Summary of Climate Change Effects on Major Habitat Types in Washington State

Forest, Alpine, and Western Prairie Habitats

Climate Change Effects on Forest, Alpine, and Western Prairie Habitats in Washington State

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PREFACE

This paper is a reference document—a "science summary"— for the Ecosystems, Species, and Habitats Topic Advisory Group (TAG), which is one of four topic groups working with Washington state agencies to prepare a statewide *Integrated Climate Change Response Strategy*. The climate change response strategy was initiated by the state legislature (SB 5560) to help the state adapt to climate change.

The purpose of this paper is to provide TAG members with information on potential effects of climate change on fish, wildlife, habitats, and ecosystems in forest and alpine environments. Although data on biological responses to climate change are limited in many cases, this paper summarizes and organizes relevant literature regarding observed changes, future projections, and implications for biological communities to inform the assessment of priorities and the development of recommendations to the Washington State legislature about possible adaptation responses.

This document draws primarily from peer-reviewed studies, synthesis reports and government publications. These include the two primary reference documents for the Integrated Climate Change Response Strategy, which are:

- *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate* (WACCIA) (CIG 2009); and,

- *Leading the Way: Preparing for the Impacts of Climate Change in Washington. Recommendations of the Preparation and Adaptation Working Groups* (PAWG 2008).

This document is for discussion purposes only and is not intended to be published or cited. In many cases, this document uses language taken directly from the cited sources. Readers should refer to and cite the primary sources of information.

Please note that we accepted information as it was presented in synthesis reports. Readers may wish to return to the primary sources utilized in those synthesis reports for more information. In cases where we accepted the interpretation of primary information as it was stated in a secondary source, we have provided the following note in the footnote: "Information as cited in [secondary source]."

As with most summary or synthesis efforts, this document reports the central findings from published literature and does not address all the inherent complexity and uncertainty that may be present in ecological and climatic systems. This is especially true of future climate projections, which are often based on multi-model ensembles that do not perfectly capture the complexity of Washington's unique climate systems and geographic variability. Future projections are valuable primarily to identify a directional trend and a sense of magnitude. As an example of the inherent uncertainty of future projections, Salathé, et al. (2009) note that multi-model ensembles of global climate projections may under-represent the local severity of climate change.[1]

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[1] Salathé, et al. (2009) Regional climate model projections for the State of Washington. In: *WACCIA*

We must emphasize that this discussion draft is neither comprehensive nor complete. In this complex and rapidly evolving field, we do not expect that we have identified all of the most up-to-date data or presented the full complexity of climate projections. In addition, there are many gaps in knowledge, especially regarding climate change effects on specific habitats or locations. Still, we hope that this provides a starting point for discussion, and that readers will augment this with additional data to advance our understanding of climate impacts and responses.

INTRODUCTION

This report summarizes literature on the effects of climate change on Washington's forests, alpine areas, and western prairies. The report is divided into six major sections.

First, *Forest Ecosystems: Background and Context* synthesizes background information on the status and extent of forests globally, nationally, and statewide. This section provides an overview of the ways in which climate change can alter forest ecosystems and the services that they provide to humans. In addition, disturbance regimes and interactions with climate change are introduced.

Second, *Global and Regional Climate Trends* presents information on three major physical environmental variables (CO_2, temperature, and precipitation) that affect forest, alpine, and western prairie ecosystems, and discusses how each environmental variable has changed over time.

Third, *Climate Change Effects on Washington's Forest Ecosystems* draws from WACCIA (CIG 2009) and PAWG (2008) to identify four major climate change effects on forest ecosystems:

- **Changes in species composition and distribution, including invasive species**
- **Changes in forest productivity and phenology**
- **Increased frequency and magnitude of wildfires**
- **Increased susceptibility to insects and disease**

Each effect is presented as a separate sub-section with information on observed climate-related changes, projected future changes, a discussion of the implications of those projections and then existing knowledge gaps.

Fourth, *Climate Change Effects on Alpine Ecosystems* describes the characteristics of alpine vegetation, evaluates links between climatic factors, vegetative growth, and climate change, and discusses how the four climate change effects described for forests also alter alpine environments.

Fifth, *Western Prairies* presents information on the historic extent and distribution of prairies in the Pacific Northwest, as well as the contemporary extent of this habitat. It then provides a brief discussion of predicted changes in climatic suitability for western prairies and opportunities for conservation.

Finally, the report provides an appendix of *Possible Adaptation Actions for Consideration*. The appendix lists climate change effects on forest ecosystems and possible actions that might help forests adapt to climate change.

FOREST ECOSYSTEMS: BACKGROUND AND CONTEXT

Globally, it is estimated that only about half of the forests that were present 8,000 years ago still remain on Earth.[2,3] A large portion of forest loss has occurred within the last 300 years, with conversion to other land uses such as agriculture and settlements.[4,5] Currently, forests in the United States occupy 740 million acres, or about one-third of the nation.[6]

More than half of Washington State, or about 9 million hectares of land, is covered by forests.[7] In general, Washington's forests are dominated by conifer species, with hardwood species prevalent only in heavily disturbed areas such as riparian zones with frequent flooding, avalanche chutes, or recently-logged sites.[8] The species that compose these conifer and hardwood forests vary across the broad climatic (i.e., west-east or maritime-continental) and elevational gradients present throughout the state.[9]

Approximately 56% (~ 5 million ha) of Washington's forested land is publicly owned and administered by federal and state agencies (primarily the U.S. Depts. of Agriculture and Interior and the WA Dept. of Natural Resources, respectively).[10] The remainder is managed by tribal, private, and corporate landowners.[11] While legal mandates and owner objectives vary, all of these forest lands may be affected by a changing climate.[12]

Climate exerts control over vegetation directly and indirectly via changes in the physical environment that affect the cycling of carbon, water, and nutrients between plants and soils.[13,14] Forest physiology, competitive interactions, and disturbance regimes may be altered as a result of climate change.[15] For

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[2] Information as cited in Hansen, et al. (2003), *Buying Time: A User's Manual for Building Resistance and Resilience to Climate Change in Natural Systems.* (non-profit report)

[3] Information as cited in Oregon Forest Resources Institute (2006), *Forests, Carbon and Climate Change: A Synthesis of Science Findings.* (synthesis document)

[4] Information as cited in Hansen, et al. (2003), *Buying Time: A User's Manual for Building Resistance and Resilience to Climate Change in Natural Systems.* (non-profit report)

[5] Information as cited in Oregon Forest Resources Institute (2006), *Forests, Carbon and Climate Change: A Synthesis of Science Findings.* (synthesis document)

[6] Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[7] Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

[8] Ibid.

[9] Ibid.

[10] Ibid.

[11] Ibid.

[12] Ibid.

[13] Aber et al. (2001), *Forest processes and global environmental change: Predicting the effects of individual and multiple stressors.* (primary literature)

[14] Information as cited in Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

[15] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

example, Blate et al. (2009) cite the following possible direct and indirect impacts of climate change on national forests:

Direct Impacts
- Shifts in seasonality of hydrological processes
- Intensified droughts
- Reduced snowpack
- Increased air and stream temperatures
- Longer, warmer growing seasons
- Altered in-stream flows

Indirect Impacts
- Altered fire regimes
- Compromised ability to maintain water quality and availability
- Shifts in forest species composition
- Altered landscape and successional dynamics
- Impaired watershed condition via increased erosion
- Increased fragmentation of ecosystems and habitats
- Interactions between climate change and current stressors
- Exacerbation of urban stressors on ecosystems.[16]

Although Earth's forests have survived past episodes of climate change throughout their evolutionary history, today their resilience is impaired by human actions.[17] (*Resilience* refers to the ability of an ecological system to absorb disturbances and retain the same basic structure, ways of functioning, and capacity to adapt to stress and change.[18]) Climate change adds further stresses to species and ecosystems that have already been altered by land-use practices, fragmentation, and the introduction of invasive species.[19]

According to Ryan and Archer (2008), U.S. forests perform or provide many ecosystem services including (1) regulation of water quality and water flow, (2) wildlife habitat, (3) raw material for wood and paper products, and (4) recreational opportunities. U.S. forests also absorb and retain atmospheric CO_2, which contributes to climate change mitigation.[20] For example, U.S. forests and forest products currently offset 12-19% of U.S. fossil fuel emissions, largely owing to continued forest recovery from past deforestation and extensive harvesting.[21] On a global scale, extant forests currently store about half of the carbon in

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[16] Blate et al. (2009), *Adapting to climate change in United States national forests.* (primary literature)

[17] Noss (2001), *Beyond Kyoto: Forest Management in a Time of Rapid Climate Change.* (primary literature)

[18] IPCC (2007) *Appendix 1: Glossary* (Working Group 2, Fourth Assessment Report)

[19] Information as cited in Noss (2001), *Beyond Kyoto: Forest Management in a Time of Rapid Climate Change.* (primary literature)

[20] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[21] McKinley et al. (2010), *A synthesis of current knowledge on forests and carbon storage in the United States.* (in review)

terrestrial ecosystems.[22] However, forest loss contributes about 20% of human carbon emissions worldwide.[23] Climate change may result in a decline or loss of these ecosystem services. Many of the most urgent forest and grassland management problems of the past 20 years, including increased area burned by wildfires, large-scale bark beetle infestation and changing water regimes have been driven in part by a changing climate.[24]

DISTURBANCE REGIMES AND CLIMATE CHANGE

Disturbances (e.g., droughts, insect outbreaks, grazing, and fire) are part of the ecological history of most ecosystems and influence ecological communities and landscapes.[25] Both human-induced and natural disturbances shape ecosystems by influencing species composition, structure, and function (e.g., productivity, water yield, erosion, carbon storage, and susceptibility to future disturbance). [26] Some disturbances are integral to maintaining healthy ecosystems. For example, fires help to recycle dead biomass in arid regions where natural decomposition occurs extremely slowly.[27] However, some disturbances (e.g., blowdowns, clear-cut logging) can also result in major changes in ecological communities and their successional trajectories.

Climate affects the timing, magnitude, and frequency of many disturbances, and climate change may therefore alter disturbance regimes in forests.[28] Many climate change impacts on forests will be expressed through alterations in disturbance regimes.[29] Climate effects on disturbance will likely shape future forests as much as the direct effects of climate change itself.[30]

Although the nature, timing, and impacts are only beginning to be understood, synergistic interactions between disturbances may produce larger effects than would occur from a single disturbance independently.[31] For example, mountain pine beetle (MPB) outbreaks have been linked to the increased likelihood of stand-replacing fire and changes

> **STAND-REPLACING FIRE**: a fire that consumes or kills a large majority of the dominant vegetation and substantially changes aboveground vegetation structure.

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[22] Information as cited in Oregon Forest Resources Institute (2006), *Forests, Carbon and Climate Change: A Synthesis of Science Findings.* (synthesis document)

[23] USFS (2008), *Forest Service Strategic Framework for Responding to Climate Change*. (U.S. government report)

[24] Ibid.

[25] Schimel et al.(2008), *Synthesis*. In: *The effects of climate change on agriculture, land resources, water resources, and biodiversity.*(U.S. government report)

[26] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[27] Running (2006), *Is global warming causing more, larger wildfires?* (commentary)

[28] Schimel et al.(2008), *Synthesis*. In: *The effects of climate change on agriculture, land resources, water resources, and biodiversity.*(U.S. government report)

[29] Hansen, et al. (2003), *Buying Time: A User's Manual for Building Resistance and Resilience to Climate Change in Natural Systems.* (non-profit report)

[30] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[31] Information as cited in Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

in fire behavior, with the nature of the effect depending on the time since infestation.[32] Combined with increasing climatic stress on tree growth, such interactions may potentially alter the structure and function of some forests more rapidly than could be predicted from models of species redistribution or disturbance alone.[33] There is still substantial uncertainty surrounding future climate and ecosystem responses and the interactions between them, particularly at regional and sub-regional scales.[34]

- WDFW reviewers commented that in some landscapes, changes may ultimately be driven more by forest management practices (e.g., fire suppression) than the effects of climate change on forest physiology or disturbance regimes (e.g., in dry forest landscapes).[35]
  - An external reviewer commented that this depends on the extent to which management practices are both effective and pervasive. Fire suppression could interact with climate change in such a way as to exacerbate projected impacts.[36]

GLOBAL AND REGIONAL CLIMATE TRENDS

The IPCC Third Assessment Report defines *climate* as the "average" weather, in terms of the mean and its variability over a certain time period and in a certain area.[37] Earth's climate system is described as an interactive system consisting of the atmosphere, hydrosphere (fresh and saline liquid waters), cryosphere (ice sheets, glaciers, snow fields), biosphere (e.g., vegetation), and the land surface (e.g., soils).[38] The climate system is influenced by a variety of external forces – the most important of which is the sun.[39] Human activities, such as the burning of fossil fuels, are also considered an external force that affects the climate system.[40]

The Greenhouse Effect and Climate Change

The sun provides a nearly constant flow of shortwave radiation toward Earth that is received at the top of the atmosphere.[41] Part of this radiation is scattered away from the Earth (e.g., by clouds and dust particles) and exits into space without being absorbed.[42] Land and ocean surfaces also reflect some shortwave radiation back into space.[43] The shortwave energy from the sun that is not scattered or reflected is absorbed by the atmosphere, land, or ocean. Although this directly raises temperatures and produces surface warming, warming also occurs as a result of the greenhouse effect.[44]

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[32] Ibid.

[33] Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

[34] Ibid.

[35] T. Quinn, WDFW (pers. comm.)

[36] J. Littell, University of Washington Climate Impacts Group, (pers. comm.)

[37] Baede et al. (2001), *The Climate System: an Overview.* (IPCC Third Assessment Report)

[38] Baede et al. (2001), *The Climate System: an Overview.* (IPCC Third Assessment Report)

[39] Baede et al. (2001), *The Climate System: an Overview.* (IPCC Third Assessment Report)

[40] Baede et al. (2001), *The Climate System: an Overview.* (IPCC Third Assessment Report)

[41] Strahler and Strahler (2005), *Physical Geography: Science and Systems of the Human Environment* (book)

[42] Strahler and Strahler(2005), *Physical Geography: Science and Systems of the Human Environment* (book)

[43] Ibid.

[44] Ibid.

The greenhouse effect develops when the atmosphere, land, and ocean re-emit energy in the form of longwave (infrared) radiation.[45] While some of this longwave radiation emitted from the Earth's surface passes directly to space, much is absorbed in the atmosphere by "greenhouse gases" such as carbon dioxide and water vapor.[46] In turn, the atmosphere re-radiates some of the longwave energy back to the Earth's surface.[47] Thus, the lower atmosphere acts like a blanket that traps heat underneath it, replacing some of the heat emitted by the surface and thereby warming the Earth.[48] Changes in the atmospheric concentration of greenhouse gases and in land cover interact with solar radiation to alter the balance of energy retained in Earth's atmosphere.[49]

The following section details changes in CO_2 concentrations in Earth's atmosphere that enhance the greenhouse effect. Warming as a result of the greenhouse effect influences air temperatures and precipitation patterns on global, regional, and local scales. For more background information on the climate system and a more thorough review of natural and human-induced climate variations, see:

- Baede, APM. E Ahlonsou, Y Ding, and D. Schimel. 2001. The Climate System: an Overview. In: Climate Change 2001: The Scientific Basis. IPCC Third Assessment Report. Available online at http://www.grida.no/publications/other/ipcc_tar/.

CO_2 CONCENTRATIONS – GLOBAL TRENDS

The National Oceanic and Atmospheric Administration (NOAA) reports that the most recent global monthly mean value for atmospheric carbon dioxide (CO_2) concentrations is about 388 parts per million (ppm; data corrected for average seasonal cycle).[50] Over the past 800,000 years, atmospheric CO_2 concentrations have varied between about 170 and 300 ppm.[51] Today's concentrations are approximately 30 percent higher than the earth's highest level of CO_2 over that historical time period.[52]

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[45] Ibid.

[46] Ibid.

[47] Ibid.

[48] Ibid.

[49] Baede et al. (2001), *The Climate System: an Overview.* (IPCC Third Assessment Report)

[50] NOAA (2010), *Earth System Research Laboratory: Global Monitoring Division.* (website)

[51] Information as cited in Karl et al. (eds) (2009) *Global Climate Change Impacts in the United States.* (U.S. government report).

[52] Ibid.

TEMPERATURE – GLOBAL AND REGIONAL TRENDS AND PROJECTIONS

Global average temperature has risen approximately 1.5°F since 1900, and is projected to rise another 2°F to 11.5°F by 2100.[53] The Puget Sound region warmed at a rate substantially greater than the global warming trend—average annual temperature increased 2.3°F (1.3°C) during the 20th century.[54] Much of this warming took place in the second half of the 20[th]century.[55] Mean winter temperatures have also increased 2.7°F (1.5°C) since 1950.[56]

In western U.S. forests, average regional spring and summer temperature increased 1.57°F (0.87°C) between the periods 1970-1986 and 1987-2003.[57] Spring and summer temperatures during the 1987 to 2003 period were the warmest recorded since the beginning of the record in 1895, with 6 years in the 90th percentile over this period, as opposed to only one year in the period 1970 to 1986.[58]

Mote and Salathé (2009) project that annual temperatures in the Pacific Northwest will increase 2.2°F on average by the 2020s and 5.9°F by the 2080s; these projections are compared to 1970 to 1999 and averaged across all climate models.[59] Projected rates of further warming range from 0.2° to 1.0°F per decade.[60] These projections are based on climate ensembles and weighted averages (see box p.10: Weighted Average Climate Projections). Mote and Salathé (2009) also state that for some applications, climate changes

> **Weighted Average Climate Projections***
>
> Mote and Salathé (2009) base their temperature and precipitation projections for Washington on both the common practice of presenting a range of projected changes from more than one climate ensemble (in this case two – the Special Report on Emission Scenarios [SRES] A1B and B1 scenarios), as well as a reliability ensemble averaging (REA) approach. Ensembles represent the average of multiple models.
>
> The REA approach is a weighted average projection -- each model's output for seasons and decades is weighted by its bias and distance from the all-model average; this approach may produce better results for the future than an unweighted average by giving more weight to models that perform well in simulating 20th century climate.[1] For more details on this approach, including graphical presentations of the average and range of values, see Mote and Salathé (2009)
>
> * <u>Source</u>: Mote and Salathé (2009), *Future Climate in the Pacific Northwest*. In: WACCIA (CIG 2009)*.

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[53] Information as cited in Karl et al. (eds) (2009) *Global Climate Change Impacts in the United States.* (U.S. government report).
[54] Information as cited in Snover et al. (2005), *Uncertain Future: Climate change and its effects on Puget Sound* (CIG report)
[55] Information as cited in Snover et al. (2005), *Uncertain Future: Climate change and its effects on Puget Sound* (CIG report)
[56] Ibid.
[57] Westerling et al. (2006), *Warming and earlier spring increase western U.S. forest wildfire activity.* (primary literature)
[58] Westerling et al. (2006), *Warming and earlier spring increase western U.S. forest wildfire activity.* (primary literature)
[59] Mote and Salathé (2009), *Future Climate in the Pacific Northwest*. In: WACCIA (CIG 2009)
[60] Ibid.

in a given season may be more important than changes in the annual mean. For both the A1B and B1 scenarios (see box p.12: A1B and B1 Emissions Scenarios), warming was projected to be largest in summer. Projected changes in temperature for each season are presented in the table below.

Table 1: Range (lowest to highest) of projected increases in temperature in the Pacific Northwest for each season and for the annual mean, relative to the 1980s. All values are presented in degrees Fahrenheit (°F). The REA mean value for projections from the two IPCC SRES scenarios used (B1 and A1B) is also presented under each range. This table was created based on data in Figure 9 of Mote and Salathé (2009).

YEAR	PROJECTED INCREASE IN SEASONAL TEMPERATURE				ANNUAL
	Winter (Dec./Jan./Feb.)	**Spring** (Mar./Apr./May)	**Summer** (June/July/Aug.)	**Fall** (Sept./Oct./Nov.)	
2020s	0.7 - 3.6	0.4 - 3.6	1.0 - 5.3	0.1 - 3.3	1.1 - 3.3
REA mean	B1: 1.8 A1B: 1.7	B1: 2.2 A1B: 2.1	B1: 2.5 A1B: 3.2	B1: 1.9 A1B: 1.9	B1: 2.1 A1B: 2.3
2040s	1.0 - 5.1	1.0 - 5.4	1.5 - 7.9	1.3 - 5.2	1.5 - 5.2
REA mean	B1: 2.5 A1B: 3.2	B1: 2.9 A1B: 3.6	B1: 3.9 A1B: 5.1	B1: 2.7 A1B: 3.6	B1: 3.0 A1B: 4.1
2080s	1.3 - 9.1	1.3 - 9.7	2.5 - 12.5	2.4 - 8.8	2.8 - 9.7
REA mean	B1: 4.2 A1B: 5.7	B1: 4.5 A1B: 6.1	B1: 6.0 A1B: 8.3	B1: 4.2 A1B: 6.2	B1: 4.9 A1B: 7.1

PRECIPITATION – REGIONAL PROJECTIONS

Mote and Salathé (2009) state that projected changes in overall annual precipitation for the Pacific Northwest (averaged across all climate models) are small: +1 to +2%.[61] However, some of the models projected an enhanced seasonal cycle in precipitation, with changes toward wetter winters and drier summers:[62]

- **Drier summers**: For summer months, a majority of models projected decreases in precipitation, with the average declining 16% by the 2080s.[63] Some models predicted reductions of as much as 20-40% in summer precipitation; these percentages translate to 3- 6 cm over the summer season (June/July/August), which is 3-6% of the all-model annual mean 20th century value (102 cm).[64] Although this change is small, summer precipitation and associated cloudiness nonetheless have an impact on evaporative demand[65] and hence on factors such as urban water use and forest fires.[66]

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[61] Ibid.
[62] Ibid.
[63] Mote and Salathé (2009), *Future Climate in the Pacific Northwest*. In: WACCIA (CIG 2009)
[64] Ibid.
[65] Ibid.
[66] Information as cited in Mote and Salathé (2009), *Future Climate in the Pacific Northwest*. In: WACCIA (CIG 2009)

- **Wetter winters:** In winter, a majority of models projected increases in precipitation, with an average value reaching +9% (about 3 cm) by the 2080s under the higher-emissions modeling scenario (A1B); this value is small relative to interannual variability.[67] Although some of the models predicted modest reductions in fall or winter precipitation, others showed very large increases (up to 42%).[68]

A1B AND B1 EMISSIONS SCENARIOS*

The A1B and B1 emissions scenarios are two of a set of emissions scenarios published by the Intergovernmental Panel on Climate Change (IPCC) in their Special Report on Emissions Scenarios (SRES) used to model climate change effects in futures with different populations, technological advancement, levels of fossil fuel reliance, etc. In the WACCIA (CIG 2009), the Climate Impacts Group chose A1B as the higher emissions scenario and B1 as the lower emissions scenario to analyze 21st century Pacific Northwest climate.

The A1B scenario represents a future of rapid economic growth in which energy sources are balanced between fossil and non-fossil fuels (with the assumption that energy use efficiency will improve with the introduction of new technologies).

The B1 scenario represents a future in which global economies are less material-intensive and based more on information and services. Clean and resource-efficient technologies are introduced and an emphasis is placed on economic, social, and environmental sustainability.

* Sources: *IPCC. 2007. AR4, Working Group 1: The Scientific Basis. Section F.1 Box 5; Mote and Salathé (2009); CIG (2009).*

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[67] Mote and Salathé (2009), *Future Climate in the Pacific Northwest*. In: WACCIA (CIG 2009)
[68] Ibid.

SNOWPACK – REGIONAL PROJECTIONS

Snowpack in the Pacific Northwest is highly temperature sensitive and long-term records show that April 1 snowpack has already declined substantially throughout the region.[69] Snover et al. (2005) cite information that April 1 snowpack (measured as snow water equivalent, or SWE) has declined markedly almost everywhere in the Cascades since 1950.[70] These declines exceeded 25 percent at most study locations, and tended to be largest at lower elevations.[71] Stoelinga et al. (in press) examined snowpack data over an even longer time period (1930-2007) and concluded that snowpack loss occurred at a rate of approximately 2.0% per decade, yielding a 16% loss over nearly 80 years.[72]

Relative to late 20th century averages (1971-2000), Elsner et al. (2009) project that April 1 SWE will decrease by 27-29% across the state by the 2020's, 37-44% by the 2040's, and 53-65% by the 2080's.[73] A study by Stoelinga et al. (in press) predicts that cumulative loss of Cascade spring snowpack from 1985-2025 will be only 9%.[74]

According to the US Forest Service's Climate Change Resource Center website, snowmelt provides approximately 70% of annual streamflow in the mountainous regions of the western U.S.[75] Both increased winter rain (as opposed to snow) and shifts to earlier spring snowmelt result in greater winter and spring streamflows and reduced summer streamflows in snowmelt dominated and transient (rain/snow) watersheds.[76] This reduction in summer streamflow could have major implications for fisheries, wildlife, water supply and agriculture, particularly in drier regions.[77] The current and expected future trends in hydrology suggest a coming crisis in water supply for the western U.S.[78]

[**Note**: For further information on climate change effects on snowpack, see the section on "Reduced Snowpack and Altered Runoff Regimes" in the summary on climate change impacts to freshwater ecosystems produced by National Wildlife Federation Science and the Washington Department of Fish & Wildlife.]

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[69] Information as cited in Karl, et al. (2009) *Global Climate Change Impacts in the United States*.
[70] Information as cited in Snover et al. (2005), *Uncertain Future: Climate change and its effects on Puget Sound*. (CIG report)
[71] Ibid.
[72] Stoelinga et al. (in press), *A New Look at Snowpack Trends in the Cascade Mountains.* (primary literature)
[73] Elsner et al. (2009), *Implications of 21st century climate change for the hydrology of Washington State*. In: WACCIA (CIG 2009)
[74] Stoelinga et al. (in press), *A New Look at Snowpack Trends in the Cascade Mountains.* (primary literature)
[75] Information as cited in CCRC (2010), *Climate Change Primer.* (website)
[76] Ibid.
[77] CCRC (2010), *Climate Change Primer.* (website)
[78] Information as cited in CCRC (2010), *Climate Change Primer.* (website)

CLIMATE CHANGE EFFECTS ON WASHINGTON'S FOREST ECOSYSTEMS

Based on information in WACCIA (CIG 2009) and PAWG (2008), the four major climate change effects on forest ecosystems appear to be:

- **Changes in species composition and distribution, including invasive species**
- **Changes in forest productivity and phenology**
- **Increased frequency and magnitude of wildfires**
- **Increased susceptibility to insects and disease**

This section addresses each of these effects, providing information on observed climate-related changes, projected future changes, a discussion of the implications of those projections and identified knowledge gaps.

CHANGES IN SPECIES COMPOSITION & DISTRIBUTION

Climate is the primary force shaping the vegetative communities that characterize the major biogeographic regions of the world.[79] For example, on the scale of individual plants, temperature may influence characteristics such as rates of leaf photosynthesis and respiration, the frost tolerance of tree needles, and processes such as flowering, bud dormancy, and the ripening of fruits and cones.[80,81] On a larger scale, the mean and variation in annual temperature and precipitation jointly determine general (biome) patterns of distribution and growth.[82, 83]

A species' distribution and abundance is governed by the birth, growth, death, and dispersal rates of the individuals in a given population.[84] In turn, these rates are influenced by environmental factors (including climate), which alter resource availability, fecundity, and survivorship.[85] Across populations, changes in rates of birth, growth, death, and dispersal become apparent as local extinction and colonization events; these are the mechanisms by which species' ranges change.[86]

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[79] Hansen et al. (2001), *Global Change in Forests: Responses of Species, Communities, and Biomes*. (primary literature)

[80] Information as cited in Aber et al. (2001), *Forest processes and global environmental change: Predicting the effects of individual and multiple stressors.* (primary literature)

[81] Boisvenue and Running (2006), *Impacts of climate change on natural forest productivity – evidence since the middle of the 20th century.* (primary literature)

[82] Information as cited in Aber et al. (2001), *Forest processes and global environmental change: Predicting the effects of individual and multiple stressors.* (primary literature)

[83] Information as cited in Hansen et al. (2001), *Global Change in Forests: Responses of Species, Communities, and Biomes*. (primary literature)

[84] Hansen et al. (2001), *Global Change in Forests: Responses of Species, Communities, and Biomes*. (primary literature)

[85] Information as cited in Hansen et al. (2001), *Global Change in Forests: Responses of Species, Communities, and Biomes*. (primary literature)

[86] Hansen et al. (2001), *Global Change in Forests: Responses of Species, Communities, and Biomes*. (primary literature).

Overall, species' distributions reflect their differential responses to climate, edaphic factors, and biotic interactions such as competition and herbivory.[87] In addition, community composition also reflects indirect effects associated with changes in disturbance regimes and land use.[88] These dynamics provide the mechanisms by which communities and biomes respond to changing conditions.[89] At the same time, community composition may constrain a species' response.[90] For example, species may not be able to shift their range without being accompanied by mutualists such as pollinators.[91] Exposure to extreme events (e.g., flooding, wind storms) also has the potential to influence species' survival and growth.[92]

In the past, the composition of forest communities and distribution of species changed gradually over time as individual species responded differentially to climate change.[93] Noss (2001) notes that today, changes that occur at a faster rate, greater intensity, different pattern, or broader spatial scale than historically are likely to fall outside the limits of adaptability for some species. While some ecosystems may be able to survive in the face of rapid change, many terrestrial species and communities do not have the natural capacity to migrate or adapt quickly enough.[94] A change in the availability of ecosystem goods and services could result.[95] For example, forests may be less able to act as "sinks" for human CO_2 emissions.

Migration, or geographically tracking suitable environmental conditions, is thought to be the main way that plant species have responded to past climate changes.[96] The migration rate of trees colonizing areas after glaciations is estimated to range from 50 m/yr (American beech) to 2000 m/yr (spruce) depending on the species.[97] Some evidence exists for more rapid, long-distance migrations, although these rare dispersal events are difficult to incorporate into models.[98] Tree species with slower migration rates may not be able to keep up with the current rate of climate change;[99] however, this may only result in extirpation or extinction if a particular species has a very limited geographic distribution. Species may also experience movement barriers in habitats fragmented by human activities,[100] and fragmented forests may therefore be more sensitive to climate change.[101]

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[87] Ibid.

[88] Information as cited in Hansen et al. (2001), *Global Change in Forests: Responses of Species, Communities, and Biomes*. (primary literature)

[89] Hansen et al. (2001), *Global Change in Forests: Responses of Species, Communities, and Biomes*. (primary literature)

[90] Ibid.

[91] Ibid.

[92] Information as cited in Aber et al. (2001), *Forest processes and global environmental change: Predicting the effects of individual and multiple stressors.* (primary literature)

[93] Noss (2001), *Beyond Kyoto: Forest Management in a Time of Rapid Climate Change.* (primary literature)

[94] USFS (2008), *Forest Service Strategic Framework for Responding to Climate Change*. (U.S. government report)

[95] Ibid.

[96] Noss (2001), *Beyond Kyoto: Forest Management in a Time of Rapid Climate Change.* (primary literature)

[97] Ibid.

[98] Ibid.

[99] Noss (2001), *Beyond Kyoto: Forest Management in a Time of Rapid Climate Change.* (primary literature)

[100] Ibid.

[101] Ibid.

With the changing distribution of species in response to climate change, plant community composition is also projected to change.[102] For long-lived species, changes in composition may lag behind changes in climate, due to trees' long lifespan.[103] Changes in composition will also depend on seed sources and appropriate environmental conditions for the establishment of new communities.[104] Species richness (i.e., the number of different species in a given area) may play a part in how changes in composition alter the ecosystem overall; species richness can provide redundancy between multiple functional groups, such that their role in an ecosystem is maintained despite alterations in member species.[105]

The *Preparation and Adaptation Working Group* (PAWG 2008) identified the following forests in Washington as the most likely to experience major change in composition as a result of climate change:

- Ponderosa Pine and Douglas-fir forests near the lower treeline in eastern Washington

- Forests near the upper treeline on both sides of the Cascade range

Climate change is predicted to affect these species and systems primarily through increasing summer temperatures and lower water availability.[106] This would decrease the growth, vigor, and fuel moisture in lower elevation forests while increasing growth and regeneration in high elevation forests.[107] Species that may be affected by climate change also include economically-valuable timber species, rare/threatened/endangered species, keystone species, and species that are or may become invasive.[108] In addition, the forests in Washington's parks, wilderness areas, and reserves are also likely to be stressed by climate change.[109] In particular, the species in protected areas may have difficulty migrating in response to climate change due to the fixed boundaries of reserves, development outside those boundaries, and large distances to other suitable habitats.[110]

In sum, the Preparation and Adaptation Working Group report (PAWG, 2008) states that forest species may respond to climate change in a variety of ways; for example, species may experience alterations in physiology, interspecies relationships, and distribution.[111] Some species may expand their ranges, while others retreat.[112] In particular, it is difficult to predict how new assemblages of species will interact as they begin to migrate in response to climate.[113]

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[102] PAWG (2008), *Leading the Way: Preparing for the Impacts of Climate Change in Washington - Recommendations of the Preparation and Adaptation Working Groups.*

[103] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[104] Ibid.

[105] Noss (2001), *Beyond Kyoto: Forest Management in a Time of Rapid Climate Change.* (primary literature)

[106] PAWG (2008), *Leading the Way: Preparing for the Impacts of Climate Change in Washington - Recommendations of the Preparation and Adaptation Working Groups.*

[107] Ibid.

[108] Ibid.

[109] Ibid.

[110] Ibid.

[111] Ibid.

[112] Ibid.

[113] Ibid.

Observed Changes

In a study of 76 forest plots in the western U.S. and southwestern British Columbia (including plots in both eastern and western Washington), Van Mantgem et al. (2009) analyzed data on tree mortality rates in old forests (mean ~450 years old) for the periods 1955-1994 and 1998-2007.

The authors found that tree mortality rates increased approximately 0.5-2% per year in 87% of their forest plots across their entire study area.[114] Regionally, mortality rates showed a statistically significant increase of about 1.0-1.5% per year in the Pacific Northwest (n=47 forest plots), with an estimated doubling in mortality rate occurring every 17 years.[115] Mortality rates increased in forests at all the elevations examined (<1000 m, 1000-2000 m, >2000 m) and for all tree sizes (stem diameter <15 cm, 15-40 cm, >40 cm). Mortality rates also increased in both abundant and non-dominant genera (n=19) with a broad range of life history traits.[116] The authors did not find a significant change or trend in the rate of tree recruitment to "offset" the increase in mortality.[117]

Van Mantgem et al. (2009) suggest that regional warming, resultant changes in hydrologic regimes, and drought stress may be the dominant contributors to the observed increases in tree mortality rates.[118] Mean annual temperature and climatic water deficit increased significantly in their study sites over the study period, and temperature and water deficit were positively correlated with tree mortality rates.[119] Increasing mortality rates could presage substantial changes in forest structure, composition, and function, and in some cases could be symptomatic of forests that are stressed and vulnerable to abrupt dieback.[120]

- Two external reviewers stated that there is debate about the strength and validity of the findings of Van Mantgem et al. (2009) for the Pacific Northwest, and that these results should be approached and used cautiously.

While several studies have attributed widespread changes in plant growth or mortality to climate change, few studies have shown evidence of widespread plant range shifts – possibly due to the limited dispersal ability of plants or to the lack of long-term records of plant distribution.[121] Recently, Kelly and Goulden (2008) documented shifts in plant distribution in Southern California that they attributed to climatic change. By comparing vegetation surveys conducted in 1977 and 2006-2007, the authors found that, although overall plant cover remained stable, the mean elevation of nine widely-distributed

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[114] Van Mantgem et al. (2009), *Widespread increase of tree mortality rates in the western United States.* (primary literature)
[115] Ibid.
[116] Ibid.
[117] Ibid.
[118] Van Mantgem et al. (2009), *Widespread increase of tree mortality rates in the western United States.* (primary literature)
[119] Ibid.
[120] Information as cited in Van Mantgem et al. (2009), *Widespread increase of tree mortality rates in the western United States.* (primary literature)
[121] Kelly and Goulden (2008) *Rapid shifts in plant distribution with recent climate change.* (primary literature)

species rose with an average elevation gain of approximately 212 feet ± 111feet (64.7 m ± 33.8 m, 95% C.I.) in 30 years.[122] The mean elevation of desert, chaparral, and montane plants all increased at about the same rate.[123]

In Kelly and Goulden's (2009) study, species shifts resulted in the upward movement of the boundaries between plant functional types; for example, the border between conifer forest and evergreen broadleaf woodland shifted upward as a result of increased mortality of a pine species at the lower part of its range, and a proliferation of an oak species in the upper part of its range.[124] According to the authors, the establishment of species at locations well above their previous ranges appeared to have been minimal, and the observed upslope movement was not an expansion into new elevations but rather a result of shifting dominance within existing communities.[125]

Shifts in tree species distributions have also been observed at mountain treelines. For example, Luckman and Kavanagh (2000) examined treeline dynamics at three sites near the Columbia Icefield in the Canadian Rocky Mountains. They found that one of the three sites studied – located on a warmer, south-facing slope – showed an increase in treeline elevation with climate changes over the 20th century.[126] This warmer site experienced extensive upslope migration of the treeline via seedling establishment and more rapid growth of seedlings into trees.[127] A nearby north-facing site experienced a significant level of seedling establishment above treeline, but the slower growth rate of trees there means that it will take some time before the position of the treeline actually changes.[128] A third site located on the valley floor exhibited no change in tree ranges.[129] The authors state that their limited studies suggest that the effects of global and regional climate changes on vegetation will be modulated by microclimatic effects and local topographic or site factors.[130]

Future Projections

On a regional scale, the details of expected changes in forests are unclear.[131] However, based on climate change alone, the global extent of tropical and temperate forests are projected to expand up to 20%, while boreal forests may decline by 50%.[132]

In Washington, WACCIA (CIG 2009) provides specific projections for Douglas-fir and pine forests. The models utilize maps of potential future climate which are based on correlative models that predict the

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[122] Ibid.
[123] Ibid.
[124] Ibid.
[125] Ibid.
[126] Luckman and Kavanagh. 2000. *Impact of climate fluctuations on mountain environments in the Canadian Rockies.* (primary literature)
[127] Ibid.
[128] Ibid.
[129] Ibid.
[130] Ibid.
[131] Noss (2001), *Beyond Kyoto: Forest Management in a Time of Rapid Climate Change.* (primary literature)
[132] Ibid.

future distribution of contemporary climate profiles; these correlative models do not explicitly account for potential human efforts to alter or restore forest systems.[133]

- **Douglas-fir**: By the end of the 2060s, independent species range modeling based on Intergovernmental Panel on Climate Change (IPCC) scenarios suggests that climate will be sufficiently different from the late 20th century to constrain Douglas-fir distribution.[134] About 32% of the area currently classified as appropriate climate for Douglas-fir would be outside the identified climatic envelope by the 2060s, and about 55% would be in the 50%-75% range of marginal climatic agreement among models.[135] Only about 13% of the area currently suitable for Douglas-fir would be suitable in >75% of the statistical species models.[136] The decline in climatically suitable habitat for Douglas-fir is most widespread at lower elevations and particularly in the Okanogan Highlands and the south Puget Sound/ southern Olympics.[137] These potential shifts would likely be due to increases in temperature and decreases in growing season water availability in more arid environments (e.g., in the Columbia Basin) but could be due to other variables in less arid parts of the species' range.[138]

- **Pine Forests**: Climate is likely to be a significant stressor in pine forests in the Columbia Basin and eastern Cascades as early as the 2040s, particularly in parts of the Colville National Forest, Colville Reservation, and central Cascades.[139] About 85% of the current habitat for pine will be outside the climatically suitable range for one or more pine species (74% area with loss of suitable climate for one species, 11% area with loss of suitable climate for two species, <1% area with loss suitable climate for three species).[140]

In the next 100 years, changes in forests may manifest as either large-scale shifts in biomes or as smaller disruptions in growth.[141] In general, species are predicted to shift their ranges northward and higher in elevation, with new vegetation communities developing over space and time.[142] Shifts in biome location depend on the movements of key species.[143] The predicted rates of climate change may push the climatic boundaries of biomes northward at a rate faster than the predicted rate of species migration, such that shifts in biomes could lag behind changes in climate.[144]

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[133] Rehfeldt et al. (2006), *Empirical analyses of plant-climate relationships for the western United States.* (primary literature)

[134] Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

[135] Ibid.

[136] Ibid.

[137] Ibid.

[138] Ibid.

[139] Ibid.

[140] Ibid.

[141] Information as cited in Spittlehouse and Stewart (2003), *Adaptation to climate change in forest management.* (primary literature)

[142] Ibid.

[143] Hansen et al. (2001), *Global Change in Forests: Responses of Species, Communities, and Biomes*. (primary literature)

[144] Information as cited in Hansen et al. (2001), *Global Change in Forests: Responses of Species, Communities, and Biomes*. (primary literature)

Competitive balances in forests are also likely to shift.[145] Where land use creates barriers to dispersal for native species and facilitates dispersal for exotic species, climate change in human-dominated landscapes is likely to favor exotic species over native species.[146] The presence of exotic species may elevate species richness but inhibit ecosystem function.[147]

- WDFW reviewers commented that perspectives of exotic species may change as vegetation begins to migrate across the landscape in response to climate change. For example, native species may take on different functional roles in new habitat areas, or possibly act like "invasive" species in their new environments.

Forest composition is highly likely to change if precipitation,[148] temperature, or both change substantially as a result of global warming. For example, trees of certain species or ages may be better adapted to surviving moisture variations than others.[149] Mature forests with well-established root systems may be better able to withstand drought and changes in moisture than forests that are young or recovering from a recent disturbance.[150] There are only a limited number of studies available that may be used to predict the rate of change in forest species composition with regards to changes in the amount of precipitation.[151]

ALTERED FOREST PRODUCTIVITY & PHENOLOGY

Productivity

Productivity refers to the rate of biomass (organic matter) produced by an individual organism or a community, measured as either energy or organic matter produced per unit area. Plants use the energy from sunlight to convert atmospheric CO_2 and water to organic sugars through photosynthesis. Plants "fix" carbon when they convert it from an inorganic form (e.g., CO_2) to an organic form (e.g., glucose).

Forest primary productivity is controlled by multiple factors. The presence of sunlight, CO_2, and water are required for photosynthesis. Additional factors that can also influence productivity include: the amount and light-use efficiency of foliage, water availability, ambient temperature, availability of soil

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[145] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[146] Information as cited in Hansen et al. (2001), *Global Change in Forests: Responses of Species, Communities, and Biomes*. (primary literature)

[147] Hansen et al. (2001), *Global Change in Forests: Responses of Species, Communities, and Biomes*. (primary literature)

[148] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[149] Hansen, et al. (2003), *Buying Time: A User's Manual for Building Resistance and Resilience to Climate Change in Natural Systems.* (non-profit report)

[150] Hansen, et al. (2003), *Buying Time: A User's Manual for Building Resistance and Resilience to Climate Change in Natural Systems.* (non-profit report)

[151] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

nutrients, species' adaptations to extreme temperatures, and a species' ability to efficiently use water and nutrients.[152]

In general, plant performance is compromised when one or more of the physical resources necessary for growth (e.g., CO_2, light, water, nutrients) are limited.[153] On a broad scale, forests in western North America can be described as either energy-limited or water-limited.[154]

- **Energy-limited forests** occur where light or temperature limits plant performance.[155] For example, densely shaded forests or high-elevation forests may experience energy limitations.[156] Tree growth in energy-limited ecosystems appears to be responding positively to warming temperatures over the past 100 years.[157]

- **Water-limited forests** occur where summer atmospheric and plant demands exceed available soil moisture.[158] Productivity in water-limited systems is expected to decline with warming temperatures, as increasing water balance deficit constrains photosynthesis across more of the West.[159] A study described by Littell et al. (2009a) found that most montane Douglas-fir (*Pseudotsuga menziesii*) forests across the northwestern United States appear to be currently water-limited; although seasonally water-limited forests occur throughout Washington, the most severely water-limited forests generally occur in the central part of the state.[160]

Temperature, water, and the amount of available solar energy interact to limit forest productivity in different ways.[161] Warmer temperatures and increased precipitation may result in extended growing seasons and biomass accumulation.[162] However, the physiological response of vegetation to climate change (i.e. increases in CO_2 or temperature) depends on which abiotic factors are limiting forest growth in a given location or at a given time of year.[163,164] Boisvenue and Running (2006) summarize this

[152] Boisvenue and Running (2006), *Impacts of climate change on natural forest productivity – evidence since the middle of the 20th century.* (primary literature)

[153] Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

[154] Information as cited in Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

[155] Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

[156] Ibid.

[157] Information as cited in Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

[158] Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

[159] Ibid.

[160] Information as cited in Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

[161] Boisvenue and Running (2006), *Impacts of climate change on natural forest productivity – evidence since the middle of the 20th century.* (primary literature)

[162] Oregon Forest Resources Institute (2006), *Forests, Carbon and Climate Change: A Synthesis of Science Findings.* (synthesis document)

[163] Boisvenue and Running (2006), *Impacts of climate change on natural forest productivity – evidence since the middle of the 20th century.* (primary literature)

[164] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

complexity through an example, stating that the productivity of temperate forests of northwestern North America may be radiation and temperature limited in winter, temperature limited in spring, and water limited by midsummer. [165] These controls depend on climate and are expressed as a mosaic of regionally varied impacts on forest systems.[166]

CO_2 is a key component in plant photosynthesis, and thus atmospheric CO_2 concentrations can influence forest productivity. Atmospheric CO_2 concentrations have increased from an historic range of about 170-300 ppm to about 388 ppm today. [167] Experiments have shown that elevated CO_2 can influence the physiology, phenology, and growth of trees.[168] Elevated CO_2 concentrations may increase rates of net photosynthesis and hence tree growth – at least in the short term – although evidence of direct responses of tree growth to increased CO_2 is limited.[169] For example, CO_2 enrichment has been shown to increase net primary productivity in a closed-canopy deciduous forest.[170] However, instead of storing more carbon in wood, the plants cycled carbon faster through their tissues.[171] Elevated CO_2 may not increase a species' productivity if other factors such as nutrients or water are limiting.[172] Elevated CO_2 may also indirectly influence the balance of other nutrients (such as nitrogen) in plants; this could alter a tree's resistance to pests and herbivores and influence rates of leaf decomposition and nutrient cycling.[173] Overall, there may not be enough information available to create generalized predictions of ecosystem responses to elevated CO_2, and many responses may be species or site-specific.[174]

Air pollutants such as nitrogen and ozone are expected to interact with climate change stressors in "novel combinations" with effects that are difficult to predict for forests.[175] Nitrogen may limit growth, or change whether a species responds to increased CO_2. Ozone directly damages species, causing a decline in their photosynthetic rate.[176] Pollution may negate some of the possible benefits of elevated CO_2 or temperature. For example, although warmer temperatures and higher CO_2 concentrations might

[165] Boisvenue and Running (2006), *Impacts of climate change on natural forest productivity – evidence since the middle of the 20th century.* (primary literature)

[166] Boisvenue and Running (2006), *Impacts of climate change on natural forest productivity – evidence since the middle of the 20th century.* (primary literature)

[167] NOAA (2010), *Earth System Research Laboratory: Global Monitoring Division.* (website)

[168] Information as cited in Aber et al. (2001), *Forest processes and global environmental change: Predicting the effects of individual and multiple stressors.* (primary literature)

[169] Ibid.

[170] Information as cited in Asshoff et al. (2006) *Growth and phenology of mature temperate forest trees in elevated CO_2.* (primary literature)

[171] Ibid.

[172] Lockwood, J.G. 1999. Is potential evapotranspiration and its relationship with actual evapotranspiration sensitive to elevated CO_2 levels? Climatic Change 41:193-212.

[173] Information as cited in Aber et al. (2001), *Forest processes and global environmental change: Predicting the effects of individual and multiple stressors.* (primary literature)

[174] Information as cited in Aber et al. (2001), *Forest processes and global environmental change: Predicting the effects of individual and multiple stressors.* (primary literature)

[175] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[176] Aber et al. (2001), *Forest processes and global environmental change: Predicting the effects of individual and multiple stressors.* (primary literature)

enhance forest productivity, air pollutants and climate stress could decrease tree growth.[177] Tree response to interactions between ozone and climate change have been poorly studied, and may differ between trees of different ages or sizes.[178]

Overall, it is difficult to predict whether increased productivity will be observable in a given forest, and if so, whether climate change is driving such an increase. For example, in fire-dominated systems such as boreal forests, changes in productivity may be obscured by the large alterations in productivity caused by wildfire disturbance.[179] Other than climate factors, variables that influence productivity can include increases in nitrogen deposition, changes in forest age structure, and management practices.[180] Interactions between all these factors, as well as a lack of data, can make it difficult to determine what is causing forest productivity to change.[181]

Phenology

Phenology refers to the timing and duration of plant life history stages. Increased temperatures may affect forest growth by influencing plant phenology.[182] The range that tree species occupy may be limited both by winter temperatures and by the species' ability to complete phenological development within the growing season.[183] For example, temperature and photoperiod are two major factors that control vegetative budding in the spring.[184] Field studies have also found that elevated atmospheric CO_2 in spring and fall can accelerate leaf development, delay leaf development, or produce no response.[185] Changes in leaf phenology can affect leaf duration and tree productivity.[186] Finally, shifts in timing of flowering and the abundance of insect pollinators could lead to the decline of some plant species if pollinators are absent during times of peak flowering.[187]

[177] Blate et al. (2009), *Adapting to climate change in United States national forests*. (primary literature)

[178] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[179] Boisvenue and Running (2006), *Impacts of climate change on natural forest productivity – evidence since the middle of the 20th century.* (primary literature)

[180] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[181] Ibid.

[182] Information as cited in Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.*

[183] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[184] Asshoff et al. (2006) *Growth and phenology of mature temperate forest trees in elevated CO_2.* (primary literature)

[185] Information as cited in Asshoff et al. (2006) *Growth and phenology of mature temperate forest trees in elevated CO_2.* (primary literature)

[186] Ibid.

[187] Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.*

Observed Changes in Forest Productivity and Phenology

Climate change over the last 55 years has generally enhanced forest productivity in places where water is not limiting.[188] However, experimental studies of the effects of climate-related change on plant productivity have had mixed results. Most evidence indicates that productivity will increase as a result of climate change, although decreases have also been reported.[189]

For example, one study found that increases in precipitation altered forest productivity only when the timing or seasonal patterns of precipitation changed – not when a greater amount of rain fell in the same temporal pattern as naturally occurred.[190] Another study reported that increased concentrations of CO_2 enhanced the maximum rate of photosynthesis for all the species observed.[191] Many studies focused on young plants have found that elevated CO_2 produced an initial stimulation in growth.[192] However, a 4-year study of CO_2 enhancement of middle-aged hardwood trees did not find any support for the idea that tree growth would be continuously stimulated by elevated CO_2, although it might serve to mitigate drought stress.[193] Asshoff et al. (2006) summarize the evidence by stating that plant responses to elevated CO_2 are species specific, and that there is even variation between individuals of the same species in terms of their sensitivity to elevated CO_2.[194]

Experiments investigating the response of individual plants or species to elevated concentrations of CO_2 may provide some indication of plant responses to atmospheric conditions under future climate scenarios. However, competitive interactions between plants and differences in growth characteristics between plant functional groups will ultimately also drive future forest community dynamics. For example, a broad screening for responsiveness to elevated CO_2 across early and late successional tropical tree species revealed that under favorable growth conditions, the early successional species with high relative growth rates were stimulated by CO_2 enhancement, but not the late successional species.[195] Recent observations have suggested that vines such as poison ivy are likely to benefit under enhanced CO_2 conditions relative to trees because vines can allocate more sugars to additional leaf tissue (as opposed to woody support structures); greater light capture by leaves could, over time, confer a competitive advantage on vines over trees.[196]

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[188] Boisvenue and Running (2006), *Impacts of climate change on natural forest productivity – evidence since the middle of the 20th century.* (primary literature)

[189] Boisvenue and Running (2006), *Impacts of climate change on natural forest productivity – evidence since the middle of the 20th century.* (primary literature)

[190] Cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[191] Asshoff et al. (2006) *Growth and phenology of mature temperate forest trees in elevated CO_2.* (primary literature)

[192] Ibid.

[193] Ibid.

[194] Ibid.

[195] Information as cited in Körner (2004), *Through enhanced tree dynamics carbon dioxide enrichment may cause tropical forests to lose carbon.* (primary literature)

[196] Ziska et al. (2007), *Rising atmospheric carbon dioxide and potential impacts on the growth and toxicity of Poison Ivy (*Toxicodendron radicans*).* (primary literature)

- Note: We could find no projections regarding how CO_2 enhancement might change forest species competition in the Pacific Northwest as a result of differential enhancements in productivity conferring competitive advantages on some species over others.

There is also some evidence to support the hypothesis that CO_2 fertilization significantly increases water-use efficiency in plants -- enough to partially offset future water demands; however, conclusive results have not been forthcoming. [197] Because an increase in water-use efficiency is uncertain, the overall expected change is that plants will experience an increase in water demand and a decrease in water availability in summer.[198]

The observed changes in forest productivity due to CO_2 and climate related factors in literature we reviewed are reported at a global/international and North American scale.

Observed changes at the global/international scale include:

- Net global primary productivity increased 6% from 1982 to 1999, although declines were observed during warmer years associated with three major El Niño Southern Oscillation events.[199]
- From 1950 to 1999, an almost constant increase in net biome production (NBP) in European forests was observed, from 0.03 PgC/yr in the 1950s to 0.14 PgC/yr in the 1990s.[200] [PgC = petagram; 1 petagram = 1 billion metric tons.] However, a few northern European temperate forests showed no change or a decrease in productivity if other factors (such as water) were limiting.[201]
- Forest productivity increases were generally observed across temperate North America, Northern Europe, most of Central Europe, some parts of Southern Europe, and Japan, although local conditions may cause exceptions.[202]

Observed changes in North American forest productivity include:

- Regional studies reported a 2% - 8% increase in net primary productivity between 1982 and 1998.[203] This increase was believed to be the result of increased precipitation, humidity, and air temperature spurring increased plant growth.[204]
- Growth increased generally in the Canadian Cordillera from 1950 to 1999. [205]

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[197] Information as cited in Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

[198] Ibid.

[199] Boisvenue and Running (2006), *Impacts of climate change on natural forest productivity – evidence since the middle of the 20th century.* (primary literature)

[200] Ibid.

[201] Ibid.

[202] Information as cited in Boisvenue and Running (2006), *Impacts of climate change on natural forest productivity – evidence since the middle of the 20th century.* (primary literature)

[203] Ibid.

[204] Ibid.

[205] Information as cited in Boisvenue and Running (2006), *Impacts of climate change on natural forest productivity – evidence since the middle of the 20th century.* (primary literature)

- In one U.S. experimental study, average productivity increased 23%. The response of tree growth and carbon storage to elevated CO_2 depended on site fertility, water availability, and stand age, with fertile, younger stands responding more strongly.[206]

Overall, the influence of climate on tree *phenology* appears to be species specific, and the effect of elevated CO_2 on leaf duration and phenology is still unclear. [207] However, there is a large body of literature that records and discusses changes in plant phenology as a result of increasing temperatures. A few examples of the changes observed in plant and forest phenology are listed below. An excellent source for further information is Khanduri et al. (2008).

- Increasing temperatures have extended the average annual growing season in Europe by 11 days since the early 1960s.[208] Spring events such as leaf unfolding have advanced by 6 days, while autumn events such as leaf coloring have been delayed by 5 days.[209] The extended growing season may result in increased productivity.[210]
- In Japan, the length of the growing season for *Ginkgo biloba* trees has increased by 12 days since 1953, as a result of changes in phenology related to a 2.34°F (1.3°C) increase in average annual air temperature from 1961-2000.[211]
- In Europe and Japan, leaf color changes have shown a delay of 0.3-1.6 days per decade, whereas the growing season has increased by up to 3.6 days per decade over the past 50 years.[212] A warmer autumn could lead to earlier fruit ripening but delayed leaf senescence.[213] In contrast to spring, there is much less information available on autumn phenology.[214]
- In Canada, researchers studying aspen trees found that a 26-day shift to earlier blooming had taken place from 1900-1997.[215] Furthermore, the study recorded that the spring flowering index (the average of the first flowering dates of three tree species) had advanced by 8 days over a period of 61 years (1936-1996).[216]
- Shifts toward earlier flowering and/or leaf unfolding in various plant species have been recorded worldwide in countries such as Hungary (0.2-0.6 days/decade over 144 years), the United States (1.7 days/decade over 35 years), Canada (2.7 days/decade over 98 years), Japan (0.8 days/decade over 48 years), and Australia (21 days/decade over 20 years), among others.[217]

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[206] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[207] Asshoff et al. (2006) *Growth and phenology of mature temperate forest trees in elevated CO_2.* (primary literature)

[208] Information as cited in Asshoff et al. (2006) *Growth and phenology of mature temperate forest trees in elevated CO_2.* (primary literature)

[209] Ibid.

[210] Ibid.

[211] Information as cited in Khanduri et al. (2008), *The effects of climate change on plant phenology.* (primary literature).

[212] Ibid.

[213] Khanduri et al. (2008), *The effects of climate change on plant phenology.* (primary literature).

[214] Ibid.

[215] Information as cited in Khanduri et al. (2008), *The effects of climate change on plant phenology.* (primary literature).

[216] Ibid.

[217] Ibid.

- In a study of young trees, no change in spring phenology was observed, although other studies report that bud break was either advanced or delayed.[218]
- Some studies have found little evidence of any changes in tree growth or phenology with increasing CO_2, supporting the conclusion that tree growth for the individuals observed was not carbon limited.[219]

Future Projections

Higher CO_2 concentrations and rising temperatures are generally projected to enhance photosynthesis, and are expected to lead to greater tree growth in the U.S.[220] However, plant metabolism generally has an optimum temperature and large departures or extreme events (i.e., too hot or too cold) can result in a decline in productivity, plant damage, or tree mortality.[221] Whether changes in climate and the growing season will support increased forest productivity will depend on regional conditions and the factors that limit productivity in a given place.[222] Other possible implications of elevated CO_2 include an increased tolerance to drought stress, changes in tree tissue quality, and effects on community dynamics.[223]

One negative consequence of climate change might be an increase in the production of isoprene and other hydrocarbons by some tree species, which could lead to higher levels of surface ozone and increased plant damage.[224] Many woody species release isoprene and other volatile organic compounds that can serve as precursors to the formation of tropospheric ozone and organic aerosols – thereby influencing air pollution.[225] Ozone is produced from reactions between nitrogen oxides and volatile organic compounds, and can damage plants and lower productivity: responses that have been documented in U.S. forests.[226] Ozone pollution will modify the effects of elevated CO_2 and changes in temperature and precipitation regimes, but these interactions are difficult to predict because they have been insufficiently studied.[227]

For forest types found in Washington State, lower water availability is expected to decrease the growth, vigor, and fuel moisture of lower elevation forests such as ponderosa pine, Douglas-fir, and western

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[218] Information as cited in Asshoff et al. (2006) *Growth and phenology of mature temperate forest trees in elevated CO_2.* (primary literature)

[219] Ibid.

[220] Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[221] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[222] Boisvenue and Running (2006), *Impacts of climate change on natural forest productivity – evidence since the middle of the 20th century.* (primary literature)

[223] Ibid.

[224] Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[225] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[226] Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[227] Ibid.

hemlock.[228] The area of forest that is severely water-limited is predicted to increase by 32% in the 2020s, and an additional 12% in both the 2040s and the 2080s (all values relative to 20th century water-limited forests).[229] Increasing water limitation appears likely across a significant portion of the northern Columbia Basin and eastern Cascades if other factors (e.g., CO_2 driven increases in water use efficiency) do not offset the climatically driven changes.[230] These projections are based on changes in climate variables alone, and do not account for human forest management.

Increased drought stress is expected to result in decreased tree growth and forest productivity in dry, northeastern forests of the Olympic Peninsula.[231] The productivity of some Douglas-fir forests in Washington is also expected to decrease.[232] The productivity of montane Douglas-fir stands in eastern Washington will initially be most vulnerable to climate change, although eventually the productive commercial forests in western Washington will also be susceptible.[233] Increasing growth may be observed in higher elevation forests such as subalpine fir, Pacific silver fir, and mountain hemlock. [234]

- An external reviewer noted that, although montane Douglas-fir stands in eastern Washington may initially be most vulnerable to climate change, other species such as ponderosa pine and lodgepole pine may also be vulnerable.[235]

Discussion

Where forests are water-limited, changes in rainfall patterns as a result of climate shifts will likely be most influential on forest productivity. [236] Similarly, forests limited by temperature or nutrients are also likely to respond more directly to changes in these variables rather than increased CO_2. [237] For example, temperature increases affect soil nitrogen (N) content and availability.[238] Verburg (2005) cites a meta-analysis of data from a wide range of soil/ecosystem warming and gradient studies that showed that warming led to significant overall increases in N mineralization (conversion of N from organic to inorganic forms that are useable by plants for growth), nitrification, and litter decomposition.[239] Despite these general patterns, effects of elevated temperature on soil nutrient pools are less clear, and few

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[228] PAWG (2008), *Leading the Way: Preparing for the Impacts of Climate Change in Washington – Recommendations of the Preparation and Adaptation Working Groups.*

[229] Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

[230] Ibid.

[231] Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.*

[232] PAWG (2008), *Leading the Way: Preparing for the Impacts of Climate Change in Washington – Recommendations of the Preparation and Adaptation Working Groups.*

[233] Ibid.

[234] Ibid.

[235] J. Littell, University of Washington Climate Impacts Group, pers. comm.

[236] Information as cited in Boisvenue and Running (2006), *Impacts of climate change on natural forest productivity – evidence since the middle of the 20th century.* (primary literature)

[237] Ibid.

[238] Ibid.

[239] Information as cited in Verburg (2005), *Soil solution and extractable soil nitrogen response to climate change in two boreal forest ecosystems.* (primary literature)

data are available addressing the effects of warming on soil extractable N.[240] It is unclear if additional N is taken up by the vegetation or accumulates in the soil, and its fate may depend on whether or not vegetation growth is N-limited.[241]

In some regions, the indirect influence of climate change on forest productivity via changes in nitrogen availability may be greater than the direct effect of increased CO_2 on carbon storage in forests; N-limited forests may become more productive with increases in atmospheric N deposition and/or increases in the content and availability of soil N.[242]It will likely be difficult to determine whether observed changes in species composition are driven by the direct effects of climate change, the secondary effects associated with climate change, or non-climate related processes such as natural vegetation succession.[243]

- An external reviewer noted that without substantial changes in precipitation, increased temperatures alone could result in increased drought stress in forests.

Finally, changes in both climate and tree growth and productivity may have implications for the amount of carbon stored in soils and released back into the atmosphere. The total global emission of CO_2 from soils is recognized as one of the largest fluxes in the global carbon cycle, and small changes in the magnitude of soil respiration could have a large effect on the concentration of CO_2 in the atmosphere.[244] The uptake and loss of carbon by land plants and soils were closely balanced before human intervention.[245] Changes in the flux of CO_2 from human activities, including the disruption of soils, play a role in the rise of atmospheric CO_2 and the potential for global climate change.[246]

The flux of CO_2 from soils is closely tied to plant growth, which supplies organic residues to decomposers.[247] Currently, soil organic matter tends to accumulate in regions where other factors (e.g., temperature) limit decomposers.[248] The rise in atmospheric CO_2, to the extent that it increases plant growth, should result in a greater delivery of plant debris to the soil, where a small fraction will remain undecomposed and contribute to a sink for atmospheric CO_2.[249]

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[240] Verburg (2005), *Soil solution and extractable soil nitrogen response to climate change in two boreal forest ecosystems.* (primary literature)
[241] Ibid.
[242] Information as cited in Boisvenue and Running (2006), *Impacts of climate change on natural forest productivity – evidence since the middle of the 20th century.* (primary literature)
[243] Information as cited in Boisvenue and Running (2006), *Impacts of climate change on natural forest productivity – evidence since the middle of the 20th century.* (primary literature)
[244] Schlesinger and Andrews (2000) *Soil respiration and the global carbon cycle.* (primary literature)
[245] Ibid.
[246] Ibid.
[247] Ibid.
[248] Ibid.
[249] Information as cited in Schlesinger and Andrews (2000) *Soil respiration and the global carbon cycle.* (primary literature)

However, estimates of soils as a global carbon sink may be overly optimistic in areas where the microbial community and decomposition rates are limited by the availability of organic substrates; in other words, if more organic carbon becomes available, this may simply increase the rate of decomposition without increasing carbon storage in soils.[250] In addition, as the planet and its soils warm, the area of temperature-limited decomposition should decline, and soils increasingly should become a source of CO_2 to the atmosphere.[251] Except in some deserts, soil respiration increases with increasing temperature.[252] Nearly all models of global climate change predict a loss of carbon from soils as a result of warmer global temperatures.[253]Losses may be greatest at high latitudes or areas that experience a greater degree of warming, such as boreal forests and tundra.[254]

Overall, scientists may be able to broadly define the effects of climate change variables – and even interactions between those variables and issues such as air pollution or nutrient limitation; however, highly localized projections are often difficult to make because of uncertainties in the many factors that influence forest productivity.[255]

Knowledge Gaps

- Synthesis compilations of growth and yield data to identify changes in forest productivity in conjunction with recent climate change are scarce.[256]
- The effects of CO_2 on growth and photosynthesis at various stages of tree and forest stand development are unclear; these variables, as well as the known effects of pollutants, are also not often incorporated into models & experiments.[257]
- The time scale and reversibility of future and present ecological changes as a result of climate change are unknown.[258]
- There is a lack of reliable data on below-ground net primary productivity, and an incomplete understanding of mechanistic processes in forests & between forest and atmosphere.[259]
- There is a lack of data on the response of mature/older trees and forests productivity to climate, nitrogen deposition, CO_2, and ozone.[260]
- WDFW reviewers commented that it is unknown how forest model projections are affected by the manner in which fire suppression is addressed.[261]

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[250] Ibid.

[251] Schlesinger and Andrews (2000) *Soil respiration and the global carbon cycle.* (primary literature)

[252] Schlesinger and Andrews (2000) *Soil respiration and the global carbon cycle.* (primary literature)

[253] Information as cited in Schlesinger and Andrews (2000) *Soil respiration and the global carbon cycle.* (primary literature)

[254] Schlesinger and Andrews (2000) *Soil respiration and the global carbon cycle.* (primary literature)

[255] J. Littell, University of Washington Climate Impacts Group, pers. comm.

[256] Boisvenue and Running (2006), *Impacts of climate change on natural forest productivity – evidence since the middle of the 20th century.* (primary literature)

[257] Ibid.

[258] Ibid.

[259] Ibid.

[260] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[261] T. Quinn, WDFW (pers. comm.)

INCREASED FREQUENCY AND MAGNITUDE OF WILDFIRES

Wildfires are an important agent of natural disturbance in western U.S. forests, including forests in both eastern and western Washington.[262] Franklin et al. (2008) offer an extensive discussion of fire regimes and forest management in eastern Washington that provides contextual background information on fire return intervals. This information is useful as a baseline for understanding how fire regimes in Washington may change as a result of climate change.

Historic fire regimes in eastern Washington varied greatly with climate, which is in turn influenced by geographic location, elevation, landform, slope, and aspect.[263] Historically, eastern Washington wildfires were generally less frequent but more severe in locations at increasing elevation and on cooler, moister landforms and aspects.[264] Historical fire regimes are typically described as low-, mixed-, or high-severity, although these regimes are recognized as existing along a continuous gradient:[265]

- **Low-severity fire regimes** have frequent fire return intervals (~1-25 years), with fires generally killing less than 25% of trees.[266]

- **Mixed-severity fire regimes** exhibit less frequent fire return (~25-100 years), and generally kill 25%-75% of trees.[267]

- **High-severity fire regimes** are characterized by infrequent (>100 years) fires that generally kill more than 75% of trees.[268] These are often called "stand-replacement" regimes because most or all of the aboveground vegetation is killed.[269]

Today, most wildfires in the western U.S. are caused by lightning or human carelessness.[270] Over short timescales, hot, dry, and windy weather conditions may influence vegetation flammability and contribute to increased fire risks.[271,272] Over interannual to decadal timescales, climate may be the main driver of wildfire risk.[273] A common working ecological hypothesis is that the relationship between climate and fire is mediated by vegetation structure and composition and sensitivity to moisture at

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[262] Johnson and O'Neil (2001), *Wildlife-Habitat Relationships in Oregon and Washington.* (book)

[263] Franklin et al. (2008), *The Case for Active Management of Dry Forest Types in Eastern Washington: Perpetuating and Creating Old Forest Structures and Functions.* (state agency publication)

[264] Information as cited in Franklin et al. (2008), *The Case for Active Management of Dry Forest Types in Eastern Washington: Perpetuating and Creating Old Forest Structures and Functions.* (state agency publication)

[265] Ibid.

[266] Franklin et al. (2008), *The Case for Active Management of Dry Forest Types in Eastern Washington: Perpetuating and Creating Old Forest Structures and Functions.* (state agency publication)

[267] Franklin et al. (2008), *The Case for Active Management of Dry Forest Types in Eastern Washington: Perpetuating and Creating Old Forest Structures and Functions.* (state agency publication)

[268] Franklin et al. (2008), *The Case for Active Management of Dry Forest Types in Eastern Washington: Perpetuating and Creating Old Forest Structures and Functions.* (state agency publication)

[269] Ibid.

[270] Running (2006), *Is global warming causing more, larger wildfires?* (commentary)

[271] Ibid.

[272] Information as cited in Westerling et al. (2006), *Warming and earlier spring increase western U.S. forest wildfire activity.* (primary literature)

[273] Ibid.

broad ecosystem scales.[274] More specifically, the area burned by fire in any given year is indirectly related to climate through climatic influence on fuels via the production and drying of vegetation.[275]

Strong relationships between climate and fire exist across the western United States, but the nature of those relationships varies with climate and vegetation.[276] Climate has been an important determinant of area burned for most of the century.[277] Over long timescales, climate drives forest composition and structure, leading to different levels of fire risk (e.g., species populations and their drought tolerance, fuel continuity).[278] Past land uses and forest management practices have also changed the quantity and distribution of fuels, likely making forests more sensitive to changes in climate and wildfire regimes. [279] Therefore, increases in wildfire frequency and severity may be caused by a combination of climate-induced drought and dense stocks of fuel. [280]

In general, air temperature and patterns of precipitation and snowmelt are two major aspects of climate that can influence the occurrence of wildfires. First, air temperature affects the onset of summer drought and therefore the flammability of live and dead fuels in forests.[281] Long-term records show that warmer and drier periods over the past 2000 years are associated with more frequent wildfires in western forests.[282] For example, severe droughts related to the Pacific Decadal Oscillation (PDO) and the El Niño Southern Oscillation (ENSO) may promote greater wildfire risks in western forests.[283] Future climate scenarios for the Pacific Northwest predict that mean annual temperatures will increase 5.9°F by the 2080s (compared with the period 1970-1999).[284] This may mean that the risk of wildfire will increase in Washington's forests.[285]

Second, fire risk is influenced by snowpack and snowmelt. For example, snowmelt keeps fire danger low in arid western forests; however, once snowmelt is complete, forests can become combustible within one month if humidity and rainfall are low.[286] Therefore, the timing of snowmelt influences the length of

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[274] Information as cited in Littell et al. (2009b) *Climate and wildfire area burned in western U.S. ecoprovinces, 1916-2003.* (primary literature)

[275] Ibid.

[276] Littell et al. (2009b) *Climate and wildfire area burned in western U.S. ecoprovinces, 1916-2003.* (primary literature)

[277] Ibid.

[278] Information as cited in Westerling et al. (2006), *Warming and earlier spring increase western U.S. forest wildfire activity.* (primary literature)

[279] Ibid.

[280] Ibid.

[281] Westerling et al. (2006), *Warming and earlier spring increase western U.S. forest wildfire activity.* (primary literature)

[282] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[283] Information as cited in Westerling et al. (2006), *Warming and earlier spring increase western U.S. forest wildfire activity.* (primary literature)

[284] Mote and Salathé. (2009), *Future Climate in the Pacific Northwest*. In: WACCIA (CIG 2009)

[285] PAWG (2008), *Leading the Way: Preparing for the Impacts of Climate Change in Washington – Recommendations of the Preparation and Adaptation Working Groups.*

[286] Running (2006), *Is global warming causing more, larger wildfires?* (commentary)

the dry season in a forest.[287] As Westerling et al. (2006) note, an earlier snowmelt can lead to an earlier, longer dry season, providing greater opportunities for large fires due both to the longer period in which ignitions could potentially occur and to the greater drying of soils and vegetation.[288]

Studies have reported the following changes in snowmelt timing in Washington state:

- 12 day shift toward earlier onset of snowmelt, between 1948 and 2003[289]
- 5 day-earlier shift in the dates of maximum snowpack and 90% melt-out since 1930[290]
- Shift in the peak of spring runoff from a few days to as many as 30 days earlier in the second half of the 20th century. [291]

Specific fire influences vary with site characteristics.[292] For example, susceptibility to fire and insect outbreaks changes with forest age.[293] Areas that experience drought may also be characterized by more frequent fires than wetter areas.[294] In places where fires are less frequent, the effects of a fire may be more intense due to fuel build-up.[295]

- A WDFW reviewer commented that fires in coastal locations tend to be stand-replacing events when ignited. Most fires result in a mosaic of burned and unburned trees within the general perimeter of the burned area.[296]

Fires have a variety of ecological functions and consequences. For example, fires increase landscape heterogeneity at multiple scales and create habitat for early seral species and wildlife that thrive in edge environments and post-fire conditions.[297] Fires help to recycle dead biomass in arid regions where natural decomposition occurs extremely slowly.[298] Fires also alter vegetation structure and composition; for example, fire maintains quaking aspen habitat by opening areas that the aspen can colonize through root sprouting.[299] Similarly, fires help the dominant vegetation in oak stands to establish in western Washington; without fire, most oak-dominated stands would convert to Douglas-fir forests.[300]

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[287] Westerling et al. (2006), *Warming and earlier spring increase western U.S. forest wildfire activity.* (primary literature)
[288] Ibid.
[289] Information as cited in Snover et al. (2005), *Uncertain Future: Climate change and its effects on Puget Sound*. (CIG report)
[290] Stoelinga et al. (in press), *A New Look at Snowpack Trends in the Cascade Mountains.* (primary literature)
[291] Information as cited in Karl et al. (eds) (2009), *Global Climate Change Impacts in the United States* (See Regional Climate Impacts: Northwest) (U.S. government report)
[292] Johnson and O'Neil (2001), *Wildlife-Habitat Relationships in Oregon and Washington.* (book)
[293] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)
[294] Johnson and O'Neil (2001), *Wildlife-Habitat Relationships in Oregon and Washington.* (book)
[295] Ibid.
[296] T. Quinn, WDFW (pers. comm.)
[297] J. Littell, University of Washington Climate Impacts Group, (pers. comm.)
[298] Running (2006), *Is global warming causing more, larger wildfires?* (commentary)
[299] Johnson and O'Neil (2001), *Wildlife-Habitat Relationships in Oregon and Washington.* (book)
[300] Ibid.

Although wildfire disturbance is important in maintaining ecosystems, wildfires can also damage timber resources. Because of the damage and economic loss associated with wildfires, forest management for fire suppression began in the late 19th century and effectively reduced the frequency of large surface fires.[301] Combined with extensive livestock grazing and forest regrowth after intensive logging, the structure and composition of some western U.S. forests (i.e., states of the Pacific Northwest, desert Southwest, and Rocky Mountain regions) changed and began to accumulate biomass.[302] These forest stands became more uniform, supported a greater density of stems, were characterized by different tree species composition and structure, and had elevated fuel loads.[303,304] This historic management strategy has made contemporary fire suppression efforts less effective in some areas. It is important to note that the effects of historic forest management policies on forests depends on the natural fire regime of a given forest type.[305] Changes in forest structure and biomass accumulation (i.e. the effects of fire exclusion) are thought to be unimportant in terms of altering fire risk in forests that previously were only subjected to very infrequent, high-severity crown fires.[306] It is also likely that not all ecosystems with increasing trends in wildfire area burned have increases in fuel accumulation caused by fire exclusion, especially when the time frame of effective fire exclusion approximates or is less than the range of return intervals characteristic of fire regimes.[307]

The *Preparation and Adaptation Working Group* (2008) notes that wildfires in Washington are strongly associated with climate, especially in forests east of the Cascade Mountain crest.[308] Washington forests, particularly those uniform and dense in structure, are more vulnerable to the spread of large, severe wildfires due to increased temperature and dryness and an abundance of trees killed or damaged by insect infestations.[309] Although eastern Washington has experienced large fires in the past, recent wildfires may be evidence of the interaction between insect infestations and increased wildfire susceptibility.[310] Fires can also have social and health impacts, such as the destruction of houses and public property and smoke inhalation.[311]

Observed Changes

The following changes have been observed in the incidence of large wildfires in the United States and Canada:

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[301] Information as cited in Westerling et al. (2006), *Warming and earlier spring increase western U.S. forest wildfire activity.* (primary literature)

[302] Ibid.

[303] PAWG (2008), *Leading the Way: Preparing for the Impacts of Climate Change in Washington – Recommendations of the Preparation and Adaptation Working Groups.*

[304] Running (2006), *Is global warming causing more, larger wildfires?* (commentary)

[305] Information as cited in Westerling et al. (2006), *Warming and earlier spring increase western U.S. forest wildfire activity.* (primary literature)

[306] Ibid.

[307] Information as cited in Littell et al. (2009b) *Climate and wildfire area burned in western U.S. ecoprovinces, 1916-2003.* (primary literature)

[308] PAWG (2008), *Leading the Way: Preparing for the Impacts of Climate Change in Washington – Recommendations of the Preparation and Adaptation Working Groups.*

[309] Ibid.

[310] Ibid.

[311] Ibid.

- The occurrence of major wildfires in the western U.S. has increased fourfold since 1986, and the area of forest burned was six times greater compared to the period from 1970 to 1986.[312,313]
- In Canada and Alaska, the area of boreal forest burned more than doubled between 1960 and 1970 and again in the 1980s and 1990s.[314] Fire activity in boreal forests across North America has increased in the last 40 years, apparently triggered by a change in the size and number of lightning-caused fires.[315]
- The northwestern U.S. experienced a 5% increase in the incidence of large wildfires since the mid-1980s.[316]
- Since the mid-1980s, increases in the incidence of large wildfires have been concentrated between 1680 m and 2590 m in elevation; areas where wildfire activity is historically episodic.[317]

While major wildfires do recur on a natural, periodic basis in many forests, Westerling et al. (2006) state that the robust statistical associations between wildfire and hydroclimate in western forests indicate that increased wildfire activity over recent decades reflects sub-regional responses to changes in climate.

Westerling et al. (2006) note that in the mid-1980s, climatic patterns began to shift toward warmer springs and longer summer dry seasons, resulting in drier vegetation (i.e. more available fuel).[318] Comparing the period 1970-1986 to 1987-2003, Westerling et al. (2006) found that the average regional spring and summer temperature in western U.S. forests increased 0.87°C. Spring and summer temperatures in the 1987 to 2003 period were the warmest since the beginning of the record in 1895, with 6 years in the 90th percentile over this period as opposed to only one year in the period 1970 to 1986.[319] In addition, Westerling et al. (2006) found that since the mid-1980s 56% of wildfires and 72% of area burned in wildfires occurred in years with earlier snowmelt, as compared to 11% of wildfires and 4% of area burned in years with later snowmelt.[320]

Future Projections

Summer precipitation and temperature play a large role in the area burned by fire according to regional models of climate-fire relationships applied to Washington State.[321] Statistical model projections suggest a doubling or tripling of area burned by the 2080s.[322] The median regional area burned, averaged over two global climate models, is projected to increase from about 0.5 million acres (0.2 M ha) to 0.8 million

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[312] Ibid.

[313] Running (2006), *Is global warming causing more, larger wildfires?* (commentary)

[314] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[315] Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[316] Westerling et al. (2006), *Warming and earlier spring increase western U.S. forest wildfire activity.* (primary literature)

[317] Ibid.

[318] Ibid.

[319] Ibid.

[320] Ibid.

[321] Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

[322] Ibid.

acres (0.3 M ha) in the 2020s, 1.1 million acres (0.5 M ha) in the 2040s, and 2.0 million acres (0.8 M ha) in the 2080s.[323] The probability of exceeding the 95% quantile area burned for the period 1916 to 2006 increases from 0.05 to 0.48 by the 2080s.[324]

Model projections for the Columbia Basin, Palouse Prairie, Okanogan Highlands, Western Cascades, Eastern Cascades, and Blue Mountains ecosystems project that mean area burned by wildfires will increase between 0 and 700% depending on the ecosystem in question, the sensitivity of the fire model, the emissions scenario used, and the time frame of the projection.[325] By the 2040s, the area burned in non-forested ecosystems (Columbia Basin and Palouse Prairies) increased on average by a factor of 2.2.[326] In forested ecosystems (Western and Eastern Cascades, Okanogan Highlands, Blue Mountains) the mean area burned increased by a factor of 3.8 when comparing 1980 to 2006.[327] The increase in area burned was accompanied by an increase in variability in some of the more arid systems: Palouse Prairie and Columbia Basin.[328] The largest proportional increases were in the Western Cascades and Blue Mountains, although the area burned in the Western Cascades is still small despite the large proportional increase.[329] The projected area burned increased at a faster rate in the Blue Mountains than in any other ecosection.[330] Projections of future fire in the wetter ecosystems of Washington (i.e., the Coast Ranges/Olympic Mountains and Puget Trough/Willamette Valley) generally have greater uncertainty, and other methods will be required to fully understand the future role of fire in these ecosystems.[331]

Discussion

Wildfires have grown in size and total area burned.[332] The area burned nationwide on federal agency lands increased since the mid-1970s, capped by a string of years with large areas burned between 2000 and 2004.[333] In the mid-1980s, large wildfires that were historically infrequent and short in duration in the western U.S. became more frequent.[334] These two trends have led to speculation that forest management practices (i.e., fire suppression) have facilitated unprecedented fuel accumulations, causing fires to burn larger areas of some western states.[335] However, fire extent and frequency are also

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[323] Ibid.

[324] Ibid.

[325] Ibid.

[326] Ibid.

[327] Ibid.

[328] Ibid.

[329] Ibid.

[330] Ibid.

[331] Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

[332] Information as cited in Westerling et al. (2006), *Warming and earlier spring increase western U.S. forest wildfire activity.* (primary literature)

[333] Information as cited in Littell et al. (2009b) *Climate and wildfire area burned in western U.S. ecoprovinces, 1916-2003.* (primary literature)

[334] Westerling et al. (2006), *Warming and earlier spring increase western U.S. forest wildfire activity.* (primary literature)

[335] Information as cited in Littell et al. (2009b) *Climate and wildfire area burned in western U.S. ecoprovinces, 1916-2003.* (primary literature)

products of interacting factors other than suppression operating at multiple spatial and temporal scales.[336] For example, climate appears to be an important driver of fire area and frequency;[337] the importance of extreme fire weather and ignitions is often contingent on climatic factors operating at longer time scales (seasonal to interannual scales) that influence fuel moisture and continuity.[338]

For example, Littell et al. (2009b) concluded that the area burned by wildfires in northern, mountainous ecoprovinces appeared to be limited by climate rather than fuel availability.[339] Littell et al. (2009b) argue that even if the predominant factor influencing increased area burned across the West is changes in fuel structure and composition, the role of climate must be understood in order to weigh the relative importance of mitigating the risk associated with increased fuels via fuels treatments and/or adapting to future fire regimes via changes in management policy.[340]

In a study elucidating climate-fire relationships in the western U.S., Littell et al. (2009b) found that dry, warm conditions in the seasons leading up to and including the fire season were associated with an increase in the area burned by wildfire in northern and mountainous ecoprovinces (such as those in Washington). Westerling et al. (2006) also found that warmer air temperatures were a key predictor of burned area in the West, with warmer summer temperatures causing an increase in burned area on scales of years to decades.[341] Westerling et al. (2006) proposed that earlier snowmelt, higher summer temperatures, a longer fire season, and a larger area of vulnerable forests at mid elevations combined to produce observed increases in wildfire activity.[342]

In contrast, Littell et al. (2009b) proposed that increases in the area burned by wildfires result from low precipitation and high evapotranspiration depleting fuel moisture over larger than normal areas.[343] The authors state that these conditions increase the probability of ignition as well as the potential for fire spread.[344] Furthermore, they found that lack of precipitation in the year of fire was more important than drought or temperature in most models of wildfire area burned for western ecoprovinces.[345] Low precipitation, high temperatures, and drought immediately preceding and during the year of fire were associated with increases in the area burned by wildfire, probably because persistent hot temperatures and low humidity are required to dry out fine fuels in these ecoprovinces.[346] Correlations between area

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[336] Ibid.

[337] Ibid.

[338] Littell et al. (2009b) *Climate and wildfire area burned in western U.S. ecoprovinces, 1916-2003.* (primary literature)

[339] Ibid.

[340] Ibid.

[341] Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[342] Running (2006), *Is global warming causing more, larger wildfires?* (commentary)

[343] Information as cited in Littell et al. (2009b), *Climate and wildfire area burned in western U.S. ecoprovinces, 1916-2003.* (primary literature)

[344] Ibid.

[345] Littell et al. (2009b), *Climate and wildfire area burned in western U.S. ecoprovinces, 1916-2003.* (primary literature)

[346] Ibid.

burned and seasonal climate suggested that the Cascades and Northern Rockies are sensitive primarily to low precipitation during the fire season (summer and growing season).[347]

Increases in fire frequency could result in shifts in vegetation community composition toward more fire-tolerant species, or otherwise alter plant communities that depend on a given fire regime to persist.[348] In addition to altering forest structure, a change in fire frequency and duration could influence the susceptibility of forests to insect attacks (either making them more or less susceptible, depending on the change).[349]

Publicly-owned forests in the coterminous western U.S. contain approximately 37% (19,000 Tg C) of the total carbon contained in U.S. forest stocks in the lower 48 states..[350] Increased wildfires could alter forest composition and reduce tree densities, changing the amount of carbon sequestered in forests.[351] Increasing frequency and severity of wildfires would also contribute further to current atmospheric carbon emissions, accelerating greenhouse gas buildup in the atmosphere.[352] Ultimately, the anticipated trends in wildfires could lead to western U.S. forests becoming a source of atmospheric CO_2 rather than a sink, even if increases in air temperature are only moderate.[353] Even if forests regrow, it may take centuries for them to recover lost carbon.[354]

Large, severe wildfires have serious economic and social consequences. The U.S. Forest Service spent $1.46 billion dollars on wildfire suppression and rehabilitation in the U.S. overall in 2008, while the costs of some single wildfire events have reportedly exceeded $1 billion dollars (e.g., the Old, Grand Prix, and Padua wildfire complex in CA in 2003).[355] Although only a small fraction of fires become large and uncontrollable, these fires may burn despite human efforts to control them.[356] Control efforts can cost over $20 million dollars every day, although control may be impossible regardless of the amount of money spent.[357] For example, 25,000 firefighters and an investment of $120 million dollars proved

[347] Ibid.

[348] Information as cited in Noss (2001), *Beyond Kyoto: Forest Management in a Time of Rapid Climate Change.* (primary literature)

[349] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[350] Information as cited in McKinley et al. (2010) *A synthesis of current knowledge on forests and carbon storage in the United States.* (in review)

[351] Westerling et al. (2006), *Warming and earlier spring increase western U.S. forest wildfire activity.* (primary literature)

[352] Information as cited in Running (2006), *Is global warming causing more, larger wildfires?* (commentary)

[353] Westerling et al. (2006), *Warming and earlier spring increase western U.S. forest wildfire activity.* (primary literature)

[354] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[355] Western Forestry Leadership Coalition (2010), *The true cost of wildfire in the western U.S.* (U.S. government report)

[356] Running (2006), *Is global warming causing more, larger wildfires?* (commentary)

[357] Ibid.

unable to control fires in Yellowstone Park in 1988 that burned 600,000 ha of forest over three months.[358]

Threats to human communities and ecosystems will likely increase as wildfire risk increases in the western U.S.[359] Westerling et al. (2006) state that although historical management for fire exclusion contributes to wildfire risk in some forests, the observed trend in increased wildfire activity across the western U.S. has been driven primarily by sensitivity of fire regimes to recent changes in climate over a relatively large area; therefore, ecological restoration and fuels management alone will not be sufficient to reverse current wildfire trends.[360]

- A WDFW reviewer commented that fire suppression effects in the Intermountain West and southern California are very substantial, and Westerling et al. (2006) also note that fire suppression has played a larger role in forests in some regions of the west. The extent to which climate and fire suppression contribute to increased risk of wildfires in particular forests is an important regional management consideration.
- A WDFW reviewer commented that thoughtful community planning that incorporates fire risk may help mitigate threats to human housing.[361]

Knowledge Gaps

- Monitoring of disturbances affecting forests is currently ineffective, fragmented, and generally unable to attribute disturbances to specific factors, including climate.[362]
- How to manage forests to increase their resilience to fire and prevent species loss and ecosystem collapse.

Suggestions for further information

- Reviewers suggested work by Jim Agee, UW College of Forest Resources, for further information on fire risk and behavior as a function of forest structure, landscape pattern, etc. that may help address knowledge gaps. An internet search suggested the following resources as a starting point:
    - Peterson, DL, MC Johnson, JK Agee, TB Jain, D McKenzie, and ED Reinhardt. 2005. Forest structure and fire hazard in dry forests of the Western United States. Gen. Tech. Rep. PNW-GTR-628. Portland, OR: U.S. Dept. of Agriculture, Forest Service, Pacific Northwest Research Station. 30 pp.
    - Franklin, JF and JK Agee. 2003. Forging a science-based national forest fire policy. *Issues in Science and Technology* Fall edition: 1-8.

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[358] Information as cited in Running (2006), *Is global warming causing more, larger wildfires?* (commentary)
[359] Westerling et al. (2006), *Warming and earlier spring increase western U.S. forest wildfire activity.* (primary literature)
[360] Ibid.
[361] T. Quinn, WDFW (pers. comm.)
[362] Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

- o Brown, RT, JK Agee, and JF Franklin. 2004. Forest restoration and fire: Principles in the context of place. *Conservation Biology* 18(4): 903-912.
- o Agee, JK. 1998. The landscape ecology of western forest fire regimes. *Northwest Science* 72. Special Issue: 24-34.

VULNERABILITY TO INSECTS AND DISEASE

Background

Insects and pathogens are the largest agents of forest disturbance in the U.S., accounting for $1.5 billion dollars in losses annually.[363] Climate is a primary factor driving or contributing to insect infestations in U.S. forests.[364] Since insects are ectotherms, temperature controls insect lifecycles.[365] Temperature therefore affects insect growth and development, the timing and synchronization of mass insect attacks on trees, and the degree of winter mortality experienced by insect populations.[366] Temperature also influences tree resistance to insect attack.[367] For example, drought stress can lower a tree's defenses or make species more palatable to certain insects.[368]

Mountain pine beetle infestations have historically occurred frequently and extensively throughout the Pacific Northwest.[369] Climate change, in particular warming and drought, affects bark beetle life stage development rates, winter mortality and host tree susceptibility.[370] In much of the West, stand structural conditions make host species susceptible to beetle attack.[371]

In Washington, increased temperatures, particularly during the dry summer months, are expected to directly stress trees in drier regions of Washington and contribute to an increase in insect damage.[372] Impacts will be even greater if summer precipitation decreases.[373] These effects will be compounded with problems stemming from past forest management practices, including decades of fire suppression

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[363] Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[364] Ibid.

[365] Information as cited in Carroll et al. (2003), *Effects of climate change on range expansion by the mountain pine beetle in British Columbia*. (conference proceedings)

[366] Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[367] Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[368] Ibid.

[369] Information as cited in Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

[370] Ibid.

[371] Ibid.

[372] PAWG (2008), *Leading the Way: Preparing for the Impacts of Climate Change in Washington – Recommendations of the Preparation and Adaptation Working Groups.*

[373] Ibid.

and more crowded, uniform forests.[374] These conditions are likely to make forests more vulnerable to epidemics of insect outbreaks.[375]

The *Preparation and Adaptation Working Group* (PAWG) on forest ecosystems in Washington State identified the mountain pine beetle (MPB) as posing the greatest threat of insect damage to Washington forests over the next several decades, because it responds directly to warmer temperatures.[376] As the authors note, MPB outbreaks in British Columbia and Idaho have already resulted in large and potentially unprecedented landscape-scale forest mortality.[377] Similarly, in the northern and central Rocky Mountains, almost 17% of the whitebark pine in the Greater Yellowstone Ecosystem was reported to be infested by MPB.[378] A more recent study (2010) reported that MPB outbreaks are occurring throughout the entire distribution of the Greater Yellowstone Ecosystem whitebark pine – in some areas resulting in mortality exceeding 95% of cone bearing trees.[379] Carroll et al. (2003) also identified MPB as one of the most significant sources of mortality in mature pine forests in western North America. Although lodgepole pine is its primary host, MPB will attack most species of western pines.[380]

Although MPB is currently of greatest concern in Washington forests, it is important to note that studies in Europe have documented other insect populations that responded to global warming with rapid ecological and genetic adaptation.[381] Climate changes may cause native insects or disease species to become aggressive in new environments.[382]

- A WDFW reviewer commented that some forests in the eastern Cascade Mountains that are impacted by spruce budworm infestations have been influenced by fire suppression. The budworm is impacting forests that may fall outside the normal range of variability with respect to contiguous patch size, species composition, etc.

Observed Changes

Major recent insect outbreaks have included western spruce budworms that affected millions of hectares in the western U.S as well as spruce beetles that attacked over 1.5 million hectares of forest in southern Alaska and western Canada.[383] The spruce beetle outbreak provides evidence for climate-change-related increases in the extent and severity of forest insect disturbance – warmer temperatures

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[374] Ibid.

[375] Ibid.

[376] Ibid.

[377] Ibid.

[378] Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[379] Information as cited in Logan et al. (2010) *Whitebark pine vulnerability to climate-driven mountain pine beetle disturbance in the Greater Yellowstone Ecosystem.* (primary literature)

[380] Information as cited in Carroll et al. (2003), *Effects of climate change on range expansion by the mountain pine beetle in British Columbia*. (conference proceedings)

[381] Ibid.

[382] Information as cited in Millar et al. (2007), *Climate change and forests of the future: Managing in the face of uncertainty.* (primary literature)

[383] Ibid.

have halved the time required for the spruce beetle to reproduce, and have contributed to unprecedented damage to spruce forests.[384]

Mountain pine beetle (MPB) infestations have also affected more than 10 million hectares of forest in British Colombia and 267,000 hectares in Colorado.[385] The current MPB outbreak in western Canada (as of 2006) is unprecedented in its scale and severity – it is an order of magnitude greater in area than previous outbreaks owing to the increased area of susceptible host (mature pine stands) and favorable climate.[386] By the end of 2006, the cumulative outbreak area was nearly 50,200 square miles.[387] Timber losses are estimated to be more than 435 million m^3, with additional losses outside the commercial forest.[388]

Beginning in the second half of the 20th century, habitats in British Columbia climatically suitable for MPB began to move northward and higher in altitude.[389] Beetle populations have appeared to follow this shift in habitat over the last 30 years, moving northward, eastward, and toward higher elevations.[390] Carroll et al. (2003) highlight that the occurrence of MPB in places that used to be climatically unsuitable can only be explained by changes in climate, and not by other factors such as changes in beetle food supply.

As MPB have moved to occupy new habitats, areas where the species was formerly prevalent have experienced declines in infestations.[391] Again, this trend occurred as a result of climate change, and not because of destruction of the beetle's food sources.[392] Rather, temperature increases in areas that were formerly climatically suitable have resulted in changes in MPB lifecycles, such that the beetles produced more than one generation per year.[393] This causes cold-susceptible life stages to overwinter and interrupts the population synchrony necessary for mass MPB attacks.[394]

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[384] Information as cited in Kurz et al. (2008), *Mountain pine beetle and forest carbon feedback to climate change.* (primary literature)

[385] Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[386] Information as cited in Kurz et al. (2008), *Mountain pine beetle and forest carbon feedback to climate change.* (primary literature)

[387] Ibid.

[388] Ibid.

[389] Carroll et al. (2003), *Effects of climate change on range expansion by the mountain pine beetle in British Columbia*. (conference proceedings)

[390] Ibid.

[391] Ibid.

[392] Information as cited in Carroll et al. (2003), *Effects of climate change on range expansion by the mountain pine beetle in British Columbia*. (conference proceedings)

[393] Ibid.

[394] Ibid.

Temperatures are currently suitable for MPB outbreaks in large areas of the Olympic Mountains, northern Rocky Mountains, in a mid-elevation band on the west and east sides of the Cascade Mountains, and to a lesser degree in the Blue Mountains of southeastern Washington.[395]

Other than changes in the distribution of MPB populations in response to climate, northwestern forests are also susceptible to disease. For example, in northeastern B.C., Canada, an unprecedented outbreak of *Dothistroma* needle blight is killing mature lodgepole pines.[396] A clear mechanistic relationship was identified that linked observed climate trends and the interaction between the pathogen and its host trees.[397]

- An external reviewer noted that Washington has also had relatively high levels of Englemann spruce mortality since 1999 in Okanogan County near the Cascade crest. The direct factors sustaining this outbreak have not yet been studied. The outbreak began following winter damage in 1999, in areas adjacent to recent wildfires. It affects trees growing in dense stands. A 2009 aerial survey mapped over 56,000 acres with elevated levels of spruce beetle mortality.

Future Projections

Because climate is the limiting factor for current MPB population ranges, climate change is expected to result in a range alteration and expansion of MPB populations into northern and eastern areas and higher elevations.[398] Appropriate temperature regimes for MPB are expected to shift more than seven degrees north latitude.[399]

Climate change is predicted to reduce the area of climate suitability for MPB at low elevations and increase climate suitability at higher elevations.[400] Simulations using climate change scenarios for 2070 to 2099 predict that the region of climate suitability will move higher in elevation as the climate warms, reducing the total area susceptible to MPB.[401] At lower elevations, increasing temperatures will cause asynchrony in adult emergence through more rapid life stage development as well as cause emergence at inappropriate times of year, which may reduce beetle populations and decrease the efficacy of mass attacks.[402] Whitebark pine may be at risk from upward shifts in the elevational range of MPB, although

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[395] Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

[396] Information as cited in Boisvenue and Running (2006), *Impacts of climate change on natural forest productivity – evidence since the middle of the 20th century.* (primary literature)

[397] Ibid.

[398] Information as cited in Carroll et al. (2003), *Effects of climate change on range expansion by the mountain pine beetle in British Columbia.* (conference proceedings)

[399] Ibid.

[400] Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

[401] Ibid.

[402] Information as cited in Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

these elevations are currently out of the range of other susceptible host species.[403] Although the MPB range may ultimately decrease if it moves upward in elevation, outbreaks of mountain pine beetle could occur across the areas "traversed" by the beetle between now and the late 21st century.[404] MPB outbreaks are therefore expected to be a continuing concern in Washington State.[405]

Increased moisture stress may also leave forests in the western United States more susceptible to insect attack.[406] Maintaining water balance is integral to a tree's survival and its ability to repel insects.[407] The greatest likelihood of MPB attack comes when average climatic conditions are hot and dry (although not extremely so).[408] Moisture stress (i.e., a change in the average water deficit) is projected for trees within the current range of lodgepole pine in Washington.[409] Because of reduced summer precipitation and increased temperature, the summer water deficit within the lodgepole pine range is predicted to increase two to three times; these projections suggest that the area of forest with climatic conditions favorable for lodgepole pine will decrease considerably.[410]

It is possible that increasing atmospheric CO_2 concentrations may offset some vulnerability of forests to insect attack by increasing the ability of trees to recover.[411] Enhanced tree productivity in response to favorable climate change, including rises in atmospheric CO_2, may lead to faster recovery of forests following outbreaks, and thus a reduction in time of susceptibility to subsequent attack.[412]

Tree disease could also potentially increase with warming.[413] The effects of climate changes on host physiology, adaptation or maladaptation, and population genetics that affect host-pathogen interactions are uncertain. [414] However, based on existing knowledge of tree disease in western North America, it can be inferred that climate change will result in reductions in tree health and improvement in conditions for some pathogens. [415] Drought stress as a result of climate change will exacerbate the impacts of many pathogens. [416]

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[403] Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

[404] Ibid.

[405] Ibid.

[406] Information as cited in Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.*

[407] Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

[408] Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

[409] Ibid.

[410] Ibid.

[411] Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[412] Ibid.

[413] Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.*

[414] Information as cited in Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.*

[415] Ibid.

[416] Ibid.

Discussion

The expansion of MPB into new habitats may provide populations with a small, continual supply of mature pine that will maintain beetle abundance at above-normal levels for decades.[417] For example, jack pine in North American boreal forests may become susceptible to MPB outbreaks.[418] In contrast, southern and low elevation areas may become less suitable for the current, local MPB populations, but these forests may still be threatened by warm-adapted populations of southern mountain pine beetles shifting northward.[419] In addition, outbreaks may become worse if cold periods and extreme winters become rarer, such that outbreaks do not entirely collapse under the stress of cold temperatures. [420]

Knowledge Gaps

- The effects of climate changes on host physiology, adaptation or maladaptation, and population genetics that affect host-pathogen interactions are uncertain.

CLIMATE CHANGE EFFECTS ON ALPINE ECOSYSTEMS

Although mountains differ considerably from one region to another, one common feature is the complexity of their topography. Because elevation changes considerably over very short distances in mountainous regions, mountains contain some of the sharpest environmental gradients found in continental areas.[421] For example, mountains exhibit rapid changes in temperature and precipitation, greatly enhanced direct runoff and erosion, and systematic variations in soil types.[422]

Mountain glaciers are particularly sensitive to changes in temperature and precipitation, and therefore the behavior of glaciers provides some of the clearest evidence of atmospheric warming and changes in precipitation regimes.[423] For example, for every degree Celsius increase in air temperature, the snowline is expected to rise by about 150 m.[424] Already, the seven-year average rate of ice loss for three glaciers monitored in the U.S. Pacific Northwest was higher for the period since 1989 than for any other period studied.[425]

Among other effects, changes in the location of the snowline and the extent and thickness of glaciers may influence the composition and distribution of alpine and subalpine ecosystems. For many mountain

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[417] Carroll et al. (2003), *Effects of climate change on range expansion by the mountain pine beetle in British Columbia*. (conference proceedings)

[418] Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands.* In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

[419] Information as cited in Carroll et al. (2003), *Effects of climate change on range expansion by the mountain pine beetle in British Columbia*. (conference proceedings)

[420] Carroll et al. (2003), *Effects of climate change on range expansion by the mountain pine beetle in British Columbia*. (conference proceedings)

[421] Beniston (2003), *Climatic Change in Mountain Regions: A Review of Possible Impacts*. (primary literature)

[422] Ibid.

[423] Beniston (2003), *Climatic Change in Mountain Regions: A Review of Possible Impacts*. (primary literature)

[424] Information as cited in Beniston (2003), *Climatic Change in Mountain Regions: A Review of Possible Impacts*. (primary literature)

[425] Ibid.

ranges, snow and ice are a key component of the hydrological cycle[426] and snow retention and snowpack are important factors limiting the growth of alpine and subalpine vegetation at high elevations. [427] Changes in the composition and abundance of treeline vegetation are clearly linked to decadal and centennial climatic variability.[428] However, climatic influences are often difficult to assess in mountainous areas because their complex topography produces steep gradients in the biophysical environment, and climate-monitoring stations are sparsely distributed, especially at the highest elevations.[429]

The biodiverse ecosystems in mountainous regions are all sensitive to climatic factors and are likely to have different vulnerability thresholds according to the species and the rate and magnitude of climatic changes. [430] In contrast to lowland vegetation communities that can occupy climatic niches over wider latitudinal belts, mountain communities are often endemic (i.e., belonging exclusively to a particular place) because many species remain isolated at high elevations.[431] This isolation may mean that the adaptive capacity of mountain ecosystems is limited, and that highly endemic alpine biota is very vulnerable to climate change and may have a disproportionately high risk of extinction.[432]

In Washington, mountain vegetation occupies a gradient from low elevation bottomlands to high elevation peaks. This vegetation is important in terms of its protective role against slope erosion and as a component of mountain hydrology and water quality.[433] Broadly, mountain vegetation in Washington may be described as alpine, subalpine, or montane:

- **Alpine** vegetation (a.k.a. "alpine tundra") is found at the highest altitudes, above the treeline.[434] For example, the ecological system of "North Pacific Dry and Mesic Alpine Dwarf-Shrubland, Fell-Field and Meadow" is found at elevations above 7200 feet in the Cascade Mountains.[435] The growth of alpine vegetation may be controlled by factors such as snow retention, wind desiccation, and a short growing season, to produce patches of plants such as shrub-form trees ("krummholz"), sedge turfs, lichens, and sparsely-vegetated snowbed communities.[436] Alpine tundra may also include other grasses, flowering herbs, and mosses.[437]

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[426] Ibid.
[427] Information as cited in Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)
[428] Information as cited in Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)
[429] Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)
[430] Beniston (2003), *Climatic Change in Mountain Regions: A Review of Possible Impacts*. (primary literature)
[431] Ibid.
[432] Information as cited in Parry et al. (2007), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (section 4.4.7)
[433] Beniston (2003), *Climatic Change in Mountain Regions: A Review of Possible Impacts*. (primary literature)
[434] Strahler and Strahler (2005), *Physical Geography: Science and Systems of the Human Environment* (book)
[435] NatureServe Explorer (2009), *North Pacific Dry and Mesic Alpine Dwarf-Shrubland, Fell-Field and Meadow* (website)
[436] Ibid.
[437] Strahler and Strahler (2005), *Physical Geography: Science and Systems of the Human Environment* (book)

- **Subalpine** vegetation occupies the transitional zone between forest and alpine communities, forming a subalpine forest-meadow ecotone.[438] For example, the ecological system of the "North Pacific Maritime Mesic Subalpine Parkland" may include areas where mountain hemlock forests grade from dense stands into clumps of trees or forest patches interspersed with low shrublands and meadows and krummholz at the system's upper elevational limit.[439] Here, deep, long-lasting snowpacks may limit tree regeneration and establishment to favorable microsites during drought or years with low snowpack.[440]

- **Montane** forests are generally found in cool upland areas[441]; for example, mesic montane mixed-conifer forests in the east Cascades are located between elevations of about 2000-4000 feet.[442]

This section of the paper does not specifically discuss montane forests, as these forests may experience climate change effects similar to those presented in the previous section (Climate Change Effects on Washington's Forests). Rather, this section focuses on changes in species composition and distribution and disturbance regimes in the two highest-elevation vegetation zones: subalpine and alpine.

CHANGES IN SPECIES COMPOSITION AND DISTRIBUTION

Plant life at high elevations is primarily constrained by direct and indirect effects of low temperatures, radiation, wind and storminess or insufficient water availability.[443] Plants respond to these climatological influences through a number of morphological and physiological adjustments such as stunted growth forms and small leaves, low thermal requirements for basic life functions, and reproductive strategies that avoid the risk associated with early life phases.[444] The length and depth of snow cover, often correlated with mean temperature and precipitation, is one of the key climatic factors controlling alpine ecosystems.[445] Snow cover provides frost protection for plants in winter, and water supply in spring.[446] Alpine plant communities are characterized by a very short growing season (i.e., the snow-free period) and require water to begin their growth cycle.[447]

For high-elevation vegetation, climate change may affect:

- seed dispersal, germination and survival by modifying soil availability, quality, and moisture;
- precipitation fraction arriving as snow;
- snow redistribution and melt;
- extent of glacial forefields;

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[438] NatureServe Explorer (2009), *North Pacific Maritime Mesic Subalpine Parkland* (website)

[439] Ibid.

[440] Ibid.

[441] Strahler and Strahler (2005), *Physical Geography: Science and Systems of the Human Environment* (book)

[442] NatureServe Explorer (2009), *East Cascades Mesic Montane Mixed-Conifer Forest and Woodland* (website)

[443] Information as cited in Beniston (2003), *Climatic Change in Mountain Regions: A Review of Possible Impacts*. (primary literature)

[444] Beniston (2003), *Climatic Change in Mountain Regions: A Review of Possible Impacts*. (primary literature)

[445] Information as cited in Beniston (2003), *Climatic Change in Mountain Regions: A Review of Possible Impacts*. (primary literature)

[446] Beniston (2003), *Climatic Change in Mountain Regions: A Review of Possible Impacts*. (primary literature)

[447] Ibid.

- extent of permanent snowfields; and
- disturbance regimes.[448]

Therefore, the composition and distribution of mountain ecosystems and communities may change as a result of climate change.[449]

Observed Trends

Change in the elevation of treeline is an expected outcome of regional climate change, and upslope and downslope movements in response to climate variability during the past 20,000 years have been recorded.[450] Paleoecological (pollen and fossil) records from the Pacific Northwest and elsewhere show that during historic warm periods many tree species moved poleward and upward in elevation.[451] Several studies have shown the range expansion of subalpine fir into alpine tundra at higher elevations in the northeastern portion of the Olympic Peninsula during historic warm periods.[452]

At a continental scale, the elevation of treeline appears to be controlled by temperature, with a decline in elevation at more northerly latitudes and in proximity to coastal locations. [453,454] Upward movement of treelines has been documented in numerous mountainous locations across the world, including locations in Canada, Russia, Sweden, Bulgaria, and New Zealand.[455] However, treeline dynamics are complex and dependent on precipitation and microsite patterns in addition to temperature.[456]

A meta-analysis of response of treelines at 166 sites (from around the world, but mostly in North America and Europe) to recent warming found that treelines at sites with greater winter warming were more likely to have advanced than treelines at sites with less warming.[457] In addition, treelines with a diffuse form, characterized by decreasing tree density with increasing altitude or latitude, were more likely to have advanced than those with an abrupt form, characterized by a continuous canopy with no

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[448] Malanson et al. (2007), *Alpine treeline of western North America: Linking organism-to-landscape dynamics.* (primary literature)

[449] Parry et al. (2007), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* (Chapter 14)

[450] Information as cited in Malanson et al. (2007), *Alpine treeline of western North America: Linking organism-to-landscape dynamics.* (primary literature)

[451] Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.* (Ch.6)

[452] Information as cited in Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.* (Ch.6)

[453] Information as cited in Malanson et al. (2007), *Alpine treeline of western North America: Linking organism-to-landscape dynamics.* (primary literature)

[454] Sveinbjörnsson (2000), *North American and European Treelines: External forces and internal processes controlling position.* (primary literature)

[455] Information as cited in Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.* (Ch.6)

[456] Ibid.

[457] Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.* (Ch.6)

decline in density right up to treeline.[458] It is possible that diffuse treelines are more responsive to warming because tree growth, but not survival, is limited by climatic factors. [459] In contrast, winter stress factors that cause plant damage and limit survival may have a stronger influence on abrupt treelines.[460]

Future Projections

In general, alpine and subalpine vegetation is expected to decline as a result of climate change.[461] In model simulations, alpine and subalpine regions in the Western U.S. migrate to higher elevations and decrease in area, while subalpine montane forest boundaries also move upward.[462] Because the amount of mountainous land area decreases as one gains in elevation, less area is available for vegetation communities to inhabit. Forest impact studies have projected that climatic change as reported by the IPCC will be more rapid than the migration capacity of forests.[463] However, the migration hypothesis may not always be applicable because of the different climatic tolerance of species involved, including genetic variability between species, different longevities and survival rates, and the competition by invading species.[464]

In Washington, a modeling study of subalpine and upper montane zones of the Olympic Mountains under a warming climate suggested that dominant tree species in the wetter southwest areas will shift upwards at least 1000ft (300m) in the next 200-300 years.[465,466] The model projects that Pacific silver fir will encroach on subalpine meadows and mountain hemlock forests, and that western hemlock will encroach on current Pacific silver fir forests. [467] In the drier northeastern portion of the Olympic Mountains, study results suggest that drought-tolerant species will become dominant at lower elevation. [468] In general, productivity will increase in the southwest due to longer growing seasons (and lack of moisture limitation), and productivity will decrease in the northeast due to increased evapotranspiration and lower soil moisture content during the summer.[469]

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[458] Information as cited in Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.* (Ch.6)

[459] Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.* (Ch.6)

[460] Information as cited in Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.* (Ch.6)

[461] Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.* (Ch.6)

[462] Information as cited in Beniston (2003), *Climatic Change in Mountain Regions: A Review of Possible Impacts*. (primary literature)

[463] Beniston (2003), *Climatic Change in Mountain Regions: A Review of Possible Impacts*. (primary literature)

[464] Information as cited in Beniston (2003), *Climatic Change in Mountain Regions: A Review of Possible Impacts*. (primary literature)

[465] Information as cited in Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.* (Ch.6)

[466] Zolbrod and Peterson (1999), *Response of high-elevation forests in the Olympic Mountains to climate change.* (primary literature)

[467] Information as cited in Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.* (Ch.6)

[468] Ibid.

[469] Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.* (Ch.6)

Future scenarios projected in a second modeling study for the Olympic Peninsula predict a decline in the extent of the high elevation tundra and subalpine vegetation types by 2040-2060; by 2070-2099 most scenarios predict an almost complete loss of high elevation tundra and subalpine vegetation. [470] This suggests that suitable conditions for tundra and subalpine vegetation will decline substantially or disappear by the end of the 21st century with warming on the peninsula. [471] In the former range of tundra and subalpine vegetation types, other species will likely become dominant, including tree species from lower elevations.[472]

Several factors may make some vegetation communities more vulnerable to climate change than others. A spatially-explicit static vegetation model applied to alpine vegetation communities suggested that forests which are distributed in regions with low precipitation and on soils with low water storage capacity are highly sensitive to shifts in climate.[473] Winter cooling reduces some species' sensitivity to droughts and frosts and may increase their regeneration rate and robustness; if periods of winter cooling decline (as a result of warmer climates), this may inhibit some upward-moving forest species from reaching their potential habitats. [474] Vegetation communities which live in snow beds and in hollows may also be highly vulnerable to climate change because they will be subject to summer desiccation.[475] Overall, the most vulnerable species may be those that are genetically poorly adapted to rapid environmental change, reproduce slowly, disperse poorly, and are isolated or highly specialized.[476]

Overall, high-elevation species ranges are expected to contract as a result of vertical migration, simply because mountain peaks are smaller than their bases.[477] Because temperature decreases with altitude by 5-10°C/km, species may only need to migrate upward relatively short-distances in order to persist in a climatically-suitable habitat. [478] However, mountain topography (i.e., steep peaks and ridges) may present obstacles that limit the extent of vertical migration.[479] Range contraction of high-elevation species is expected to reduce species' genetic diversity and increase the risk that a species will become extinct due to a random disturbance event. [480]

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[470] Information as cited in Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.* (Ch.6)

[471] Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.* (Ch.6)

[472] Ibid.

[473] Information as cited in Beniston (2003), *Climatic Change in Mountain Regions: A Review of Possible Impacts*. (primary literature)

[474] Ibid.

[475] Ibid.

[476] Parry et al. (2007), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Ch. 14)

[477] Ibid.

[478] Ibid.

[479] Ibid.

[480] Ibid.

Discussion

Mountain regions support many different ecosystems and increasingly serve as refuges from direct human impacts for many endemic species.[481] Unfortunately, changes in the position of the treeline will affect high elevation tundra ecosystems.[482] Genetic diversity, habitat for alpine animals, and overall alpine biodiversity are likely to be reduced.[483] Reductions in tundra areal extent, coupled with changes in treeline community structure, may affect the water and nutrient budgets of mountain watersheds.[484]

Besides altering the location of the treeline, climate change may also affect other important alpine habitat characteristics. A lack of snow cover could expose plants and animals to frost and influence water supply in spring.[485] Changing snow patterns could disrupt animal movements and increase wildlife mortality.[486] Changes in nutrient availability and interspecies competition could limit the establishment of tree species and affect the upper elevational limit of alpine forested tundra ecotones.[487] In the Pacific Northwest, shorter snow durations could favor an increased density of tundra or meadow plants.[488] Species that are currently dominant may be replaced by those favoring warming climates or by pioneer species that have a greater adaptive capacity.[489] Alternatively, environmental change may favor less dominant species such that these become more prevalent than currently-dominant species.[490] However, these scenarios are based on the assumption that other limiting factors such as soil type or moisture will remain relatively unaffected by a changing environment.[491]

ALTERED PRODUCTIVITY

Rising temperature is expected to lead to increased plant productivity in alpine and subalpine systems. At high elevations on the Olympic Peninsula, tree growth and establishment are limited by snowpack amount and duration and hence growing season length; greater snowpack amount and duration leads to a shorter growing season and decreased growth in high elevation trees (i.e., subalpine fir).[492] Increasing temperatures with climate change may lead to more precipitation falling as rain rather than

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[481] Parry et al. (2007), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Ch. 14)

[482] Malanson et al. (2007), *Alpine treeline of western North America: Linking organism-to-landscape dynamics.* (primary literature)

[483] Information as cited in Malanson et al. (2007), *Alpine treeline of western North America: Linking organism-to-landscape dynamics.* (primary literature)

[484] Information as cited in Malanson et al. (2007), *Alpine treeline of western North America: Linking organism-to-landscape dynamics.* (primary literature)

[485] Parry et al. (2007), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*

[486] Ibid.

[487] Malanson et al. (2007), *Alpine treeline of western North America: Linking organism-to-landscape dynamics.* (primary literature)

[488] Ibid.

[489] Information as cited in Beniston (2003), *Climatic Change in Mountain Regions: A Review of Possible Impacts*. (primary literature)

[490] Ibid.

[491] Beniston (2003), *Climatic Change in Mountain Regions: A Review of Possible Impacts*. (primary literature)

[492] Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.* (Ch.6)

snow, earlier snowmelt, and thus lower snowpacks and longer growing seasons.[493] A longer growing season will alleviate growth-limiting factors and likely result in increased growth and productivity in high-elevation forests. Longer growing seasons could also lead to an increase in tree establishment at higher elevations.[494]

INCREASED FIRES

Increasing temperatures and corresponding increases in summer drought stress and fire frequency in the Pacific Northwest will lead to changing species distribution in the region.[495] On the eastern half of the Olympic Peninsula, fires occurred historically in subalpine fir vegetation with a return period of about 208 years.[496] Increasing fire frequency in subalpine fir systems would likely favor tree species that can survive fires or regenerate after fires, such as Douglas-fir and lodgepole pine, at the expense of less fire tolerant species.[497]

VULNERABILITY TO INSECTS

The suitability for mountain pine beetle (MPB) outbreaks at higher elevations in the Olympic Mountains is expected to increase under moderate warming due to increasing climatic suitability for both the beetles and their host trees.[498,499] In addition, the negative effects of balsam woolly adelgid (*Adelges piceae* – an invasive, wingless insect from Europe) on Olympic Peninsula forests may increase with warmer temperatures.[500] The balsam woolly adelgid can infest both Pacific silver fir and subalpine fir on the Olympic Peninsula. This insect generally does not kill trees quickly, but will result in the slow demise of infested trees. Three to four years of warmer than average summers were observed to result in an increase in adelgid damage in subalpine fir at higher elevations in Oregon and Washington.[501] A long-term (decades) or permanent increase in summer temperatures could cause a range expansion of the balsam woolly adelgid in subalpine fir ecotypes, upward in elevation and into other new

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[493] Information as cited in Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.* (Ch.6)

[494] Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.* (Ch.6)

[495] Ibid.

[496] Information as cited in Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.* (Ch.6)

[497] Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.* (Ch.6)

[498] Information as cited in Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.* (Ch.6)

[499] Littell et al. (2009a), *Forest ecosystems, disturbance, and climatic change in Washington State, USA.* In: WACCIA (CIG 2009)

[500] Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.* (Ch.6)

[501] Information as cited in Halofsky et al. (in press), *Adapting to climate change at Olympic National Forest and Olympic National Park.* (Ch.6)

environments.[502] The widespread loss of trees in some areas from insect infestations may reduce the seeds available for dispersal to alpine forested tundra ecotones.[503]

WESTERN PRAIRIES

Members of the TAG3 working group identified "western prairies" as a unique ecological system of high conservation priority within Washington State; hence, individuals requested further information on climate change impacts to this ecosystem. NatureServe (2009) has identified three major types of prairies in Washington State: (1) Willamette Valley Upland Prairie and Savanna, (2) Willamette Valley Wet Prairie, and (3) Columbia Basin Palouse Prairie.[504] The Willamette Valley Upland Prairie and Savanna ecosystem was identified as the "western prairie" ecosystem of interest to the TAG3 group.

This section incorporates information on the characteristics, history, status, and trends in Willamette Valley Upland Prairie and Savanna ecosystems. This ecosystem includes habitats identified as South Puget Lowland Prairies, Garry Oak (*Quercus garryana* Dougl. *ex* Hook.) woodlands, native grasslands, and "balds." These terms are briefly described below:

- **Bald** – Rocky soil complexes consisting of heterogeneous bedrock-derived soils that support some percentage of their area in grasslands[505]
- **Forest** – woody ecosystems that are dominated by trees (perennial woody plants taller than 5 meters at maturity, where the tree crown cover exceeds 10% and the area is larger than 0.5 hectares)[506]
- **Grassland** – a bunchgrass-dominated vegetation complex (as defined for southern Puget Sound prairies)[507]
- **Prairie** – conventionally, a flat or rolling stretch of predominantly treeless grassland
- **Savanna** – a grassland with scattered individual trees[508]
- **Woodland** – generally an area with lower crown cover of tall, mature, perennial woody plants (trees) and/or higher shrub cover than a forest[509]

Note that these are intended as basic descriptions of the component habitats of Western Prairies; other definitions may be used in particular management and conservation contexts.

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[502] Ibid.

[503] Malanson et al. (2007), *Alpine treeline of western North America: Linking organism-to-landscape dynamics.* (primary literature)

[504] NatureServe (2009), *NatureServe Explorer: An Online Encyclopedia of Life* (search term: "prairie") (website)

[505] Chappell et al. (2001), *Distribution and decline of native grasslands and oak woodlands in the Puget Lowland and Willamette Valley ecoregions, Washington.* (book)

[506] Shvidenko et al. (2005), *Forest and Woodland Systems.* Ch. 21 in: *Ecosystems and Human Well-being: Current State and Trends.* (Millenium Ecosystem Assessment)

[507] Crawford and Hall (1997), *Changes in the South Puget Prairie Landscape.* In: *Ecology and Conservation of the South Puget Sound Prairie Landscape.* (non-profit publication)

[508] Chappell et al. (2001), *Distribution and decline of native grasslands and oak woodlands in the Puget Lowland and Willamette Valley ecoregions, Washington.* (book)

[509] Shvidenko et al. (DATE) *Ecosystems and Human Well-being: Current State and Trends* Ch. 21

DESCRIPTION OF WESTERN PRAIRIES

NatureServe (2009) describes the Willamette Valley Upland Prairie and Savanna ecosystem as an endemic grassland system located in the Puget Trough and Willamette Valley that occurs on well-drained soils. These prairie soils have a texture of sandy to gravelly loam and primarily exist in five counties in Washington: Grays Harbor, Thurston, Lewis, Mason and Pierce. [510] Dominant vegetation in this ecosystem includes perennial bunch grasses with abundant and diverse forbs, with some scattered deciduous and coniferous trees. [511] More specifically, NatureServe (2009) characterizes these ecosystems by the following vegetation associations[512]:

- *Danthonia california* (valley grassland herbaceous vegetation)
- *Festuca roemeri-Sericocarpus rigidus* (herbaceous vegetation)
- *Quercus garryana/ Festuca roemeri* (wooded herbaceous vegetation)
- *Elymus caninus-Festuca roemeri-Koeleria macrantha* (herbaceous vegetation)
- *Pinus ponderosa/ Carex inops-Festuca roemeri* (woodland)

Descriptions by Chappell et al. (2001) support this characterization of native grasslands and oak woodlands in the Puget Lowland and Willamette Valley ecoregions. They cite information that native grasslands and oak woodlands in these ecoregions are found in well-drained sites formerly influenced by frequent fires. The authors cite information that characterizes these systems in the following way:

- **Oak woodlands**: Dominated by Garry Oak (*Quercus garryana* Dougl. *ex* Hook.), or co-dominated by that species and Douglas-fir (*Pseudotsuga menziesii*), Oregon ash (*Fraxinus latifolia*), bigleaf maple (*Acer macrophyllum*), or Pacific madrone (*Arbutus menziesii*). These systems range from open savannas of scattered trees to dense-canopied forests, with a range of herbaceous or shrubby understory types. These ecosystems primarily occur on dry sites or in moist riparian environments within prairie, or formerly prairie landscapes. [513]

- **Native grasslands**: Dominated or co-dominated primarily by Roemer's fescue (*Festuca idahoensis* var. *roemeri* Pavlick), or California oatgrass (*Danthonia californica* Boland.). These systems harbor a great variety of forbs that sometimes co-dominate with the grasses or occasionally have greater total cover than the grasses. Native grasslands sometimes occur as large "prairies" on level or mounded plains, with deep, uncompacted, relatively well-drained soils, especially glacial outwash deposits. Puget grasslands also occur as "balds" on shallow, rocky soils, especially on moderate to steep south- to west-facing slopes. A few native grasslands are also located on sandy or gravelly coastal bluffs.[514]

HISTORICAL INFORMATION

Prairies and savannas were historically a dominant habitat of interior valleys along the Pacific

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[510] Crawford and Hall (1997), *Changes in the South Puget Prairie Landscape.* In: *Ecology and Conservation of the South Puget Sound Prairie Landscape.* (non-profit publication)

[511] NatureServe (2009), *Willamette Valley Upland Prairie and Savanna.* (website)

[512] Ibid.

[513] Chappell et al. (2001), *Distribution and decline of native grasslands and oak woodlands in the Puget Lowland and Willamette Valley ecoregions, Washington.* (book)

[514] Chappell et al. (2001), *Distribution and decline of native grasslands and oak woodlands in the Puget Lowland and Willamette Valley ecoregions, Washington.* (book)

coast from California to Canada.[515] These ecosystems formed a complex mosaic of patches associated with wet prairies and riparian forests in the Willamette Valley and with forested landscapes in the Puget Trough.[516] Historically, these ecosystems also occurred in the Georgia Basin in both Washington and British Columbia. Pre-European settlement grasslands (i.e., prairies and balds) are estimated to have occupied about 180,444 acres of land in the Puget Lowland and Willamette Valley ecoregions of Washington.[517]

Many of the biological components of the original prairie landscape arrived during a warmer and drier climatic period about 4,000 years ago.[518] Since then, high frequency/low intensity fires and periodic soil drought maintained characteristic prairie vegetation.[519] Researchers generally affirm that many of the fires that maintained prairie ecosystems were intentionally set by Native Americans.[520,521,522] American Indians maintained the open landscape by burning the prairies, which prevented invasions by shrubs and trees and maintained a good crop of Camas bulbs (a food source).[523] Hence, this grassland vegetation exists under a climatic regime that would otherwise support forest vegetation.[524]

ECOSYSTEM STATUS

Native grasslands and oak woodlands have been identified as some of the most imperiled ecosystems in western Washington.[525] Urbanization, forest invasion or conversion, non-native species invasions, fire suppression, and agriculture have caused extensive loss and degradation of prairie habitats since Euro-American settlement.[526,527,528] The following estimates of change in prairie habitats have been documented for Washington:

- In the last 150 years, the prairie or grassland-savanna vegetation that historically covered a tenth of the landscape in the southern Puget Lowland was reduced by 90%.[529] Extant grasslands occupy only 9.3% of their estimated extent prior to European settlement.[530]

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[515] Bachelet (2010), *Climate Change Impacts on South Puget Lowland Prairies.* (conference abstract)
[516] NatureServe (2009), *Willamette Valley Upland Prairie and Savanna.* (website)
[517] Chappell et al. (2001), *Distribution and decline of native grasslands and oak woodlands in the Puget Lowland and Willamette Valley ecoregions, Washington.* (book)
[518] Crawford and Hall (1997), *Changes in the South Puget Prairie Landscape.* In: *Ecology and Conservation of the South Puget Sound Prairie Landscape.* (non-profit publication)
[519] Ibid.
[520] Ibid.
[521] Bachelet (2010), *Climate Change Impacts on South Puget Lowland Prairies.* (conference abstract)
[522] NatureServe (2009), *Willamette Valley Upland Prairie and Savanna.* (website)
[523] Bachelet (2010), *Climate Change Impacts on South Puget Lowland Prairies.* (conference abstract)
[524] Information as cited in Crawford and Hall (1997), *Changes in the South Puget Prairie Landscape.* In: *Ecology and Conservation of the South Puget Sound Prairie Landscape.* (non-profit publication)
[525] Chappell et al. (2001), *Distribution and decline of native grasslands and oak woodlands in the Puget Lowland and Willamette Valley ecoregions, Washington.* (book)
[526] Bachelet (2010), *Climate Change Impacts on South Puget Lowland Prairies.* (conference abstract)
[527] Information as cited in Crawford and Hall (1997), *Changes in the South Puget Prairie Landscape.* In: *Ecology and Conservation of the South Puget Sound Prairie Landscape.* (non-profit publication)
[528] Information as cited in Chappell et al. (2001), *Distribution and decline of native grasslands and oak woodlands in the Puget Lowland and Willamette Valley ecoregions, Washington.* (book)
[529] Crawford and Hall (1997), *Changes in the South Puget Prairie Landscape.* In: *Ecology and Conservation of the South Puget Sound Prairie Landscape.* (non-profit publication)

- Known native grasslands occupy only 2.6% of the remaining area of extant grasslands. [531]
- Known, restorable grasslands (native and semi-native) occupy 5.1% of the remaining area of extant grasslands. [532]
    - An external reviewer commented that this percentage may increase as new methods are being developed to restore highly degraded landscapes back to native prairie.

Many former native grasslands are now dominated or co-dominated by non-native grasses or have been invaded by shrubs: especially Scot's broom, Nootka rose, and common snowberry.[533] Deciduous and coniferous savannas historically covered about one-third of the total acreage of Willamette Valley Upland Prairie and Savanna, but these are now rare; in the absence of disturbance (i.e., fire), many savannas have succeeded to forest.[534] The remaining prairie grasslands, oak woodlands, and balds are highly fragmented, due both to natural factors that limit their distribution to specific physical environments and to anthropogenic habitat conversion.[535] Oak woodlands and balds are historically patchy habitats, and this landscape pattern may be little changed; however, the matrix in which these patches occur has shifted from a matrix of prairie grasslands and forests to a matrix with large amounts of suburban development and agricultural land. [536] Prairie grasslands were historically more extensive than either of the former two habitats, and fragmentation has certainly increased as a result of land conversion and habitat degradation. [537]

The following geographic areas of pre-settlement grasslands have been functionally extirpated in Puget Sound:[538]

- Cowlitz-Newaukum glacial deposits of central Lewis County
- Sifton soils of Clark County
- Central Whidbey Island prairies
- Sequim prairie of Clallam County

The following geographic areas in Washington have remaining elements of prairies (either soils or vegetation):[539]

- South Puget Sound (primarily Pierce & Thurston counties) has the largest area of pre-settlement grassland soils, extant grasslands, and oak canopies.

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[530] Chappell et al. (2001), *Distribution and decline of native grasslands and oak woodlands in the Puget Lowland and Willamette Valley ecoregions, Washington.* (book)

[531] Ibid.

[532] Ibid.

[533] Ibid.

[534] NatureServe (2009), *Willamette Valley Upland Prairie and Savanna.* (website)

[535] Chappell et al. (2001), *Distribution and decline of native grasslands and oak woodlands in the Puget Lowland and Willamette Valley ecoregions, Washington.* (book)

[536] Ibid.

[537] Ibid.

[538] Ibid.

[539] Chappell et al. (2001), *Distribution and decline of native grasslands and oak woodlands in the Puget Lowland and Willamette Valley ecoregions, Washington.* (book)

- The San Juan Archipelago has the most extensive rocky soil complex.
- Parts of Whidbey Island, Island County, and the northeastern parts of the Olympic Peninsula, Clallam, and Jefferson counties have extensive prairie soils (although there are few extant, untilled grasslands on them).
- The southern Puget Lowland and northern Willamette Valley have many small oak stands and a few areas of prairie soil (but no extant untilled grasslands).
- Thurston, Clark, and Skamania Counties have the largest contiguous areas of oak-dominated canopies.

Reviewers noted that Kittitas County also has significant areas of oak savanna, although this is not generally considered part of the western Washington prairie complex.

Washington State threatened & candidate species found in western prairies include:

- Mazama pocket gopher
- Streaked horned lark
- Taylor's checkerspot butterfly

ECOSYSTEM TRENDS, CLIMATE CHANGE, AND CONSERVATION

A modeling study conducted by Bodtker et al. (2009) for Washington, Oregon, and British Columbia, Canada, found that climate suitability for Garry oak is likely to improve over the entire study area since Garry oak is suited to a warmer climate; however, climate suitability in specific areas that currently support Garry oak is projected to decline.[540] In British Columbia, suitability was projected to decline in the near future and then improve later in the century, although it was not projected to return to current conditions.[541] The northward expansion of Garry oak may be limited to the Georgia Depression by the dispersal and climatic limitations presented by the surrounding mountain ranges of coastal British Columbia.[542] The model used did not account for site factors such as soil properties or disturbance regimes that will likely continue to play a role in determining the distribution of Garry oak at finer scales.[543] Despite projected increases in climatic suitability in the future, Bodtker et al. (2009) report that climate change is currently having negative effects on Garry oak ecosystems that may continue as a result of changes in ecosystem structure, invasive species, suppression of natural disturbance regimes, and habitat fragmentation.[544]

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[540] Bodtker et al. (2009), *A bioclimatic model to assess the impact of climate change on ecosystems at risk and inform land management decisions.* (Canadian government report)
[541] Ibid.
[542] Ibid.
[543] Ibid.
[544] Ibid.

Projected changes in climate may exacerbate the continuing human pressure on prairie ecosystems.[545] Warmer springs and associated shifts in stream peak flows, longer and drier summers, and more intense rainfall events may affect species composition and competition between native and invasive species.[546] While some of the impacts might be deleterious for vulnerable endemic species, there might also be opportunities created for oak-woodland restoration efforts as climatic conditions for oak growth and development improve.[547]

South Puget Sound prairies have ecoregional significance for biodiversity conservation in Washington State because these are the few remaining habitats where relatively large areas of grassland and oak woodland remain.[548] Many species of flora and fauna associated with these unique habitats are of conservation concern due to declines in population, local extirpation, or close associations with declining habitat (see Chappell et al. 2001 p.124 for a list of species).[549] In addition to providing habitat, prairies render valuable ecosystem services to our region including flood mitigation, soil carbon sequestration and stabilization, pollinator services, and resilience to frequent fires.[550]

Beyond Puget Sound, other conservation opportunities for these imperiled plant communities may include:[551]

- Numerous small grasslands and oak woodlands remaining in the San Juan archipelago
- Oak woodlands of the Chehalis River Valley
- Oak woodlands in the vicinity of Cowlitz Prairie and Lacamas Creek in Lewis County
- Oak woodlands near Kalama in Cowlitz County
- Oak woodlands east of Washougal in Clark and Skamania counties.

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[545] Bachelet (2010), *Climate Change Impacts on South Puget Lowland Prairies.* (conference abstract)
[546] Ibid.
[547] Ibid.
[548] Chappell et al. (2001), *Distribution and decline of native grasslands and oak woodlands in the Puget Lowland and Willamette Valley ecoregions, Washington.* (book)
[549] Ibid.
[550] Bachelet (2010), *Climate Change Impacts on South Puget Lowland Prairies.* (conference abstract)
[551] Chappell et al. (2001), *Distribution and decline of native grasslands and oak woodlands in the Puget Lowland and Willamette Valley ecoregions, Washington.* (book)

APPENDIX 1: SOME POSSIBLE ADAPTATION ACTIONS FOR CONSIDERATION

***NOTE**: The issues and potential responses listed in this section represent ideas from the surveyed literature as well as adaptation responses suggested by others. It is not exhaustive, and we encourage readers to critically consider the applicability of each response in Washington State. The choice of response strategy may be influenced by a range of factors, including degree of impact, irreversibility, risk, vision for the future, and goals. Readers are encouraged to add further suggestions for issues or responses.

CHANGES IN SPECIES COMPOSITION AND DISTRIBUTION	
Issue	Possible Adaptation Action(s)
• Changes in climatic suitability	○ Replant with different species[552] (Consider this as part of a hierarchy where managers first plan for more dominance by better-adapted natives, then plant for using better-adapted genotypes of the same species, and THEN use different species).[553] ○ Shift desired species to new plantations or forest locations[554]
• Lack of data on how distribution & composition are likely to change	○ Conduct experiments and/or use opportunistic assessment opportunities such as horticultural plantings of native species in landscaping, gardens, roadsides, or parks to better understand how species respond in different locations as climate changes[555]
• Economic losses: Increased likelihood of regeneration failure	○ Develop new reforestation systems for landowners that incorporate elements such as clear information on weather and climate predictions for future decades, additional species, stock type and seedling form options, planting techniques, and timing guidance. Replanting is often required to comply with Forest Practices regulations, but regeneration failure has high associated costs (cost of seedlings, planting labor, loss of years of growth, consequences of planting tree species that are a poor choice for the rotation of that crop).

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[552] Millar et al. (2007), *Climate change and forests of the future: Managing in the face of uncertainty.* (primary literature)

[553] Suggested by an external reviewer.

[554] Millar et al. (2007), *Climate change and forests of the future: Managing in the face of uncertainty.* (primary literature)

[555] Millar et al. (2007), *Climate change and forests of the future: Managing in the face of uncertainty.* (primary literature)

• Economic losses: Increased necessity to conduct treatments such as control of competing vegetation, thinning and slash abatement under new climate pressure and growth regimes.	○

ALTERED FOREST PRODUCTIVITY & PHENOLOGY	
Issue	Possible Adaptation Action(s)
• Decreases in forest productivity	○ Develop silvicultural treatments to reduce drought stress[556] ○ Modify harvest schedules[557] ○ Alter thinning prescriptions and other silvicultural treatments[558] ○ Develop approaches for mitigating likely increases in stress on trees[559]

INCREASED FREQUENCY, MAGNITUDE AND INTENSITY OF WILDFIRES	
Issue	Possible Adaptation Action(s)
• Increased risk of wildfire (due to factors such as higher temperatures and drought)	○ Manage to reduce the number of small trees, & allow remaining trees to grow larger (reduce risk of damaging wildfire)[560] ○ Incorporate long-term climate change into wildland fire planning[561]Use new state authority to create forest health scientific advisory committees to assist decision-makers in responding to extreme forest health and fire hazard problems.[562]
• Increased wildfire frequency	○ Address fire suppression at landscape levels in dry forest environments.
• Increased wildfire duration	○ Reduce fuel loads in forests[563]; thin overstocked stands[564]
• Increase in wildfire area burned	○ Thin to alter species composition[565] ○ Use of prescribed fire[566]

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[556] Blate et al. (2009), *Adapting to climate change in United States national forests*. (primary literature)

[557] Millar et al. (2007), *Climate change and forests of the future: Managing in the face of uncertainty.* (primary literature)

[558] Millar et al. (2007), *Climate change and forests of the future: Managing in the face of uncertainty.* (primary literature)

[559] Millar et al. (2007), *Climate change and forests of the future: Managing in the face of uncertainty.* (primary literature)

[560] USFS (2008), *Forest Service Strategic Framework for Responding to Climate Change*. (U.S. government report)

[561] Blate et al. (2009), *Adapting to climate change in United States national forests*. (primary literature)

[562] PAWG (2008), *Leading the Way: Preparing for the Impacts of Climate Change in Washington - Recommendations of the Preparation and Adaptation Working Groups.*.

[563] Blate et al. (2009), *Adapting to climate change in United States national forests*. (primary literature)

[564] USFS (2008), *Forest Service Strategic Framework for Responding to Climate Change*. (U.S. government report)

[565] Ibid.

• Loss of biodiversity	○ Maintain large patches of old growth forest (intensity & rate of change is buffered in forest interiors, where mature, long-lived species may persist through centuries of unfavorable climate)[567]
• Increased risk of property damage from wildfires	○ Provide comprehensive data and information to landowners, policy makers, and the public about existing and developing forest health and fire hazard conditions[568] ○ Incorporate climate change and fire behavior information into growth management and rural interface community planning initiatives.
• Economic losses: timber plantations	○ Manage timber plantations with an emphasis on mixed species and native vegetation, allow migrating species to be incorporated (plantations of a single species are often more subject to disturbance)[569]
• Economic losses: Direct and opportunity costs associated with salvage following disturbance events such as fire	○ Manage to reduce susceptibility to likely extreme weather events
• Lack of public awareness & scientific data	○ Implement an active communication and education strategy.[570] ○ Fully fund and implement on the ground pilot programs in Eastern Washington to test site-specific forest health and fire hazard treatments, with an emphasis on multiple, broad multi-landowner areas in an explicit adaptive management context.[571] ○ Foster a collaborative atmosphere across multiple jurisdictions, landowners, and stakeholders to promote agreement on forest health and fire hazard response approaches.[572]
• Implementing adaptation efforts	○ Provide public financial and technical assistance to owners of small forestland parcels.[573] ○ Improve coordination of regulatory requirements to remove unnecessary barriers while ensuring program objectives are being met.[574] ○ Engage the private sector as a partner through market and investment opportunities.[575]

[566] Ibid.
[567] Noss (2001), *Beyond Kyoto: Forest Management in a Time of Rapid Climate Change.* (primary literature)
[568] PAWG (2008), *Leading the Way: Preparing for the Impacts of Climate Change in Washington - Recommendations of the Preparation and Adaptation Working Groups.*.
[569] Noss (2001), *Beyond Kyoto: Forest Management in a Time of Rapid Climate Change.* (primary literature)
[570] PAWG (2008), *Leading the Way: Preparing for the Impacts of Climate Change in Washington - Recommendations of the Preparation and Adaptation Working Groups.*.
[571] Ibid.
[572] Ibid.
[573] Ibid.
[574] Ibid.
[575] Ibid.

VULNERABILITY TO INSECTS & DISEASE	
Issue	Possible Adaptation Action(s)
• Increased forest susceptibility to pest outbreaks	o Prescribed burning to reduce vulnerability[576] o Nonchemical pesticides to reduce leaf mortality from insects[577] o Biological control (e.g. baculoviruses) used to attack pest species while leaving other species & the environment unharmed[578] o Thinning to support risk reduction o Employing forest management practices to improve tree vigor o Sanitation strategies (already employed by forest managers) o Increase options for utilization of forest waste biomass and slash to increase the likelihood that treatments will be applied and risk reduction achieved. o Employ novel insect management techniques (such as pheromones) to trap, confuse, or repel insects (to avoid use of chemicals).
• New invasions in northern & high elevation places	o Take defensive actions at key insect migration points to remove and block invasions[579] o Plan for higher-elevation insect and disease outbreaks[580] o Support seed collection, direct tree protection, and species conservation efforts at key locations…even if barriers to invasions are attempted.
• Increased susceptibility to pathogens and disease	o Implement traditional and innovative forest management techniques to increase tree vigor and reduce specific pathways of pathogen transmission. o Direct suppression of pathogens and sanitation to remove or discriminate against diseased trees. o Support adaptive monitoring techniques and actions to detect new occurrences of pathogens and develop appropriate response strategies. o Identify innovative funding sources to protect vulnerable, valued areas (such as subalpine forests) that are outside of the industrial forest lands that are protected and monitored by timber industries.
• Economic losses: Cost of insect suppression to protect forest products, rare habitats, and/or legacy features	o Develop technical assistance and extension resources for efficient monitoring and management techniques that will increase stand vigor and resistance and enable rapid, effective detection of and response to pest activity.

[576] Information as cited in Hansen, et al. (2003), *Buying Time: A User's Manual for Building Resistance and Resilience to Climate Change in Natural Systems.* (non-profit report).
[577] Ibid.
[578] Ibid.
[579] Millar et al. (2007), *Climate change and forests of the future: Managing in the face of uncertainty.* (primary literature)
[580] Ibid.

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