Project Title: The Western Mountain Initiative: Vulnerability and Adaptation to Climate Change in Western Mountain Ecosystems

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Biogeographic Feature/Region(s): Montane Regions, Forests, Semi-arid Systems

Thematic Area(s): Climate-fire-vegetation interactions; Carbon sequestration; Biogeochemical cycles; Climate variability & extreme events; Disturbance; Watershed response; Hydrology; Modeling (vegetation, ecosystems, spatial/temporal scaling)

Keywords: Adaptation, disturbances, forests, hydrology, mountain ecosystems, resource vulnerability, thresholds

Abstract: Climate warming is affecting Western mountain ecosystems, directly through changes in water dynamics and indirectly through altered disturbance regimes. The Western Mountain Initiative (WMI; http://www.cfr.washington.edu/research.fme/wmi) team explores the effects of climate change on ecological disturbance, responses of forest vegetation, mountain hydrology, and the coupled hydro-ecological responses that determine vulnerability of Western mountain ecosystems to change. Extensive data sets, empirical studies, surveys, and monitoring programs are linked via models to hindcast and forecast the effects of changing climate on forest dynamics, distribution, and productivity; fire occurrence and insect outbreaks; recovery of vegetation after disturbance; hydrologic changes and glacier dynamics; and the consequences of an altered water cycle for terrestrial and aquatic ecosystems and chemistry. We will address the extent to which climate drivers are mediated by regional- or watershed-scale controls on ecosystem processes, thus quantifying vulnerability to climate change in mountain ecosystems. Region-specific results and emergent West-wide patterns will be shared with resource managers through workshops and a comprehensive web-based toolkit on climate-change science and adaptation management.

WMI seeks to understand climate-ecosystem interactions, forecast ecological change, and provide adaptation information for managers. We build on the foundation of our ongoing research program, which includes hundreds of publications, long-term datasets, and a mature network of collaborators. WMI addresses Ecosystem and Climate Change goals of the USGS Global Change Science Strategy, and Goals 4 and 5 of the U.S. Climate Change Science Program Strategic Plan. Both the National Park Service and US Forest Service are developing science-based management approaches for adapting to climate change, and WMI will collaborate directly with both agencies to ensure scientific consistency in the implementation of adaptation strategies.

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I. OBJECTIVES AND JUSTIFICATION

Need

Western mountains are beginning to see changes in ecosystem processes primarily from climate-forced changes in water dynamics. With earlier snowmelt and increasing proportions of rain versus snow (Mote 2003, Stewart et al. 2005, Knowles et al. 2006), drought stress is increasing. Cascading effects include increasing vegetation mortality (van Mantgem & Stephenson 2007, van Mantgem et al. in review), dieback of entire forest stands (Breshears et al. 2005, Allen & Breshears 2007), longer and more intense fire seasons (McKenzie et al. 2004, Westerling et al. 2006, Margolis et al. 2007, Swetnam & Anderson 2008, Littell et al. in press), and increasing susceptibility to insects and pathogens (Carroll et al. 2004, Breshears et al. 2005). Climate model projections suggest all these phenomena will become more pronounced in coming years (IPCC 2008).

Climate-forced changes in hydrology at high elevations are being caused by temperature-driven changes in winter precipitation form and snowmelt and by direct summer warming (Stewart et al. 2005, Knowles et al. 2006). Permanent snow and glaciers are retreating rapidly (Hall and Fagre 2003, Granshaw & Fountain 2006, Hoffman et al. 2007), portending the loss of smaller glacier masses in the continental U.S. within the century (Dyurgerov & Meier 2000). Water chemistry is changing as weathering rates increase and new sediments are exposed (Williams et al. 2007, Thies et al. 2007, Baron et al. in review). Increased stream temperature and decreased summer flow will strongly affect mountain aquatic ecosystems.

These ongoing and forecasted changes in Western mountains are important for both people and ecosystems in the western U.S. Western mountains provide water for agriculture and 60 million people, as well as timber and other commodities, and support recreational activities. National parks and national forests contain large areas of reasonably intact natural ecosystems, protect critical wildlife habitat, and maintain natural ecological processes. The Western Mountain Initiative (WMI) addresses how climate change influences forest processes, disturbance dynamics, mountain hydrologic changes, and ecohydrological interactions between climate, water, and vegetation. We use an ecosystem approach to understand how Western mountain ecosystems respond, now and in the future, to climate variability and change.

Understanding how mountain ecosystems respond to climate change is essential to natural resource management, and including climate change effects in management planning and implementation will reduce surprises and damage to natural resources (Millar et al. 2007, Julius et al. 2008). Ongoing climate change requires resource managers to change how they think about ecosystems. Therefore, preparing for and adapting to climate change is a cultural and institutional challenge as well as an ecological one, and the need for adaptive management has been clearly stated by the U.S. Climate Change Science Program (Julius et al. 2008).

We build on the past five years of WMI research. Broad-scale climate drivers can induce region-wide responses, but directional changes in systems must be distinguished from sources of variability related to normal climate variation and other factors. Long-term studies by WMI have identified regional responses in disturbance patterns, vegetation dynamics, and hydrology caused by a combination of regional climate patterns (van Mantgem & Stephenson 2007, Littell et al. in press), topographic complexity (Hicke et al. 2006, Christensen et al. 2008), and landscape controls (Tague et al. 2008). As in the preceding phase of WMI research, we will continue to investigate spatial and temporal aspects of ecosystem dynamics, but emphasis will shift to understanding and distinguishing processes controlled by climate versus processes modulated by local or regional characteristics across the mountainous West.

Our broad goal is to develop and synthesize empirical and modeled results to infer mountain ecosystem resistance and resilience to climate change. Specifically, we will (1) determine vulnerability (rapidity and magnitude of change) of forest and hydrologic processes, and (2) develop adaptation methodologies tailored to regions and issues. This new five-year phase of the WMI program will focus on forest vegetation and disturbance, mountain hydrology, and ecohydrology. We will:

- Enlarge studies of forest dynamics across 7 Western states, project forest changes into the future, and assess forest vulnerability to dieback at extensive spatial scales;
- Quantify variability in fire severity among mountain ecosystems and estimate future burn patterns based on climate, particularly duration and intensity of summer drought;
- Quantify and partition the relative roles of climate effects on trees versus climate effects on insect populations in causing insect outbreaks, and use this knowledge to model potential future epidemics;
- Evaluate effects of fires and insect outbreaks on forest carbon in the Western states, and include these estimates in evaluation of potential future forest carbon sequestration;
- Analyze trends in timing and magnitude of snowpack accumulation and ablation and mountain hydrology for five national parks and environs, and use these data to estimate future trends;
- Develop mass balances for many remaining glacier bodies in the conterminous U.S., and forecast rates of glacier recession;
- Survey changes in water quality from glacier and cryospheric wasting, and produce maps and forecasts of the risks to water quality and aquatic ecosystems from heavy metals and nutrients in five Western states;
- Work closely with National Park Service and U.S. Forest Service managers to craft and implement site-specific adaptation strategies.

WMI objectives address goals and priorities of the U.S. Climate Change Science Program (CCSP), especially Goal 4 (“understand the sensitivity and adaptability of different natural and managed ecosystems ...”) and its priority topics “thresholds of change ...,” “relationship between observed ecosystem changes and climate change,” and “preliminary review of adaptation options ...” WMI also addresses Goal 5 (“explore the uses and identify the limits of evolving knowledge to manage risks ...”) and its priority topics “uses and limitations of observations, data, forecasts, and other projections in decision support ...” and “best-practice approaches to characterize, communicate, and incorporate scientific uncertainty in decisionmaking.”

WMI also aligns with USGS climate change strategic goals for 2007-2017, USGS-BRD climate change goals established in 2003, and each of the five-year goals and objectives of the BRD Global Change Program. WMI focuses on sensitivities and response thresholds of resources to climatic stressors (Goals 1.1, 1.3) and identification of critical areas (Goal 1.2). Causal mechanisms driving ecosystem responses to climatic variability (Goal 2) are addressed by regional expansion, modeling, and continued monitoring across five mountain regions. Spatial scaling (plot to sub-continent) and temporal scaling (daily to millennial) are strong features of WMI and address Goals 3.1-3.4. Carbon sequestration and flux (Goal 5) in mountain regions are evaluated through modeling and field studies and will likely be a future strategic DOI concern (Goal 5.6). We incorporate federal land managers through formal (e.g., workshops) and informal avenues to test management relevance of research products (Goal 4). We will build on our track record of effective communication with DOI managers and other stakeholders by providing the Multiagency Toolkit for guiding decisions under the uncertainties of global change (Goal 6).

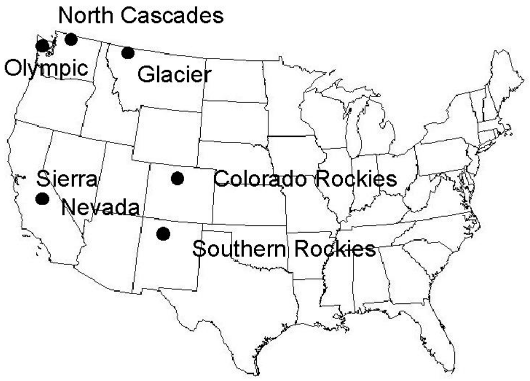

Figure 1. Western Mountain Initiative core sites.

Background

In 2003, a consortium of USGS and US Forest Service scientists associated with long-term global change research collectively initiated an integrated project, *Response of Western Mountain Ecosystems to Climatic Variability and Change: The Western Mountain Initiative*. The co-PIs have long-term studies and datasets for national parks and forests in the Sierra Nevada, Cascade Range, and Rocky Mountains (Figure 1). Since 2003, we have focused on synthesis and integration across the West, with studies that provide regional perspectives of how climate variability and change affect disturbance regimes, vegetation dynamics, and hydrologic processes. The WMI consortium has been highly productive scientifically, engaged with managers and policy makers, and publicly visible (see IV. PAST PRODUCTS below). Our results are providing the scientific basis for quantifying vulnerability of mountain ecosystems to climate change and developing adaptation strategies for resource management. WMI has been cited internationally as a model for interdisciplinary research and science delivery to resource managers (CIRMOUNT 2006, Drexler 2008, Greenwood 2008).

II. PROCEDURES and METHODS

Conceptually, WMI addresses three activities (Figure 2):

Understand climate/ecosystem interactions, and detect and attribute change. Land managers and policy makers need evidence that ecosystems are changing (*detection*), and that those changes are caused by specific agents (*attribution*), to develop and implement adaptive management. Proposed studies expand the geographic scope of current WMI study sites and provide long-term empirical data and mechanistic understanding for modeling.

Ecological forecasting: identify thresholds and vulnerabilities. Building on previous modeling efforts, we will provide forecasts of specific changes across the West, which in turn will provide the scientific basis for developing descriptions of future ecosystem conditions in Western mountains. We will emphasize the local and regional *vulnerabilities* of ecosystem components or processes to climate variability and change, *thresholds* at which specific forest or hydrologic ecosystems may experience state changes, and *uncertainties* associated with the forecasts.

Develop adaptation strategies. Our studies and model results will provide scenarios of future ecosystem conditions, a necessary first step in identifying adaptation options. In collaboration with land managers and specific places, we will incorporate the results of our research to develop a range of tools and strategies for adapting to climate change and its effects, driven by the goal of maintaining critical ecosystem structures and functions, along with associated native biodiversity.

We organize our work as follows:

Forest vegetation and disturbance – Changes in productivity, forest dynamics, and large-scale dieback; changes in fire, insect outbreaks, and disturbance interactions; and variability of these disturbances across time, space, and land use.

Mountain hydrology – Consequences for ecosystems of receding glaciers and earlier snowmelt, including altered biogeochemistry and hydrology.

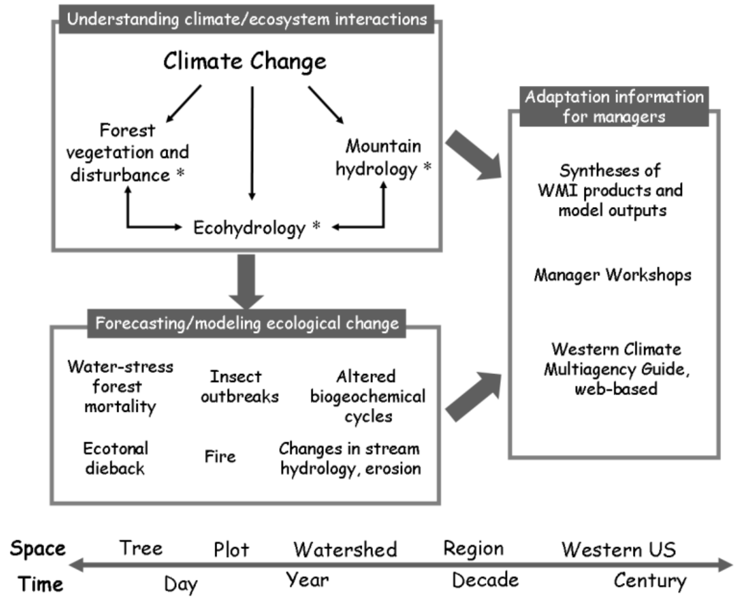

Figure 2. The Western Mountain Initiative addresses climate change in mountainous ecosystems of the West. Three themes (*) address the WMI activities (boxes) that span a broad range of spatial and temporal scales. Delivery of research findings in the form of adaptation options is the focus of right box.

Ecohydrology – Coupled impact of changes in snow and glaciers with vegetation drought stress and disturbance regimes, and the impact of changes in vegetation on the timing, magnitude of streamflow, water quality, and erosion.

Adaptation – Expand the Forest Service project “A toolkit for adapting to climate change on western national forests: incorporating climate into resource management and planning,” into national parks and explicitly incorporate WMI research and modeling findings into place-based scenarios of future climates and ecosystem responses.

1. Forest Vegetation and Disturbance

1.1. Climate-induced mortality and dieback

WMI has documented chronic and acute increases in tree mortality across the West (e.g., Breshears et al. 2005, van Mantgem & Stephenson 2007, Allen 2007, van Mantgem et al. in review). Although the increases are correlated with regional warming, causation has not been established. We therefore propose four complementary tasks that address the hypothesis that climate is the underlying cause for increased tree mortality across the West:

Task 1.1.1. Quantify tree water stress with carbon isotopes. Annual-resolution carbon isotope ratios (δ^{13}C) in tree rings from permanent plots in 7 Western states will determine if water stress increased over the period of chronically increasing mortality. The relative roles of climatic stress effects on trees versus insect infestation in episodes of acute forest dieback will be determined using δ^{13}C series for trees in Colorado and New Mexico, where acute dieback has been well documented. The δ^{13}C series of genera that have (*Pinus*, *Abies*, *Pseudostuga*, *Picea*) and have not (*Calocedrus*, *Juniperus*) experienced increased mortality rates will be compared and contrasted in light of isohydric and anisohydric tree responses to drought (cf. McDowell et al. 2008a). Work will be conducted in collaboration with Nate McDowell (Los Alamos National Lab) following methods of McDowell et al. (2008b).

Task 1.1.2. Identify drivers of mortality and improve model mortality functions. Collect forest demography measurements in Sierra Nevada and Southern Rockies plot network. In the Sierra Nevada, we will interpret our continuing long-term tree mortality measurements in light of soil moisture and tree sap flow measurements in the associated NSF Critical Zone Observatory. In the Jemez Mountains (NM), we will use aerial photo imagery, QuickBird imagery, and ground surveys (supplemented by dating of tree death) to map the magnitude, extent, and causes of forest dieback in the Southern Rockies, comparing effects of 1950s (cool) and 2000s (warm) droughts (cf. Allen & Breshears 1998, Mueller et al. 2005, Breshears et al. 2005). We will ordinate long-term data used to demonstrate increased tree mortality to determine if differing mortality rates among tree species are driving compositional shifts. We will use repeated tree diameter measurements from the same data set to determine long-term trends in tree growth rates (Jump et al. 2006, Feeley et al. 2007), interpreted in light of ongoing work relating growth and mortality (Das et al. 2007).

Task 1.1.3. Incorporate measured forest drought stress response into a statistical and a process-based model to forecast mortality under a range of climate scenarios. We will use measurements and analysis from Tasks1.1.1 and 1.1.2 to refine model estimates of forest response in RHESSys (Tague & Band 2004; discussed below in Ecohydrologic Response), which was used extensively by WMI in the past. For comparison, we will also forecast mortality rates with a statistical model that links climate to increased tree mortality rates across the West (van Mantgem & Stephenson 2007; van Mantgem et al. in review). Model results will be compared and presented as “risk maps” for forest lands in the West.

Task 1.1.4. Use multiple approaches to scale up assessments of forest dieback vulnerability from sites to larger landscapes, regions, the West, and globally, including: (a) work with DIRENET colleagues (cf. https://mprlsrvr1.bio.nau.edu/direnet/) to assess forest/species dieback patterns across montane environmental gradients using West-wide Forest Inventory and Analysis (FIA) data (e.g., Shaw et al. 2005, Cobb et al. 2007); (b) convene an international forest dieback workshop (cf. Allen & Breshears 2007); and (c) work with other modeling groups and collaborators (Bigler et al. 2006, Das et al. 2007, Dobbertin et al. 2007, McDowell et al. 2008a, Breshears et al. 2008, Gonzalez et al. in review) to refine forest mortality thresholds in the models.

1.2. Causes and consequences of altered disturbance regimes

Recent increases in annual area burned and fire size are attributed to a warming climate (Westerling et al. 2006, Littell et al. in press). Similarly, outbreaks of bark beetles in the western U.S. and Canada are linked to temperature effects on insect populations (Logan et al. 2003, Carroll et al. 2004). But there is process variability within these broad patterns at the scale of mountain landscapes where changes in disturbance regimes affect ecosystems and the people who use or manage them. We will focus on quantifying large-scale influences on extent and severity of fires, and relative contributions of host vulnerability and beetle population dynamics to extent and severity of outbreaks. Specifically, we will:

Task 1.2.1. Quantify fire severity and changes in high-severity patch size in wildfires, using existing fire records (1916 - present) and Landsat scenes (1970s - present). Many of the records are held by WMI researchers (Gedalof et al. 2005, Lutz 2008, Littell et al. in press), and some fire severity information is available from the USGS Monitoring Trends in Burn Severity project (http://svinetfc4.fs.fed.us/mtbs/). We will focus on patterns of high-severity patches for fires >40 ha. Specific goals include identifying trends and interannual variability in fire severity, and isolating the proportion of variability associated with seasonal and annual variability in summer drought, snowpack (Lutz 2008), and synoptic conditions (Gedalof et al. 2005).

Task 1.2.2. Increase mechanistic understanding of how climate affects mountain pine beetle and tree vulnerability in initiating outbreaks. We will (a) assemble 25-year records of climate, drought, and soil moisture using output from the VIC hydrologic model (http://www.hydro.washington.edu/Lettenmaier/Models/VIC/VIChome.html), weather stations, and climate data; (b) collect tree-ring samples to characterize growth responses to climate conditions at the time of outbreak; (c) use empirical models of host vulnerability (Shore & Safranyik 1992, Oneil 2007) to identify stand-scale and climate variables associated with beetle attacks; and (d) use insect population models driven by changing climate (Logan et al. 2003, Carroll et al. 2004, Hicke et al. 2006).

Task 1.2.3. Quantify the effects of fires and bark beetle outbreaks on forest carbon stocks across the western U.S. We will estimate affected carbon stocks beginning in 1980 (for fires) and 1997 (for outbreaks) through the present using existing data for these disturbances together with an established database of carbon stocks developed from U.S. Forest Service inventories. Annual statistics and maps will be produced at county, state, regional, and subcontinental (Westwide) scales (Hicke et al. 2007).

Task 1.2.4. Increase understanding of forest recovery after disturbance. Climate variability (e.g., drought) can markedly affect post-disturbance ecosystem recovery (Mayor et al. 2007). We will assess post-fire recovery of ecosystem structure and function along climatic gradients in dry forests using remotely sensed and ground data on post-fire recovery of vegetation and surface cover (Mayor et al. 2007, van Leeuwen 2008), and Landscape Function Analyses (Tongway & Hindley 2004) in post-fire watersheds to determine linkages between ground cover/pattern and soil/ecological function. We will conduct comparative studies in the Southern Rockies, Arizona, and the Mediterranean Basin (van Leeuwen et al. in review).

Task 1.2.5. Increase quantitative understanding of disturbance interactions. The effects of interacting disturbances on ecosystems (Allen 2007) are sensitive to timing and magnitude of individual events, and the magnitude of synergistic effects can be quantified (e.g., Bigler et al. 2005) given a sufficiently deep temporal record. A WMI-sponsored workshop established that minimal ecological theory exists on which to base predictions of the magnitude or direction of disturbance interactions in a changing climate (McKenzie and Allen 2007). We will redress this gap with empirical and modeling studies of fire-insect interactions and ecosystem effects by (a) simulating wildfire and mountain pine beetle in the Greater Yellowstone Ecosystem, using FireBGC (Keane et al. 1999), and (b) analyzing of beetle outbreaks in conjunction with the Hayman fire in the Central Rockies.

2. Mountain Hydrology and Dynamics

Snow is a critical driver of Western ecosystem processes, affecting streamflow and vegetation susceptibility to fire and insect outbreaks (Stewart et al. 2005, Westerling et al. 2006, van Mantgem & Stephenson 2007). We will provide historic snow and hydrologic analyses and quantify the role and rates of recession of the remaining 8303 glaciers and permanent snow and ice features in the continental U.S. (Fountain et al. 2007). Although West-wide trends, such as earlier onset of snowmelt, have been documented for Western mountains (Mote 2003, Stewart et al. 2005), our analysis will link additional metrics of change and additional data for a finer-resolution evaluation of current WMI study sites. We will build on previous WMI work that combined streamflow data and RHESSys hydrologic estimates to examine interactions between snowpack dynamics and streamflow for each WMI study sites. Results will be used in virtually all other WMI activities outlined in this proposal.

As mountain ice shrinks and the dynamics of seasonal snowpack change, an unexpected response appears to be altered water quality via increased heavy metal concentrations and nitrogen from newly-exposed sediments (Thies et al. 2007, Williams et al. 2007, Baron 2008, Baron et al. in review). This phenomenon has implications for high elevation aquatic ecosystems where slight increases in nutrients trigger eutrophication and where heavy metals pose a water quality risk. In the western U.S. there are many high elevation, ultra-oligotrophic water bodies as well as glacierized mineral belts with heavy metals (Fenn et al. 2003, Church et al. 2007). Based on water quality changes from melting rock glaciers in Colorado (Williams et al. 2007, Baron et al. in review), Canada (Lafrenière & Sharp 2005), and the Alps (Thies et al. 2007), we will explore this same phenomenon in Western mountains.

Task 2.1. Analyze trends in timing and magnitude of snowpack accumulation and ablation and mountain hydrology. We will focus on Rocky Mountain, Sequoia, and North Cascades National Parks and Bandelier National Monument; Glacier National Park has been completed. We will characterize: (a) changes in the evolution of snowpack through accumulation and melt seasons (onset of snow accumulation, date/magnitude of maximum snowpack, number of snow-free days; (b) regional rates of temperature change, especially changes in the 0°C threshold, and changes in precipitation phases (rain:snow ratio) (sensu Knowles et al. 2006); and (c) changes in amount and timing of regional streamflows (peak runoff and 50% cumulative stream discharge) (e.g., Maurer et al. 2007). We will investigate relationships between changes in evolution of regional snowpack and streamflow to determine the predominant climate controls (e.g., Mote 2003, Barnett et al. 2008).

Task 2.2. Quantify glacier volume. We will estimate the volume of most glaciers (N=8303) in 8 states with statistical models (e.g., Granshaw & Fountain 2006), and for selected glaciers, use photo-modeling software validated with ground-based measurements. Change in glacier volume (shrinkage) defines the volume of water from storage supplied to late summer runoff and is critical to the hydrologic balance. This broad analysis will be supported by identifying two new benchmark glaciers (one currently exists in the North Cascades) in Rocky Mountain and Glacier National Parks. Detailed field-based measurements at these new benchmark glaciers will provide insight into local influences of topography, microclimate, and regional climate critical to interpreting regional-scale changes identified in aerial photos and satellite imagery (Fountain et al. 1997).

Task 2.3. Forecast rates of glacier recession for the American West. We will examine four modeling approaches to determine the best application for our needs: a simple scaling algorithm (Bahr et al. 1997), a cellular automata approach (Harper & Humphrey 2003), a geospatial model (Hall & Fagre 2003), and a mass/energy balance model (e.g., Plummer & Phillips 2003).

Task 2.4. Evaluate changes in climate-driven headwater chemistry. We will survey a range of Western headwaters in WA, ID, MT, WY, CO selected from the 1985 EPA Western Lake Survey (Eilers et al. 1986) and Regional Environmental Monitoring and Assessment Program Southern Rockies case study (http://www.epa.gov/nerlesd1/land-sci/southern_rockies) to capture bedrock spanning highly unreactive to strongly mineralized geochemistry. Late summer surveys will include major ions, heavy metals, and stable isotopes of C, N and O. We will continue intensive process-based studies in the Colorado Rockies to determine the source of late summer flow and solutes using stable isotopes of C, N, and O in inorganic and organic solutes in glacierized and non-glacial catchments. We will also initiate water quality measurements at all benchmark glacier sites to track changes as glaciers recede.

3. Coupled Ecohydrologic Responses

Ecohydrology couples climate-caused changes in mountain hydrology with the responses of forest vegetation and disturbance (Breshears 2005). Changes in glaciers, snowpacks, streamflow, and water quality directly affect terrestrial and aquatic ecosystems, and changes in water relations in the coupled atmosphere-soil system affect vegetation through stress and altered disturbance regimes. Empirical studies will focus on semi-arid watersheds, in which vegetation responses are especially sensitive to drought and disturbances, and subalpine forests in Loch Vale (Central

Rockies) where we build on existing long-term geochemical measurements. Modeling studies will use our existing set of case-study watersheds, addressing the full range of environmental gradients across the West.

3.1. Ecohydrology empirical studies

Task 3.1.1. Ecohydrologic response in semi-arid systems. The mountain West is largely a dry region, and "many semi-arid and arid areas (e.g., the Mediterranean basin, western USA) are particularly exposed to the impacts of climate change and are projected to suffer a decrease of water resources due to climate change" (IPCC 2008). We will use a multi-scale analysis in the southern Rockies to examine semi-arid ecohydrology in detail, with specific attention to climate-mediated degradation (increased runoff, erosion, desertification), the potential for extreme events, and the interactive effects of climate change on runoff and erosion; surface vegetation cover, pattern, and diversity; and tree population dynamics. WMI has intensive data at the Frijolito watershed since 1993 encompassing very wet to very dry climate, runoff and erosion, soil cover and patterns, microtopography, tree population dynamics, and soil carbon (Wilcox et al. 2003). These data will be used to analyze multi-scale runoff and erosion rates linked to climate-driven changes in vegetation, and will be further scaled up to assess climate-driven erosion rates for downstream tributary watersheds in the Rio Grande system. We will quantify responses (including thresholds) of runoff and erosion to changes in vegetation cover and spatial pattern and to precipitation amount and intensity (cf. Bautista et al. 2007, Mayor et al. in press), and project vulnerability under climate-change scenarios. We will conduct adaptation-related experimental research on management options to foster drought resilience or recovery of dry forests after desertification, comparing treatment effects on runoff, erosion, and tree mortality during drought in an ongoing extensive (>1000 hectares) thinning/mulching treatment of semiarid woodland in the Southern Rockies (USDI NPS 2007), including intensively studied control plots.

Task 3.1.2. Ecohydrologic response in subalpine systems. Ecohydrological studies will be initiated in Loch Vale, a subalpine forest watershed in Central Rockies, to quantify hydrologic conditions across a gradient in soil moisture availability while combining field and chamber measurements of tree carbon gain and water loss. In conjunction with researchers at Colorado State University (Kampf, Bauerle) and Los Alamos National Laboratory (McDowell) we will: (a) characterize hydrologic conditions by monitoring spatially distributed soil moisture, matric potential, soil temperature, and saturated water levels; (b) use leaf and whole-tree gas exchange, sap flow, spectroradiometry, soil moisture, plant water status, stable carbon isotopes, and LiDAR to quantify tree responses to elevated temperature and water stress; and (c) evaluate model estimates under natural and N-fertilized conditions, taking advantage of a 10-year fertilization experiment. Parameter values from these multi-scale measurements, in conjunction with RHESSys, will quantify levels of past and current water stress and hillslope hydrology and forecast the fate of subalpine forests under climate change.

3.2. Simulation modeling and ecosystem forecasting

In the preceding phase of WMI research, we used RHESSys to model ecosystem processes and hydrology in five forested montane watersheds representing diverse conditions across the western U.S. (sites in MT, CO, NM, CA, WA) (Christensen et al. 2008). In addition, ongoing RHESSys applications as part of other projects include a range of watersheds throughout the West (Tague et al. 2008; Tague et al. in review). Analysis at the scale of these sites (<800 km^2) is critical given that management of resources takes place at small watershed scales where process-based interactions are determined by gradients in snow, temperature, and radiation; spatial distribution of moisture; vegetation structure and pattern; and disturbances (fire, insects, mass movements). This abundant RHESSys model output is ready to be carried to the next level of interpretation. Models are useful as hypothesis-generating tools, and we will use observations and analysis from Sections 1, 2, and 3.1 above to iteratively refine model estimates of coupled ecohydrologic responses, thereby maximizing the value of previous simulations while integrating new data. Models are also valuable tools for generating scenarios; we will use RHESSys to forecast ecosystem responses (hydrology, vegetation, disturbance, aquatic habitat) to climate change.

Task 3.2.1. Quantify streamflow responses to coupled climate-ecologic drivers. Using RHESSys we will develop streamflow estimates for existing and projected future climates for the five WMI core site watersheds discussed above. We will assess how different controls on streamflow, including changing snow and glacier melt dynamics and changing vegetation water use interact to alter the magnitude and timing of streamflow. Previous work (Richter et al. 1996, Poff et al. 1997) has developed streamflow metrics that link changes in streamflow dynamics with stream habitat characteristics and aquatic ecosystem health. We will compute these ecologically relevant streamflow metrics for climate scenarios at each site and use results to assess vulnerability of aquatic biota under future climates.

Task 3.2.2. Quantify interactions between hydrology, vegetation, and disturbance. Our earlier analysis with RHESSys did not incorporate effects of fire and post-fire succession. We will develop an integrated modeling framework that couples spatially explicit carbon cycling and hydrological modeling in RHESSys with (a) a forest successional model that distinguishes individual species (Miller & Urban 1999), and (b) a raster-based fire-spread and fire-effects model coupled to watershed hydrology via fuel-moisture algorithms (Cohen & Deeming 1985, Nelson 2000). We will use downscaled meteorology for current and future decades to produce climate drivers (from Ojima, forthcoming) and fire management scenarios (Loehman et al. 2008) to capture the expected range of variability from climate and human factors. We will begin with the five watersheds discussed above and expand to at least five other montane watersheds to capture an even greater range of environmental conditions across the West.

4. Adaptation

Meeting the challenges that climate change poses to Western mountain ecosystems requires a shift in how we use science, how we plan, and how we implement adaptation strategies (GAO 2007). Taking no action in the face of climate change is a decision that may carry the greatest risk. Results of our research and modeling activities will be directly applicable to adaptation activities in two ways. First, they will provide evidence of past and current rates and mechanisms of change and recovery from disturbance. One of many examples is found in Task 3.1 above, where vegetation type and pattern will be quantitatively related to rates of runoff and erosion as climate varies. Second, our model results provide scenarios of vulnerability to possible future conditions that can be used directly in landscape to region-specific planning for climate change. For instance, ecologically relevant streamflow metrics (Task 3.2.1) provide the requisite flow regime targets necessary for maintaining or restoring aquatic habitat. These and other results will be synthesized and transferred directly to resource managers via a multiagency website similar to (and building from) the “MultiAgency Guide to Adapting to Climate Change”, and through workshops planned and supported by the U.S. Forest Service and National Park Service. As authors of recent works describing the necessary steps for adapting to climate change (Millar et al. 2007, Baron et al. 2008, Fagre et al. in prep, Joyce et al. 2008), we have the credibility to transfer specific information and new methods of planning and managing resources, including adaptive management and scenario planning skills. WMI will contribute materials to the web-based Multi-Agency Guide based on the results of research and modeling, and in years 2012-13 will take on management and maintenance of the website.

III. EXPECTED PRODUCTS (see Table 1)

Publications and Reports

- Peer-reviewed articles. Given past productivity in this area, we expect >150 articles in a wide range of journals, book chapters, agency publications, and proceedings.
- Dissertations and theses. We expect >15 student dissertations and theses.
- Multi-agency Adaptation Guide (see II.4 above).
- Fact sheets and reports. A series of brief common-language documents will be sent directly to resource managers.

Data and metadata. Metadata will be prepared for all data sets compiled by WMI, and metadata and data sets compiled through WMI will be made available through links on the NBII Clearinghouse.

The WMI *web site* will be a focus for all activities and products, and will contain the following sections: (1) overview and site descriptions, (2) program activities and schedule, (3) project personnel, (4) products, (5) technical transfer and interpretive section, including summaries of major findings.

IV. PAST PRODUCTS

Publications: From 2004 to the present, WMI has produced 170 publications, 6 PhD. dissertations, 12 M.S. theses and 2 books; results have also been presented in 360 talks. We highlight a few publications below; all are listed at http://www.cfr.washington.edu/research.fme/wmi/pubs.htm.

- Sustaining Rocky Mountain Landscapes, Prato & Fagre, eds. (RFF Press 2007).
- Adaptations of National Parks to Climate Change, Baron et al. (U.S. Climate Change Science Program, Synthesis and Assessment Product 4.4, 2008).
- 11-paper climate-fire section, International Journal of Wildland Fire 17(1) (2008).

Models and software:

- RHESSys (Regional HydroEcological Simulation System, //fiesta.bren.ucsb.edu/~rhessys)
- CHARSTER software manages and analyzes sedimentary charcoal data, http://geography.uoregon.edu/gavin/charster/Introduction.html).

Data sets (selected examples):

- Glaciers Online provides interactive maps, photos, and data for glaciers and glacier change in the western U.S. (http://www.glaciers.us); U.S. Geological Survey Open File Report 2006-1340, 23 pp., http://pubs.usgs.gov/of/2006/1340/
- Sierra Nevada forest dynamics: A globally-unique 27-year time series of annual-resolution data for forests has provided insights into environmental controls of forest dynamics, and evidence of increases in background tree mortality rates.
- Loch Vale Watershed Long-Term Ecological Research and Monitoring Program: Since 1983, the continuous record of ecosystem and physico-chemical trends in Colorado alpine and subalpine processes has been central to National Park Service and Colorado air quality policy and climate change - air pollution interactions.
- Fire area database for the western United States: Reconstructions of area burned for 20 ecoprovinces in the western United States, 1916 to 2004. These data form the basis for predictive models of the effects of climate variability on fire area.

Engagement with managers and policy makers (selected examples):

WMI scientists were active invited members of the Dept. of Interior Climate Change Task Force, the GAO Expert Panel on guidance to federal land managers for addressing climate change, lead and contributing authors to the CCSP, invited/keynote speakers on adaptation to climate change at the 2006 George Wright Society and 2008 Association for Fire Ecology meetings, heavily engaged as local experts in western national parks, and invited participants in many state, regional, and national level climate change advisory panels, workshops, etc.

Media and Public Visibility (selected examples):
WMI's work regularly attracts national attention, and has been carried by AP, written up in Science, National Geographic, Audubon, OnEarth Magazine, High Country News, Landletter and Greenwire, broadcast on local radio, NPR and the BBC, and spotlighted in television specials and news for PBS, ABC, CBS, and the Discovery Channel.

V. TECHNOLOGY AND INFORMATION TRANSFER

A primary means for knowledge transfer to land managers will be the Multi-Agency Guide to Adapting to Climate Change, its associated website, and workshops conducted as case studies for developing and implementing adaptation options. USGS will build on the Climate Change Resource Center (http://www.fs.fed.us/ccrc), a Forest Service compendium of climate-change and adaptation resources; web specialists and students at the Fort Collins Science Center will work with their counterparts at the U.S. Forest Service, Pacific Northwest Research Station. Frequent interactions with resource managers, media, and the general public will continue, as will our participation in the scientific training of graduate and undergraduate students, many of whom become resource management professionals. We will also provide many contributions to the scientific literature and summaries of peer-reviewed findings in common language articles and fact sheets.

VI. DATA MANAGEMENT

Each WMI site manages multiple long and short-term datasets compiled over the past ~20 years, including empirical data collected by the PIs and cooperators, as well as other place-based data sources (e.g., local climate and stream gage data). We will review the quality of all data sets prior to aggregating and analyzing data through WMI. We will develop metadata for WMI datasets according to National Biological Information Infrastructure (NBII) protocols. Metadata records and data will be posted on the WMI web site and NBII and Science Center Clearinghouses. In addition, all manuscripts, reports, fact sheets, maps, PowerPoint material, and other products conducive to electronic format will be posted on the WMI web site. Dave Peterson has considerable experience in bioinformatics and was PI for the NBII Pacific Northwest node; he will lead this effort, assisted by Paige Eagle (data manager, webmistress).

VII. PERSONNEL

WMI Principal Investigators	Responsibility
Craig Allen (Southern Rockies) USGS Fort Collins Science Center	Analyze effects of drought, fire, and insects on vegetation; analyze ecohydrology; synthesize data for Southwest and forest dieback.
Jill Baron (Central Rockies) USGS Fort Collins Science Center	Provide oversight for biogeochemical studies; analyze effects on aquatic ecosystems, analyze effects of atmospheric deposition; develop and help implement adaptation strategies; coordinate internal and external WMI communication.
Dan Fagre (Northern Rockies) USGS N. Rocky Mountains Science Center	Analyze effects on hydrologic resources; synthesize data for Rocky Mountains.
Nate Stephenson (Sierra Nevada) USGS Western Ecological Research Center	BRD principal contact; analyze effects of multiple stressors on vegetation; synthesize data for Sierra Nevada.

Don McKenzie (Pacific Northwest) U.S. Forest Service, PNW Research Station	Analyze effects of fire and insects on vegetation; provide oversight for fire and vegetation modeling; synthesize data for Northwest.
Dave Peterson (Pacific Northwest) U.S. Forest Service, PNW Research Station	Quantify vulnerability across WMI ecosystems; develop and help implement adaptation strategies; coordinate internal and external communication

VIII. MANAGEMENT PLAN

Jill Baron will provide administrative leadership for WMI, ensuring that meetings are convened, conference calls are held, milestones are met, and products are completed in a timely way. She will be assisted by a graduate student (K. Galles), who will do much of the hands-on work of administration, keeping the WMI calendar, planning meetings, dealing with publishers, compiling the annual report, and general outreach. Communication will be ensured by: (1) an annual meeting for PIs, collaborators, and managers convened at a WMI research site, (2) quarterly conference calls for PIs, (3) and special sessions at professional meetings (e.g., Ecological Society of America, AGU, MTNCLIM).

IX. COOPERATORS/PARTNERS

Only primary research partners ("lead collaborators") are listed below; summaries of their qualifications are attached. In the process of doing broadly synthetic research on Western mountains, we will continue interacting with many colleagues including international scientists. Collaborative research will be formalized by updating and renewing agreements with universities; international expertise will be formally incorporated where appropriate.

Lead Collaborators	Responsibility/contribution
John Battles, University of California, Berkeley, jbattles@nature.berkeley.edu	Collaboration on causes of increasing tree mortality, and modeling tree mortality
William Bauerle, Colorado State Univ., bauerle@colostate.edu	Collaborate on studies of ecohydrology.
Susana Bautista, Univ. Alicante (Spain), sbautista@ua.es	Collaborate on studies of ecohydrology and post-fire forest recovery
Dave Breshears, Univ. Arizona daveb@lanl.gov	Collaborate on studies of forest dieback and ecohydrology
Adrian Das, University of California, Berkeley, adas@nature.berkeley.edu	Collaboration on causes of increasing tree mortality, and modeling tree mortality
Andrew Fountain, Portland State Univ. andrew@pdx.edu	Analyze effects on snow and glaciers; synthesize data across the West.
Jeff Hicke, Univ. Idaho jhicke@uidaho.edu	Analyze effects of insects and fire on vegetation and C; conduct ecosystem modeling of climate/insects/fire; synthesize model output across WMI ecosystems
Stephanie Kampf, Colorado State Univ. kampf@colostate.edu	Collaborate on studies of ecohydrology.
Nate McDowell, Los Alamos National Laboratory, mcdowell@lanl.gov	Collaborate on tree physiology/mortality; carbon isotope studies.

Dennis Ojima, Colorado State University, dennis@nrel.colostate.edu	Provide downscaled climate scenarios and collaborate in interpreting model results
Christina Tague, Univ. California, Santa Barbara ctague@bren.ucsb.edu	Conduct hydrological, biogeochemical, and productivity modeling using RHESSys; synthesize model output across WMI ecosystems
Wim van Leeuwen, Univ. Arizona leeuw@ag.arizona.edu	Collaborate on studies of post-fire forest recovery and ecosystem functioning.
Phil van Mantgem, USGS Western Ecological Research Center, pvanmantgem@usgs.gov	Detection, attribution, and causes of increasing tree mortality

X. FACILITIES/EQUIPMENT/STUDY AREAS

Each participating office has multiple powerful computer workstations, software for GIS, model development, and data analysis and display, and both internal and external networking capability. The participants in Seattle are also networked to the University of Washington system, one of the nation's largest and most advanced computing and communications facilities. We have access to chemical and analytical labs in Seattle and Fort Collins. Field study areas in national parks and elsewhere are described on the WMI web site (http://www.cfr.washington.edu/research.fme/wmi) and linked regional web sites, and have access to onsite NPS facilities, equipment, and support personnel. Each office is equipped with data collection equipment, including data loggers, laptop computers, and field gear.

XI. LEGAL AND POLICY-SENSITIVE ASPECTS

We have longstanding relationships with the National Park Service, U.S. Forest Service, and several universities, and have earned their trust with our scientific activities and technology transfer over the past decade. Research permitting will mostly consist of extending existing permits. We expect no extraordinary measures in terms of other permits or data embargos.

XII. BUDGET

Annual and total budget information is attached at the end of the proposal.

XIII. WORK AND REPORTING SCHEDULE

See Table 1.

XIV. REPORTING REQUIREMENTS

Annual Progress reports, reviewed and approved by the appropriate Science Center or Cooperative Research Unit will be submitted no later than January 15 of the following fiscal year. The Final Project report will be submitted within 4 months of project completion.

XV. QUALIFICATIONS OF PROJECT PERSONNEL

One-page summaries of the qualifications of each WMI PI and the lead collaborators are attached (following References Cited) in alphabetical order in two sets (PIs and key collaborators).

Table 1. Work and reporting schedule.

Task	**2009**	**2010**	**2011**	**2012**	**2013**
1 Forest Vegetation and Disturbance: 1.1 Climate-induced mortality and dieback					
1.1.1 Tree water stress	Collect and process cores	Conduct δ^{13}C analyses	Cross-site data analyses, publications	Publications	
1.1.2 Drivers of mortality	Collect field demography data; remote sensing of spatial patterns	Continue demography fieldwork, remote sensing of spatial patterns	Data analyses; publications; fieldwork	Data analyses; publications; fieldwork	Data analyses; publications; fieldwork
1.1.3 Drought stress responses	Risk maps with statistical model	Integrate drought stress field results into RHESSys; publication	RHESSys forecasts of mortality under climate change scenarios	Model inter-comparison; publications	
1.1.4 Scale up	Conduct WMI international workshop; FIA analyses	FIA analyses, publish West-wide & global syntheses	Refine mortality models	Run new models West-wide and globally	Synthesis paper on mortality projections
1. Forest Vegetation and Disturbance: 1.2 Altered disturbance regimes					
1.2.1 Fire severity and severity change	Compile fire records and remote sensing data	Data analysis: changes in severity and drivers	Publications and presentations		
1.2.2 Bark beetle outbreaks	Assemble climate info for major insect outbreaks; collect tree ring data	Analyze tree ring data; model historic climate suitability and stand susceptibility	Data analysis: determine climate drivers; publications	Update climate suitability models/add missing processes	Model with climate change, analyze results; publications, presentations
1.2.3 Fire and beetle effects on C stocks	Assemble insect outbreak, fire occurrence and severity data	Develop modeling methods	Apply model, analyze results; publications, presentations		
1.2.4 Forest recovery	Conduct remote sensing intepretations; LFA fieldwork	Conduct remote sensing intepretations; LFA fieldwork; data analysis	Conduct remote sensing intepretations; LFA fieldwork; data analysis	Cross-site analyses; publication	Synthesis publication
1.2.5 Disturbance interactions	Publish manuscripts from 2007 workshop; begin YNP case study	Develop space-time model for fire-insect interactions	Central Rockies case study (empirical analysis)	Reconcile case studies/model to identify couplings and thresholds	Publications, presentations, and adaptation guidelines

2. Mountain Hydrology and Dynamics					
2.1 Snow accumulation, ablation, and hydrology	Publish snow synthesis for Glacier; begin Cascades analysis	Finish Cascades, start Sierras analysis	Publish Cascades, finish Sierras, start Rocky Mtn analysis	Publish Sierras, finish Rocky Mtn, start Bandelier analysis	Finish Bandelier, WMI-wide synthesis publication
2.2 Glacier volume	Acquire photos, target benchmark glaciers, begin field surveys, test modeling software	Continue photos, establish benchmark glacier, field surveys for validation, synthesis paper	Contine photos, field surveys for validation, produce first glacier volume estimates	Continue photos, field surveys, establish 2nd benchmark glacier, synthesis paper	Produce volume change estimates and impacts to western water supplies, new maps, other syntheses
2.3 Glacier recession	Update glacier area database for west	Examine four models	Finish modeling, compare results	Forecast recession rates	Publish forecasts and implications for water
2.4 Headwater chemistry	Gather historic data, select and sample headwaters, maintain and evaluate time series from instrumented sites	Process studies, continue sampling, monitor instrumented sites, publication	Process studies, continue sampling, monitor instrumented sites, publication	Process studies, continue sampling, monitor instrumented sites, publication	Monitor instrumented sites, publications
3. Coupled Ecohydrological Response: 3.1 Empirical studies					
3.1.1 Semi-arid systems	Collect field data, ecohydrological responses to climate	Field data, analyze/model responses, publication, incorporate field data into RHESSys	Field data, model responses, comparative site analyses;	Field data, project climate change vulnerabilities, publication	Publication, field data
3.1.2 Subalpine systems	Instrument sites, collect field data, update RHESSys for CO	Field data	Field data, analyze/model responses	Field data, comparative site analyses, publication	Field data; project climate change vulnerabilities; publication
3. Coupled Ecohydrological Response: 3.2 Modeling and forecasting					
3.2.1 Streamflow and aquatic ecosystems	RHESSys estimates of streamflow metrics under historic climate	Iterate/improve streamflow estimates, refine RHESSys (from 1, 2, 3.1)	RHESSys analysis of streamflow with climate change scenarios	Assess aquatic ecosystem vulnerability, publication	Publication
3.2.2 Coupled hydro/veg/disturbance interactions	Identify existing succession and raster fire models or create specs for new models.	Develop succession and fire modules for coupling with RHESSys	Couple fire effects: severity; run model for WMI watersheds. Publication	Evaluate, test model, expand to other watersheds West-wide.	Publications, presentations, dissemination of working version(s) of models.
4. Adaptation					
4.1 Multiagency Guide	Gather, develop, and synthesize materials for Guidebook, workshops	Continue Guidebook, workshops, publication	Continue Guidebook, workshops	Support/update Web portal to Guidebook, publication	Support/update Web portal to Guidebook, publication

REFERENCES CITED

Allen, C.D. 2007. Cross-scale interactions among forest dieback, fire, and erosion in northern New Mexico landscapes. Ecosystems. 10: 797-808.

Allen, C.D.; Anderson, R.S.; Jass, R.B.; Toney, J.L.; Baisan, C.H. 2008. Paired charcoal and tree-ring records of high-frequency fire from two New Mexico Bog Sites. International Journal of Wildland Fire. 17: 115–130.

Allen, C.D.; Breshears, D.D. 1998. Drought-induced shift of a forest/woodland ecotone: rapid landscape response to climate variation. Proceedings of the National Academy of Sciences, U.S.A. 95: 14839-14842.

Allen, C.D.; Breshears, D.D. 2007. Meetings: oganized oral session on "climate-induced forest dieback as an emergent global phenomenon: patterns, mechanisms, and projections", Annual Meeting of Ecological Society of America, San Jose, California, 7 August 2007. EOS. 88(47): 504.

Bahr, D. B.; Meier, M.; Peckham S.D. 1997. The physical basis of glacier volume area scaling. Journal of Geophysical Research. 102(B9), 20,355-20,362.

Barnett, T.P.; Pierce, D.W.; Hildago, H.G.; Bonvils, C.; Santer, B.D.; Das, T.; Bala, G.; Wood, A.W.; Nozawa, T.; Mirin, A.A; Cayan, D.R.; Dettinger, M.D. 2008. Human-induced changes in the hydrology of the western United States. Science. 319: 1080-1083.

Baron, J.S.; Allen, C.D.; Fleishman, E.;Gunderson, L.; McKenzie, D.; Meyerson, L.P Oropeza, J.; Stephenson, N. 2008. National parks. In: Julius, S.H.; West, J.M., eds. Baron, J.S.; Joyce, L.A.; Keller, B.D.; Palmer, M.A.; Peterson, C.H.; Scott, J.M., authors. Preliminary review of adaptation options for climate-sensitive ecosystems and resources. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC: U.S. Environmental Protection Agency: 4-1 to 4-68.

Baron, J.S. 2008. Interactions between atmospheric nitrogen deposition and climate change in the Colorado Front Range. Talking points editorial for environmentalresearchweb.org. http://environmentalresearchweb.org/cws/article/opinion/33501

Baron, J.S.; Schmidt, T.W.; Hartman, M.D. Climate-induced changes in nitrogen dynamics in Loch Vale watershed, Rocky Mountain National Park. In review for submission to Global Change Biology.

Bautista, S.; Mayor, A.G.; Bourakhouader, J.; Bellot, J. 2007. Plant spatial pattern predicts hillslope runoff and erosion in a semiarid Mediterranean landscape. Ecosystems. 10(6): 987-998.

Bigler, C.; Braker, O.U.; Bugmann, H.; Dobbertin, M.; Rigling, A. 2006. Drought as an inciting factor in Scots Pine stands of the Valais, Switzerland. Ecosystems. 9:330-343

Bigler, C.; Kulakowski, D.; Veblan, T.T. 2005. Multiple disturbance interactions and drought influence fire severity in Rocky Mountain subalpine forests. Ecology. 86: 3018-3029

Breshears, D.D. 2005. An ecologist's perspective of ecohydrology. Bulletin of the Ecological Society of America. 86: 296-300.

Breshears D.D.; Cobb, N.S.; Rich, P.M.; Price, K.P.; Allen, C.D.; Balice, R.G.; Romme, W.H.; Kastens, J.H.; Floyd, M.L.; Belnap, J.; Anderson, J.J.; Myers, O.B.; Meyer, C.W. 2005. Regional vegetation die-off in response to global-change-type drought. Proceedings of the Nnational Academy of Sciences, U.S.A. 102: 15144-15148.

Breshears, D.D.; Myers, O.B.; Meyer, C.B.; Barnes, F.J.; Zou, C.B.; Allen, C.D.; McDowell, N.G.; Pockman, W.T. Tree die-off in response to global-change-type drought: mortality insights from a decade of plant water potential measurements. Frontiers in Ecology and the Environment. In press.

Carroll, A.L.; Taylor, S.W.; Regniere, J.; Safranyik, L.2004. Effects of climate change on range expansion by the mountain pine beetle in British Columbia. *In*: Mountain pine beetle symposium: challenges and solutions. Kelowna, BC: Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre: 223-232.

Christensen, L.; Tague, C.; Baron, J. 2008. Spatial patterns of transpiration response to climate variability in a snow-dominated mountain ecosystem. Hydrological Processes. In press.

Church, S.E.; von Guerard, P.; Finger, S.E., eds. 2007. Integrated investigations of environmental effects of historical mining in the Animas River Watershed, San Juan County, Colorado: U.S. Geological Survey Professional Paper 1651, 6 plates, 1 DVD, 1,096 p., URL: http://pubs.usgs.gov/pp/1651/

CIRMOUNT (Report of the Consortium for Integrated Climate Research in Western Mountains). 2006. Mappng new terrain: climate change and America's West. Misc. Pub. PWS-MISC-77, Albany CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Forest Service. 29 p.

Cobb, N.; Ironside, K.; Shaw, J.D.; Ogle, C.D.; Allen, C.D.; Breshears, D.D.; Clifford, M. 2007. Dieback of forests and woodlands across elevational gradients in response to global-change-type drought in the Southwestern U.S., North America. Invited presentation, Organized Oral Session on "Climate-Induced Forest Dieback as an Emergent Global Phenomenon: Patterns, Mechanisms, and Projections", Annual Meeting of Ecological Society of America, San Jose, California, 7 August 2007.

Cohen, J.D.; Deeming, J.E. 1985. The national fire danger rating system: basic equations. Gen. Tech. Rep. PSW-82. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station.

Das, A.; Battles, J.; Stephenson, N.L.; van Mantgem, P.J. 2007. The relationship between tree growth patterns and likelihood of mortality: a study of two tree species in the Sierra Nevada. Canadian Journal of Forest Research. 37: 580-597.

Dobbertin, M.; Wermelinger, B.; Bigler, C.; Burgi, M.; Carron, M.; Forster, B.; Gimmi, B.; Rigling, A. 2007. Linking increasing drought stress to Scots Pine mortality and bark beetle infestations. TheScientificWorldJOURNAL. 7: 231-239.

Drexler, C. 2008. MRI Newsletter 10: The Western Mountain Initiative (WMI). Mountain Research and Development 28(1): 86-87.

Dyurgerov, M.B.; Meier, M.F. 2000. 20th century climate change: evidence from small glaciers. Proceedings of the National Academy of Sciences, U.S.A. 97(4): 1406–1411.

Eilers, J.M.; Kancriuk, P.; McCord, R.A; Overton, W.S.; Hook. L.; Blick, D.J.; Brakke, D.F.; Keller, P.; Silverstein, M.E.; Landers, D.H. 1986. Characteristics of lakes in the western United States: Vol II Data compendium for selected physical and chemical variables. EPA-600/3-86/054B. Washington, DC: U.S. Environmental Protection Agency.

Fagre, D.; Charles, C.; Allen, C.; Birkeland, C.; Chapin, T.; Groffman, P.; Guntenspergen, G.; Knapp, A.; McGuire, D.; Mulholland, P. Peterson, D.; Roby, D.; Sugihara, G. Synthesis and Assessment Product 4.2, Thresholds of Change in Ecosystems. Washington, DC: U.S. Climate Change Science Program. In preparation.

Feeley, K.J.; Wright, S.J.; Nur Supardi, M.N.; Kassim, A.R.; Davies, S.J. 2007. Decelerating growth in tropical forest trees. Ecology Letters. 10: 461-469

Fenn, M.E., J.S. Baron, E.B. Allen, H.M. Rueth, K.R. Nydick, L. Geiser, W.D. Bowman, J. O. Sickman, T.Meixner, and D. W. Johnson. 2003, Ecological Effects of Nitrogen Deposition in the Western United States. BioScience 53: 404-420.

Fountain, A.G.; Hoffman, M.; Jackson, K.; Basagic, H.; Nylen, T.; Percy, D. 2007. Digital outlines and topography of the glaciers of the American West. U.S. Geological Survey Open File Report 2006-1340, 23pp. http://pubs.usgs.gov/of/2006/1340/.

Fountain, A.G.; Krimmel, R.M.; Trabant. 1997. A strategy for monitoring glaciers. U.S. Geological Survey Circular 1132. 16 p.

GAO. 2007. Climate change: agencies should develop guidance for addressing the effects on federal land and water resources. GAO-07-863.

Gedalof, Z.; Peterson, D.L.; Mantua, N. 2005. Atmospheric and climatic controls on severe wildfire years in the northwestern United States. Ecological Applications. 15: 154-174.

Gonzalez, P.; Neilson, R.P.; Lenihan, J.M.; Drapek, R.J.; Bachelet, D.; Wells, J.R. Observations and projections show global vulnerability to climate change vegetation shifts. Ecological Applications. In review.

Granshaw, F.D.; Fountain, A.G. 2006. Glacier change (1958-1998) in the North Cascades National Park Complex. Washington, USA. Journal of Glaciology. 52(177): 251-256.

Greenwood, G.B. 2008. The MRI and CIRMOUNT – a lofty symbiosis? Mountain Views 2(1):2-4.

Hall, M.P.; Fagre, D.B. 2003. Modeled climate-induced glacier change in Glacier National Park, 1850-2100. BioScience. 53:131-140.

Harper, J.T.; Humphrey, N.F. 2003. High altitude Himalayan climate inferred from glacial ice flux. Geophysical Research Letters. 30(14), 1764, doi:10.1029/2003GL017329.

Hicke, J.A.; Logan, J.A.; Powell, J.; Ojima, D.S. 2006. Changing temperatures influence suitability for modeled mountain pine beetle (*Dendroctonus ponderosae*) outbreaks in the western United States. Journal of Geophysical Research-Biogeosciences. 111, G02019, doi:02010.01029/02005JG000101.

Hicke, J.A.; Jenkins, J.C.; Ojima, D.S.; Ducey, M. 2007. Spatial patterns of forest characteristics in the western United States derived from inventories. Ecological Applications. 17: 2387-2402.

Hoffman, M.J.; Fountain, A.G.; Achuff, J.M. 2007. Twentieth-century variations in area of cirque glaciers and glacierets, Rocky Mountain National Park, Rocky Mountains, Colorado, USA. Annals of Glaciology. 46: 349-354.

Intergovernmental Panel on Climate Change (IPCC). 2008. Climate change 2007: impacts, adaptation, and vulnerability. Working group II contribution to the fourth assessment report. Cambridge: Cambridge University Press.

Joyce, L.A.; Blate, G.M.; Littell, J.S.; McNulty, S.G.; Millar, C.I.; Moser, S.C.; Neilson, R.P.; O'Halloran, K.; Peterson, D.L. 2008. National forests. In: Julius, S.H.; West, J.M., eds. Preliminary review of adaptation options for climate-sensitive ecosystems and resources. A report by the U.S. Climate Change Science Program and the subcommittee on global change research. Washington, DC: U.S. Environmental Protection Agency: 3-1 to 3-127.

Julius, S.H.; West, J.M., eds. 2008. Preliminary review of adaptation options for climate-sensitive ecosystems and resources. A report by the U.S. Climate Change Science Program and the subcommittee on global change research. Washington, DC: U.S. Environmental Protection Agency. 873 p.

Jump A.S.; Hunt, J.M.; Peñuelas, J. 2006. Rapid climate change-related growth decline at the southern range-edge of *Fagus sylvatica*. Global Change Biology. 12: 2163-2174.

Keane, R.E.; Morgan, P.; White, J.D. 1999. Temporal patterns of ecosystem processes on simulated landscapes in Glacier National Park, Montana, USA. Landscape Ecology. 14: 311-329.

Knowles, N.; Dettinger, M.D.; Cayan, D.R. 2006: Trends in snowfall versus rainfall in the Western United States. Journal of Climate. 19(18): 4545-4559.

Lafrenière, M.J., M.J. Sharp. 2005. A comparison of solute fluxes and sources from glacial and non-glacial catchments over contrasting melt seasons. Hydrol Proc. 19:2991-3012.

Littell, J.S.; McKenzie, D.; Peterson, D.L.; Westerling, A. Climate and wildfire area burned in western U.S. ecoprovinces. Ecological Applications. In press.

Loehman, R.; Keane, R.E.; Keyser, A. 2008. Simulating the effects of climate change and wildfire on forest landscapes. Presented at the 2008 meeting of the International Association for Landscape Ecology, Madison, WI.

Logan, J.; Regniere, J.; Powell, J.A. 2003. Assessing the impacts of global warming on forest pest dynamics. Frontiers in Ecology and the Environment. 1:130-137.

Lutz, J.A. 2008. Climate, fire, and vegetation change in Yosemite National Park. Seattle: University of Washington. Ph.D. dissertation.

Margolis, E.Q.; Swetnam, T.M.; Allen, C.D. 2007. A stand-replacing fire history in upper montane forests of the Southern Rocky Mountains. Canadian Journal of Forest Research. 37: 2227-2241.

Maurer, E.P.; Stewart, I.T.; Bonfils, C.; Duffy, P.B.; Cayan, D. 2007. Detection, attribution, and sensitivity of trends toward earlier streamflow in the Sierra Nevada. Journal of Geophysical Research. 112, D11118, doi: 10.1029/2006JD008088.

Mayor, A.; Bautista, S.; Llovet. J.; Bellot, J. 2007. Post-fire hydrological and erosional responses of a Mediterranean landscape: Seven years of catchment-scale dynamics. Catena. 71: 68-75.

Mayor, A.G, Bautista, S., E. Small, M. Dixon, and Bellot, J. (in press). Measurement of the connectivity of runoff-source areas as determined by vegetation pattern and topography –A tool for assessing potential water and soil losses in drylands. Water Resources Research.

McDowell, N.; Pockman, W.T.; Allen, C.D.; Breshears, D.D.; Cobb, N.; Kolb, T.; Plaut, J.; Sperry, J.; West, A.; Williams, D.G.; Yepez, E.A. 2008a. Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? New Phytologist. (2008) doi: 10.1111/j.1469-8137.2008.02436.x

McDowell, N.; Allen, C.; Marshall, L. 2008b. Growth, carbon isotope discrimination and mortality across a ponderosa pine elevational transect. In revision for Oecologia.

McKenzie, D.; Allen, C.D. 2007. Meetings: climate change and disturbance interactions: workshop on climate change and disturbance interactions in western North America, Tucson, Ariz., 12-15 February 2007. EOS. 88(21): 227.

McKenzie, D.; Gedalof, Z.M.; Peterson, D.L.; Mote, P. 2004. Climatic change, wildfire, and conservation. Conservation Biology.18: 890-902.

Millar, C.I., N.L. Stephenson, S.L. Stephens. 2007. Climate change and forests of the future: managing in the face of uncertainty. Ecol. Appl. 17:2145-2151. Moody, J.A. and D.A. Martin. 2001. Hydrologic and Sedimentologic Response of Two Burned Watersheds in Colorado. U. S. Geological Survey Water-Resources Investigations Report 01-4122.

Miller, C., and D.L. Urban. 1999. Forest pattern, fire, and climate change in the Sierra Nevada. Ecosystems 2:76-87.

Mote, P.W. 2003. Trends in snow water equivalent in the Pacific Northwest and their climatic causes. Geophys. Res. Lett. 30: 1601, doi:10.1029/2003GL017258.

Mueller, R.C.; Scudder, C.M.; Porter, M.E.; Trotter, R.T., III; Gehring, C.A.; Whitham, T.G. 2005. Differential tree mortality in response to severe drought: evidence for long-term vegetation shifts. Journal of Ecology. 93:1 085–93.

Nelson, R.M. 2000. Prediction of diurnal change in 10-hr fuel stick moisture content. Canadian Journal of Forest Research. 30: 1071–1087.

Oneil, E.E. 2007. Developing stand density thresholds to address mountain pine beetle susceptibility in eastern Washington forests. Seattle: University of Washington. Ph.D. dissertation.

Plummer, M.A.; Phillips, F.M. 2003. A 2-D numerical model of snow/ice energy balance and ice flow for paleoclimatic interpretation of glacial geomorphic features. Quaternary Science Reviews. 22, 1389-1406.

Poff, N.L.; Allan, J.D.; Bain, M.B.; Karr. J.R.; Prestegaard, K.L; Richter, B.D.; Sparks, R.E.; Stromberg, J.S. 1997. The natural flow regime: a paradigm for river conservation and restoration. BioScience. 47: 769-784.

Richter, B.D.; Baumgartner, J.V.; Powell, J.; Braun, D.P. 1996. A method for assessing hydrologic alteration within ecosystems. Conservation Biology. 10: 1163-1174.

Shaw, J.D.; Steed, B.E.; DeBlander, L.T. 2005. Forest inventory and analysis (FIA) annual inventory answers the question: What is happening to our pinyon-juniper woodlands? Journal of Forestry. 103(6):280-285.

Shore, T. L.; Safranyik, L. 1992. Susceptibility and risk rating systems for the mountain pine beetle in lodgepole pine stands. BC-X-336, Forestry Canada.

Stewart, I.T.; Cayan, D.R.; Dettinger, M.D. 2005. Changes toward earlier streamflow timing across western North America. Journal of Climate. 18: 1136-1155.

Swetnam T.W.; Anderson, R.S. 2008. Fire climatology in the western United States: Introduction to special issue. International Journal of Wildland Fire. 17: 1–7.

Tague, C.L.; Band, L.E. 2004. Regional hydro-ecologic simulation system: an object-oriented approach to spatially distributed modeling of carbon, water and nutrient cycling. Earth Interactions. 8: 1–42.

Tague, C.; Grant, G.; Farrell, M.; Choate, J.; Jefferson, A. 2008. Deep groundwater mediates streamflow response to climate warming in the Oregon Cascades. Climatic Change. 86: 189–210.

Tague, C.;, Seaby, L.; Hope, A. in review. Modeling the eco-hydrologic response of a Mediterranean type ecosystem to the combined impacts of projected climate change and altered fire frequencies. Climatic Change.

Thies, H; Nickus, U.; Mair, V.; Tessadri, R.; Tait, D.; Thaller, B.; Psenner, R. 2007. Unexpected response of high alpine lake waters to climate warming. ES&T: 10.1021/es0708060

Tongway, D.; Hindley, N. 2004. Landscape function analysis: a system for monitoring rangeland function. African Journal of Range and Forage Science. 21(2): 109–113.

U.S. Department of Interior, National Park Service. 2007. Ecological Restoration Plan, Final Environmental Impact Statement, Bandelier National Monument, New Mexico.

van Leeuwen, Willem J.D., 2008. Monitoring the effects of forest restoration treatments on post-fire vegetation recovery with MODIS multitemporal data. Sensors. 8: 2017-2042.

van Leeuwen, W. J. D.; Casady, G.M.; Neary, D.G.; Bautista, S.; Alloza, J.A.; Carmel, Y.; Wittenberg, L.; Malkinson, D.; Orr, B.J. Monitoring post-wildfire vegetation recovery with remotely sensed time-series data in Spain, USA and Israel. International Journal of Wildland Fire. In review.

van Mantgem, P.J.; Stephenson, N.L. 2007. Apparent climatically induced increase of tree mortality rates in a temperate forest. Ecology Letters. 10: 909-916.

van Mantgem, P.J.; Stephenson, N.L.; Byrne, J.C.; Daniels, L.D.; Franklin, J.F.; Fulé, P.Z.; Harmon, M.E.; Smith, J.M.; Taylor, A.H.; Veblen, T.T. Widespread increase of tree mortality rates in the western United States. Science. In USGS internal review.

Westerling, A.L.; Hidalgo, H.g.; Cayan, D.R.; Swetnam, T.W. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science. 313(5789), 940-943.

Wilcox, B.P.; Breshears, D.D.; Allen, C.D. 2003. Ecohydrology of a resource-conserving semiarid woodland: Temporal and spatial scaling and disturbance. Ecological Monographs. 73(2): 223-239.

Williams, M.W.; Knauf, M.; Cory, R.; Caine, N.; Liu, F. 2007. Nitrate content and potential microbial signature of rock glacier outflow, Colorado Front Range. Earth Surf. Process. Landforms. DOI: 10.1002/esp.145