

## EFFECTS OF WHITE-TAILED DEER ON VEGETATION AT MANASSAS NATIONAL BATTLEFIELD PARK



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# THE WESTERN MOUNTAIN INITIATIVE

By Nate Stephenson, Dave Peterson, Dan Fagre, Craig Allen, Don McKenzie, Jill Baron, and Kelly O'Brian

Mountain ecosystems within our national parks and other protected areas provide valuable goods and services such as clean water, biodiversity conservation, and recreational opportunities, but their potential responses to expected climatic changes are inadequately understood. The Western Mountain Initiative (WMI) is a collaboration of scientists whose research focuses on understanding and predicting responses of western mountain ecosystems to climatic variability and change. It is a legacy of the Global Change Research Program initiated by the National Park Service (NPS) in 1991 and continued by the U.S. Geological Survey (USGS) to this day as part of the U.S. Climate Change Science Program (http://www.climatescience.gov/).

## FRAMING THE QUESTIONS

The rate and magnitude of ecosystem responses to climatic warming are variable and uncertain, ranging from gradual to abrupt, from moderate to profound. The least understood and least predictable responses are perhaps those of greatest importance to NPS natural resource managers: responses that are both abrupt and profound (NRC 2001; Gunderson and Pritchard 2002). Recent examples of such responses include ongoing drought-induced tree mortality on millions of hectares of forest in New Mexico, Arizona, and southern California (Breshears et al. 2005; U.S. Forest Service 2003), and an increase in area burned by severe wildfires in the western United States during the past two decades (Westerling and Swetnam 2003). In both cases, thresholds of ecosystem resistance to change were quickly exceeded, leading to large and often unexpected changes that will have long-term consequences for protected areas.

Against this backdrop, the Western Mountain Initiative is guided by four major questions that address ecosystem patterns and processes at large spatial scales across the West, with an emphasis on mountainous national parks:

1. How are climatic variability and change likely to affect spatial and temporal patterns of ecological disturbance (particularly fire)?
2. How are changing climate and disturbance likely to affect the composition, structure, and productivity of vegetation (particularly forests)?
3. How will climatic variability and change affect hydrologic processes in the mountainous West?
4. Which mountain resources and ecosystems are likely to be most sensitive to future climatic change, and what are possible management responses?

Western mountain ecosystems are well suited to address these and related questions because they have (1) compressed climatic and biogeographic zones containing many ecosystems within relatively small areas, (2) rich paleoecological resources, which record past environmental changes and consequent ecosystem responses, and (3) common ecological drivers, such as snowpack and fire, which facilitate comparisons across ecosystems.

## THE WMI NETWORK—
### HISTORICAL PERSPECTIVE

Data collected in several western national parks since the inception of this research program in 1991 have improved our understanding of the effects of climatic variability on mountainous ecosystems. Most of the major forested and alpine ecosystems in the West are represented within the WMI network (fig. 1). A brief summary of the sites and results to date follows.

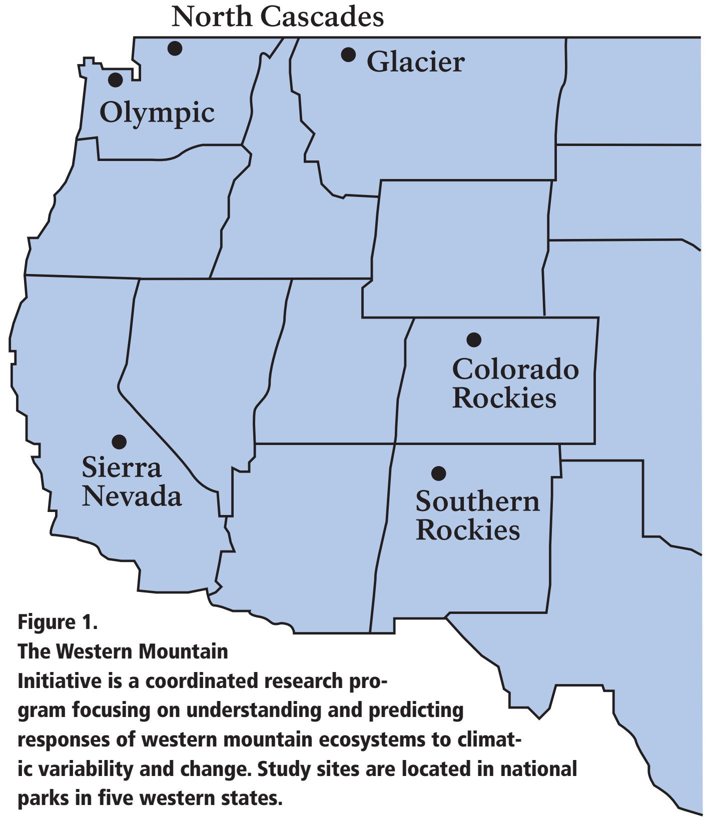



**Figure 1.**
**The Western Mountain Initiative is a coordinated research program focusing on understanding and predicting responses of western mountain ecosystems to climatic variability and change. Study sites are located in national parks in five western states.**

## Pacific Northwest and northern Rockies

Global change research projects within Olympic, North Cascades, and Glacier national parks (Washington and Montana) joined forces in 1998 to form the CLIMET (Climate-Landscape Interactions on a Mountain Ecosystem Transect) research program. This transect ranges from maritime to continental climates, with striking westside (wet) versus eastside (dry) contrasts at each of the three primary study locations. CLIMET focuses on ecosystem productivity, hydrology, and fire, with empirical studies at a variety of spatial and temporal scales.

Simulation modeling was used to quantify responses of natural resources to climatic variability and change (Fagre et al. 2005), and statistical modeling was used to establish the biophysical "niche" of dominant tree species in the region (McKenzie et al. 2003). Ecosystem models were used to quantify potential major changes in snow distribution, annual watershed discharge, and stream temperature under the warmer, wetter climate for the Pacific Northwest region. For example, if warming continues at the current rate (about $0.16^\circ$ C or $0.29^\circ$ F per decade) all glaciers in Glacier National Park are predicted to disappear by 2030 (Hall and Fagre 2003); there were 150 glaciers in 1850, but today only 27 persist (fig. 2, pages 26–27). Modeling also predicts increased productivity in some low-elevation forests, which could generate higher fuel loads that in turn could increase fire severity, particularly in a changing climate (McKenzie et al. 2004).

**If warming continues at the current rate ... all glaciers in Glacier National Park are predicted to disappear by 2030.**

CLIMET documented growth increases in high-elevation tree species over the past century (McKenzie et al. 2001) and widespread establishment of trees in subalpine meadows (Peterson 1998). This research program also demonstrated strong relationships between regional tree growth patterns and variability of snowpack and drought. Rapid establishment of subalpine fir (*Abies lasiocarpa*) has occurred in meadows in response to reduced snow duration, paralleled by increased krummholz (shrubby tree growth) density at tree line and increased colonization of alpine tundra by upright trees. Major fire years were linked to drought and may be associated with cycles of El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation.

## Sierra Nevada

With Sequoia, Kings Canyon, and Yosemite national parks (California) forming the core study areas, the Sierra Nevada project has focused on understanding the effects of changing climate and fire regimes on montane and subalpine forests, combining contemporary ecology (emphasizing natural climatic gradients), paleoecology (emphasizing tree-ring and palynological, or pollen, studies), and modeling. Scientists have found that forests in warmer climates are more dynamic than those in cooler climates, with higher rates of tree birth and death (Stephenson and van Mantgem 2005). Thus, climatic warming might lead to higher forest turnover rates, hence younger forests, with potentially cascading effects on wildlife, biodiversity, and ecosystem services.

Investigations of fire effects on forest pattern and dynamics have led to modifications in prescribed fire programs. Modeling results provided land managers with projections of the consequences of natural fire, prescribed fire, mechanical thinning, and climatic change on Sierra Nevada forests. The project's detailed reconstructions of past fire regimes (Swetnam and Baisan 2003) are now used by land managers to help set targets for restoring fire to mixed-conifer forests.

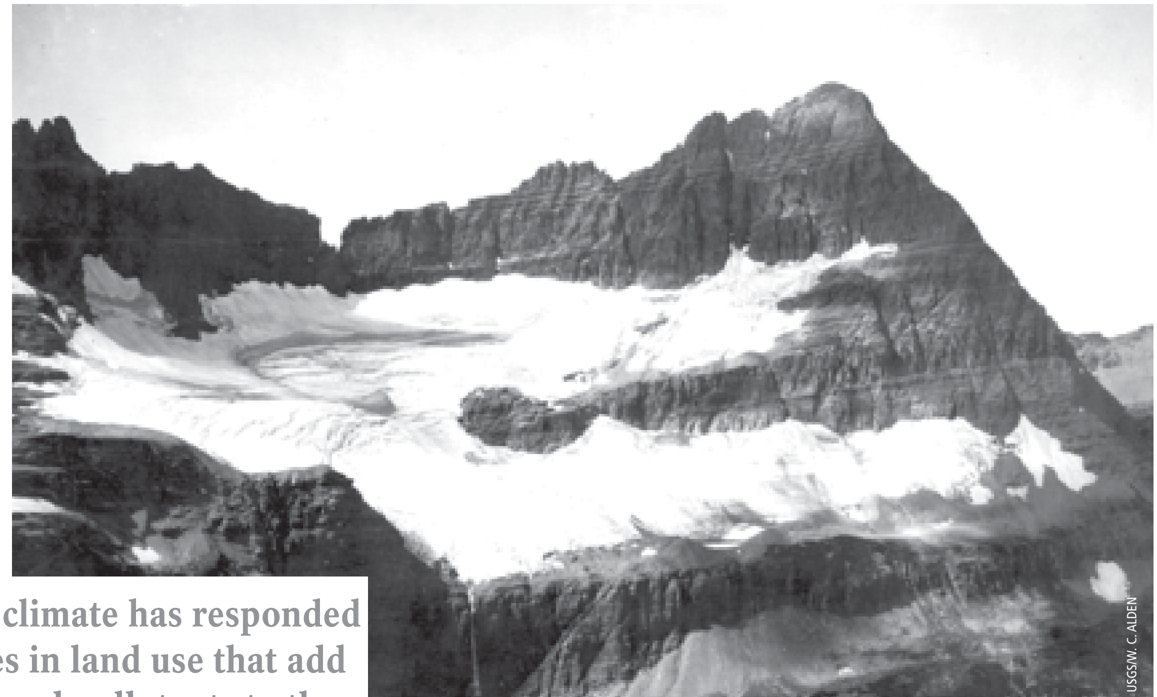



**Figure 2. Photographs from 1913 (above) and 2005 (right) vividly illustrate a decline in glacial mass at Shepard Glacier in Glacier National Park, Montana. Modeling conducted as part of the Western Mountain Initiative research project predicts that all park glaciers will disappear by 2030 if the current rate of climate warming continues.**

## Central Rockies

Located in Rocky Mountain National Park (Colorado) the central Rockies project has focused on the vulnerability of forest ecosystems, aquatic ecosystems, and hydrology to variability in climate, fire, insect outbreaks, and herbivory by large mammals. Empirical data, modeling, and monitoring have quantified the effects of climatic variability (e.g., ENSO) on fire and insect outbreaks over the past 400 years. Tree line expansion into tundra has not occurred since the mid-1800s, although changes in growth form from krummholz to upright trees have occurred. Old coniferous forests responded to changes in disturbance regimes rather than directly to changing climate. Quaking aspen (*Populus tremuloides*) forests, which have high native plant and insect diversity, are also the vegetation type most heavily invaded by nonnative species (Chong et al. 2001).

Regional climate has responded to changes in land use that add moisture and pollutants to the atmosphere near mountains.

Research has shown that hydrologic systems in the central Rockies are particularly sensitive to variation in temperature and precipitation. Simulations of stream discharge and ecosystem processes show that the timing of snowmelt, though not water volume, is particularly sensitive to climatic warming (Baron et al. 2000a). In addition, regional climate has responded to changes in land use that add moisture and pollutants to the atmosphere near mountains (Baron et al. 2000b). Finally, elevated deposition of atmospheric pollutants, especially nitrogen, has affected the vegetation and soils of some alpine and subalpine ecosystems in the central Rockies.

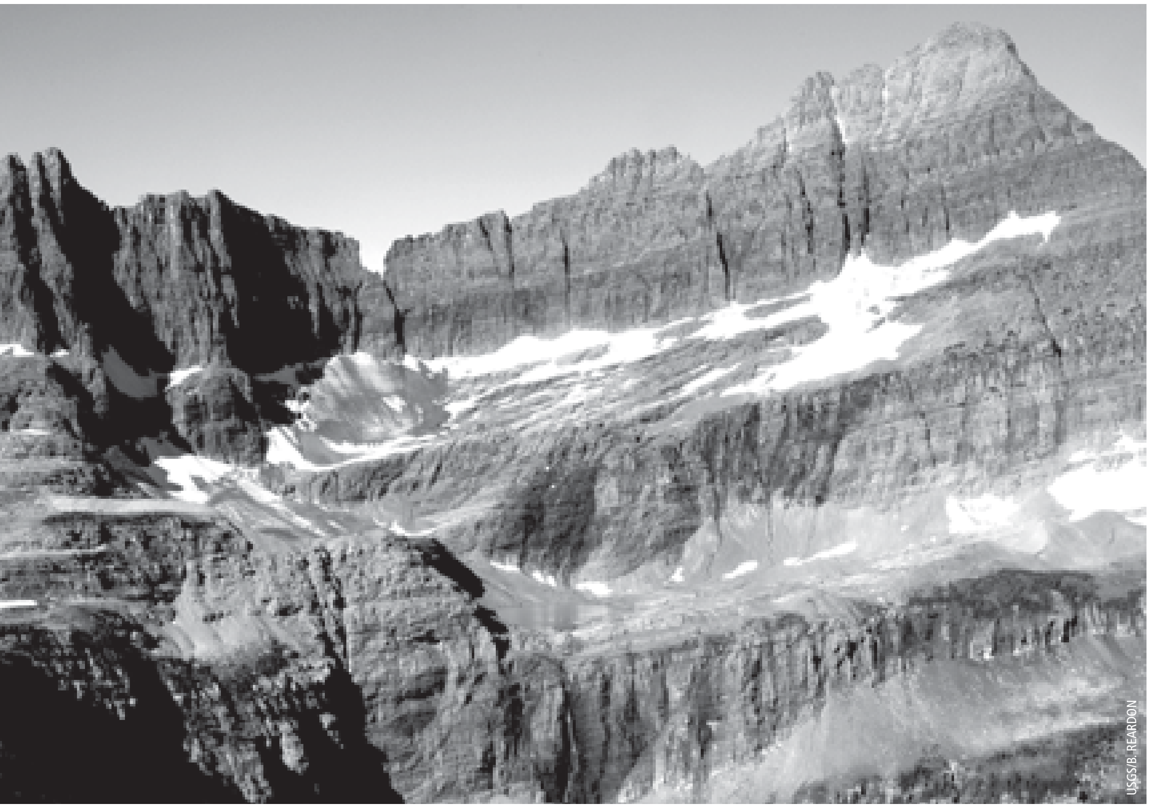
## Southern Rockies

Focused on locations in New Mexico and Colorado, the southern Rockies project assesses the sensitivity of semiarid forests and woodlands to climatic change. The project analyzed recent forest dieback caused by past droughts (Allen and Breshears 1998) and extensive dieback of woody plants caused by the extended current drought, which began in 1996 (Breshears et al. 2005) (fig. 3). The dominant vegetation across extensive portions of this region has shifted in just a few years from pinyon pine (*Pinus edulis*) forest to juniper (*Juniperus* species) forest as a result of pinyon pine dieback, with associated changes in understory vegetation and wildlife habitat.

Also in the southern Rockies, tree-ring reconstruction of crown-fire dates revealed strong associations between past droughts and regional-scale surface-fire years. Charcoal deposits from sediment cores recorded abundant evidence of past fires during the Holocene and suggest that the post-1900 cessation of widespread fire is a phenomenon that has not occurred during the past 9,000 years (Allen 2002). Monitoring of responses of vegetation cover and composition, tree growth, water runoff, and surface erosion to interannual climatic variation started in 1991 during the wettest 15-year period of the last millennium. This monitoring has continued through the ongoing severe drought that began in 1996, documenting ecosystem responses to different climatic conditions.

# Scientific approach

Building on the strengths of these regionally focused projects, the Western Mountain Initiative emphasizes synthesis across sites and regions. WMI is conducting modeling and cross-site syntheses of long-term data, and sponsors workshops that bring together regional and


USGS/B. REARDON

ecosystem modeling in order to best examine responses of western mountain ecosystems to climatic variability and change.

For example, previous WMI studies and other sources have developed proxy reconstructions (natural experiments in time) of past changes in climate, fire regimes, and ecosystem responses that provide an important context for evaluating future trends in climate and natural resources. At millennial time scales, pollen and charcoal in sediments reveal ecosystem responses to widespread and long-term climatic shifts (Whitlock and Anderson 2003). At decadal to millennial time scales, tree rings reveal annual to seasonal changes in climate and fire (Swetnam and Baisan 2003) and consequent trends in populations of forest trees (Swetnam and Betancourt 1998). At time scales of a few years to a century, instrumental records, written records, photographs, and plot data offer fine resolution for mechanistic understanding. Also, quasi-periodic climatic phenomena such as the Pacific Decadal Oscillation (Mantua et al. 1997) and El Niño-Southern Oscillation (Diaz and Markgraf 2000) offer a context for climatic change, particularly when they drive climatic extremes.

Regarding natural experiments in space, our network of research and monitoring sites allows us to generalize across temperature regimes (continental vs. maritime [longitudinal comparisons], warm vs. cool [latitudinal comparisons]), and precipitation regimes (e.g., Mediterranean vs. monsoonal [Sierra Nevada vs. southern Rockies], wet vs. dry [Pacific Northwest to southern Rockies]).

subject-matter experts. We seek to further improve our mechanistic understanding of how climatic variability and change affect western mountain ecosystems directly (e.g., by affecting plant populations and vegetative productivity) and indirectly (as mediated through altered patterns of ecological disturbance and hydrology). To this end, we organize our work around (1) natural experiments in time, (2) natural experiments in space, and (3)

**The Western Mountain Initiative is a collaboration of scientists whose research focuses on understanding and predicting responses of western mountain ecosystems to climatic variability and change.**

**Figure 3. In the southern Rocky Mountains, dieback of around 2.5 million acres (1 million ha) of pinyon pine in 2002–2003 was the result of an extended drought that began in 1996. Researchers with the Western Mountain Initiative have documented a shift in portions of this extensive regional vegetation type toward juniper dominance, with significant implications for wildlife habitat.** USGS/CRAIG ALLEN

The network also offers researchers steep elevational gradients that are associated with steep temperature and moisture gradients.

Finally, the RHESSys (Regional Hydro-EcoSystem Simulation) model (Tague and Band 2001, 2004; Band et al. 1993, 1996) provides a framework for organizing our understanding of ecosystem change. This modeling approach relies on empirical data collected in western mountain ecosystems to (1) frame hypotheses based on past modeling results, (2) scale up empirical results, and (3) identify sensitivities of specific mountain landscapes to climatic change (Urban 2000).

## Western mountains in the greenhouse: A sense of urgency

The past century has been a period of dynamic change for many western mountain ecosystems. By documenting the past response of natural resources to climatic variability at annual, decadal, and centennial scales we have established an important context for inferring the effects of a warmer climate.

Forest dieback in the southern Rockies and parts of the Sierra Nevada is a particular concern because it signals that long-term drought caused an ecological threshold to be exceeded. Dieback at large scales not only changes the structure of current forests, but may be a precursor to future changes in forest composition and structure. Dieback also alters fire behavior, likely predisposing forests to more widespread or severe wildfires. Insect outbreaks appear to be increasing throughout much of the Rockies and eastern Cascades, causing even more concern about dieback and fire (Logan and Powell 2001).

The effects of a warming climate must be assessed in the context of contemporary land use and other human-caused changes. For example, elevated nitrogen deposition in some western mountains is affecting high-elevation lakes and streams and the aquatic organisms that inhabit them (Fenn et al. 2003). Similarly, oxidant air pollutants transported from the San Francisco Bay area and San Joaquin Valley of California are reducing photosynthesis and productivity in ponderosa pine (*Pinus ponderosa*) and Jeffrey pine (*Pinus jeffreyi*) in the mixed conifer forests in the Sierra Nevada (Bytnerowicz et al. 2003). These findings suggest that natural resources in locations with multiple stresses may be more susceptible to climatic change in the future than those resources in locations that experience few to no such stresses.

Based on empirical data and modeling, we expect several significant changes in western mountain ecosystems during this century. The extent and severity of wildfire will likely increase as a result of increased temperature and drying of fuels (McKenzie et al. 2004), compounded in areas where fuels have accumulated for several decades in the absence of fire. Warmer winters will mean less snowpack, earlier melting, and less water storage as snow during summer, lowering summer streamflows in creeks and rivers and reducing water supply for downstream uses such as irrigation, recreation, and municipal consumption (Stewart et al. 2004). At the current rate of warming, most glaciers will disappear from the northern Rockies and will continue to decrease in the Cascades (Hall and Fagre 2003). Finally, continued warming may alter species composition at upper and lower treelines, as species that are better adapted to the new conditions begin to dominate (McKenzie et al. 2003).

The Western Mountain Initiative has demonstrated the value of long-term research and monitoring in U.S. national parks to detect significant changes over time and their causes—including climate and other factors. It has linked with international efforts to monitor mountain ecosystems, and national parks in the western United States are now contributing to a global network seeking early warnings of the effects of climatic variability and change on natural resources. The activities of the Western Mountain Initiative permit resource managers to be better prepared for a climate altered by greenhouse gases wherever they have high-quality scientific data available to detect changes in the condition of natural resources.

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