Appendix 3: Western Mountain Initiative Synthesis

Response of Western Mountain Ecosystems to Climatic Variability and Change: A Synthesis From the Western Mountain Initiative

Crystal L. Raymond[1]

Introduction

The Western Mountain Initiative (WMI), a consortium of research groups in the Western United States, focuses on understanding and predicting responses—especially sensitivities, thresholds, resistance, and resilience—of mountain ecosystems to climatic variability and change (Peterson et al. 2012). The WMI addresses how climatic variability and change influence forest processes, disturbance dynamics, hydrologic changes, and hydroecological interactions in five bioregions: Pacific Northwest, Sierra Nevada, Northern Rocky Mountains, Central Rocky Mountains, and Southern Rocky Mountains. A guiding theme of WMI research is understanding the linkages among these processes. This focus on linkages (e.g., climate change affects disturbance regimes, hence vegetation, hence erosion) and the depth and breadth of place-based knowledge represented by this work contribute to multisite regional comparisons.

Research addresses four key questions: (1) How are climatic variability and change likely to affect disturbance regimes? (2) How are changing climate and disturbance regimes likely to affect the composition, structure, and productivity of vegetation? (3) How will climatic variability and change affect hydrologic processes in the mountainous West? and (4) Which mountain resources and ecosystems are likely to be most sensitive to future climatic change, and what are possible management responses? Results to date have documented how climatic variability and change affect several trends: long-term patterns of snow, glaciers, and water geochemistry; forest productivity, vigor, and demography; and changing patterns of treeline dynamics and forest disturbances. Empirical and simulation modeling indicates that major changes in hydrologic function and ecological disturbance will occur as the climate continues to warm.

The WMI research has documented trends in temperature, precipitation, and snowpack, and the exceedance of biological and ecologically meaningful thresholds of these variables in the mountainous West. In the northern Rocky Mountains, trends show that extremely cold days (≤ -18 °C) end on average 20 days earlier and have declined in number, and the number of extremely hot days (≥ 32 °C) has increased over the last 100 years (Pederson et al. 2011). Trends in snowpack observations in the northern Rocky Mountains indicate declines in snowpack and earlier arrival and melt of peak snow water equivalent over the last 40 years (Pederson et al. 2011). Although much of this change in snowpack is attributed to climatic variability, an extension of this analysis to the whole Rocky Mountains region and to the last 800 years using tree-ring based reconstructions of snowpack shows only two periods of sustained low snowpack comparable to those observed in the 20th century (Pederson et al. 2011).

Here we focus on WMI results in three areas related to forest ecosystem response to climatic variability and change: (1) trends in the structure and function of western forest ecosystems, (2) the effects of exceeding critical thresholds, and (3) the potential for future changes in these systems. Changes have been documented in forest demography, treeline dynamics, and ecological disturbances and interactions. Although it is not possible to definitively attribute recent changes as being caused by climate change, the effects of dominant modes of climatic variability can be used

[1] **Crystal L. Raymond** is a postdoctoral research ecologist, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory, 400 N, 34th Street, Suite 201, Seattle, WA 98103. Raymond is currently located at the U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Forestry Sciences Laboratory, 507 25th Street, Ogden, UT 84401.

with some confidence to infer expected changes in ecosystems in a warmer climate. For example, relationships have been documented between the Pacific Decadal Oscillation (20- to 30-year cool and warm phases) and temporal variation in regional-scale tree growth (Peterson and Peterson 2001, Peterson et al. 2002), wildfire (Hessl et al. 2004), and long-term drought (Gedalof et al. 2004). These relationships suggest that significant changes in ecosystem processes will occur as temperature, and extremes in temperature, continue to increase.

Forest Die-Off and Demography

Recent broad-scale syntheses have documented climate-induced forest mortality in some locations (Allen 2009, Allen et al. 2010). These syntheses reveal diverse patterns in forest die-off attributed to drought and heat, including localized increases in background mortality and regional-scale forest die-off linked to biotic agents (Allen et al. 2010). Drought-induced die-off is commonly observed at the elevation and geographic margins of species ranges and is often associated with prolonged periods of moisture stress. Recent and ongoing WMI research continues to address key uncertainties in forest mortality processes (Breshears et al. 2009; McDowell et al. 2008, 2010).

Based on demographic trends in long-term plot data, mortality rates in old forests have increased in each of three subregions (Northwest, California, and interior West) and across elevation zones and tree size classes (van Mantgem et al. 2009), and tree recruitment rates have not changed, contributing to lower stem density and basal area of old forests. Since 1955, both temperature (particularly at the higher elevations occupied by forests) and climatic water deficit (evaporative demand that is not met by available water) increased, and both were positively correlated with tree mortality rates (van Mantgem et al. 2009). Warming-induced tree mortality is consistent with the apparent role of warming in recent forest dieback in western North America (Adams et al. 2009) and the positive correlation between short-term fluctuations in background tree mortality and water deficits in California and Colorado (Bigler et al. 2007, van Mantgem and Stephenson 2007).

Treeline Dynamics

One of the most distinctive features of mountain environments is the transition from subalpine forest to alpine tundra (alpine forest-tundra ecotone, AFTE), and climate change is likely to affect these environments in the mountainous West. Advance of trees into tundra can alter cycling of water, carbon, and nutrients and the maintenance of biodiversity. Treeline advance and changes in treeline patterns have the potential to alter snow retention and hydrology, with implications for local soil moisture and nutrient transport.

Studies of treeline phenomena and limiting factors among the five WMI bioregions have demonstrated that although ecological dynamics of the AFTE are influenced by climate, mechanistic processes that shape the ecotone—seed rain, seed germination, seedling establishment, and subsequent tree growth form—also depend on microsite patterns (Malanson et al. 2007). In the West, these mechanistic processes are similar among AFTEs, but other processes—prior climate, geomorphology, genetics, and historical grazing practices—create geographic differences in responses of ecotones to climate change. Climate change may affect successful seed dispersal, germination, and survival by modifying the biophysical environment. The three-dimensional pattern at treeline is typically patchy, including krummholz and dwarf trees, with expansion often facilitated by other plants (Resler 2006). The formation of vegetation structures that add wind protection, snow collection, and soil development allows subalpine forest species to initiate patches and expand in the upper treeline (Smith et al. 2003). Climate and variation in geomorphology, geology, and disturbances (e.g., snow avalanches) also control mortality at treeline and limit treeline elevation.

At regional to continental scales, control of the AFTE by temperature is locally modified by moisture (Malanson and Butler 2002). Evidence for AFTE response to climatic variability suggests upslope advance during warmer conditions, but advance in many sites may be limited by moisture. For example, in the 19th century, Glacier National Park experienced upward expansion of the ecotone (Bekker 2005), although in the 20th century, density of existing patches increased but advance was limited (Klasner and Fagre 2002).

Treeline advances in the latter half of the 20th century coincided with the cool (wet) phase of the Pacific Decadal Oscillation, and advance stopped during the warm (dry) phase of the 1980s and 1990s (Alftine et al. 2003).

A warmer, wetter climate could alter the structure of treeline in all WMI bioregions. In the Pacific Northwest, high snowpack inhibits establishment and growth of trees, so at the highest treeline elevations, increased snow plus increased winter precipitation could limit expansion of krummholz higher in the ecotone. The other WMI bioregions are drier, so higher precipitation could improve conditions for tree establishment and growth. For example, in Sierra Nevada treelines, tree growth increased during warmer, wetter periods in the 20th century (Millar et al. 2004). At all sites, effects are likely to be greatest in the lower AFTE, where deeper soils and root zones can use increased water (Malanson et al. 2007).

A warmer, drier climate could reduce tree establishment in the ecotone of all WMI treeline sites except the Pacific Northwest. In the Pacific Northwest, less moisture is unlikely to reduce tree establishment and growth in the AFTE. A warmer climate could increase tree growth in the AFTE, and less snow could facilitate expansion in the upper ecotone and encroachment in meadows in the lower ecotone. Conversely for the other WMI bioregions, a drier climate could further limit tree establishment, growth, and species diversity in the AFTE (Malanson et al. 2007).

Ecological Disturbance and Interaction of Stressors

Empirical and process-based models have been used to estimate the extent and magnitude of future disturbances across the West. The indirect effect of climate change on forests through changing disturbance regimes is likely to cause more rapid changes than the direct effects of higher temperatures on trees (fig. A3-1), and accelerated species turnover will occur after severe disturbance because seedlings are less resistant to changing climate than are mature individuals (McKenzie et al. 2009). In light of the importance of disturbance in Western forests, WMI research has emphasized quantifying the effects of climatic variability and change on the areal extent and broad-scale spatial patterns of wildfire and insect outbreaks (Littell et al. 2010).

Of particular concern are increases in fire area in a warming climate and the effects of extreme wildfire events on ecosystems (Gedalof et al. 2005, Littell et al. 2009, McKenzie and Littell 2011). Strong climatic controls exist on area burned by wildfire across the West at the spatial scales of entire states (McKenzie et al. 2004), ecoprovinces (Littell et al. 2009), and sections within ecoprovinces (Littell et al. 2010). In forests across the Northwestern United States, climate during the fire season appears to control area burned, whereas in arid mountains and shrublands, antecedent climate (e.g., wetter, cooler summers or winters preceding the fire season) can increase area burned during the fire season by increasing fuel abundance and continuity (Littell et al. 2009, 2010). Research has also quantified sediment yields after wildfire in different rainfall regimes across the Western United States (Moody and Martin 2008), providing a key context for potential climate-mediated watershed changes in postfire runoff and erosion relationships.

Mountain pine beetle (*Dendroctonus ponderosae* Hopkins) infestations have historically occurred frequently and extensively throughout western North America (Logan and Powell 2001). Warming and drought affect development rates of beetle life stages, winter mortality, and host tree susceptibility (Carroll et al. 2004). Across the West, current stand structural conditions make host species susceptible to beetle attack (Hicke and Jenkins 2008), and as warming continues, we might expect that forests will become susceptible to insect attack more frequently (Raffa et al. 2008). Mountain pine beetle outbreaks are facilitated when the insect's reproductive cycle is very close to one year and when larvae emerge at an optimal time for feeding, dispersal, and survival of cold seasons (Logan and Powell 2001). As temperatures increase, the life cycle shortens; therefore, a warmer climate is projected to reduce the area of climatic suitability for the beetle at low elevations but increase suitability at higher elevations (Hicke et al. 2006, Littell et al. 2010). Increases in mountain pine beetle outbreaks with climate

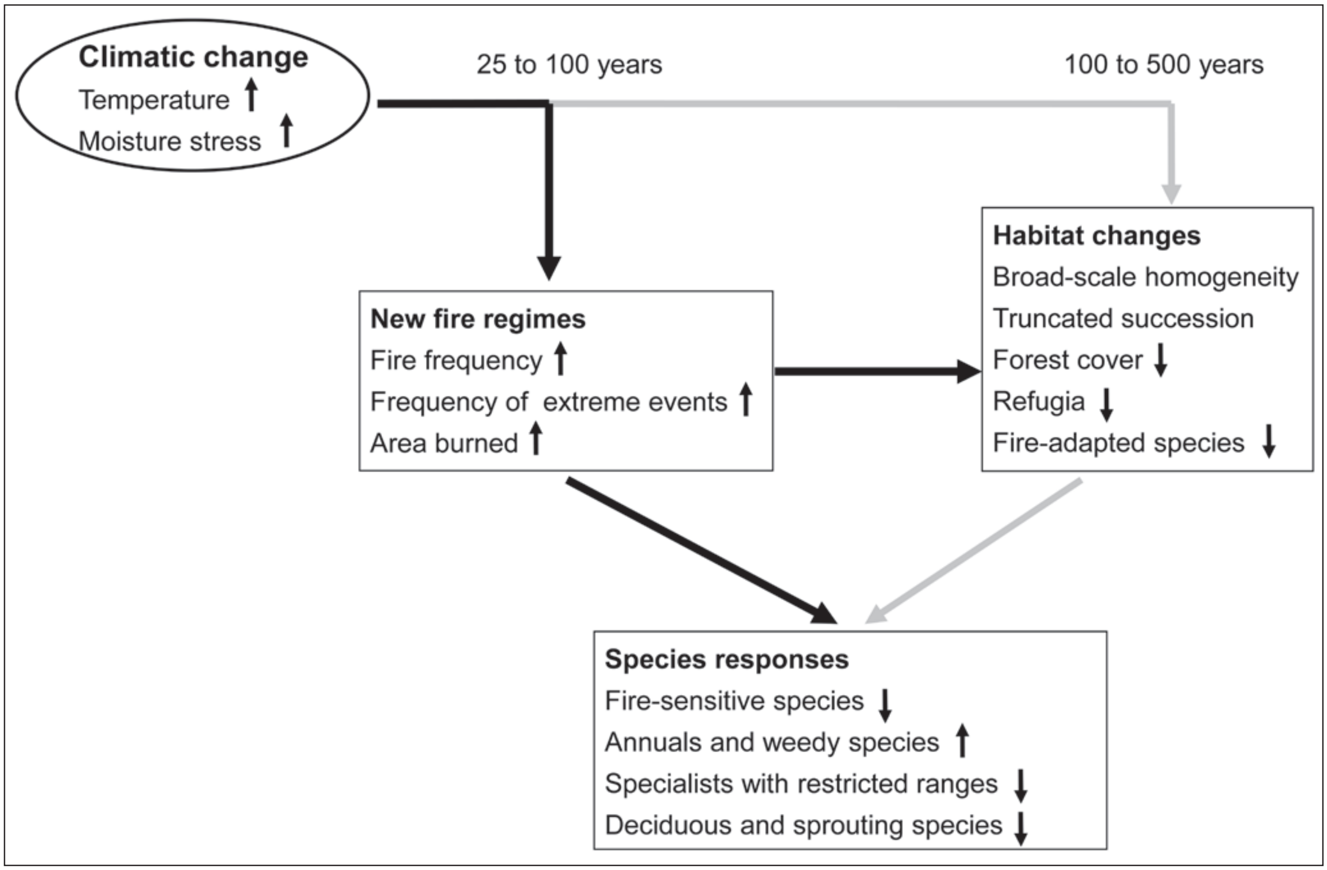

Figure A3-1—Conceptual model of the relative time scales for disturbance versus climate change alone to alter ecosystems. Times are approximate. The focus here is on fire, but much of the same logic applies to insect outbreaks. Adapted from McKenzie et al. (2004).

change will affect the carbon cycle in forest ecosystems and have feedbacks to the climate system (Hicke et al. 2012a).

Research on disturbance interactions and their effects on ecosystem processes (Allen 2007, McKenzie and Littell 2011, McKenzie et al. 2009) suggests that synergistic interactions between disturbances produce larger effects than would occur from an individual disturbance. For example, bark beetle outbreaks have been linked to increased likelihood of stand-replacing fire and changes in fire behavior, with the nature of the effect depending on the time since infestation (Jenkins et al. 2008, Lynch et al. 2006), although there is conflicting evidence about whether fire hazard is higher following bark beetle outbreaks (Hicke et al. 2012b). Combined with increasing climatic stress on tree populations and growth, disturbance interactions can alter forest structure and function faster than could be expected from species redistribution or disturbance alone (fig. A3-1). Simultaneous climatically driven shifts in the locations of species optima, ecosystem productivity, disturbance regimes, and interactions between them could reset forest succession over large areas and short timeframes.

Literature Cited

Adams, H.D.; Guardiola-Claramonte, M.; Barron-Gafford, G.A. [et al.]. 2009. Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global change-type drought. Proceedings of the National Academy of Sciences, USA. 106: 7063–7066.

Allen, C.D. 2009. Climate-induced forest dieback: an escalating global phenomenon? Unasylva. 231/232: 43–49.

Allen, C.D.; Macalady, A.; Chenchouni, H. [et al.]. 2010. A global overview of drought and heat-induced forest mortality reveals emerging climate change risks. Forest Ecology and Management. 259: 660–684.

Alftine, K.J.; Malanson, G.P.; Fagre, D.B. 2003. Feedback-driven response to multi-decadal climatic variability at an alpine forest-tundra ecotone. Physical Geography. 24: 520–535.

Bekker, M.F. 2005. Positive feedback between tree establishment and patterns of subalpine forest advancement, Glacier National Park, Montana, U.S.A. Arctic, Antarctic, and Alpine Research. 37: 97–107.

Bigler, C.; Gavin, D.G.; Gunning, C.; Veblen, T.T. 2007. Drought induces lagged tree mortality in a subalpine forest in the Rocky Mountains. Oikos. 116: 1983–1994.

Breshears, D.D.; Myers, O.B.; Meyer, C.W. [et al.]. 2009. 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. 7: 185–189.

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: Shore, T.L.; Brooks, J.E.; Stone, J.E., eds. Mountain pine beetle symposium: challenges and solutions. Information Report BC-X-399. Kelowna, British Columbia: Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre: 223–232.

Gedalof, Z.; Peterson, D.L.; Mantua, N.J. 2004. Columbia River flow and drought since 1750. Journal of the American Water Resources Association. 40: 1579–1592.

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

Hessl, A.E.; McKenzie, D.; Schellhaas, R. 2004. Drought and Pacific Decadal Oscillation linked to fire occurrence in the inland Pacific Northwest. Ecological Applications. 14: 425–442.

Hicke, J.A.; Allen, C.D.; Desai, A.R. [et al.]. 2012a. Effects of biotic disturbances on forest carbon cycling in the United States and Canada. Global Change Biology. 18: 7–34.

Hicke, J.A.; Jenkins, J.C. 2008. Mapping lodgepole pine stand structure susceptibility to mountain pine beetle attack across the western United States. Forest Ecology and Management. 255: 1536–1547.

Hicke, J.A.; Johnson, M.C.; Hayes, J.L.; Preisler, H.K. 2012b. Effects of bark beetle-caused tree mortality on wildfire. Forest Ecology and Management. 271: 81–90.

Hicke J.A.; Logan, J.A.; Powell, J.A.; 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. 111: G02019, doi: 10.1029/2005JG000101.

Jenkins, M.J.; Hebertson, E.; Page, W.; Jorgensen, C.A. 2008. Bark beetles, fuels, fires and implications for forest management in the Intermountain West. Forest Ecology and Management. 254: 16–34.

Klasner, F.L.; Fagre, D.B. 2002. A half century of change in alpine treeline patterns at Glacier National Park, Montana, USA. Arctic, Antarctic and Alpine Research. 34: 49–56.

Littell, J.S.; McKenzie, D.; Peterson, D.L.; Westerling, A. 2009. Climate and wildfire area burned in western U.S. ecoprovinces. Ecological Applications. 19: 1003–1021.

Littell, J.S.; Oneil, E.E.; McKenzie, D. [et al.]. 2010. Forest ecosystems, disturbance, and climatic change in Washington State, USA. Climatic Change. 102: 129–158.

Logan J.A.; Powell, J.A. 2001. Ghost forests, global warming and the mountain pine beetle (Coleoptera: Scolytidae). American Entomologist. 47: 160–173.

Lynch, H.J.; Renkin, R.A.; Crabtree, R.L.; Moorcroft, P.R. 2006. The influence of previous mountain pine beetle (*Dendroctonus ponderosae*) activity on the 1988 Yellowstone fires. Ecosystems. 9: 1318–1327.

Malanson, G.P.; Butler, D.R. 2002. The western cordillera. In: Orme, A., ed. Physical geography of North America. Oxford, United Kingdom: Oxford University Press: 363–379.

Malanson, G.P.; Butler, D.R.; Fagre, D.B. [et al.]. 2007. Alpine treeline of western North America: linking organism-to-landscape dynamics. Physical Geography. 28: 378–396.

McDowell, N.; Allen, C.D.; Marshall, L. 2010. Growth, carbon isotope discrimination, and climate-induced mortality across a *Pinus ponderosa* elevation transect. Global Change Biology. 16: 399–415.

McDowell, N.; Pockman, W.T.; Allen, C.D. [et al.]. 2008. Mechanisms of plant survival and mortality during drought: Why do some plants survive while others succumb to drought? New Phytologist. 178: 719–739.

McKenzie, D.; Littell, J.S. 2011. Climate change and wilderness fire regimes. International Journal of Wilderness. 17: 22–26.

McKenzie, D.; Peterson, D.L.; Littell, J.S. 2009. Global warming and stress complexes in forests of western North America. In: Bytnerowicz, A.; Arbaugh, M.; Riebau, A.; Anderson, C., eds. Wildland fires and air pollution. Amsterdam, The Netherlands: Elsevier Science: 319–337.

Millar, C.I.; Westfall, R.D.; Delany, D.L. [et al.]. 2004. Response of subalpine conifers in the Sierra Nevada, California, USA, to 20th-century warming and decadal climate variability. Arctic, Antarctic, and Alpine Research. 36: 181–200.

Moody, J.A.; Martin, D.A. 2008. Synthesis of sediment yields after wildland fire in different rainfall regimes in the western United States. International Journal of Wildland Fire. 18: 96–115.

Pederson, G.T.; Graumlich, L.J.; Fagre, D.B. [et al.]. 2009. A century of climate and ecosystem change in Western Montana: What do temperature trends portend? Climatic Change. 98: 133–154

Pederson, G.T.; Gray, S.T.; Ault, T. [et al.]. 2011a. Climatic controls on the snowmelt hydrology of the Northern Rocky Mountains. Journal of Climate. 24: 1666–1687.

Pederson, G.T.; Gray, S.T.; Woodhouse, C.A. [et al.]. 2011b. The unusual nature of recent snowpack declines in the North American Cordillera. Science. 333: 332–335.

Peterson, D.L.; Allen, C.D.; Baron, J.S. [et al.]. 2012. Response of Western mountain ecosystems to climatic variability and change: a collaborative research approach. In: Bellant, J.; Beever, E., eds. Ecological consequences of climate change: mechanisms, conservation, and management. New York: Taylor and Francis Publishing: 163–190.

Peterson, D.W.; Peterson, D.L. 2001. Mountain hemlock growth responds to climatic variability at annual and decadal scales. Ecology. 82: 3330–3345.

Peterson, D.W.; Peterson, D.L.; Ettl, G.J. 2002. Growth responses of subalpine fir (*Abies lasiocarpa*) to climatic variability in the Pacific Northwest. Canadian Journal of Forest Research. 32: 1503–1517.

Raffa, K.F.; Aukema, B.H.; Bentz, B.J. [et al.]. 2008. Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions. Bioscience. 58: 501–517.

Resler, L.M. 2006. Geomorphic controls of spatial pattern and process at alpine treeline. Professional Geographer. 58: 124–138.

Smith, W.K.; Germino, M.J.; Hancock, T.E.; Johnson, D.M. 2003. Another perspective on altitudinal limits of alpine timberlines. Tree Physiology. 23: 1101–1112.

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. [et al.]. 2009. Widespread increase of tree mortality rates in the western United States. Science. 323: 521–524.