Oregon’s Biodiversity in a Changing Climate

Prepared for The Climate Leadership Initiative, University of Oregon

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Preface

The following report was developed for the Climate Leadership Initiative at the University of Oregon. The purpose of the report is to describe the current state of knowledge about the potential future changes in Oregon's climate and the potential impact of those changes on Oregon's biodiversity. What follows is based on an earlier report developed for the state of Washington's Biodiversity Council. Much of the material in the Washington report addressed climate change in the Pacific Northwest in general and thus is applicable to Oregon as well. Several sections of the report (e.g., sections 1, 2, 3, and 7) largely were taken unaltered from the Washington report. To this material, we added detailed information specific to Oregon's climate and biodiversity. For example, this report contains more detailed maps of historic climate trends for the state as well as more comprehensive assessments of potential future changes in temperature and precipitation. In addition, the report includes specific examples of potential climate impacts on Oregon's biodiversity and natural resources.

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1. Executive Summary

In the coming century, average annual temperatures in the Pacific Northwest are projected to rise at a rate of 0.1 to 0.6 °C (0.2 to 1.0 °F) per decade. Although there is more uncertainty in projected changes in precipitation, in general, winters are projected to be wetter and summers are projected to be drier. These changes will have profound effects on many ecological systems across the state. For example, temperature-driven reductions in snowpack will affect stream-flow patterns and in turn many freshwater systems. Increasing temperatures will result in drier fuels leading to more frequent, intense, and/or extensive wildfires and rising sea levels will inundate many low-lying coastal areas. All of these changes have the potential to alter habitat and other finely balanced ecological relationships. As species move in response to these climate-driven changes, some will leave areas in which they are currently protected and others will replace them. Designing a network of protected lands that adequately conserves Oregon's biodiversity into the future will require taking climate change into account. Planning for climate change will require a new set of tools including state-wide and regional assessments to determine which species and lands are most vulnerable to climate change and which lands are most isolated, synthetic analyses of regional climate and climate-impact projections, and regional cooperation among state, federal, and private landowners. Despite the challenges inherent in addressing climate change in the conservation-planning process, it may not be possible to protect biodiversity in the coming century unless we do.

2. Introduction

Global average temperatures have increased by 0.7 °C (1.3 °F) over the last century and are projected to rise between 1.1 and 6.4 °C (2.0 and 11.5 °F) by 2100 (IPCC 2007). The changes of the past century have had clear effects on many ecological systems. Most notably, we have seen changes in the timing of ecological events and shifts in the distributions of species (Walther et al. 2002, Parmesan and Yohe 2003, Root et al. 2003, Parmesan 2006). For example, spring events such as flowering, mating, and migration are occurring earlier. In addition, many species have shifted their ranges upward in elevation or poleward in latitude at rates that correspond to warming trends. Recent changes in climate have also been linked to changes in hydrology and wildfire frequency and severity (Poff et al. 2002, Westerling et al. 2006) —changes that have important implications for ecological systems. Given that future changes in climate are projected to be much greater than those of the past century, ecological systems will likely undergo even more dramatic changes in the coming decades.

Conservation-planning efforts are generally based on the current distribution of biodiversity. However, as climate changes, species will clearly move in response to physiological temperature constraints, changes in habitat, food availability, new predators or competitors, and new diseases and parasites. Thus, it is unlikely that today's protected lands will provide protection for the same species and same ecological systems in the future. Developing a network of lands that will adequately protect biodiversity into the future will require explicitly taking climate change into account. In the following pages, we provide an overview of recent and projected future climate impacts on the physical and biological systems of Oregon as well as summarize the state of knowledge about potential methods for addressing climate change in future planning efforts.

3. Global Climate Change, an Overview

3.1 Recent and Projected Future Climatic Trends

The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report provides a clear picture of how the Earth's climate has been warming and how precipitation trends in many places have been changing. Over the last 100 years, average annual global temperatures have risen 0.7 °C (1.3 °F). Furthermore, the increasing trend in global temperatures over the last 50 years is approximately twice the trend of the previous 50 years (IPCC 2007). Average annual temperatures in the U.S. have risen 0.8 °C (1.4 °F) and increases in Alaska over the same period have been even greater (2-4 °C [3.6-7.2 °F]) (Houghton et al. 2001). Additionally, much of the U.S. has experienced increased precipitation in the last century, primarily as increases in the amount of heavy precipitation (Groisman et al. 2001).

There is a large degree of confidence that these trends will continue into the future. Global average surface temperatures are projected to rise between 1.1 and 6.4 °C (2.0-11.5 °F) by 2100 with most areas in the U.S. projected to experience greater than average warming (IPCC 2007). The largest increases are projected for the high northern latitudes where average annual temperatures may increase more than 7.5 °C (13.5 °F) (Fig. 1). There is far less agreement among projections of future precipitation patterns. In the winter months, climate models generally agree that there will be an increase in precipitation in the mid to high northern latitudes including the northern U. S. In the summer months, most land-masses are projected to experience less precipitation. However there is less confidence in these projections than for winter projections. Of the summer projections, there is more confidence in the summer drying trends projected for Europe, around the Mediterranean, Southern Africa, and in the Pacific Northwestern U. S. (Fig. 2).

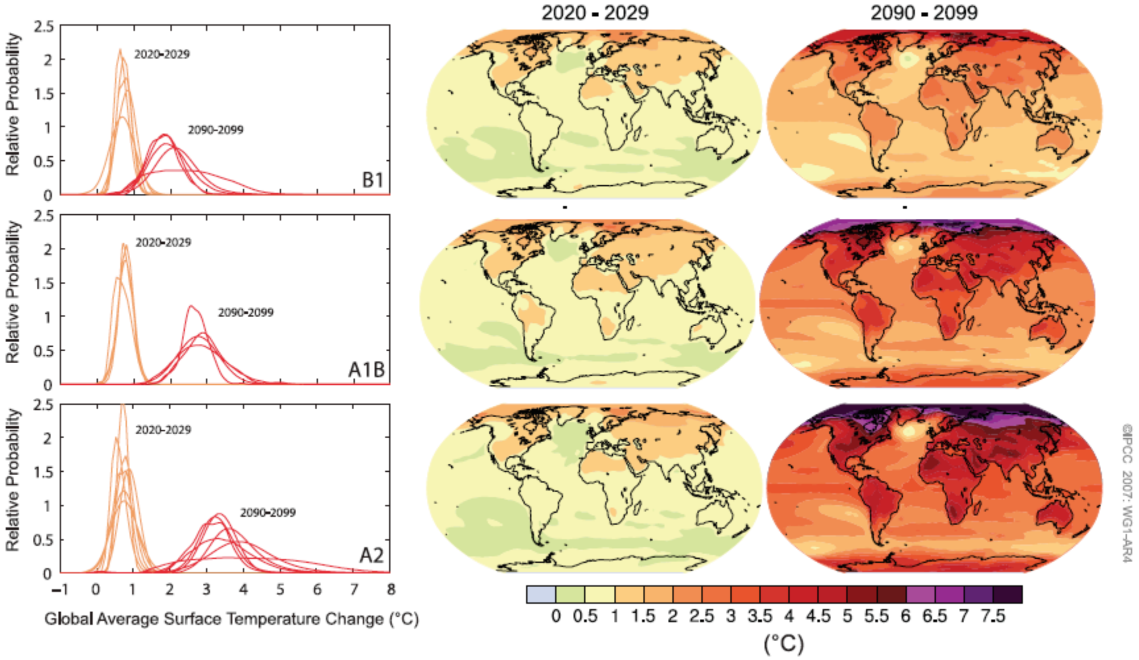


Figure 1. Projected temperature changes for the early and late 21st century relative to the period 1980–1999. The central and right-hand panels show averaged model projections from multiple GCMs for the B1 lower (top), A1B mid (middle) and A2 mid-high (bottom) greenhouse gas emissions scenarios. The left-most panels show corresponding uncertainties in the model projections. The larger spread in the red curves (on the right) indicate larger uncertainties for the 2090-2099 period.

Source: Climate Change 2007: The Physical Science Basis, Summary for Policy Makers, Intergovernmental Panel on Climate Change

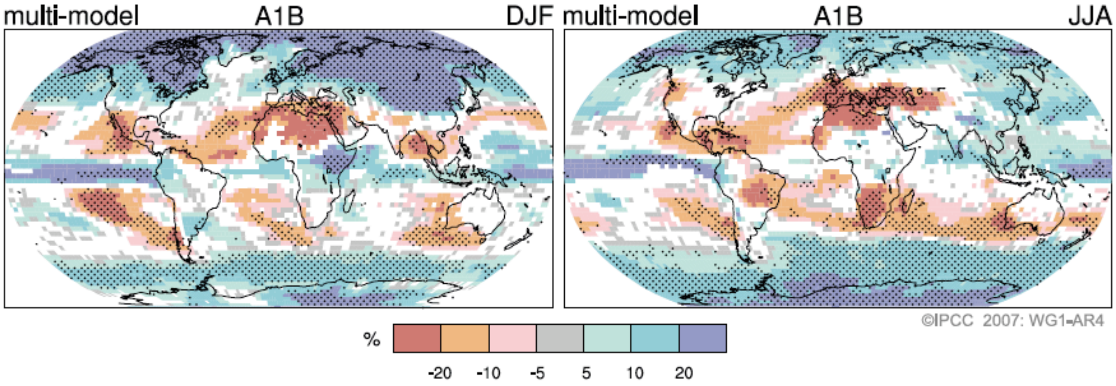


Figure 2. Relative changes in precipitation (in percent) for the period 2090–2099, relative to 1980–1999. Values are multi-model averages based on the SRES A1B mid-level greenhouse-gas emission scenario for December to February (left) and June to August (right). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change.

Source: Climate Change 2007: The Physical Science Basis, Summary for Policy Makers, Intergovernmental Panel on Climate Change

3.2 Climate Impacts on Physical Systems

Climatic changes affect the Earth's physical systems that in part structure ecosystems, communities, and biodiversity. The most studied physical systems with respect to climate change include hydrological systems, coastal processes, and the cryosphere (ice and snow). Even with no change in precipitation, increased temperatures are likely to result in decreases in ice cover and snowpack. Over the past 150 years, 110 glaciers have disappeared. The number of glacial lakes, glacial runoff, and spring peak discharge in glacial streams and rivers have all increased (Adger et al. 2007). Not surprisingly, the western U.S. has experienced reductions in the area of spring snow cover (Groisman et al. 2001).

Projected climatic changes will also affect inland hydrology including streams, lakes, and wetlands (Frederick and Gleick 1999, Poff et al. 2002). Reduced snowpack and earlier spring melts will mean changes in the timing and intensity of spring and summer stream flows (Barnett et al. 2005, Milly et al. 2005). Furthermore, small changes in temperature and precipitation have historically resulted in dramatic changes in flood magnitudes (Knox 1993) and larger climatic changes have redistributed lakes and wetlands across the landscape (Poff et al. 2002). Wetlands are likely to be the most susceptible to climate change of all aquatic systems and wetlands that are dependant on precipitation will be the most vulnerable (Burkett and Keusler 2000, Winter 2000).

Increased global temperatures also have profound ramifications for coastlines. Many coastal areas have experienced sea-level rise, as global average sea level has risen between 10 and 25 cm (3.9 – 9.8 inches) over the last 100 years (Watson et al. 1996). In the coming century, global average sea level is projected to increase by 18-59 cm (7.1 – 23.2 inches) (Alley et al. 2007). Due to thermal expansion of the oceans, even if greenhouse-gas emissions were stabilized at year-2000 levels, we would still likely be committed to between 6 and 10 cm (2.4 – 3.9 inches) of sea-level rise by 2100 and sea level would continue to rise for four more centuries (Meehl et al. 2005). These estimated ranges do not include the potential effects of future rapid changes in ice flows. Sea-level rise has the potential to inundate approximately 50% of North American coastal wetlands and a 50-cm rise in sea level would result in the loss of 17-43% of U.S. coastal wetlands (Watson et al. 1998).

In addition to changing hydrology, climate change will affect other physical factors such as fire and storm intensity. Recent changes in moisture levels have been linked to changes in the frequency and severity of wildfires in the western U.S. (Westerling et al. 2006). In addition, it is likely that future tropical cyclones will be more intense and it is very likely that the frequency of heavy precipitation events and heat waves will increase in the coming century (Alley et al. 2007).

3.3 Climate Impacts on Biological Systems

The climate-induced changes to physical systems will have cascading effects on ecological systems. Many ecological effects of climate change have already been documented providing a clear fingerprint of climate change on ecological systems (Walther et al. 2002, Parmesan and Yohe 2003, Root et al. 2003, Parmesan 2006). These include changes in phenology, changes in species distributions, and physiological changes. Phenological changes have been noted in many different systems (Sparks and Carey 1995). Birds are laying eggs earlier (Brown et al. 1999, Crick and Sparks 1999b), plants are flowering and fruiting earlier (Cayan 2001), and frogs are mating earlier (Beebee 1995, Gibbs and Breisch 2001b). In general, over the last decade, spring events have been occurring earlier at an average rate of 2.3 days per decade (Parmesan and Yohe 2003). These changes in phenology are likely to lead to mismatches in the timing of interdependent ecological events with likely consequences for community composition and ecosystem functioning (Stenseth and Mysterud 2002).

Shifts in species ranges have also been documented across a range of species. Species of birds, butterflies, and amphibians have shifted their distributions in patterns and at rates that are consistent with recent climatic changes (Parmesan 2006). Amphibians are moving up-slope in the Andes in response to warming temperatures and retreating glaciers (Seimon et al. 2007). European butterflies have been seen expanding their ranges northward (Parmesan et al. 1999). And, bird species have been recorded as expanding their ranges upward in elevation and poleward in latitude (Thomas and Lennon 1999). In some instances, the losses of populations and even the extinction of species have been attributed to climate change (Pounds et al. 1999). The redistribution of fauna that will result from future climatic changes will create new ecological communities, new invasive species, and will disrupt the functioning of ecosystems.

Plants have shown clear physiological responses to climate change. Increases in water-use efficiency in response to increases in atmospheric CO_2 concentrations have been documented and are likely to lead to shifts in community composition and in dominant vegetation types (Policy et al. 1993). Changes in water-use efficiencies also have been shown to have unforeseen implications for the global hydrological cycle (Gedney et al. 2006). We have already seen shifts in vegetation that track recent changes in climate. Some of the most well documented shifts are in the increased elevation of tree-line and the advance of the boreal forest north into the Arctic tundra (Caccianiga and Payette 2006)

4. Climate Change in Oregon

4.1 Oregon’s Climate

Elevation and distance from the coast, coupled with the atmospheric circulation patterns over the northern Pacific Ocean, play a large role in shaping the climate across the state. East of the Cascade Range is drier year round, warmer in the summer, and colder in the winter than the west side of the Cascades. Total annual precipitation west of the Cascades varies geographically with annual precipitation in coastal areas generally ranging from 75 to 1000 cm (60-80 inches). The Coast Range experiences some of the greatest precipitation with 457 to 508 cm (180-200 inches) per year. The Willamette Valley averages 89 to 114 cm (35-45 inches) per year. East of the Cascade Range is high desert where the driest area, the Alvord Desert, annually receives less than 13 cm (5 inches) of precipitation. Most other areas east of the Cascade Range receive less than 30.5 cm (12 inches) per year. The highest precipitation amounts east of the Cascade Range fall in other areas of relatively high elevation. The Blue Mountains, for example, receive 127 to 203 cm (50-80 inches) per year. Annual and daily temperatures are much more variable east of the Cascades compared to the relatively consistent maritime climate west of the range. For example, average maximum summer temperatures east of the Cascades range from 34 to 42 °C (93 to 107 °F) and west of the Cascades from 29 to 41 °C (84 to 105 °F). Average minimum winter temperatures east of the Cascade Range are between -30 and -16 °C (-22 and 4 °F) whereas west of the Cascades average minimum temperatures are between -11 and -4 °C (12 and 24 °F). Colder temperatures at high elevations in the west are more comparable to eastern winter temperatures. These basic differences shape the diverse ecosystems that can be found in the two regions and have significant implications for the ways in which climate change will affect those systems.

4.2 Recent Climate Trends

Temperatures have generally increased in Oregon over the last 100 years by about 0.8 °C (1.5 °F) (Mote 2003b). Although some particular weather stations have reported cooling trends over this period, most of the state has warmed over the last century (Fig. 3 & 4). Both trends in annual maximum temperature (Fig. 3) and annual minimum temperatures (Fig. 4) have varied spatially over the last century. Two of the few areas that have shown cooling trends over the last 100 years include the southern portion of the John Day Basin and parts of the west slope of the central Cascade Range. It is important to note, however, that these cooling trends are far weaker and less significant than the majority of the warming trends over this period (Fig. 5 and 6). In addition, warming trends generally have been strongest in the winter months and weakest in the autumn months.

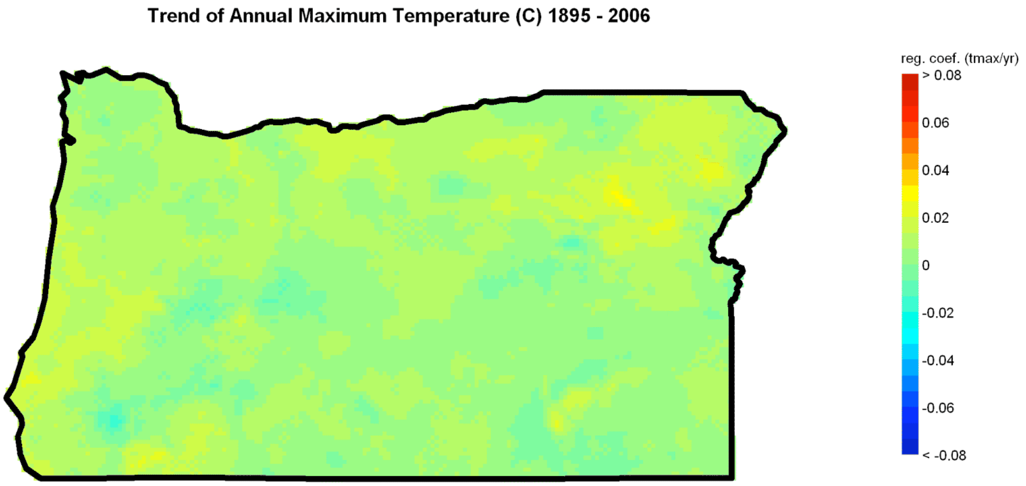


Figure 3. Trends in annual maximum temperatures from 1895-2006. The trends expressed in the map are derived from observed weather station data that has been interpolated to a 4-km^2 grid using a technique that accounts for changes in landscape terrain (Daly et al. 1994). The trends are the coefficients of regression equations resulting from individual regression analyses of yearly temperatures for each 4-km^2 grid cell in the state. The data for the trend analyses were obtained from the PRISM group at Oregon State University.

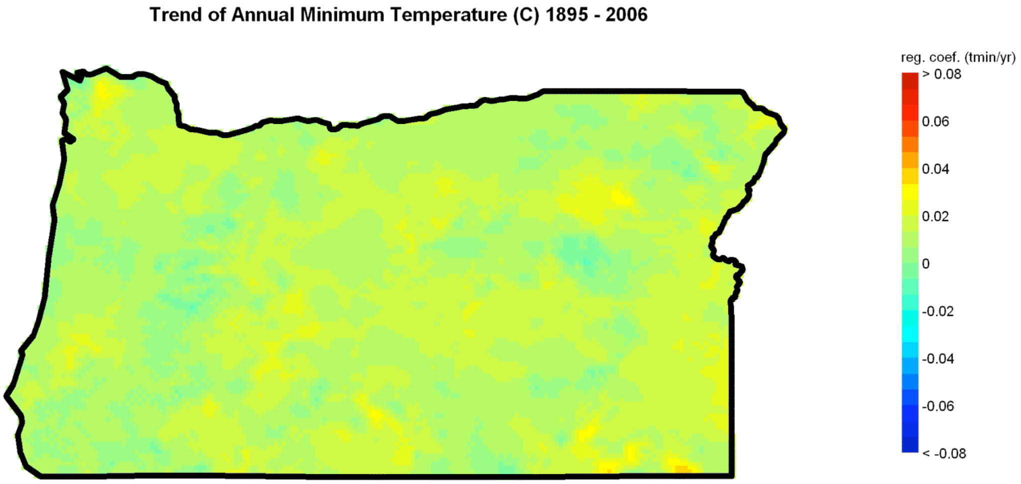


Figure 4. Trends in annual minimum temperatures from 1895-2006. The trends expressed in the map are derived from observed weather station data that has been interpolated to a 4-km^2 grid using a technique that accounts for changes in landscape terrain (Daly et al. 1994). The trends are the coefficients of regression equations resulting from individual regression analyses of yearly temperatures for each 4-km^2 grid cell in the state. The data for the trend analyses were obtained from the PRISM group at Oregon State University.

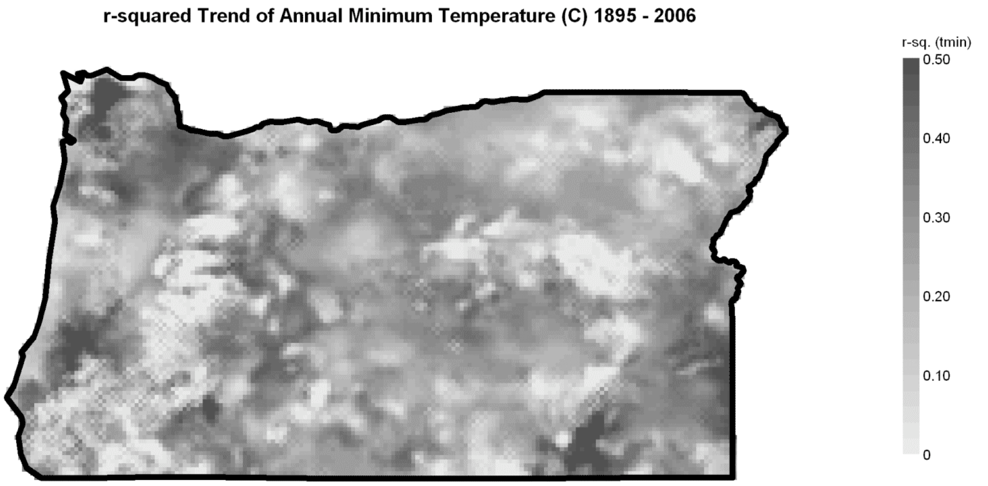


Figure 5. Strength of the trend in annual minimum temperatures from 1895-2006.. Values in the map represent r-squared values from regression analyses described in the legend for Figure 4.

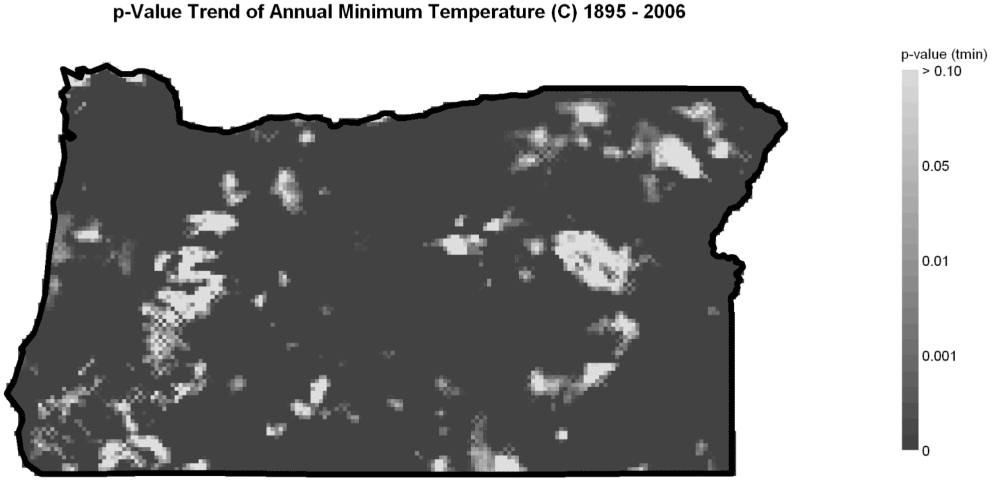
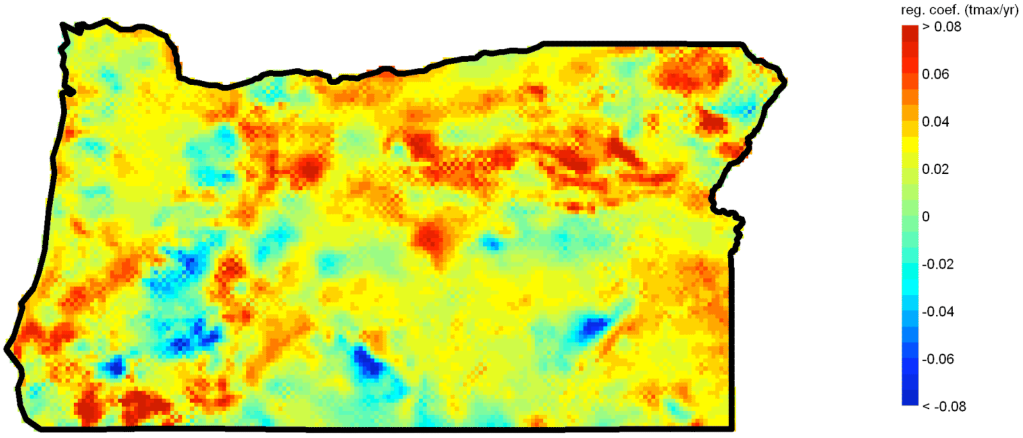


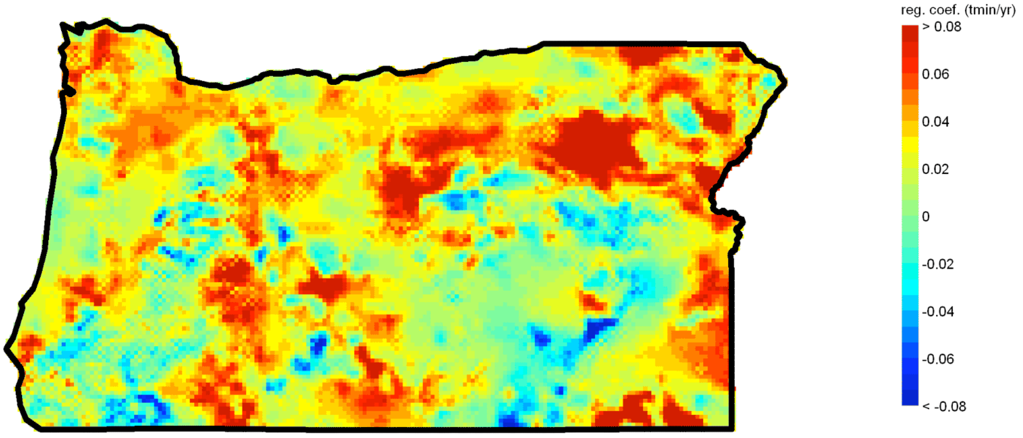
Figure 6. Significance of the trends in annual minimum temperatures from 1895-2006.. Values in the map represent P values from regression analyses described in the legend for Figure 4.

In more recent years, temperatures have increased more dramatically. Temperature trends from 1970 to 2006 reveal much quicker warming with some areas increasing at rates over 0.7 °C (1.3 °F) per decade (Fig. 7 and 8). The greatest increases in annual maximum temperatures have generally been in the southwest, and northern portions of the state (Fig. 7). The greatest increases in annual minimum temperatures have also been in the northern portion of the state but have included much of the Cascade Range, the Blue Mountains, and the southeast corner of the state. A few areas of the state have cooled from 1970 to 2006. Again, the most dramatic cooling trends generally had low r-squared values (Fig. 9). Nonetheless, most of the more dramatic warming and cooling trends are significant (Fig. 10).



Trend of Annual Maximum Temperature (C) 1970 - 2006

Figure 7. Trend in annual maximum temperatures from 1970-2006. The trends expressed in the map are derived from observed weather station data that has been interpolated to a 4-km^2 grid using a technique that accounts for changes in landscape terrain (Daly et al. 1994). The trends are the coefficients of regression equations resulting from individual regression analyses of yearly temperatures for each 4-km^2 grid cell in the state. The data for the trend analyses were obtained from the PRISM group at Oregon State University.



Trend of Annual Minimum Temperature (C) 1970 - 2006

Figure 8. Trend in annual minimum temperatures from 1970-2006. The trends expressed in the map are derived from observed weather station data that has been interpolated to a 4-km^2 grid using a technique that accounts for changes in landscape terrain (Daly et al. 1994). The trends are the coefficients of regression equations resulting from individual regression analyses of yearly temperatures for each 4-km^2 grid cell in the state. The data for the trend analyses were obtained from the PRISM group at Oregon State University.

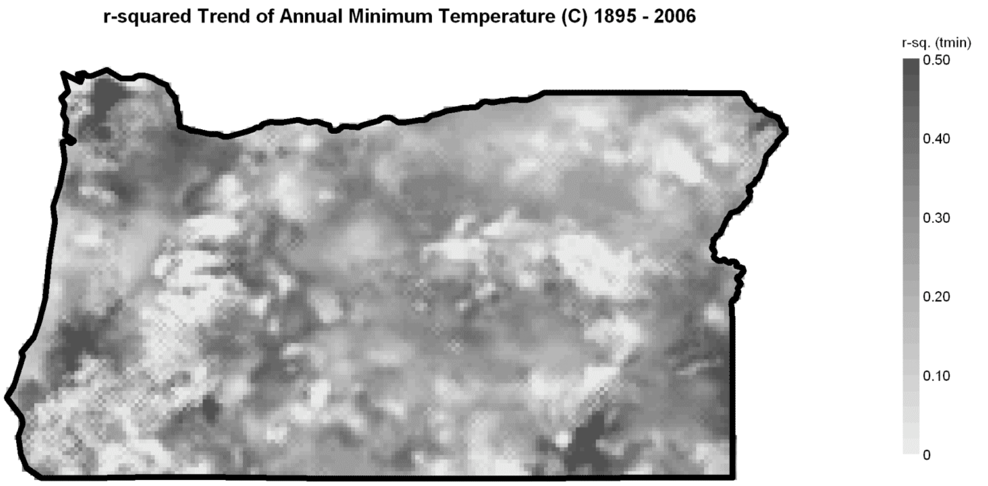

r-squared Trend of Annual Minimum Temperature (C) 1895 - 2006

Figure 9. Strength of the trend in annual minimum temperatures from 1970-2006. Values in the map represent r-squared values from the linear regression analyses described in the legend for Figure 8.

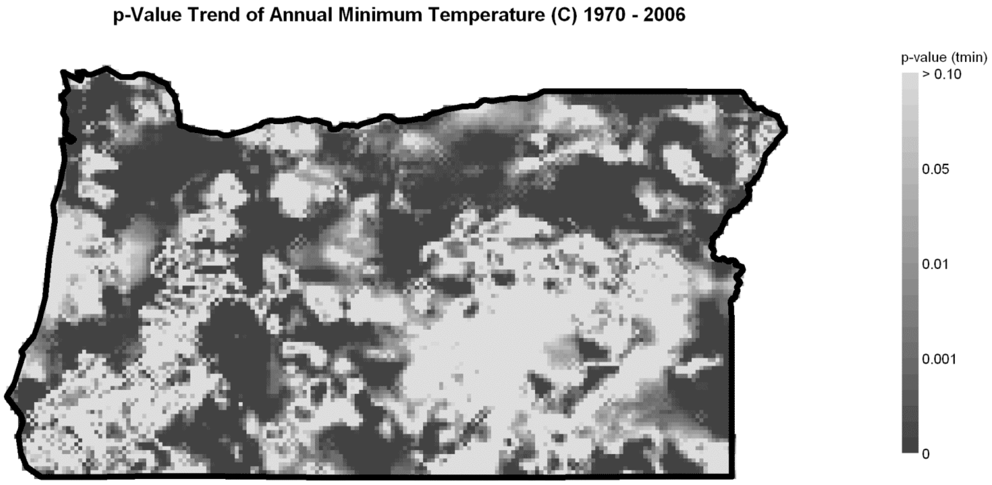

p-Value Trend of Annual Minimum Temperature (C) 1970 - 2006

Figure 10. Significance of the trends in annual minimum temperatures from 1970-2006. Values in the map represent P values from the linear regression analyses described in the legend for Figure 8.

In general, precipitation in Oregon has also been increasing over the past century (Fig. 11). The largest increases have been in the Cascade Range. The decreases in precipitation along the northern coast are driven largely by a relatively wet period that occurred at the beginning of the century. Unlike the trends in temperature, the trends in precipitation are relatively weak and in only a few areas are they significant (Fig. 12 and 13). In general, the largest relative increases in precipitation have been recorded in the spring (Mote 2003b).

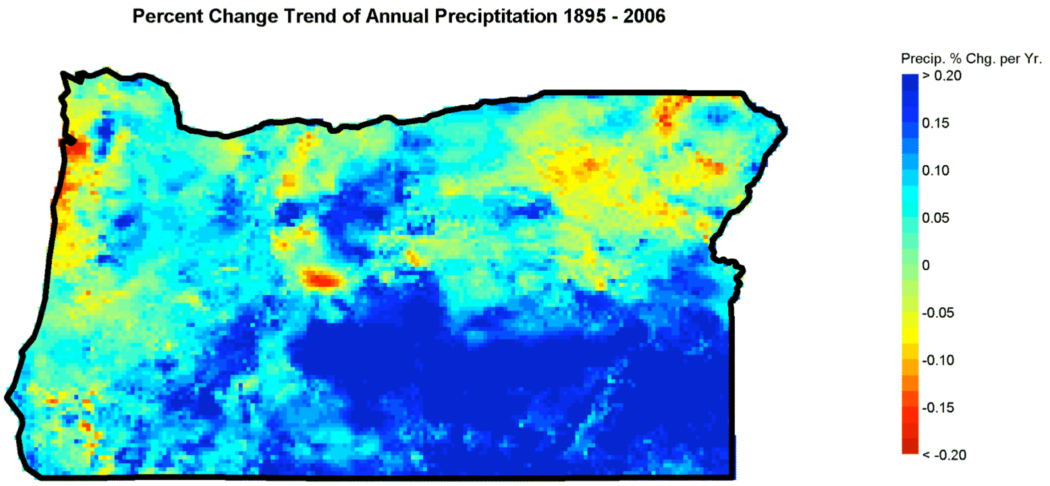

Percent Change Trend of Annual Preciptitation 1895 - 2006

Figure 11. Trends in annual precipitation from 1895-2006. The trends in the map are expressed as a percent change in annual precipitation per year. The data used to calculate the trends were derived from observed weather station data that has been interpolated to a 4-km^2 grid using a technique that accounts for changes in landscape terrain (Daly et al. 1994). The trends are the coefficients of regression equations resulting from individual regression analyses of yearly temperatures for each 4-km^2 grid cell in the state. The coefficients were divided by the mean precipitation for the period and multiplied by 100. The data for the trend analyses were obtained from the PRISM group at Oregon State University.

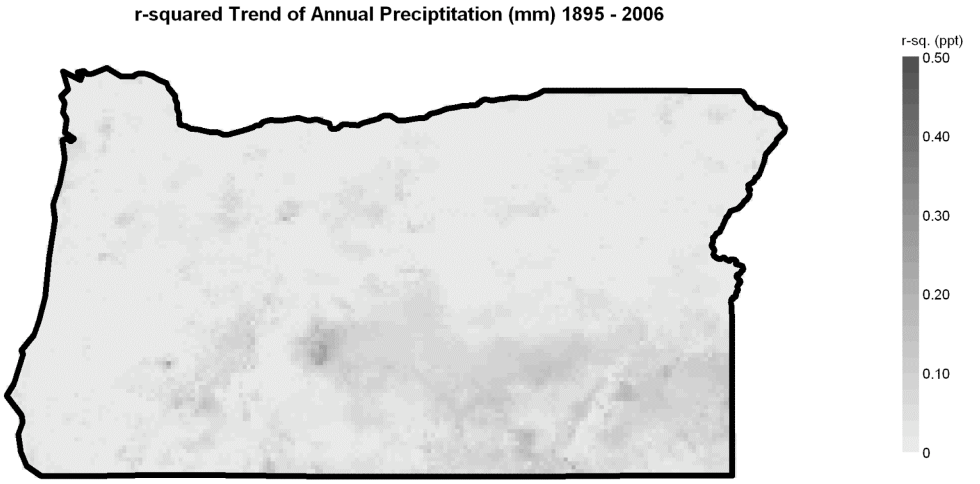

r-squared Trend of Annual Preciptitation (mm) 1895 - 2006

Figure 12. Strength of the trend in annual precipitation from 1895-2006.. Values in the map represent r-squared values from the linear regression analyses described in the legend for Figure 11.

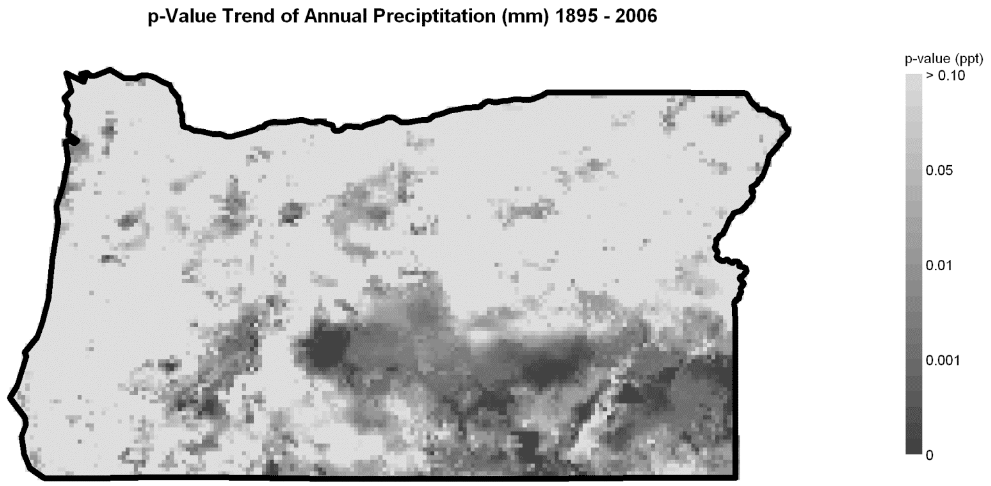


Figure 13. Significance of the trends in annual precipitation from 1895-2006. Values in the map represent P values from the linear regression analyses described in the legend for Figure 11.

More recent trends in precipitation are strikingly different (Fig. 14). Trends in annual precipitation from 1970 to 2006 are much more spatially variable than the trends over the last century. At least half of the state has experienced drying trends from 1970 to 2006. Much of this drying has occurred in the Coast Range, the Cascade Range, and the mountains of northeastern Oregon. Similar to the precipitation trends over the last century, the more recent trends in precipitation are also far weaker than the trends in temperature (Fig. 15 and 16).

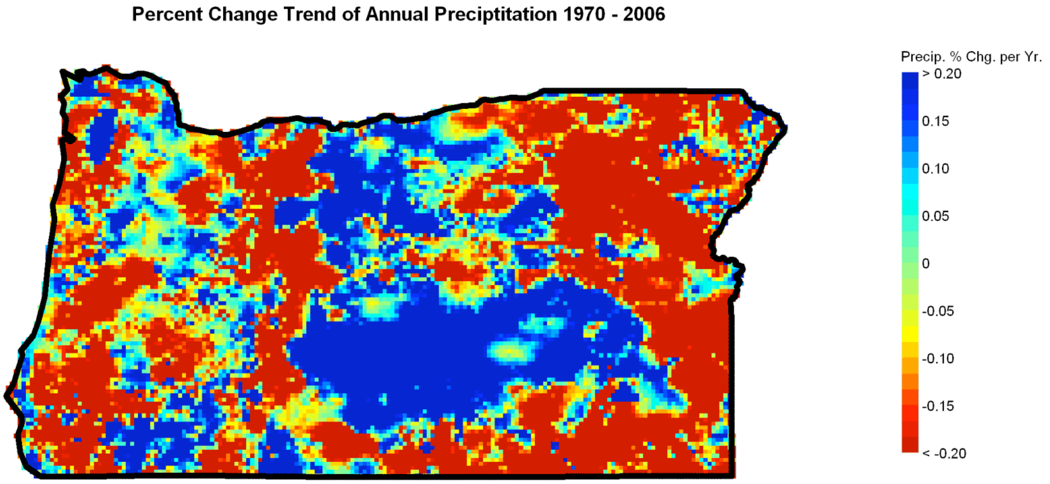


Figure 14. Trends in annual minimum precipitation from 1970-2006. The trends in the map are expressed as a percent change in annual precipitation per year. The data used to calculate the trends were derived from observed weather station data that has been interpolated to a 4-km^2 grid using a technique that accounts for changes in landscape terrain (Daly et al. 1994). The trends are the coefficients of regression equations resulting from individual regression analyses of yearly temperatures for each 4-km^2 grid cell in the state. The coefficients were divided by the mean precipitation for the period and multiplied by 100. The data for the trend analyses were obtained from the PRISM group at Oregon State University.

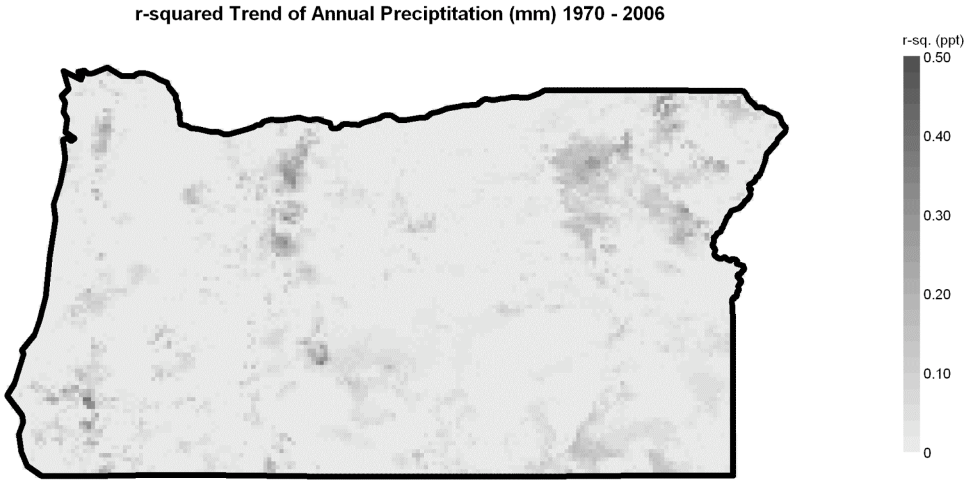


Figure 15. Strength of the trends in annual precipitation from 1970-2006. Values in the map represent r-squared values from the linear regression analyses described in the legend for Figure 14.

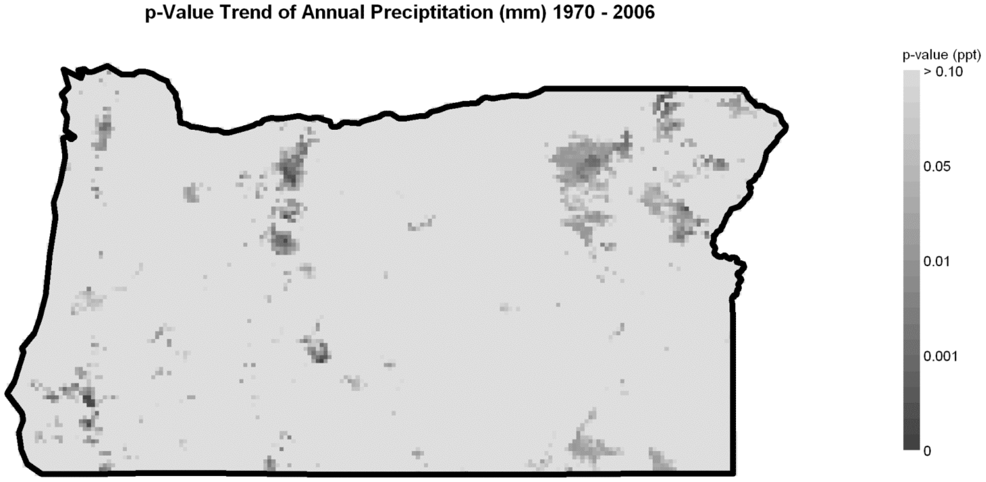


Figure 16. Significance of the trends in annual precipitation from 1970-2006. Values in the map represent P values from the linear regression analyses described in the legend for Figure 14.

In summary, over the last century, much of Oregon has gotten hotter and wetter (Fig. 17). A few areas in northern parts of the state, particularly along the north coast have gotten hotter and drier over this period. Relatively few areas have gotten either cooler and wetter or cooler and drier. From 1970 to 2006, trends have been markedly different. Much of the state has gotten hotter and drier, with a few isolated areas showing cooling trends (Fig. 18).

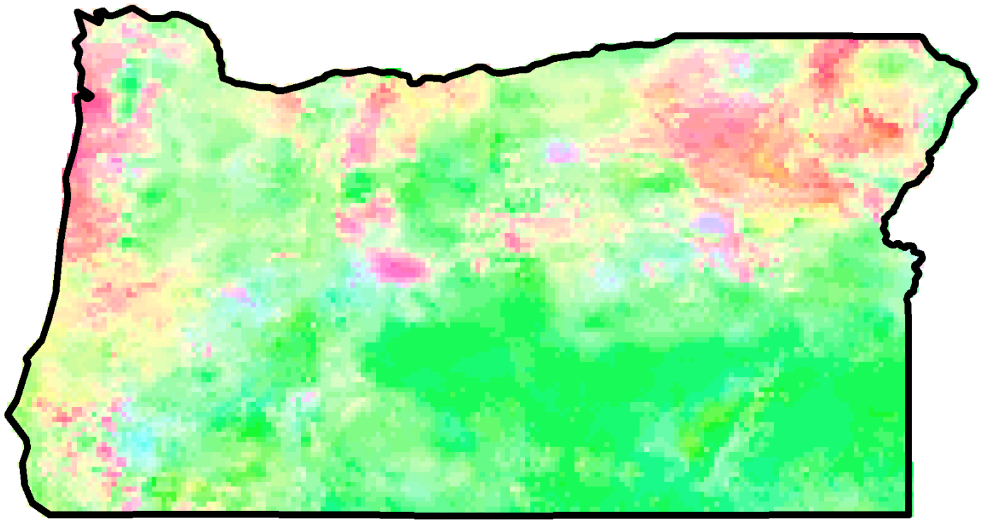


Figure 17. Trends in both annual minimum temperatures and annual precipitation from 1895-2006. The colors represent different combinations of directional changes in precipitation and temperature. The intensity of the color depicts the magnitudes of the trends. Refer to Figures 4 and 11 for descriptions of the contributing analyses.

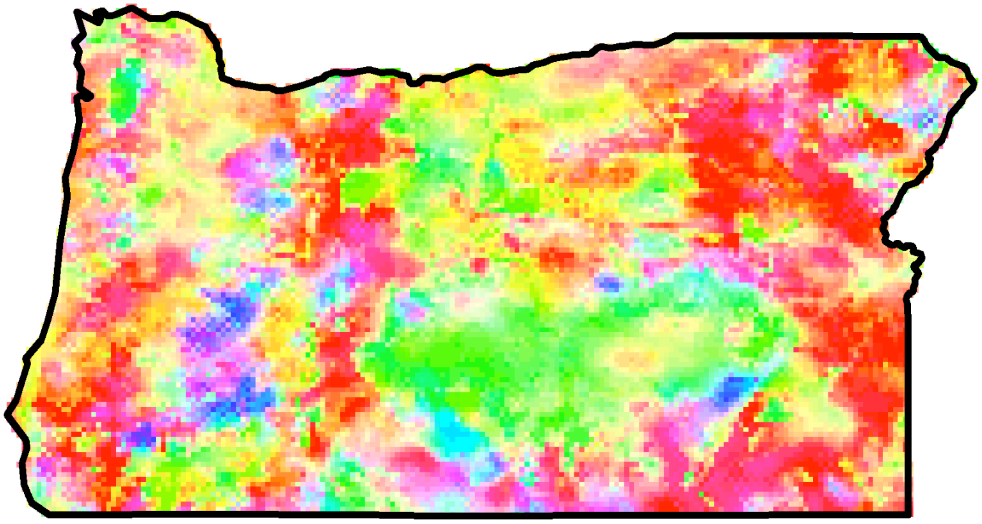


Figure 18. Trends in both annual minimum temperatures and annual precipitation from 1970-2006. The colors represent different combinations of directional changes in precipitation and temperature. The intensities of the colors depict the magnitudes of the trends. Refer to Figures 8 and 14 for descriptions of the contributing analyses.

4.3 Predicted Future Climate Trends

The Climate Impacts Group at the University of Washington has projected potential future changes in the climate of the Pacific Northwest based on general circulation model (GCM) projections produced for the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (Mote et al. 2005a). They predict that temperatures will rise at a rate of 0.1 to 0.6 °C (0.2 to 1.0 °F) per decade over the next 100 years. This is potentially a much larger rate of increase than the 0.1 °C per decade experienced in the Pacific Northwest over the last century. The low, average, and high projected temperature increases from the multiple GCMs for the years 2040 and 2080 are 0.8 °C, 1.6 °C, and 2.6 °C (1.4 °F, 2.9 °F, and 4.6 °F) and 1.6 °C, 3.1 °C, and 4.9 °C (2.9 °F, 5.6 °F, and 8.8 °F) respectively.

Downscaled temperature projections from 30 GCM runs generated for the IPCC Fourth Assessment Report depict a similar future warming trend. For Oregon, average annual temperatures for a 30-year period from 2011-2040 are predicted to increase from 0.5 to 1.6°C (0.9 to 2.8°F) under a lower greenhouse-gas scenario, from 0.5 to 1.9°C (1.0 to 3.4°F) under a mid-level greenhouse-gas scenario, and from 0.6 to 1.8°C (1.1 to 3.2°F) under a mid-high greenhouse-gas emissions scenario (Fig. 19). For the period from 2041-2070, average annual temperatures are predicted to increase from 1.1 to 2.6°C (2.0 to 4.7°F) under a lower greenhouse-gas scenario, from 1.5 to 3.3°C (2.8 to 5.9°F) under a mid-level greenhouse-gas scenario, and from 1.3 to 3.0°C (2.4 to 5.3°F) under a mid-high greenhouse-gas emissions scenario (Fig. 20). For the period from 2071-2100, average annual temperatures are predicted to increase from 1.6 to 3.6°C (2.9 to 6.5°F) under a lower greenhouse-gas scenario, from 1.7 to 4.6°C (3.1 to 8.4°F) under a mid-level greenhouse-gas scenario, and from 2.1 to 4.9°C (3.9 to 8.7°F) under a mid-high greenhouse-gas emissions scenario (Fig. 21). For all of these projections, the lower, mid, and mid-high greenhouse-gas emissions scenarios correspond to the B1, A1B, and A2 scenarios developed by the IPCC as part of their Special Report on Emissions Scenarios (SRES) (Nakicenovic et al. 2000). In general, warming trends are predicted to be greater in the eastern part of the state (e.g., Fig. 20 and 21).

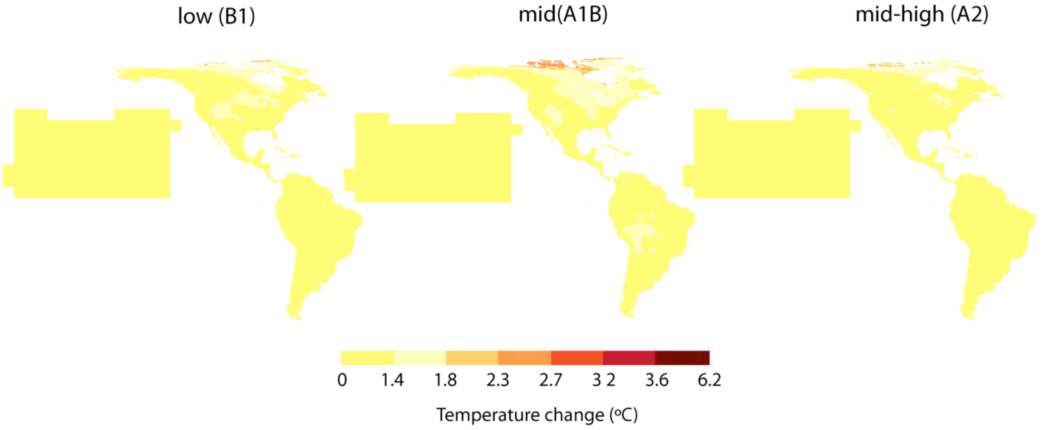


Figure 19. Projected future changes in temperature for the western hemisphere and Oregon averaged for the period of 2011-2040. The maps depict consensus across projections from 10 different GCMs for each of three different greenhouse-gas emissions scenarios. Eighty percent (8 of the 10) GCMs project temperature increases equal to or greater than those shown in the maps (Lawler et al. *In review*).

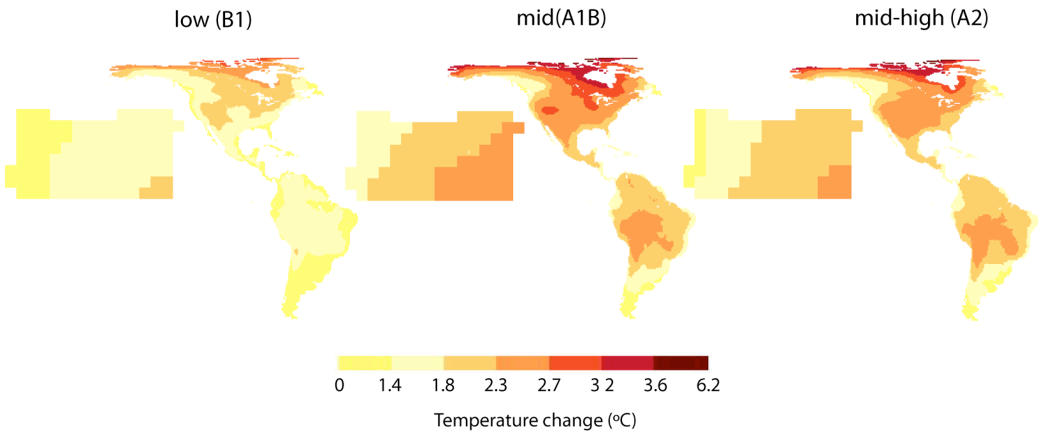


Figure 20. Projected future changes in temperature for the western hemisphere and Oregon averaged for the period of 2041-2070. The maps depict consensus across projections from 10 different GCMs for each of three different greenhouse-gas emissions scenarios. Eighty percent (8 of the 10) GCMs project temperature increases equal to or greater than those shown in the maps (Lawler et al. *In review*).

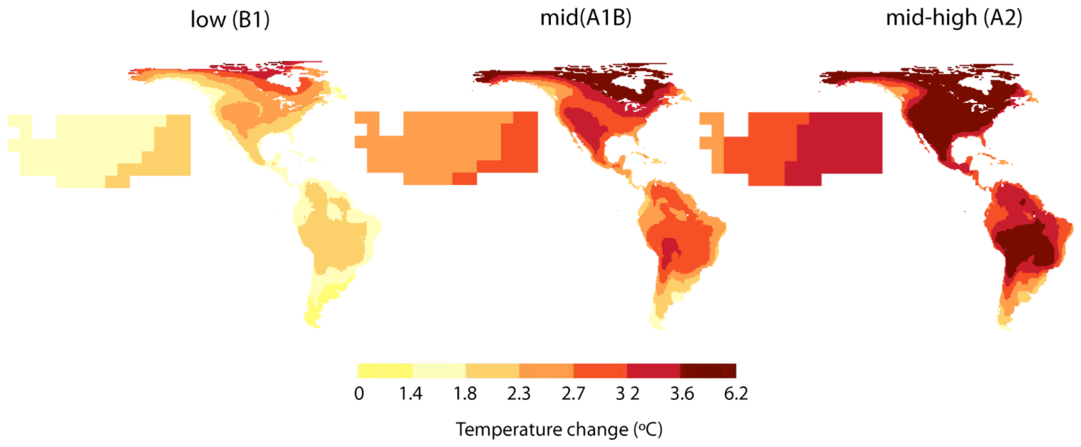


Figure 21. Projected future changes in temperature for the western hemisphere and Oregon averaged for the period of 2071-2100. The maps depict consensus across projections from 10 different GCMs for each of three different greenhouse-gas emissions scenarios. Eighty percent (8 of the 10) GCMs project temperature increases equal to or greater than those shown in the maps (Lawler et al. *In review*).

Precipitation projections for the region, as for the globe as a whole, are more variable. However, in general, the GCMs tend to predict increases in winter precipitation and decreases in summer precipitation. The low, average, and high projected change in precipitation for the Pacific Northwest from the multiple GCMs analyzed by Mote et al.

(2005a) for the years 2040 and 2080 are -4%, 2%, and 9% and -2%, 6%, and 18% respectively. Again, future climate-change projections made for the IPCC Fourth Assessment Report provide a similar picture with respect to precipitation. In general, across the state, precipitation is predicted to increase in the winter (Fig. 22) and decrease in the summer (Fig. 23). The maps in Figures 22 and 23 depict projected directional changes in winter and summer precipitation only. These maps do not show the projected magnitude of changes in precipitation.

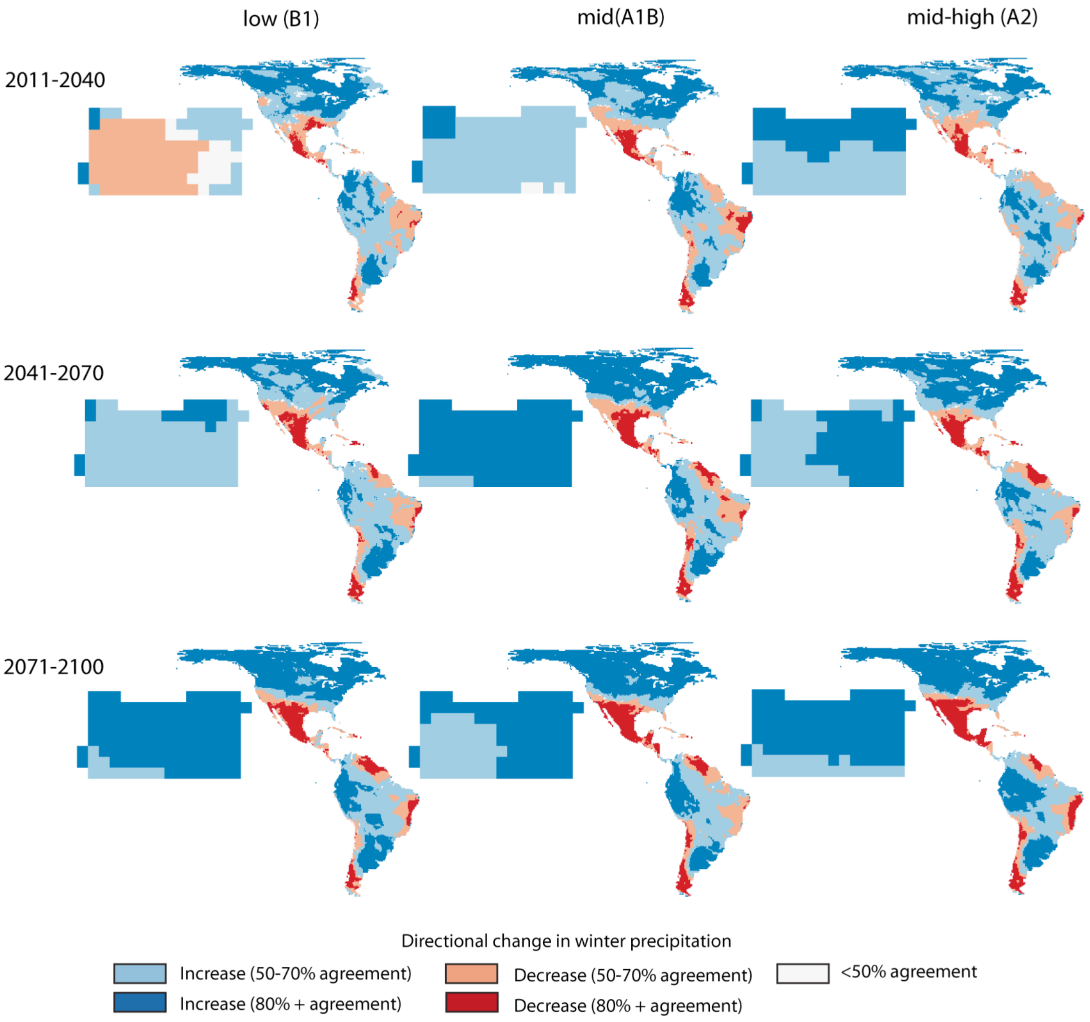


Figure 22. Projected directional changes in winter precipitation for the western hemisphere and Oregon state averaged for the periods of 2011-2040, 2041-270, and 2071-2100. The maps depict consensus across projections from 10 different GCMs for each of three different greenhouse-gas emissions scenarios. These maps only depict the level of agreement in the direction of change in winter precipitation across GCM projections, they do not depict the projected magnitude of change (Lawler et al. *In review*).

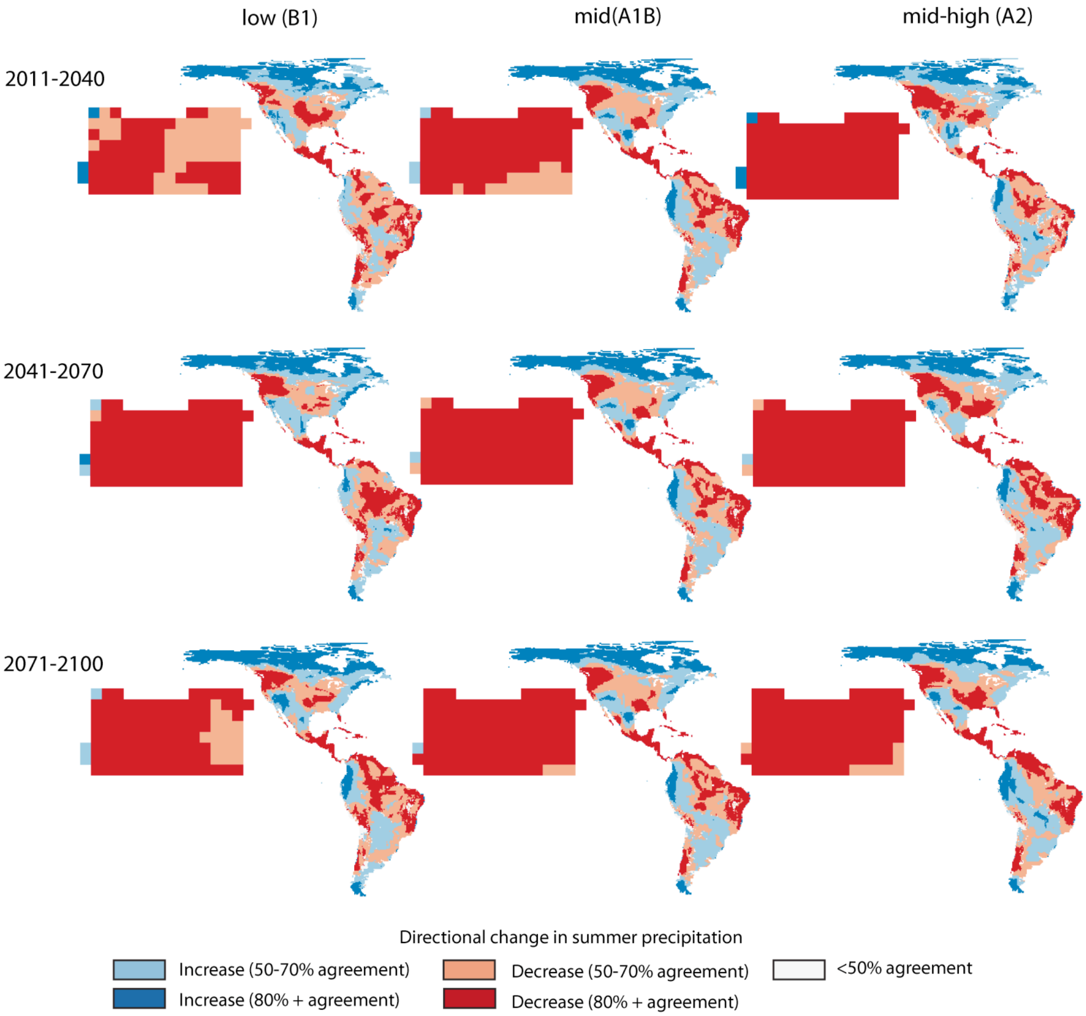


Figure 23. Projected directional changes in summer precipitation for the western hemisphere and Oregon state averaged for the periods of 2011-2040, 2041-270, and 2071-2100. The maps depict consensus across projections from 10 different GCMs for each of three different greenhouse-gas emissions scenarios. These maps only depict the level of agreement in the direction of projected changes in summer precipitation across GCMs, they do not depict the projected magnitude of change (Lawler et al. *In review*).

5. Physical Impacts of Climate Change in Oregon

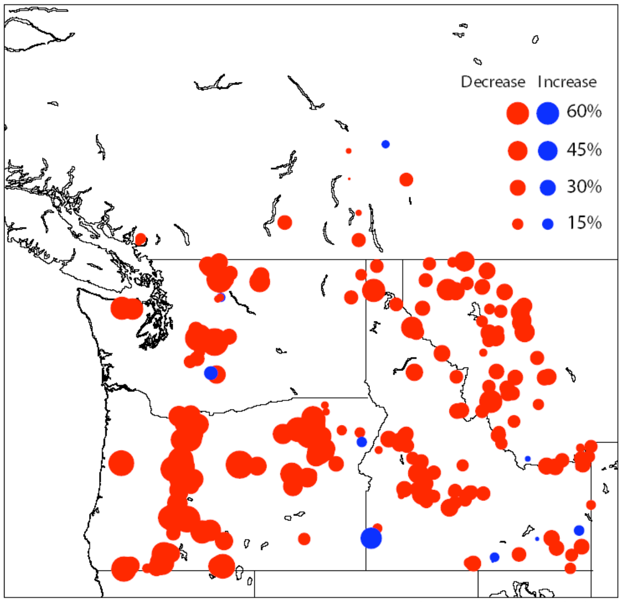
Although there is a growing body of global and even continental scale climate-change impact projections, there are relatively few projections at state and regional scales. Below, we summarize climate-impact projections that have been made for the Pacific Northwest, and when available, the state of Oregon.

5.1 Hydrology

5.1.1 Recent Trends

Hydrological systems are driven in part by regional climate. In the Pacific Northwest, the timing and amount of stream flow is intimately linked to temperature, precipitation through winter snowpack (Hamlet et al. 2005, Mote 2006, Hamlet et al. 2007), and groundwater discharge (Tague et al. 2007). Winter temperatures play a large role in determining how much precipitation falls as snow and how much falls as rain. Increased temperatures reduce the length of the snow season and increase the elevation of snowline. Thus, despite increases in precipitation, warming temperatures have led to decreases in snowpack over much of Oregon. Mote (2003a) reports decreases in April 1st snowpack from 1950-2000 over much of Oregon. At sites in the Cascade Range, Coast Range, and the Blue Mountains, there have been decreases in April 1st snowpack of 30-80%, linked not only to temperature increases, but also to increased melting events prior to April 1st (Mote et al. 2005b). The largest decreases have been at lower elevations (e.g., below 1800 m [5900 ft]) where small changes in temperature have the ability to move snowline upward in elevation (Fig. 24).

The reduction in snowpack over the last 50 years has resulted in changes in flow regimes in some western streams. In particular, streams are experiencing more March streamflow, reduced summer streamflow, increased winter runoff, and earlier snow-derived spring streamflow (Cayan 2001, Stewart et al. 2005). Although these trends depict clear changes in hydrological processes over the last 50 or so years, there is another, more cyclical trend in hydrological drivers that forms a clear pattern in the recent climate record of the Pacific Northwest. This underlying variability in precipitation is associated with the Pacific Decadal Oscillation (PDO) and thus there will likely continue to be alternating wetter and drier periods in the region in the future (Hamlet et al. 2005, Hamlet et al. 2007).



Source: Climate Impacts Group, University of Washington

Figure 24. Trends in April 1st snow water equivalent from 1950-2000. This figure was reproduced with permission from the University of Washington Climate Impacts Group (URL http://cses.washington.edu/cig).

5.1.2 Predicted Future Trends

Projected temperature increases for the coming century are expected to increase the proportion of winter precipitation falling as rain, increase the frequency of winter flooding, reduce snowpack, increase winter streamflow, result in earlier peak streamflow, and decrease late spring and summer streamflows (Hamlet and Lettenmaier 1999a, Mote et al. 2003, Payne et al. 2004, Mote et al. 2005a, Hamlet et al. 2007, Tague et al. 2008). Groundwater flows into streams and rivers of the Oregon Cascades provide one mechanism that may potentially offset the effects of rising air temperatures on stream temperatures. For example, the volcanic substrate of the High Cascades facilitates direct groundwater recharge from precipitation and snow melt, resulting in a spring-dominated hydrology leading into the McKenzie River (Tague et al. 2007). Depending on the depth of spring sources, groundwater springs can be a source of cold-water inflows. At one point on the McKenzie River, 83% of the August streamflow is from groundwater springs, which in turn accounts for 34% of the total August discharge of the Willamette River (Tague et al. 2007).

Snowpack in the Oregon Cascades is projected to decrease by 44% by 2020 and by 58% by 2040 relative to 20th century snowpack. In addition, peak spring-snow runoff is expected to occur 4-6 weeks earlier (Climate Impacts Group 2004). Summer streamflow reduction is expected to continue and become more widely spread (Mote et al. 1999b, Miles et al. 2000, Snover et al. 2003, Mote 2003a, 2003b, Climate Impacts Group 2004, Stewart et al. 2004). For example, July-October decreases in the Tualatin Basin streamflows are expected to reach 10-20% by 2040 (Climate Impacts Group 2004). Predictions for the Upper Clackamas Basin include increased mean winter flows of 9.8-

16.4% (15.9 - 48.7%) and decreased summer flows of 15.3 - 16.3% and 17.8 - 24.7% by 2020 and 2080, respectively (Graves & Chang 2007). The geologic and hydrologic setting of the High Cascades may provide some regional resilience to stream temperature changes, however streamflow reductions may be amplified by climate change in High Cascades systems (Tague et al. 2008). Stream flows will also be reduced in the Western Cascades, where, in combination with increased temperatures, streams will likely become more ephemeral with climate change (Tague et al. 2008). While the region is forecast to become wetter overall, the projected increase in precipitation is less than the precipitation range associated with natural decadal variability (Hamlet et al. 2005). Furthermore, most increases in precipitation are projected for the winter months. Any small amounts of additional summer precipitation will not be enough to overcome the region's dry summers or mitigate the decreased soil moisture caused by increased evaporation at higher temperatures (Hamlet and Lettenmaier 1999a).

The hydrology of some Oregon watersheds will be more sensitive to changes in temperature than others. Generally watersheds that span the snow line and/or generally receive a mixture of rain and snow can be expected to be more sensitive to increased temperatures (Hamlet 2007). These "transition" watersheds will likely experience the largest changes in the timing and magnitude of spring flows (Fig. 25).

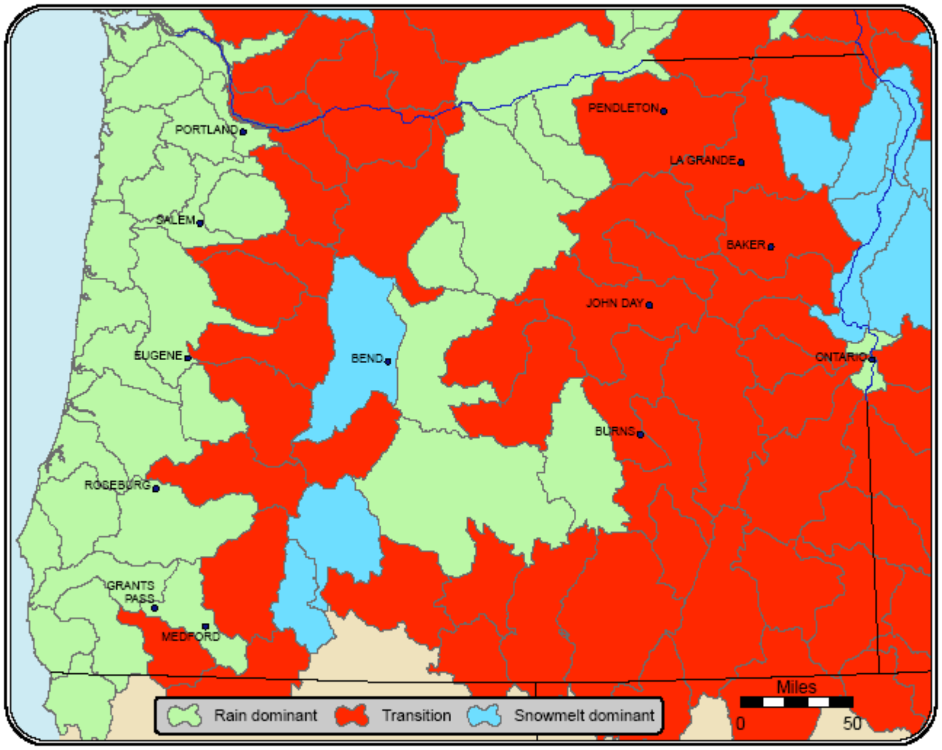


Figure 25. Classification of Oregon HUC4 watersheds as snow dominated, rain dominated, or transition. The classification was calculated as the long-term average of the peak SWE divided by the long-term average of total cool season (October through March). This figure (reprinted with permission) was originally produced by Dr. Alan F. Hamlet of the CSES Climate Impacts Group and the Department of Civil and Environmental Engineering at the University of Washington as part of a report for the Climate Leadership Initiative, University of Oregon (Hamlet 2007).

5.2 Fire

5.2.1 Recent Trends

Fire is perhaps the most important natural disturbance in much of the western U.S. and in much of Oregon as well (McKenzie et al. 2004). Not surprisingly, there is a strong and critical link between climate and the extent, severity, and frequency of wildfires in the western U.S. (Agee 1993, Dale et al. 2001, McKenzie et al. 2004). In the Pacific Northwest, there is a clear relationship between the area of land that is burned, regional drought patterns, and the phase of the PDO (Mote et al. 1999b, Gedalof et al. 2005). As in other parts of the west, this relationship was stronger in the era before intense fire suppression was instigated in the early twentieth century (Mote et al. 1999b).

Fire regimes differ significantly across the state between the west and east sides of the Cascade Range. The wetter western forests experience fewer fires, with an interval of up to 1000 years between fires. In contrast, in the drier forests, grasslands, and shrublands on the east side of the Cascades, fires typically occur at < 10 year intervals. Historically, climate has been the limiting factor for fires on the west side of the Cascades where fuels are plentiful, but higher moisture levels prevent ignition and spread (Bessie and Johnson 1995). Prolonged dry and hot periods are generally required for large fires in the west-side forests (Gedalof et al. 2005). In contrast, fires in drier systems on the east side of the Cascades are generally limited by fuel availability (McKenzie et al. 2004).

In the mid 1980's, the size and intensity of large wildfires in the western U.S. increased markedly (Westerling et al. 2006). The frequency of large fires has increased four fold from 1970-1986 to 1987-2003, and, on average, fire-season length has increased by 78 days in the same period. These increases can, in part, be attributed to decreases in fuel moisture which in turn is driven by increased temperatures and decreased precipitation and snowpack (Westerling et al. 2006). In addition to changes in climate, the increase in fire risk and fire severity has, in part, been driven by fire suppression practices and inter-decadal climate variability (McKenzie et al. 2004, Gedalof et al. 2005, Running 2006).

5.2.2 Predicted Future Trends

Projected increases in spring and summer temperatures will exacerbate the conditions favorable for large fires in the western U.S. (McKenzie et al. 2004, Westerling et al. 2006). In general, we should expect longer fire seasons and more fires (Wotton and Flannigan 1993, McKenzie et al. 2004). However regional variation will occur. The south Santiam watershed on the west side of the Cascades is one area where model predictions do not simulate drier conditions, and where fire regimes may not shift dramatically from their current state (Busing et al. 2007). Nonetheless, even under relatively modest greenhouse-gas emissions scenarios, we may expect to see a doubling in the area burned in western states (McKenzie et al. 2004). For example, total area burned is likely to increase with climate change in southern Oregon forests, such as those found at the Deschutes, Winema, and Fremont National Forests (Gedalof et al. 2005). Generally, the most important factor affecting the area burned is the combination of spring and summer temperature and summer precipitation (Gedalof et al. 2005). Because the climate-modeling community has the most confidence in future projected changes in temperature, the projected increases in wildfire should be seen as highly likely. In addition to the drying effects of increased temperatures, interannual changes in the PDO, projected decreases in summer precipitation and increased fuels resulting from CO_2 fertilization (increases in atmospheric CO_2 have the potential to increase plant growth) may further increase the trends towards more and larger fires in the coming century (Price and Rind 1994, Lenihan et al. 1998, Gedalof et al. 2005).

5.3 Sea-level Rise

5.3.1 Recent Trends

In general, the rugged coast of the Pacific Northwest makes the region less susceptible to sea-level rise than many parts of the eastern and particularly southeastern United States. Nonetheless, sea-level rise has the potential to alter the Oregon coast and change coastal systems. Changes in apparent sea level are a product of several different processes. In the Pacific Northwest, the two most important processes are sea-level rise (predominantly driven by thermal expansion and snow and ice melt) and changes in the relative height of the land (subsidence and uplift). Sea-level rise in Oregon has generally tracked global sea-level rise at a rate of 1 to 2.5 mm/year (Canning 2001). However, local uplift and subsidence of the coastal lands has resulted in differing degrees of apparent sea-level change along different parts of the coast.

5.3.2 Predicted Future Trends

Globally, average sea-level has risen 17 cm (6.7 inches) during the last century, and is projected to rise by 18-59 cm (7-23 inches) by 2100 according to the IPCC (IPCC 2007), with newer estimates suggesting a 50-140 cm (19.7-55.1 inches) sea-level rise in that time (Rahmstorf 2007). Given subsidence and uplift, apparent future sea-level rise on the Oregon coast will differ (as have changes over the past century) from location to location. The area extending from the north central coast inland to the Willamette valley is experiencing a 1 mm/year subsidence. Thus the north-central coast may experience greater than average global projected changes in sea level (Verdonck 2006). In contrast, the coast near Florence is not experiencing great changes in land height, and will likely reflect global sea-level changes. The coast south of Florence and the mouth of the Columbia River appear to be lifting. For example, Astoria may be lifting by 2.3 mm/year (Verdonck 2006), a rate that roughly matches that of sea-level rise resulting in no net change of sea-level in Astoria. These areas will likely experience less apparent sea-level rise in the future.

Future sea-level rise may be significantly underestimated if the rates and subsequent effects of ice-sheet melting in response to increasing temperatures are inaccurate. The West Antarctic ice sheet and the Greenland ice sheet have the potential to increase sea-level rise above predicted levels if one or both were to lose the majority of their mass. Several of the proposed mechanisms for the rapid loss of these ice sheets, such as the lubrication of base of the ice sheets by percolating melt water, are difficult to model, making any estimates of the probabilities of rapid disintegration relatively uncertain (Oppenheimer and Alley 2005, Shepherd and Wingham 2007).

Rising sea levels will result in physical changes to low-lying coastal areas in Oregon. Examples of particularly vulnerable areas include portions of the coast north of Florence, Tillamook bay, and Coos Bay, the Columbia River delta, and low-lying areas of the Willamette River near Portland. These physical changes will include coastal erosion, landslides, saltwater intrusion into freshwater wetlands and water tables, and river-mouth flooding. There will likely be additional impacts on human structures including sewage management systems, underground storage tanks, and hazardous-waste storage sites (Canning 1991, Canning 2001).

6. Potential Climate Impacts on the Biodiversity of Oregon

In addition to affecting physical systems, climate change has had broad and pervasive impacts on ecological systems. Although much evidence of these impacts exists, there is (with a few exceptions) far less information about how the ecological systems and species of Oregon in particular have been changing and are projected to change. In this section, we draw on global, regional, and local studies that can provide some evidence of how biodiversity in Oregon has likely changed and is likely to change in response to climate change. We have organized our discussion of these changes around ecological systems and around broad taxonomic groups. Not all systems or groups present in Oregon are represented in our discussion. Those included are the ones for which the most information exits.

6.1 Ecological systems

6.1.1. Freshwater systems

The combination of changes in hydrology and changes in temperature will have significant impacts on freshwater systems throughout the state. The reduction of snowpack and the resulting changes in spring runoff and summer flows discussed above (section 5.1) will have serious implications for areas in which competition for scarce water resources is already intense, for salmon, and for other freshwater species in Oregon (Mote et al. 1999a, Miles et al. 2000, Battin et al. 2007). Likewise, increases in winter streamflows have the potential to increase the risk of winter floods, and streambed scouring events (Climate Impacts Group 2004).

Increased summer temperatures resulting in increased evaporation, combined with a trend towards drier summers, will result in reduced summer water levels for precipitation fed systems. Reductions in water levels and increases in water temperatures will potentially lead to reduced water quality both in terms of increased turbidity and decreases in dissolved oxygen concentrations (Poff et al. 2002). Furthermore, increased productivity, driven by increased temperature, may lead to increases in algal blooms and more frequent anoxic conditions (Allan et al. 2005). Increases in water temperatures will also facilitate the expansion of ranges of warm-water fish species and the contraction of ranges of cool- and cold-water fish species (Carpenter et al. 1992, Eaton and Scheller 1996). This may mean an increase in competition between non-native fish such as smallmouth bass and native salmon and trout species and an overall reduction in native cold-water species populations.

Together, these factors have the potential to significantly alter aquatic communities. Of all aquatic systems, wetlands will likely be the most susceptible to climate change. Shallow wetlands that are dependant on precipitation will be the most vulnerable to drying, warming, and changes in water quality (Burkett and Keusler 2000, Winter 2000). Intermittent and perennial streams, vernal pools, and coastal wetlands and marshes will also be particularly vulnerable to projected changes in temperature, precipitation, and sea-level rise.

6.1.2. Forests

Oregon has two, very distinct basic forest types. West of the Cascades is dominated by wetter, denser conifer forests whereas the forests east of the Cascade crest are dry, more open conifer forests often blending into open woodlands at lower elevations. Tree growth rates, seedling establishment, and disturbance regimes such as fire and insects are markedly different in the two regions, such that the two forest types are likely to be differentially affected by climate change.

Climate change will likely have the largest effect at forest boundaries where seedlings have a hard time establishing due to cold temperatures or dry conditions (Peterson and Peterson 1994, Bachelet et al. 2001b, Peterson and Peterson 2001, Peterson et al. 2002, Nakawatase and Peterson 2006). At high elevation tree lines, seedling establishment is often limited by cold temperatures and spring snowpack. Thus, in both eastern and western forests, growth and seedling establishment at alpine treeline may be enhanced by warmer temperatures and reduced snowpack. Correspondingly, we should expect to see expansions of forests upward in elevation into alpine zones (Busing et al. 2007). Conversely, the lower treeline of the eastern forests is determined by water availability such that drier conditions at lower elevations prevent trees from growing. Thus, at lower elevations, decreased summer precipitation, decreased snowpack, and increased temperatures have the potential to shift treeline up in elevation (Mote et al. 2003, Neilson et al. 2005).

Unfortunately, these simple predictions alone are unlikely to give us an accurate picture of how Oregon's forests will respond to climate change. There are several other factors that will influence future forest distributions and species composition. For example, the upslope contraction of eastern forests in response to warmer and drier conditions may be offset by increased water-use efficiency resulting from increased atmospheric CO_2 concentrations (Bachelet et al. 2001b, Krajick 2004). This increased water-use efficiency occurs because plants are able to keep their stomata closed for longer periods of time (they open their stomata to take in CO_2 and in the process lose moisture). Correspondingly, models that take this CO_2 effect into account predict expansions of the eastern forests into lower elevations (Neilson and Drapek 1998, Daly et al. 2000). However, the magnitude of the potential CO_2 effect is not well understood and thus the degree to which it will offset forest contractions due to reduced water availability is still uncertain (Bachelet et al. 2001b).

Climate-driven changes in fire regimes will likely be the dominant driver of change in western U.S. forests over the next century (McKenzie et al. 2004). Due to increased temperatures and reduced snowpack and summer precipitation, models predict an increase in the length of the fire season and in the likelihood of fires east of the Cascades (Bachelet et al. 2001a, McKenzie et al. 2004). Due to the wetter conditions, predicting changes in the fire regime west of the Cascades is more difficult (Mote et al. 2003). Changes in the fire regime east of the Cascades will likely result in changes in species composition, habitat availability, and the prevalence of insect outbreaks (McKenzie et al. 2004). All this said, as discussed in section 5.2 above, the frequency and severity of fires in the future will depend not only on the climate but also fuel availability and thus forest management will, as it does today, affect fire regimes east of the Cascades (McKenzie et al. 2004).

Drier, warmer conditions and drought stress are also likely to directly lead to increased disease and insect infestations and outbreaks. Swiss needle cast on Douglas-fir (*Pseudotsuga menziesii*) is shown to increase with increasing temperature in the Oregon Coast Range (Manter et al. 2005). Some insect pests are already expanding their ranges northward in response to warming and others have switched from a two-year to a one-year life-cycle allowing them to generate large outbreaks (Logan and Powell 2001a).

Climate-driven change in disturbance regimes in Oregon forests will also incur economic costs. Increases in the size and intensity of wildfires will exacerbate insect and disease problems, increase costs associated with forest management, and lead to reduced revenue from timber and recreation (Climate Leadership Initiative 2007). Currently, wood and paper product manufacturing and forestry, fishing, and related activities account for 4% of Oregon's $134.6 billion total Gross Domestic Product (Climate Leadership Initiative 2007). For the projected doubling of acreage burned by wildfires in 2040 (estimated at 209,800 – 293,700 acres in Oregon), the associated cost of fire suppression is estimated to increase from the 1993-1995 average of $40 million to between $80 (conservative) and $128 million (inflation adjusted) (Climate Leadership Initiative 2007). Additional costs relative to lost ecological services are not included in these estimates.

6.1.3. Mountains

Ecological systems at high elevations are particularly sensitive to climate change (Woodward et al. 1995, Rochefort and Peterson 1996, Hessl and Baker 1997, Luckman and Kavanagh 2000, Fagre et al. 2003). As temperatures increase, treeline is expected to move upslope resulting in an overall loss of alpine areas (Beever et al. 2003a). There is already evidence that treeline is advancing upslope in many systems replacing alpine meadows (Inouye et al. 2000). The loss of alpine habitats has serious implications for high elevation species that will be forced up slope until there is nowhere else to go. The pika, a small rabbit-like mammal that lives on rocky slopes at high elevations, has already experienced several population extinctions throughout the west over the last 50 years

(Parmesan and Yohe 2003, Root et al. 2003). Pikas require cool conditions and can only leave their burrows to forage when temperatures are cool enough. As the climate warms, they are able to spend less and less of each summer day foraging and consequently are able to store less and less forage for the long winter.

Mountains are also likely to be sites where mismatches between the timing of ecological events are pronounced (Inouye et al. 2000). Many birds in particular, spend winters at lower elevations and migrate upslope in the spring to make use of summer resources at higher elevations. Warming on wintering grounds has caused many species to begin their spring migrations earlier (Neilson et al. 2005). Although this warming is enough to trigger earlier migrations it is not necessarily enough to completely melt the snow at high elevations and thus the summer breeding grounds for these animals may not be suitable when they arrive (Chambers et al. 2005). Birds forced to search for food in the snow or wait at lower elevations may be less likely to find food and be in poorer condition when they are able to breed. Likewise, increasing temperatures have the potential to trigger early emergence from hibernation for marmots and bears and resulting in similar asynchronies with food resources.

Finally, mountains are likely to serve as refuges for some species attempting to move to cooler climates. The strong elevational gradients associated with mountains provide a diversity of climates and habitats for species. Some of these habitats are likely to shift upslope. Others will be altered as plant species respond to climate change in different ways and at different rates. Despite the changes that are likely to occur on mountain slopes, the strong environmental gradients they produce will provide a diversity of environments for species responding to climate change.

6.1.4. Sagebrush steppe

Sagebrush habitats are currently some of the most imperiled systems in North America. It is estimated that 60% of their original extent has been significantly degraded due to overgrazing, fire, and invasive species (West 2000). Much of what remains of the whole sagebrush steppe is threatened by external forces (Welch 2005). This degradation, conversion, and consequent fragmentation poses a significant threat to a number of sagebrush steppe obligate species such as Sage Sparrows, Sage Thrashers, Greater Sage Grouses, ground squirrels, and pygmy rabbits, which require intact shrublands for persistence (Knick et al. 2003).

The sagebrush steppe is predicted to undergo substantial changes in the coming century. Due to expanding woodlands driven in part by increased water-use efficiency associated with increased atmospheric CO_2 concentrations, much of the steppe is predicted to be converted into woodland (Neilson et al. 2005) (also see section 6.1.2). Juniper and piñon woodlands have been rapidly expanding since the late 1800's and have displaced shrub-steppe communities. This shift has changed ecological processes including fire dynamics, wildlife habitat availability, and erosion rates. In addition, recent years have seen the invasion of the exotic annual cheatgrass (*Bromus tectorum*) which can dominate disturbed areas following fire, out-compete native perennials, and further alter the fire regime in sagebrush-dominated ecosystems (Breshears et al. 2005).

Warmer, drier summers will make the sagebrush steppe highly vulnerable to fire and drought-induced dieback mediated by insect outbreaks (Root and Schneider 2002, Parmesan 2006). Increases in insect outbreaks have already changed the vegetation in much of the arid western U.S. (Hobbie et al. 1999). The increased frequency of fire will facilitate additional invasions by cheatgrass and other non-native annuals. These exotic species can create a positive feedback loop by providing more fuel for yet larger and more intense fires (Zedler et al. 1983, Harrod and Reichard 2001, Keeley and Fotheringham 2003, Brooks et al. 2004).

6.1.5. Coastal systems

Sea-level rise will severely impact low-lying coastal areas. Coastal marshes, estuaries, and beaches are the most at risk. Many of these systems will be inundated and with time may shift inland. Mitigating the loss of these habitats will be difficult as areas just inland of these systems are often developed.

Climate-driven changes in ocean currents may shift the timing of resource availability. For example, delayed upwelling due to anomalous weather off the Oregon coast in 2005 resulted in prey reduction and subsequent decline of resident gray whale health (Newell and Cowels 2006). Upwelling is the process in which nutrient rich waters are brought up from the deep ocean. Upwelling is driven by wind patterns, the nature and timing of which are in part dictated by climate (Logerwell et al. 2003). Projected climatic changes are likely to result in range shifts and the contraction of the ranges of marine and intertidal species. For example, over the last 30 years, flat abalone appear to have declined in California and are experiencing a range contraction at their southern range boundary (Rogers-Bennett 2007). In addition, growth rates of one of the dominant members of the rocky intertidal community along much of the Oregon coast are closely linked to temperatures and thus increases in sea temperatures have the potential to alter intertidal communities (Menge et al. 2008).

In general, there is less information about how climate change may impact near-shore marine biodiversity. There is, however, some evidence that increased estuary temperatures will have adverse effects on salmon by degrading estuarine habitat (Climate Impacts Group 2004). Additionally, temperature changes may have different effects on intertidal organisms based on small-scale regional variations in temperature and exposure tolerances, such that local resilience or extinction patterns may occur within the species' ranges, rather than only at the edges (Helmuth et al. 2006). Finally, changes in upwelling patterns have the potential to cause extreme events such as dead zones in which low oxygen levels preclude most marine life (Barth et al. 2007).

6.2 Taxonomic groups

Different species respond to climate change in different ways and hence will vary in their susceptibility to the climatic changes predicted for the coming century (Hobbie et al. 1999, van Wijk et al. 2004). As discussed above (section 3.3), some of the best-documented ecological effects of climate change are changes in species distributions (Hobbie et al. 1999) and phenologies. In addition to direct effects of climate change on phenology and behavior, potential indirect effects may occur, such as changes in habitat and other necessary resources due to altered hydrology, fire regimes, and distribution or phenology of keystone species or primary producers. Below, we discuss some of these changes as well as the relative sensitivity of species to potential climatic changes in Oregon on a taxon-by-taxon basis.

6.2.1 Non-vascular plants

Relatively little research has been done on the effects of climate change on temperate non-vascular plants, although much work has been done on arctic tundra systems at the plant, community, and ecosystem levels (van Herk et al. 2002). For example, experimental increases in temperature have led to reduced growth of non-vascular plants in the Alaskan tundra (Parmesan 2006). In a more temperate study in The Netherlands, observed climatic changes over the past 22 years have been correlated with increases in epiphytic lichen diversity resulting from new species arriving from more southerly locations (Crozier 2003, 2004).

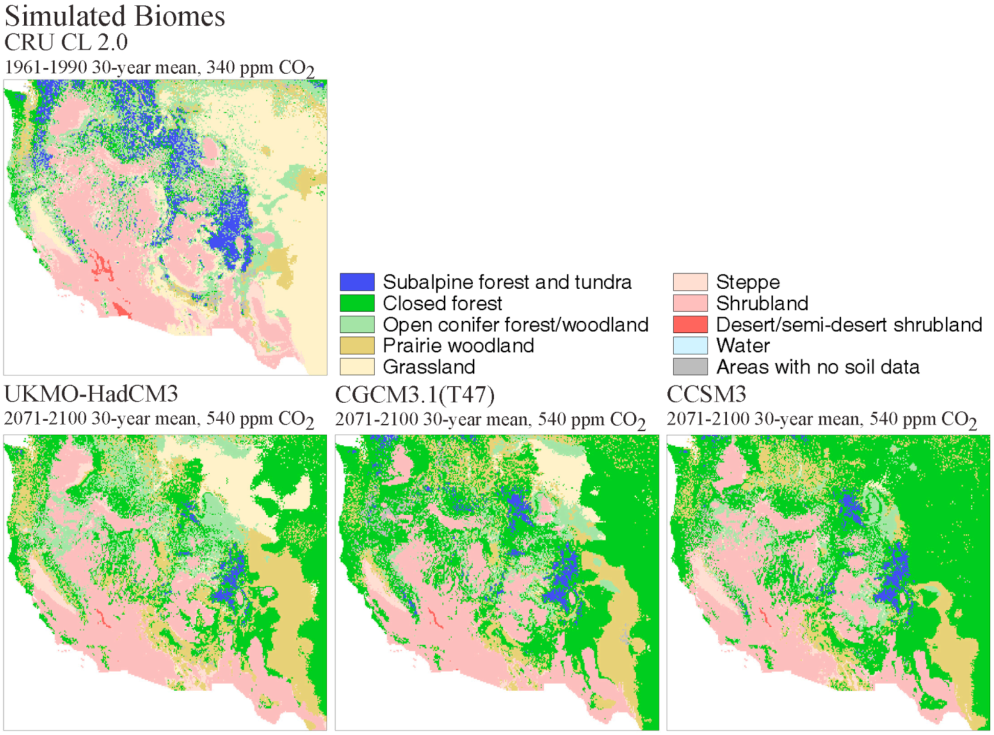
As discussed above (section 6.1.3), alpine plants and animals are particularly susceptible to climate change. Given the predicted contraction of the alpine zone across much of the Cascade Range (section 6.2.2), non-vascular plants limited to these environments are likely to be at risk of losing substantial portions of their ranges.

6.2.2. Vascular Plants

There are well-documented changes in the phenology and distributions of vascular plants in response to climate change, both in the historic record and in the past century. In general, the length of the growing season has been increasing (Myneni et al. 1997, White et al. 1999, Menzel et al. 2003). This lengthening is reflected in earlier flowering and leaf-out in individual species (Bradley et al. 1999, Cayan 2001, McCarty 2001). Phenological changes such as advances in flowering date have the potential to create mismatches between pollinators and plants, between parasites and hosts, and between herbivores and their food resources. Species that are directly linked to a specific other species may be at higher risk of these types of phenological changes than species that have more general resource requirements.

Plants are often directly limited by water availability and thus, increased summer temperatures and decreased snowpack and summer precipitation will likely lead to changes in the distributions of some species. Although some species distributions and habitats may change relatively quickly in response to climate change (Allen and Breshears 1998), others will be limited by seed dispersal rates, competition with existing species, and barriers to dispersal. Projected vegetation patterns through the year 2050 for the south Santiam watershed on the west side of the Cascade Range show continued dominance of Douglas-fir despite continued harvest and climate-change effects (Busing et al. 2007). These model simulations also predicted range expansions for western hemlock (*Tsuga heterophylla*) including upslope migration, and the contraction of ranges for silver fir (*Abies amabilis*) at lower elevation boundaries.

A number of studies of projected changes in vegetation for the Pacific Northwest have simulated 1) reduced alpine zones due to upward expansion of forests, 2) expansion of dry forests and woodlands into the sagebrush steppe and grasslands, and 3) the resulting contraction of sagebrush steppe and grasslands (e.g., Hansen et al. 2001). The results displayed in Figure 26 are equilibrium vegetation simulations for 2071-2100 created using recent GCM climate projections from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (S. L. Shafer, U.S. Geological Survey, unpbl. data). Although the simulated future vegetation patterns differ slightly across the three projections, the general trends are the same. As discussed in section 6.1.4, the potential expansion of woodlands and dry conifer forests into the sagebrush steppe and grasslands will depend in part on the effect that increased atmospheric CO_2 has on plant water-use efficiencies and the role that changing fire regimes play in structuring vegetation communities on the east side of the Cascades. The model results in Figure 26 display the potential influence of changing climate and atmospheric CO_2 concentrations on vegetation, but do not include the potential impacts of changing fire regimes and other important ecological processes, such as plant migration rates.



Vegetation model: Modified version of BIOME4 (Kaplan et al. 2003); Modern climate data: CRU CL 2.0 (New et al. 2002); Future climate data: UKMO-HadCM3 (Gordon et al. 2000; Johns et al. 1997), CGCM3.1(T47) (McFarlane et al. 1992, Flato et al. 2005), CCSM3 (Collins et al. 2006a, Collins et al. 2006b); Soil data: CONUS-Soil (Miller and White 1998); Mapping and climate interpolation programs: P. J. Bartlein (Univ. of Oregon, pers. comm.). (S. L. Shafer, USGS, unpublished data)

Biomes simulated using a modified version of BIOME4, an equilibrium vegetation model, run under modern (top row) and simulated future (bottom row) climates for the western United States. The climate data for 2071-2100 were produced by three coupled ocean-atmosphere general circulation models (OAGCMs), UKMO-HadCM3, CGCM3.1(T47), and CCSM3, for the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset.

Figure 26. Simulated current and future potential vegetation in the western U.S. based on historic climate data and three future climate projections (S. L. Shafer, U.S. Geological Survey, unpbl. data).

6.2.3. Insects

Many insects have been documented to be undergoing changes in phenology and moving northward and poleward in response to increasing temperatures from climate change (Logan and Powell 2001b). For example, the dates that butterflies first appear in the spring is often strongly correlated with spring temperatures. Those spring dates have been advancing in the United Kingdom (Roy and Sparks 2000), Spain (Stefanescu et al. 2003), and central California (Forister and Shapiro 2003).

More complex climate-change impacts on insects are likely to result from mismatches in the timing of biological events. The mismatch in the timing of butterfly hatching and host-plant flowering in extreme drought and low snowpack years has resulted directly in population crashes and extinctions (Singer and Thomas 1996, Thomas et al. 1996). Consequently, remaining populations have moved to higher elevations and more northern locations (Parmesan 1996, Parmesan 2003, 2005). The synchrony of butterfly hatching and parasitoid activity may be significantly influenced by early spring temperatures (Van Nouhuys and Lei 2004). Changes in the dynamics between hosts and parasites can lead to reductions in the host population and potentially skew the sex ratio of butterflies and other species in which sex is determined in part by the time of hatching.

Butterflies and moths (Lepidoptera) have been shown to have expanded their northern range boundaries in Finland (Mikkola 1997), Great Britain (Pollard 1979, Warren 1992, Pollard and Eversham 1995, Hill et al. 2002), and across Europe (Parmesan et al. 1999). Many insects that spend the winter in a dormant state are limited by winter temperatures or by the length of the non-winter season. However, changes in the distribution of insects that are active year-round have also been noted. For example, in a 30-year period, the sachem skipper butterfly has expanded the northern edge of it's range from California to Washington State, a distance of 420 miles (Logan and Powell 2001b). Of the resident Dragonflies and Damselflies (Odonata) in the United Kingdom, 23 of the 24 temperate species were documented to have had expanded their northern range limit between 1960–1995, with mean northward shift of 88 km (Hickling et al. 2005). Insects are also experiencing contractions at the southern edges of their northern hemisphere ranges. For example, Edith's checkerspot butterfly (*Euphydryas editha*) has experienced multiple population extinctions at the southern extent of its range in the last century resulting in a shift in average location of populations 92 km to the north (Parmesan 1996, Parmesan 2003, 2005).

Some of the largest climate-driven impacts to both ecological and agricultural systems may be mediated by changes in insect populations. Changes in winter temperatures have led to an expansion of the range of the mountain pine beetle (*Dendroctonus ponderosae*) in the western U.S. (Logan et al. 2003). Previously unexposed whitebark pine stands at high elevations are now being attacked resulting in reductions in the availability of pinenuts, a key winter food source for grizzly bears (Hannah et al. 2007). Other forest pests and pathogens have also been found to be expanding their ranges in response to climate change (Gunderson 2000, Folke et al. 2004).

6.2.4 Birds

As for most other taxonomic groups, the best-documented effects of climate change on birds are changes in phenology and changes in species distributions. For example, across North America, Tree Swallows (*Tachycineta bicolor*) have shifted the dates on which they begin breeding earlier by 5-9 days from 1959 to 1991. Over the same time period, there is a clear relationship between average May temperatures and the date of egg-laying (Dunn and Winkler 1999). A study in the U.K. found over a period from 1971 to 1995 that 20 species (31%) of 65 bird species had earlier laying dates by an average of 9 days with only one species laying significantly later (Crick et al. 1997). Again, in this case, there was a strong link between climate and the date of breeding activity "laying date is related to temperature or rainfall for 31 of 36 species (86%), and that 53% of species show long-term trends in laying date over time, of which 37% can be statistically accounted for by changes in climate" (Crick and Sparks 1999a). Several other studies have demonstrated clear links between recent changes in climate and the timing of bird behavior (McCarthy et al. 2001, Walther et al. 2002, Parmesan and Yohe 2003, Parmesan 2006).

Birds have also been shifting their ranges both poleward in latitude and upward in elevation in response to recent warming trends (Root 1992, Root 1993, Thomas and Lennon 1999). In general, over the last century and across all species (not just birds), range shifts, when they have occurred, have been on the order of 6 km per decade (Parmesan and Yohe 2003). Given that in the coming century projected changes in temperature are likely to be 2-10 times the magnitude of the changes observed in the last century, it is likely that there will a greater movement of species and reordering of ecological communities (Figs. 27 and 28). Birds, more so than many other organisms, will likely be able to move as climate changes their habitats. Other, less mobile species, will be less likely to be able to track climate-induced changes and hence for those species we are more likely to see range contractions than expansions.

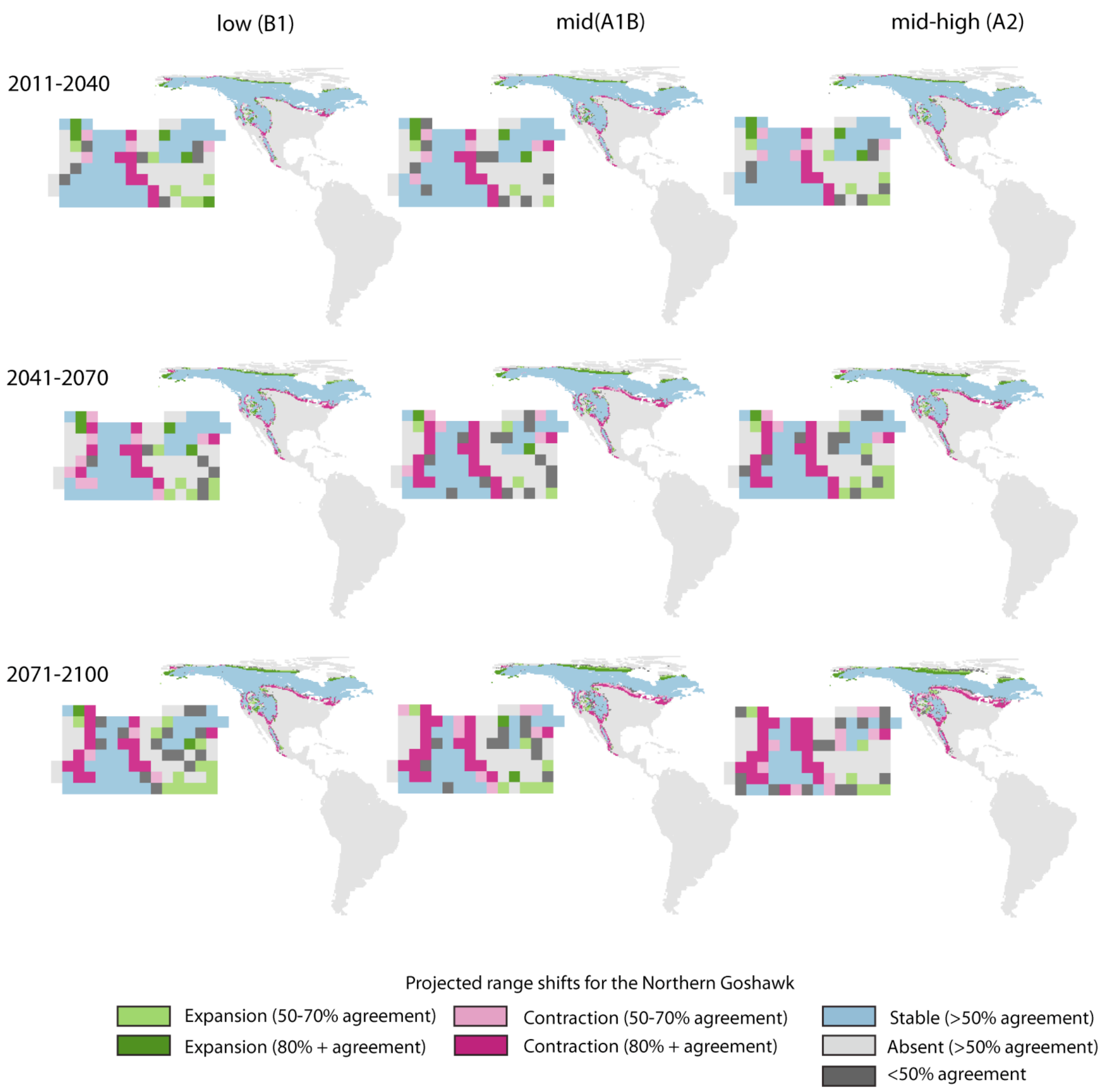


Figure 27. Predicted changes in the range of the Northern Goshawk across the western hemisphere and Oregon state for the period of 2071-2100. The maps depict consensus across projections from 10 different GCMs for each of three different greenhouse-gas emissions scenarios.

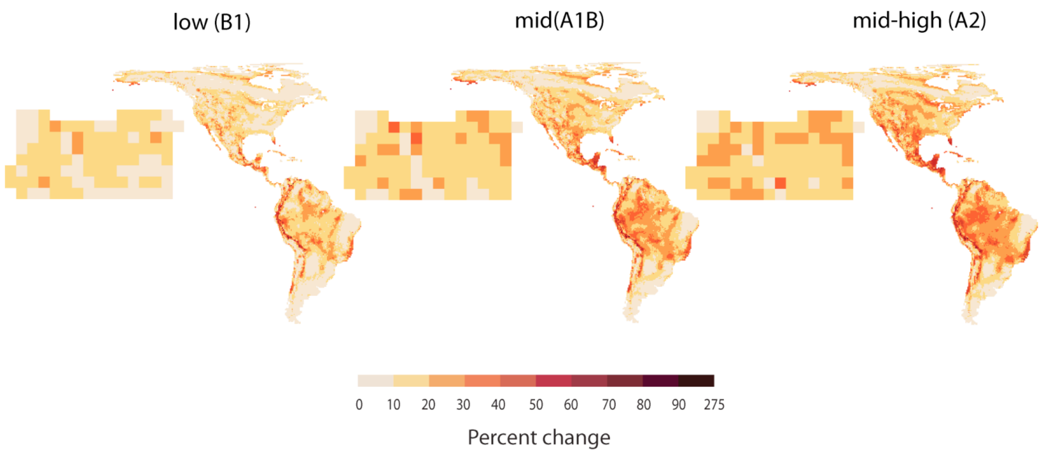


Figure 28. Predicted bird species losses across the western hemisphere and Oregon state for the period of 2071-2100. The maps depict consensus across projections from 10 different GCMs for each of three different greenhouse-gas emissions scenarios. Seventy percent of the climate-change projections (7 of the 10) for each greenhouse-gas emissions scenarios result in species losses greater than those depicted in the maps. Loss was calculated on a grid-cell by grid-cell basis as the number of species whose ranges were predicted to contract from a cell, expressed as a percentage of the current species in that cell. The maps are based on projected range shifts for 1818 bird species. (Lawler et al. *In review*)

6.2.5 Mammals

There is less evidence of the effects of climate change on mammals than for some of the other taxonomic groups. Nonetheless, there are known relationships between fecundity and juvenile survival and winter temperatures (Milner et al. 1999, Post and Stenseth 1999, Forchhammer et al. 2001). As discussed in section 6.1.3, the American pika is one mammal that has likely been adversely affected by recent warming trends (Beever et al. 2003b). As for other taxonomic groups, shifts in climate will likely result in shifts in the distributions of mammals both upward in elevation and poleward in latitude as well in conjunction with finer-scale changes in habitat.

6.2.6 Amphibians

Amphibians have been seen as potential sentinels for changes in the environment. The past century has seen relatively rapid global declines in amphibian populations world wide (Blaustein and Wake 1990, Stuart et al. 2004). Amphibians are likely to be some of the most susceptible animals to climate change due in part to their dependence on hydrological regimes and specific mirohabitats (protective cover and specific temperatures and moisture levels) and their limited dispersal abilities (Blaustein et al. 1994, Blaustein et al. 2001). Amphibian extinctions in the tropics have been clearly linked both directly and indirectly to climate change (Pounds and Crump 1994, Pounds et al. 1999, Pounds et al. 2006).

Again, as with other taxonomic groups, amphibians have exhibited changes in the timing of their behavior that coincides with recent changes in climate. Amphibians have been documented to have advanced calling (Gibbs and Breisch 2001a) and breeding phenology (Beebee 1995) in the spring. Gibbs and Breisch (2001a) showed a 10–13-day advance in calling associated with a 1.0–2.3 ˚C rise in temperature during breeding months for six frog species in New York. Beebee (1995) documented advanced amphibian breeding phenology of 2-7 weeks earlier over 17 years in England. For some species, however, recent changes in climate do not appear to have affected the timing of breeding (Blaustein et al. 2001).

Climate may indirectly affect amphibian populations through modification of habitat as a result of changes in hydrology or changes in fire regimes and through changes in the prevalence or severity of disease. Amphibians are dependant on water bodies, many of which will experience changes in water levels, water quality, and water temperature as a result of climate change (section 6.1.1). As temperatures increase, more frequent or widespread fires could significantly eliminate amphibian habitat through large-scale declines in large woody debris, particularly in advanced decay classes (Gustafson et al. 2001). In addition, recent studies have linked climate-driven changes in the distribution of pathogens and diseases with amphibian extinctions (Pounds et al. 2006).

6.2.7 Reptiles

Like amphibians, reptiles may be more sensitive to climate change due to specific physiological temperature constraints and limited dispersal abilities. For example, there are direct links between climate and reproduction and development in many reptiles. In temperate reptiles egg and sperm development in part depend on seasonal temperatures. Some species, such as the painted turtle (*Chrysemys picta*) have temperature dependant sex ratios, meaning that sex of offspring is determined by the temperature that eggs experience. In the case of the painted turtle, even a modest (2˚C) temperature increase would alter the sex ratio of the species and an increase of 4 ˚C would effectively eliminate the production of male offspring (Janzen 1994).

6.2.8 Fish

Increases in temperature and changes in hydrology are expected to change fish habitat (Preston 2006) and will likely induce shifts in fish and other aquatic species distributions in marine (Perry et al. 2005) and freshwater systems (Carpenter et al. 1992, Eaton and Scheller 1996). For example, on the east coast, the timing of peak migration for adult Atlantic salmon (*Salmo salar*) is occurring earlier in response to climate change (Juanes et al. 2004) . Due to their cultural value and endangered status, salmon are the most extensively studied fish in the Pacific Northwest. Here, we focus primarily on salmon; however, many of the climate impacts to salmon will also likely affect other fish in Oregon's freshwater and marine ecosystems.

Salmon are sensitive to temperature at a number of different life stages (Mote et al. 2003). In general, the distribution of salmon is in part dictated by temperature tolerances. Most adult salmon cannot survive for long periods in water that is over 21 ˚C (McCullough 1999). However, tolerances are different for different species at different life stages. For example, the upper lethal temperature limit for Chinook Salmon is estimated to be 18.9 ˚C for the egg and alevin stages, 25.1 ˚C for the juvenile stage, and 22 ˚C for the adult stage (Table 1). Growth, however, can be limited at lower temperatures. For Chinook, the upper temperature limit for growth is estimated at 12.8 ˚C for the egg and alevin stages and 15.6 ˚C for the juvenile stage. The upper limit of the preferred temperature range of this species is even lower still. In general the egg and alevin stages are most often found in temperatures between 6.0 ˚C and 10.0 ˚C, the juvenile stage is most often found between 12.0 ˚C and 13.3 ˚C, and the adult stage is generally found in waters between 7.2 ˚C and 14.5 ˚C.

Table 1. Stream temperature ranges and tolerances (°C) for Chinook salmon. Lethal limits represent the temperatures at which a 10-minute exposure resulted in 50% mortality given a prior acclimation to temperatures within the tolerance zone. The tolerance zone is the range of temperatures that the species can tolerate without physiological damage. The growth zone is the range of temperatures for which growth is positive. The preferred temperatures are those that the fish most frequently inhabits when allowed to freely select temperatures along a thermal gradient. Migration, holding and spawning temperatures are the temperature ranges within which these activities typically occur in natural populations. Data sources include Brett (1952), Amour (1991), Eaton and Scheller (1996), Smale and Rabeni (1995), McCullough (1999, and references therein), and Moyle (2002).

Parameter	**Chinook salmon**		
	Egg/Alevin	**Juvenile**	**Adult**
Lower lethal limit	1.7	0.8	0.8
Lower tolerance limit	4.0	4.5	3.3
Lower growth limit	4.5	10.0	-
Preferred temperature	6.0-10.0	12.0-13.3	7.2-14.5
Upper growth limit	12.8	15.6	-
Upper tolerance limit	14.4	19.1	21.0
Upper lethal limit	18.9	25.1	22.0
Migration	-	-	3.3-13.3[a]
Holding	-	-	6.0-14.0[b]
Spawning	-	-	5.6-12.8[c]

Notes: "-" values are not applicable; [a] >21.0°C (19.0-23.9°C) represents a thermal barrier to migration; [b] >15.0°C cause thermal stress in holding salmon; [c] >12.8°C inhibits spawning,

Salmon are also sensitive to other indirect effects of climate change. Salmon eggs are sensitive to the timing and magnitude of stream flow. Heavy winter and spring floods and flows may scour streams and dislodge eggs washing them downstream. The timing of spring stream flows also affects both the timing and the ability of juvenile salmon to migrate from their natal streams to the ocean (Mote et al. 2003). The survival of the juveniles once they reach the ocean is highly dependent on the timing of spring upwelling, however fall upwelling, the PDO, and ocean conditions during early marine life are important as well (Logerwell et al. 2003). Although, as mentioned above, upwelling patterns are influenced by climate, the seasonality and timing of upwelling may not change much with future climatic changes (Mote and Mantua 2002).

Salmon in the Pacific Northwest face many threats making it difficult to weigh the relative threat of climate change. However, there is recent evidence that climate change may play a key role in limiting populations by altering mid- to high-elevation habitat through changes in stream flow (Battin et al. 2007). The most sensitive habitats appear to be those at mid to high elevations where changes in the percentage of precipitation falling as rain and resulting reductions in snow pack will be the greatest. Habitat, stream temperatures, and the presence or abundance of invasive competitors are all likely to change with climate producing negative effects on salmon and many other native fish.

Many other cold-water and cool-water fish in Oregon will likely be vulnerable to changes in climate. For example adult bull trout have been shown to have upper incipient lethal temperatures of 23.5 ˚C and 20.9 ˚C for periods of 7 days and 60 days, respectively (Selong et al. 2001). As for salmon, temperatures that limit growth and reproduction are likely to be lower. For Lahontan cutthroat trout, the upper temperature limit for growth and long-term survival has been estimate to be between 22 ˚C and 23 ˚C. Again, although we have discussed thermal tolerances here, changes in flow regimes and other aspects of water quality will also be influenced by climatic changes, potentially having even larger effects than changes in stream temperature.

7. Conserving Biodiversity in a Changing Climate

Conservation generally takes a static approach to biodiversity. That is, areas are selected and managed to protect the biodiversity of today or to restore the landscape to a historic, baseline condition. Such an approach will no longer work in a rapidly and dramatically changing environment. Recent studies have demonstrated that areas selected to protect biodiversity today will not likely protect biodiversity in a future that is altered by climate change (Bengtsson et al. 2003). For example, as plants and animals change their range in response to climate change, they will move in and out of protected areas. Additionally, shifts in fire and hydrological regimes will make restoration to historic conditions difficult in some areas and futile in others. Successful conservation planning for biodiversity will require directly taking the potential impacts of climate change into account when selecting areas for protection as well as when determining how those areas will be managed.

A network of lands that adequately protects biodiversity in a changing climate will have to be highly resilient to the effects of climate change. Resilience refers to the ability of a system to return to its original state after experiencing a disturbance or a change. Some simple examples include forest regeneration after a severe fire, the recovery of local fish populations after major flooding and scouring of a stream reach, and the rebound of a bird population following a hurricane that destroyed all the spring nests. In recent years, much thinking and research has gone into defining resilience (Pearsons et al. 1992), but unfortunately we still know little about what exactly produces resilience in a particular system. Nonetheless, there are some basic attributes of systems that lend them to being more resilient to climate change than others.

The resilience of specific sites will depend on how far they are from a climate related threshold. These thresholds are determined by where the site is located and the functioning of the ecosystems at the site. For example, a site that straddles the boundaries of two adjoining biomes or ecoregions will be more likely to experience a dramatic shift in vegetation and hence habitat in response to climate change than will a site that is far from an ecoregional boundary. Likewise, sites that harbor species at the very edge of their range have a greater potential to lose or gain new species in response to changing climates and shifting species distributions. Consider two land parcels in central Oregon. One straddles the boundary of piñon-juniper woodland and sagebrush steppe in the foothills of the Cascades and the other is about 100 km farther east in a remnant patch of sagebrush. Given the potential expansion of piñon-juniper woodlands and dry eastside forests, all else being equal, the first site which lies at a bioclimatic threshold for woodlands and sagebrush steppe is more likely to undergo larger changes in vegetation and habitat.

The condition and functioning of ecosystems also help to determine resilience (Bengtsson et al. 2003, Folke et al. 2004). For example, streams with more complex habitats are likely to have fish populations that are more resilient to changes in stream flow (Bengtsson et al. 2003). Forest stands that are close to other stands with similar tree species will be more likely to quickly regenerate after a fire than highly isolated stands. And in general, more intact systems with the full complement of their native plants and animals are likely to be more resilient and able to adapt to changes than are less intact systems (Rodrigues et al. 2000).

Planning for biodiversity cannot be done without considering the potential effects of climate change. Areas set aside to protect biodiversity based solely on the current distributions of species may fail to protect those species in the future (Hannah et al. 2007). Although some work has been done to determine how to manage lands in a changing climate (e.g., Noss 2001), there are few agreed-upon prescriptions for designing networks of protected lands in a changing climate. Below, we provide one potential set of steps that could be integrated into the conservation planning process to help select a network of areas that will be more resilient to climate change.

1. *Conduct a vulnerability assessment to determine which species and systems will likely be most susceptible to projected climatic changes.* Are these adequately represented in the current set of protected lands? These are species and systems that might need additional protection. Which sites are predicted to experience the largest climate-driven changes? Are there additional, less vulnerable sites where the most sensitive species and systems could be protected? Are there sites that could be added to the network that would span transition zones or provide connectivity across areas where the largest changes are predicted to occur?

2. *Conduct a connectivity assessment for all protected lands in the state.* Determine which state lands are best connected to other protected lands and which are most isolated. Future acquisitions could be used to increase connectivity for isolated sites or to bridge particular gaps in connectivity.

3. *Assess the current level of protection for the "ecological stage."* How well are the different combinations of geological features, elevations, slopes, aspects, and soil types represented in the current set of protected lands?

4. *Share results regionally.* Because species will move in response to climate change, it will be important to coordinate conservation-planning efforts regionally. Are there sensitive species in surrounding states that are less vulnerable to climate change in Oregon and hence might be afforded additional

protection in Oregon? Are there species that are projected to move out of the state and would require coordinated planning and management efforts to make sure they can move successfully and have habitat available in different states?

5. *Set priorities locally and regionally.* Using the information gathered in steps 1-4, prioritize sites for acquisition, easements, or sale. Integrating this new information into the planning process will not necessarily be easy, and will require weighing new priorities in addition to those currently used to prioritize sites. In some cases, priority setting may have to include triage. There may be some species for which it is not feasible to provide protection in a changing climate. Making triage-type decisions will likely be the hardest. Priority setting, including triage should take place both within the state and in conjunction with management agencies in surrounding states and provinces.

6. *Select monitoring targets and initiate monitoring.* In addition to selecting particularly sensitive systems or species to monitor, it may also be necessary to gather baseline data for sites or taxonomic groups for which we have little information about their distribution or status. It will be impossible to track changes without a good set of baseline data.

7. *Repeat.* As climate changes and new data become available (both from the scientific community in general and from targeted monitoring in Oregon), it will be necessary to update vulnerability assessments and set new priorities.

8. Links to Climate-Change Information

Intergovernmental Panel On Climate Change
http://www.ipcc.ch/
Climate change reports, graphics, summaries

Climate Impacts Group, University of Washington
http://www.cses.washington.edu/cig/
Climate-change research and projections for the Pacific Northwest

Pew Center on Global Climate Change
http://www.pewclimate.org/what_s_being_done/
Background on climate change, policy implications

U.S. Global Change Research Information Office
http://www.gcrio.org/
Reports and information about climate change

Real Climate
http://www.realclimate.org/
This site contains in-depth discussions with scientists about many different aspects of climate change. It is a good source for definitions of scientific terms and for learning the facts behind highly contested or debated issues.

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