Climate Change Impacts on Western Pacific Northwest Prairies and Savannas

Author(s) :Dominique Bachelet, Bart R. Johnson, Scott D. Bridgham, Pat V. Dunn, Hannah E. Anderson and Brendan M. Rogers

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Dominique Bachelet[1], Conservation Biology Institute, Olympia, Washington 98501,

Bart R. Johnson, Scott D. Bridgham, University of Oregon, Eugene, Oregon 97403,

Pat V. Dunn, Hannah E. Anderson, The Nature Conservancy, Olympia, Washington 98501,

and

Brendan M. Rogers, University of California Irvine, Irvine, California 92697

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Abstract

This paper represents a collaboration by conservation practitioners, ecologists, and climate change scientists to provide specific guidance on local and regional adaptation strategies to climate change for conservation planning and restoration activities. Our geographic focus is the Willamette Valley-Puget Trough-Georgia Basin (WPG) ecoregion, comprised of valley lowlands formerly dominated by now-threatened prairies and oak savannas. We review climate model strengths and limitations, and summarize climate change projections and potential impacts on WPG prairies and oak savannas. We identify a set of six climate-smart strategies that do not require abandoning past management approaches but rather reorienting them towards a dynamic and uncertain future. These strategies focus on linking local and regional landscape characteristics to the emerging needs of species, including potentially novel species assemblages, so that prairies and savannas are maintained in locations and conditions that remain well-suited to their persistence. At the regional scale, planning should use the full range of biological and environmental variability. At the local scale, habitat heterogeneity can be used to support species persistence by identifying key refugia. Climate change may marginalize sites currently used for agriculture and forestry, which may become good candidates for restoration. Native grasslands may increasingly provide ecosystem services that may support broader societal needs exacerbated by climate change. Judicious monitoring can help identify biological thresholds and restoration opportunities. To prepare for both future challenges and opportunities brought about by climate change, land managers must incorporate climate change projections and uncertainties into their long-term planning.

Introduction

Prairies and oak savannas have historically been the dominant vegetation of the interior valleys along the Pacific coast from central California to southern British Columbia. The geographic focus of this paper is the Willamette Valley-Puget Trough-Georgia Basin (WPG) ecoregion (Floberg et al. 2004) that comprises valley lowlands formerly dominated by now-threatened prairies and oak savannas, flanked by the Cascades on the east and the coastal mountains on the west. A combination of wildfires during periods of drought and Native American burning maintained these extensive grasslands over millennia by preventing succession to woodland and forest (Boyd 1999, Walsh 2008). At the time of Euro-American settlement (circa 1840), prairies and savannas accounted for 49% of Oregon's Willamette Valley ecoregion. Today, however, they account for less than 2% and are all in degraded conditions (Hulse et al. 2002). Since the 1850s, alteration of historical fire regimes (cessation of Native American burning followed by active fire suppression), land use change (expansion of agriculture, livestock grazing, and urbanization), and invasion by exotic species have all contributed to the degradation of this ecosystem, which is now ranked among the most endangered in the United States (Noss et al. 1995). Climate change may add to or exacerbate existing threats to native grasslands. Alternatively, new climate conditions and increased wildfire may render portions of the landscape less suitable for forests or agriculture and thus create new opportunities for prairie restoration. To prepare for both future challenges and opportunities brought about by climate change, land managers must gain a solid foundation for incorporating climate change projections and uncertainties into their long-term planning.

Large changes in climate have already been observed in the Pacific Northwest region (PNW) over the past

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[1] Author to whom correspondence should be addressed. Email: bachelet@fsl.orst.edu

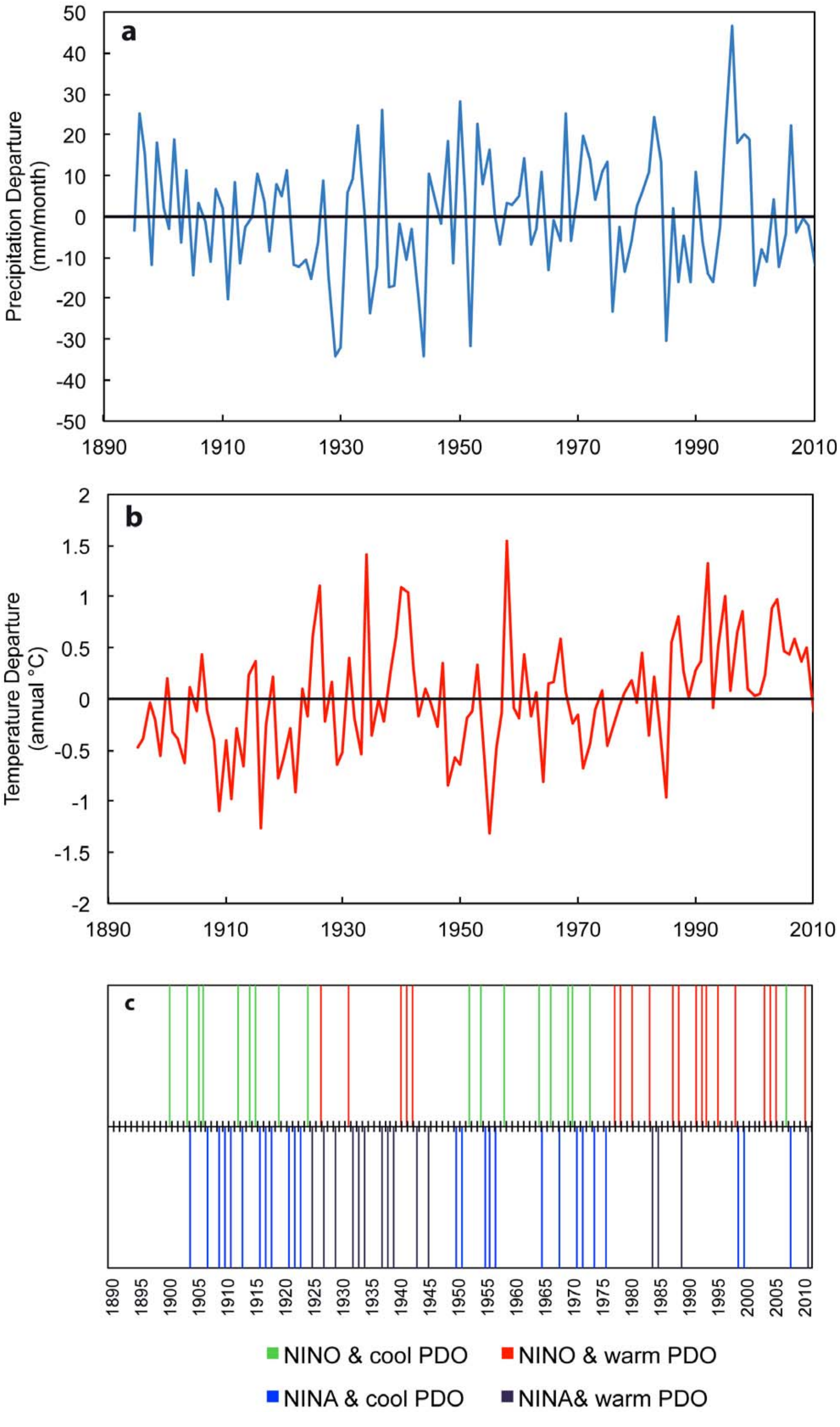

Figure 1. Changes in a) average monthly precipitation (mm) and b) mean monthly temperature (°C), derived from PRISM data at 30-arc second spatial grain (Daly et al. 2008) for the WPG ecoregion; c) occurrence of large El Niño Southern Oscillation events (El Niño and La Niña), as well as timing of the Pacific Decadal Oscillation warm and cool phases during the same period.

century. Annual average temperatures have increased by 0.5 - 1.5 °C and annual precipitation has increased by 10% (National Assessment Synthesis Team 2001, Millar et al. 2006, Climate Impacts Group 2009, Rogers 2009, Mote and Salathé 2010) (Figure 1). Most climate models project these trends will accelerate and that the PNW will become progressively warmer and wetter, although summer drought may worsen. Fortunately, WPG prairies and oak savannas span a wide geographic and climatic range. A rich variety of soil types, vegetation cover, and weather patterns confer valuable heterogeneity to the ecoregion suggesting that impacts of change, and the timing of these impacts, will vary not just along geographic or elevation gradients, but also within sections of the ecoregion, presenting conservation practitioners with a wide palette of habitats to use when developing adaptation strategies.

Explicit conservation goals or visions are needed to assess conservation strategies and measure their eventual success (or failure) in the face of climate change (Thorpe and Stanley 2011). Numerous principles have been put forth for successful conservation but many, including some of the most widely cited (National Park Commission, http://www.npca.org/commission/), are based on static visions of returning to historical conditions. Climate change projections, on the other hand, emphasize a high likelihood of vegetation shifts and altered community composition, possibly including novel species assemblages without any historical or contemporary precedent. While understanding the ecological history of a place can help shape a vision for conservation success, one of the greatest contributions climate change discussions have brought to the conservation community is an appreciation of the dynamic nature of natural systems. Any static vision will likely fail in the face of climate change.

This paper represents a unique collaborative effort between conservation practitioners, academic researchers, and climate change scientists, working together to help protect and sustain functional prairies and oak savannas in the WPG. Because interpreting climate change science into specific guidance for land managers is a challenge, we have tried to summarize the state of knowledge in each of our disciplines that helped us formulate specific strategies. We begin with some background information about climate models and briefly introduce a range of possible climate futures for the Pacific Northwest. We then review experimental and simulation results of climate change impacts relevant to grassland species, and conclude with specific recommendations based on this knowledge to increase prairie resilience to change.

Climate Change Science Review for Western PNW

When considering the potential impacts of climate change, conservation practitioners usually look for reliable future climate projections and likely emission scenarios. The various Intergovernmental Panel on Climate Change (IPCC) reports (http://www.ipcc.ch/) have been the repository of the state-of-the-art information on climate modeling and climate impacts projections. In these reports, including the upcoming 2013 version, an international group of scientists compile published results and summarize current knowledge on climate change issues ranging from atmosphere and ocean dynamics to plant and animal responses. However, these reports are long, technical, and global to continental in scope. Consequently they include information not directly relevant to land managers and are rarely the primary source of climate change information for managers. We have tried to address this problem by summarizing the most important information about the IPCC climate models and their limitations. We follow with a brief review of climate and impacts projections specific to the Pacific Northwest region.

Background Information on Climate Models and Projections

Atmosphere-Ocean General Circulation Models (AOGCMs or GCMs for short) are currently the best sources of climate projections because they synthesize current knowledge about interactions between atmosphere, ocean, and land processes. Their complexity is constantly growing as new information is discovered (Lawrence et al. 2011). Fossil fuel emission scenarios derived from potential demographics and assumed societal choices are the major source of uncertainty associated with GCM projections because of our inability to forecast future human behavior (Appendix - Table 1). Other major sources of uncertainty include the imperfect knowledge of initial conditions such as sea surface temperatures that are difficult to measure, and of general system behavior such as cloud formation or ice sheet melt rate, that continues to be the subject of basic climate research and monitoring as it constitutes the “known unknowns” of the climate system. While surprises have been projected for the biological world as the climate changes, events such as the unexpected Larsen B ice shelf rapid collapse, the “unknown unknowns”, also bring climate scientists back to the drawing board to improve existing models.

Although GCMs are becoming better at simulating present-day climate (Reichler and Kim 2008), their wide range of future projections introduces a large degree of uncertainty to ecosystem impact assessments. Consequently, ensembles of GCMs and emission scenarios are used to bracket possible changes. When managers use these, they need to remember that ensembles of projections provide an estimate of the range of potential future conditions simulated by about 20 research groups around the world but in truth, future climate is not necessarily bounded by those projections. As change occurs today and continues to do so (e.g., ice-free poles, glacier retreat and disappearance, new wind patterns, changes in ocean temperature and current direction, increasing atmospheric carbon dioxide concentration), some of the basic assumptions at the core of the climate models may become obsolete and the future may lie entirely outside of the envelope climate modelers have so far provided (Raisanen 2006).

GCM projections cannot be used directly for regional or local impact assessment because they were designed to simulate the entire planet's climate and their accuracy declines at the local scale due to their inherent coarse spatial resolution. GCM grids are on the order of 2° latitude x 2° longitude (~200 km on the side, Appendix - Table 2). Researchers must therefore downscale (statistically or dynamically) the original global climate model results to their grid size of interest. Dynamic downscaling involves using a regional climate model (RCM) embedded within a GCM. RCMs incorporate local topography and land-atmosphere feedbacks, and are the most mechanistic way to simulate regional to local climate variables. However, GCMs provide RCM boundary conditions so any bias in GCM results will automatically carry to the embedded RCM. Currently, research teams are working on allowing feedbacks from local climate processes (simulated by the RCM) to the GCM, a process that is still lacking (Rummukainen 2010). Despite their superior skill at simulating local weather, RCMs have large computing and data storage requirements, so often only short time periods rather than full time series of results are saved, resulting in limited temporal extent of the available data (e.g., North American Regional Climate Change Assessment Program, http://www.narccap.ucar.edu/). RCMs tend to also remain too spatially coarse for management needs (Fowler et al. 2007). Alternatively, statistical techniques of varying complexity can be used to link large-scale GCM fields with local climate variables, and these methods often compare well with regional climate models, depending on the region and scale (Wilby and Wigley 2000, Diez et al. 2005).

PNW Climate Change Projections

Two local climate change research groups, the Climate Impacts Group (CIG) (http://cses.washington.edu/cig/pnwc/cc.shtml) in Seattle, Washington, and the MAPSS team (http://www.fs.fed.us/pnw/mdr/mapss/index.shtml) in Corvallis, Oregon, have provided much of the information that is summarized below and more details can be found on their respective web sites.

Future Temperatures

All of the 23 GCMs used in the 2007 IPCC report project a general warming in the PNW with annual average temperature increases of 3 to 6 °C by the end of the 21st century (National Assessment Synthesis Team 2001, Millar et al. 2006, Mote and Salathé 2010). The frost-free period is expected to increase by at least a month and periods of extremely warm summer days to become more common (Spittlehouse 2008). Future climate projections from three general circulation models (GCMs) chosen for their representative range of temperature changes (Rogers 2009) and forced by the IPCC SRES A2 emissions scenario (Nakicenovic and Swart 2000) are illustrated on Figure 2: CSIRO Mk3 (Gordon 2002), hot and wet MIROC 3.2 medres (Hasumi and Emori 2004), and hot and dry Hadley CM3 (Johns et al. 2003).

Future Precipitation

Precipitation projections vary, but most GCMs show an overall annual increase from a few percent up to 50% by the end of the 21st century (National Assessment Synthesis Team 2001, Mote 2003, Millar et al. 2006, CIG 2009, Mote and Salathe 2010). However, projected higher temperatures will likely increase evapotranspiration during the growing season such that even with an increase in the overall precipitation, a decrease of summer soil moisture of up to 25% is predicted over much of the PNW (National Assessment Synthesis Team 2001, CIG 2009, Elsner et al. 2010). Precipitation projections for the three GCMs discussed above are illustrated on Figure 3. Models consistently show that most of this precipitation increase will occur in the already wet winter months, with little change or even a decrease in precipitation in the dry summer months. Observed trends in snowpack have confirmed early projections of decreasing snowfall at mid and lower elevations affecting the seasonality of stream flow. Most rivers are expected to experience higher winter discharge when a greater proportion of the precipitation falls as rain rather than snow, a decline and eventual disappearance of the springtime snowmelt peak, and lower summer baseflows (Elsner et al. 2010, Vano et al. 2010).

Natural Climate Variability

The Pacific Northwest (PNW) is very responsive to global circulation anomalies linked to vari-

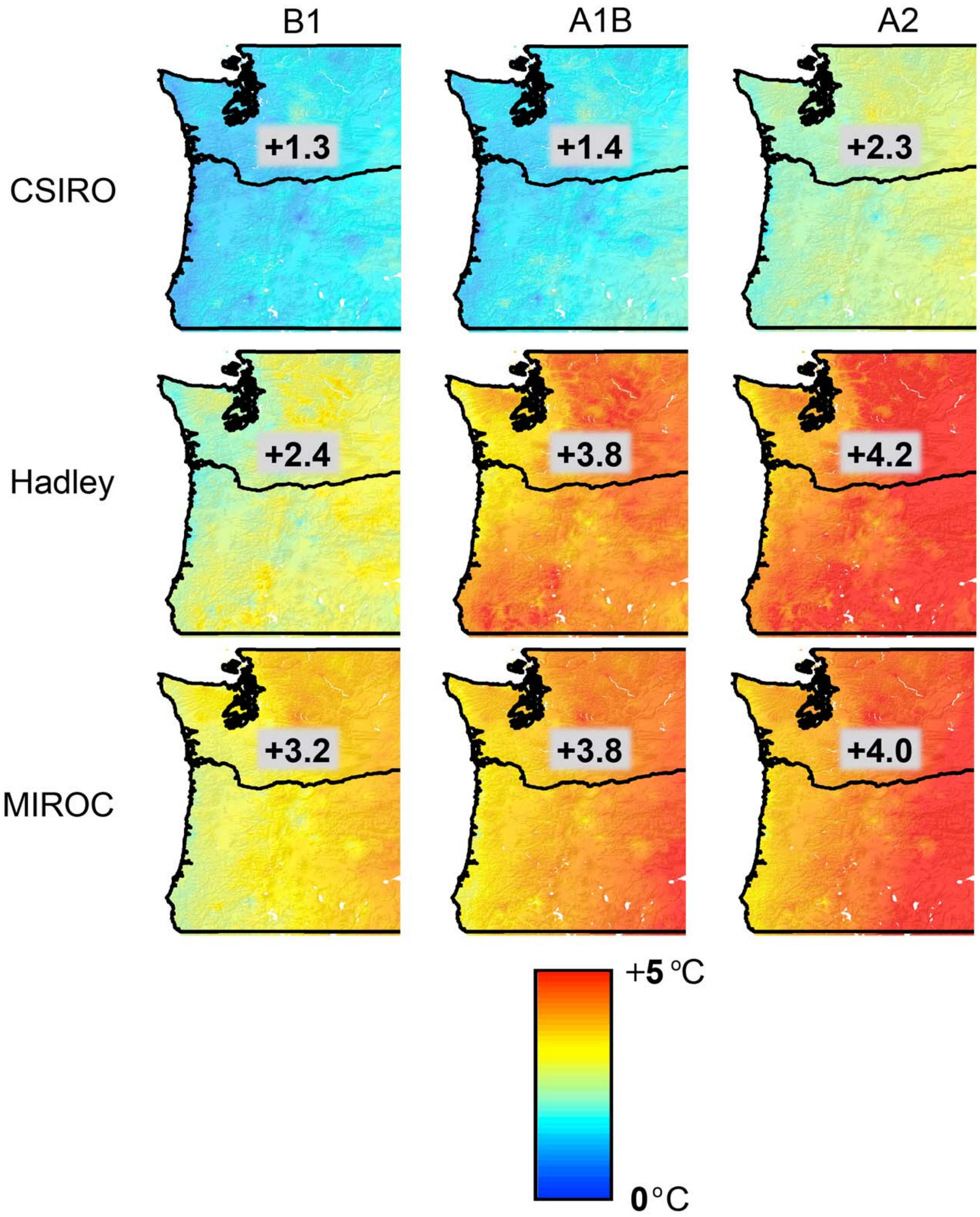

Figure 2. Projected differences in maximum monthly temperature (°C) calculated as the average difference between 2070-2099 and 1970-2000 means under 3 anthropogenic emission scenarios (SRES B1, A1B and A2) and 3 general circulation model projections (CSIRO Mk3, MIROC 3.2 medres, Hadley CM 3).

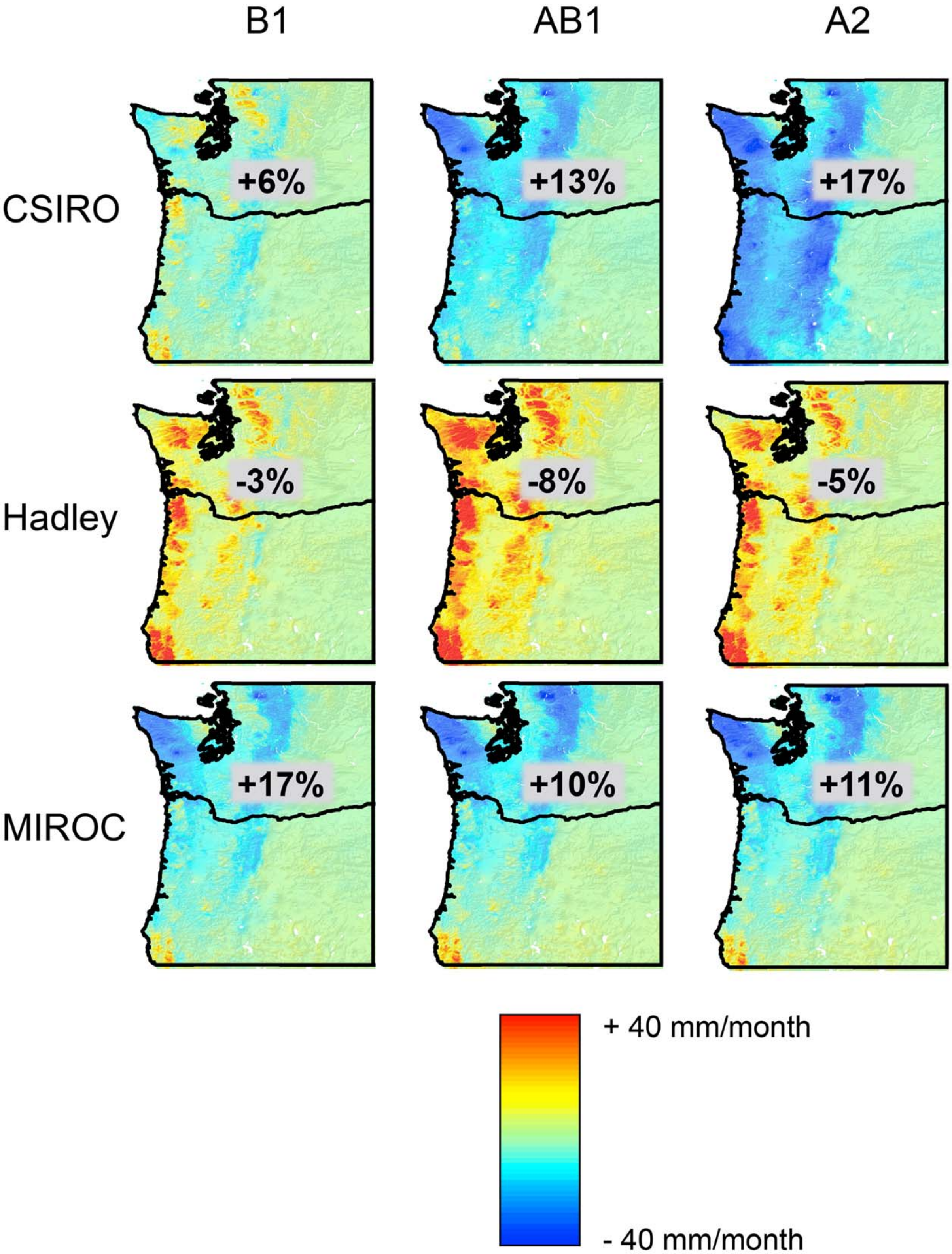

Figure 3. Projected differences in mean monthly precipitation (mm) calculated as the average difference between 2070-2099 and 1970-2000 means under 3 anthropogenic emission scenarios (SRES B1, A1B and A2) and 3 general circulation model projections (CSIRO Mk3, MIROC 3.2 medres, Hadley CM 3).

ations in sea surface temperatures described by indices such as El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). When both ENSO and PDO enter a warm phase (El Niño, positive PDO), winters are much drier and warmer than normal, and summers are more drought-prone, resulting in increased fire risk. When cooler phases of the two oscillations (La Niña, negative PDO) occur simultaneously, winters are cooler and wetter than normal, resulting in higher than average snowpack, more runoff, and a reduced chance of summer drought (Mote et al., 2003, Schoennagel et al. 2007). These two anomalies oscillate on very different frequencies, with ENSO changing states every 3-7 years and PDO changing states every 20-40 years. The warm phase of the PDO prevailed from 1977 through at least the 1990s, but the PDO may now be entering its cool phase (http://jisao.washington.edu/pdo/).

It is unclear how climate change might affect the frequency of PDO shifts from warm to cool phases. However, ENSO is now an emergent property of many GCMs as a result of the complex interplay of dynamic thermal components in the coupled atmosphere–ocean system. It remains an important challenge for modelers as the theoretical understanding of ENSO continues to evolve (Collins et al. 2010, Vecchi and Wittenberg 2010). One hypothesis suggests that a warmer world will cause stronger or more frequent El Niño events, which could strain water resources in the PNW and cause an increase in fire risk. The other hypothesis calls for a spike in La Niña events. A recent study shows that the easterly trade winds have weakened and suggests this may be behind the prevalence of more El Niño-like conditions in recent years. Other studies have documented a change in the location of intense rainfall and the pattern of sea surface temperatures of El Niño events. Unfortunately, even these observations and projections are still insufficient to predict what the future might really bring.

Climate Change Impacts on WPG Prairies and Oak Savannas

Prairies and oak savannas of the Willamette Valley-Puget Trough-Georgia Basin ecoregion comprise a continuum of related plant communities. Both are characterized by a continuous ground layer of graminoids and forbs. While prairies are generally treeless, oak savannas have scattered trees whose canopies generally do not overlap, thus preserving the grassland ground layer. In contrast to upland prairies, wetland prairies have shallow standing water during part of the rainy season. The dominant savanna tree species in the WPG is Garry oak (or Oregon white oak, *Quercus garryana*), frequently accompanied by conifers such as Douglas-fir (*Pseudotsuga menziesii*), ponderosa pine (*Pinus ponderosa*), and, in the south, California black oak (*Quercus kellogii*).

Warmer and Drier Summers

Prairies and oak savannas likely established during the early Holocene (circa 11,000-7,250 YPB) under warm and dry conditions and were maintained over time by a combination of wildfires and Native American burning, the importance of each varying in both time and space as cooler and wetter conditions developed (Walsh 2008). During the late Holocene (ca. 5200 cal yr BP-present), frequent burning by Native Americans was probably the main driver to maintain prairies and oak savannas, but the impact of natural climate variability, e.g., the Medieval Climate Anomaly (or Medieval Warm Period—AD 950-1250) and the Little Ice Age (1600-1850), is also evident in the fire history record of native grasslands in the Willamette Valley, illustrating the complex interactions between human activity and climate conditions (Walsh 2008). High frequency/low intensity fires and periodic soil drought maintained characteristic prairie vegetation under a climatic regime that would otherwise support forest vegetation (Agee 1993). Consequently, future increased summer drought seems unlikely to disadvantage prairie and savanna communities. Instead, it may well affect less drought-tolerant trees and other forest species adjacent to prairies, possibly resulting in prairie expansion. The simulated 21st century PNW carbon budget is a balance between carbon losses from intensified summer drought and fire, and carbon gains from higher fall, winter, and spring net primary production due to increased precipitation, longer growing seasons, and/or CO_2 fertilization effect, which as atmospheric concentration increases, may enhance water use efficiency (e.g., Knapp and Soule 2011).

Many of the aggressive exotic species that occur in both wet and dry prairies in western PNW currently have wide range distributions in the U.S. (Dennehy et al. 2011), so it is reasonable to assume that they will be relatively adaptable to changing climate. Consequently, they may provide even more of a competitive challenge to native PNW prairie species in the future than they do currently. However, as we mentioned above, many native prairie species are well adapted to summer drought, which could give them an advantage over many exotic species as summer drought extends and intensifies.

Review of Simulated Impacts of Warmer Drier Conditions

A suite of simulation results points to regional changes ranging from climatic conditions conducive to evergreen forest growth to a drier environment more conducive to the expansion of prairies and savannas. While there have been many studies documenting the vulnerability of Douglas-fir, the dominant conifer and primary timber resource in the Pacific Northwest, to climate change, there is little information on dominant native grasses. However, from these studies, we can learn about the projected magnitude of the impacts on the region and the possible opportunities for prairie expansion in areas of Douglas-fir dieback.

Littell et al. (2009, 2010) and Hamann and Wang (2006) showed an increase in habitat suitability for Douglas-fir in British Columbia, the northern edge of its distribution, while Rehfeldt et al. (2006) showed that climate change would cause an overall uphill shift throughout the region. Coops and Waring (2011), using a mechanistic model, showed that Douglas-fir should become more competitive with subalpine and high latitude species while losing its advantage at lower elevation and southern latitudes where late summer drought may increase their mortality rates. Similarly, Shafer et al. (2001) simulated a decline in the range of Douglas-fir west of the Cascades while Littell et al. (2010) projected that increased summer water deficit would increase fire risks and tree vulnerability to insect outbreaks, possibly causing more change in forests than direct responses to climate such as species shifts or declines in productivity.

Simulations of vegetation dynamics and wildfires using the dynamic global vegetation model MC1 (Bachelet et al. 2001) and three GCM climate futures under the A2 emission scenario (see Appendix - Table 1) show either a westward movement of the drier eastern coniferous forest under the hot and dry scenario or a northward movement of warmer ecosystems currently observed in southwestern Oregon under the hot and wet scenario, accompanied by significant carbon losses due to more wildfires (Rogers 2009, Figure 4). The simulations did not project a shift to grasslands or savannas west of the Cascades, partially due to an enhanced CO_2 fertilization effect that increases the water use efficiency of trees and reduces the stress caused by the increased summer drought. To the extent that a warmer and drier climate might increase wildfire on the landscape beyond that which can be effectively suppressed, it will likely lead to more grasslands again west of the Cascades, but the MC1 model did not simulate that possibility before the end of the 21st century based on the available climate scenarios and averaged soil characteristics. Furthermore, in this highly fragmented landscape, where agricultural and urban areas are unlikely to burn, land use patterns may reduce the impacts climate change might otherwise have on fire incidence and spread.

Directly relevant to the future of prairies and oak savannas, Shafer et al. (2001) showed significant contraction of the range of Garry oak on the west side of the Cascades and a shift and expansion to the east side of the mountains by the end of the 21st century. However, a recent study conducted by Bodtker et al. (2009) found that climate suitability for Garry oak is likely to improve overall in Washington, Oregon, and British Columbia, where it is the dominant oak species, with some declines in specific areas. In British Columbia, suitability was projected to decline in the near future and improve later in the century, although not as far as a full return to current conditions. The northward expansion of Garry oak may be limited to the Georgia Basin by the oak's dispersal capabilities and by the limiting climatic conditions of the coast range of British Columbia. The model did not account for site factors such as soil properties or disturbance regimes that will likely continue to play a role in determining the distribution of Garry oak at finer scales.

Review of Results from Warming Experiments

The effects of warming on grasslands have been experimentally studied by a variety of scientists who focused on plant community structure, productivity, or phenology (Harte and Shaw 1995, De Valpine and Harte 2001, Shaw et al. 2002, Dunne et al. 2003, Zavaleta et al. 2003a, Zavaleta et al. 2003b, Klein et al. 2004, Dukes et al. 2005). Warming often causes a decrease in plant biodiversity (Zavaleta et al. 2003a, Klein et al. 2004, Walker et al. 2006), while species-specific effects are mediated through changes in litter quantity (Weltzin et al. 2001, Klein et al. 2004, Weltzin et al. 2005, Suttle et al. 2007) and nutrient availability (Shaver et al. 2000, De Valpine and Harte 2001, Rustad et al. 2001, An et al. 2005, Suttle et al. 2007). Pfeifer-Meister and Bridgham (2007) showed strong seasonal controls of temperature and moisture on carbon and nutrient cycling in a WPG prairie, with competition between native and exotic species mediated by moisture and nutrient availability (Pfeifer-Meister et al. 2008). Experimental warming of an annual-dominated grassland in California enhanced spring soil moisture by 5-10% by causing earlier senescence, and hence lowered transpiration

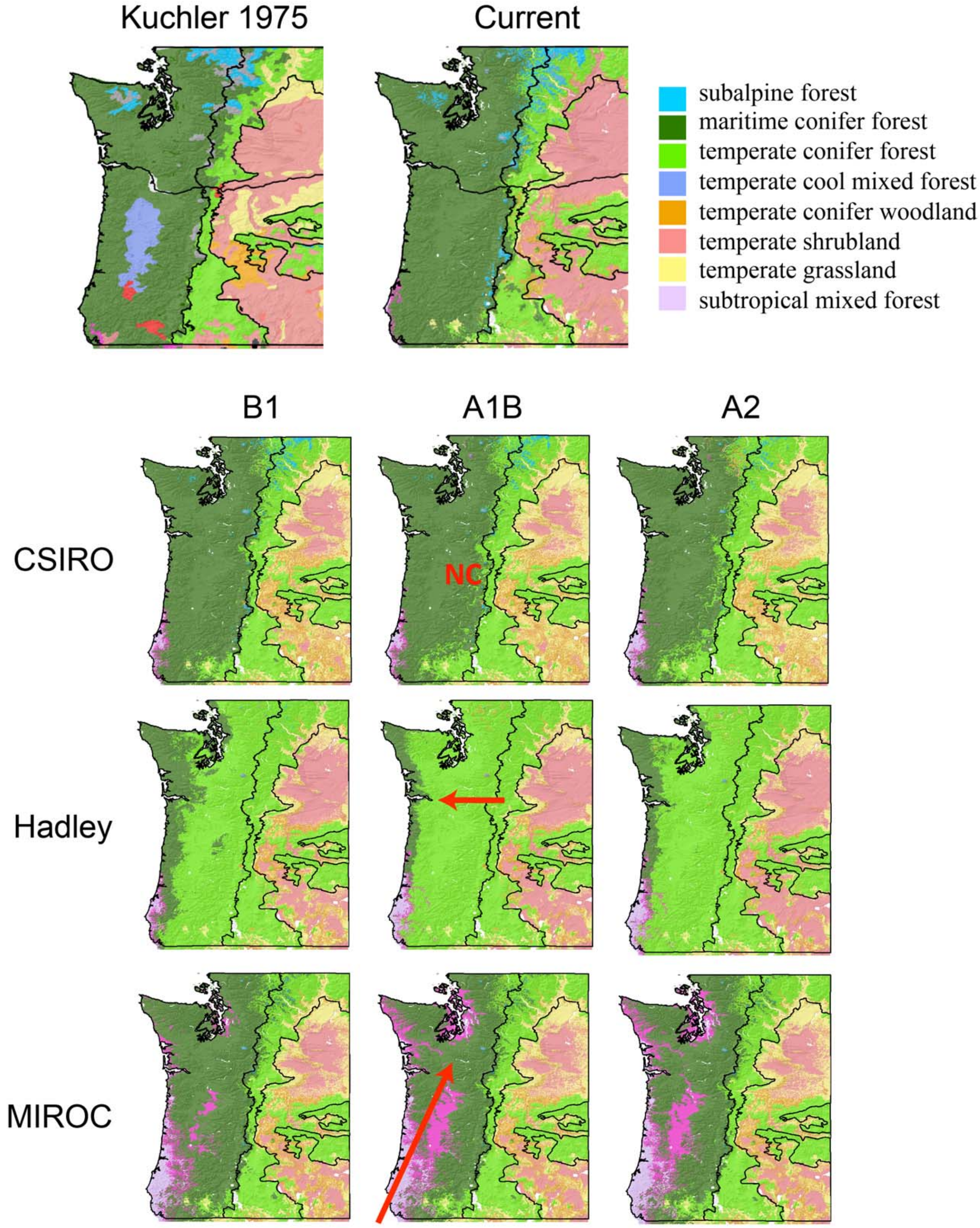

Figure 4. Projected shifts in vegetation types simulated by the dynamic global simulation model MC1 for the historical period (modal mean for 1970-2000) and for the end of the 21st century (modal mean for 2070-2099) under 3 anthropogenic emission scenarios (SRES B1, A1B and A2) and 3 general circulation model (CSIRO Mk3, MIROC 3.2 medres, Hadley CM 3) projections. Note: Spatial datasets from figures 2-4 are available for visualization and free download from the web-based conservation-related database called Data Basin (databasin.org). (http://app.databasin.org/app/pages/galleryPage.jsp?id=aa6df43ee7f745d6a7b5f65bb0092e43).

(Zavaleta et al. 2003). However, most WPG prairies and oak savannas are dominated by perennial grasses and forbs that senesce late in the growing season. Thus, future potential warming will likely cause a decline in soil moisture during the growing season unless species composition shifts are sufficiently extreme that annuals begin to dominate.

Wetter Winters

Increased winter rainfall seems unlikely to substantially alter grasslands that occur on well-drained glacial outwash soils, but may in fact increase the amount of wetland prairies on poorly drained soils in areas like the South Puget Sound, benefiting a suite of currently rare prairie species.

Extreme Events

If extreme events increase in frequency or intensity as some scientists project (IPCC 2007), they will have longer-term consequences on trees than on grasses. For example, heat waves during the summer of 2003 in western Europe caused massive tree die-offs (Ciais et al. 2005), intense rainfall events caused extensive flooding and tree-uprooting by landslides in Washington State in 2006-08, in 2007 hurricane-strength winds caused extensive wind throw and timber losses along the west coast of Washington and Oregon, and extensive drought-driven fires in 2002 in southern Oregon released large amounts of forest carbon (Campbell et al. 2007). Since grasses accumulate most of their carbon belowground, potential carbon losses through disturbances such as fire or pest outbreaks are significantly reduced in grasslands.

"Climate-Smart" Conservation Strategies

The primary mission of many conservation groups is to preserve native biodiversity. The intention of conserving the full range of existing species in a region, including those threatened and endangered, is commendable. Yet in the context of dynamic systems, conservation practitioners may need to reconsider the fundamental conception of what is being conserved. A broader view would require revising traditional definitions of natural communities, allowing consideration of new communities of species that may include climate refugees.

Ecosystem processes and environmental constraints such as nutrient-poor, well-drained soils, summer drought, and fire are all part of the forces that have maintained prairies and oak savannas over time. Preserving these physical and biological interactions *in situ* is the key to successful long-term conservation, and differentiates natural lands conservation from species preservation in zoos or botanical gardens. Moreover, maintaining healthy ecosystems can also help to sustain valuable ecosystem services (e.g., by enhancing native pollinator populations).

Current conservation plans for prairies and oak savannas include continued land management actions such as prescribed fire and control of aggressive introduced plant species, both of which can be expensive and have so far been insufficient to meet current species conservation goals. In the context of climate change, developing new conservation strategies should focus on taking advantage of opportunities (e.g., warmer, longer and drier summers) and facilitate the minimization of long-term land management and management expenses. Conservation of prairies and savannas should also take into account other threats besides climate change. Several of these threats (e.g., land conversion, landscape fragmentation) are likely to be of more immediate consequence to grassland species than is climate change. Therefore, effective conservation strategies need to assess how climate change may exacerbate the impacts of these other threats, for example, impacts due to likely human immigration from warmer and drier areas.

Based on these considerations, the following strategies are proposed as, "climate-smart" approaches to meet the challenges of a dynamic landscape responding to individual and interacting threats, including climate change.

1 – Utilize the full geographic and climatic range of prairies and oak savannas within the WPG ecoregion

Taking advantage of the 800 km north-south range of prairies and oak savannas in the WPG ecoregion is crucial for conservation actions to mitigate local constraints. Mean annual temperature varies by nearly 3 °C from north to south, with large relative changes in local and regional precipitation patterns, providing broad climatic range opportunities for species conservation. Individual species may experience shifts in both their fundamental and realized niches (Hutchison 1957) across these gradients, facing local extirpation in some areas and opportunities for range expansions in others. Despite its controversial aspect (e.g., Stone 2010), assisted colonization and similar translocations within the ecoregion may become critical to ensure the conservation of at-risk individual species or plant assemblages that support target faunal communities. For example, conservation efforts to translocate western bluebirds (*Sialia mexicana*) from the Puget Sound, where they are threatened by habitat loss and nesting competition, northward to the San Juan Islands have been very successful (Slater and Altman 2011). Consideration is now underway to extend this translocation into British Columbia.

Research experiments simulating increases in temperature and rainfall are underway at three prairie sites extending from southern Oregon to southern Washington. This project includes reciprocal translocations of a number of plant species from the full range of prairies and oak savannas with the goals of providing empirical data on the direct impacts of climate change on species from geographically disjunct sites and on their adaptation capability to new sites and new climates.

2 – Use habitat heterogeneity to sustain populations and functions in place

When populations of a particular species become small or disjunct, they may find refuge in local microhabitats that buffer them from altered disturbance regimes, climate change and/or competitive exclusion in the surrounding landscape (Johnson 1995). Potential refugia may include such features as rock outcrops that offer a diversity of micro-environmental conditions along gradients of light, moisture and temperature (Johnson 1995), or riparian corridors where shading and ground water availability buffer them from warming and drought, or even disturbances such as fires. Managers of protected sites should harness the existing heterogeneity of their sites to sustain species and processes in the face of climate change. This may mean facilitating species shifts into new microhabitat types or even new community types. For example, some plant species currently found in upland prairies may need to shift their distribution to wetland prairies or vernal pools under increased summer drought stress. Similarly, tree shade in oak savannas and the presence of microtopographic heterogeneity, such as mounds and swales, affect the distribution of prairie species (del Moral & Deardoff 1976) which may allow some to persist under a warmer, drier, climate, and also extend the flowering period of plants, potentially helping to maintain key plant-pollinator interactions. Managers working to conserve grassland species may also find it necessary to shift their attention from the hot, dry south-facing slopes that currently support much of the remnant prairie and savanna habitat to include the adjacent, cooler northern aspects that are currently dominated by Douglas-fir, especially if Douglas-fir should begin to decline on these sites.

Refugia can also include environments that buffer species from changes in disturbance regimes in the broader landscape and subsequent competitive exclusion by more generalist species. The recent history of WPG prairies and savannas provides a good example. Prairies and oak savannas were widespread prior to Euro-American settlement, occupying a wide range of soils, including fertile valley bottoms. Agriculture transformed much of the former grassland to crops and pasture. Following the loss of historical fire regimes, most of the remaining grassland began to succeed to forest. Much of the current habitat for prairie, savanna and oak woodlands consists of small areas of shallow soils and harsh exposures that have reduced or prevented conifer on small areas of historical prairie and savanna, allowing the drought-tolerant oaks, along with many associated prairie grasses and forbs, to persist in small pockets, often surrounded by dense conifer forest (Bart Johnson and Scott Bridgham, unpublished data; Murphy 2008). The challenge for today's managers is to identify current and future refugia that will serve key species and valuable ecosystems. Such refugia may need to be protected from further land use changes (e.g., urbanization or intensification of other land uses) while managers work to determine how both at-risk species and at-risk communities respond to their presence and abundance in the landscape, and identify the physiological thresholds beyond which such refugia become critical to the survival of those species or communities.

3 –Manage current sites adaptively and strategically expand prairie conservation areas

Managers should prepare for the likelihood that future plant community composition may not reflect current or historical assemblages. Adding certain species or functional groups, as well as increasing population sizes, may facilitate changes in community composition and phenology that still support conservation goals. For instance, in several South Puget Sound prairies, conservation practitioners have begun to increase the amount of annual forbs and non-native plant species that can fill the need for early season food, especially in cool wet springs, for larvae of the Taylor's checkerspot butterfly (*Euphydryas editha taylori*) (Fimbel et al. 2010). These efforts can be combined with the reintroduction of local species to either historical sites or to new, more favorable sites that can help boost local populations. Examples include efforts to establish new populations of the endangered golden paintbrush (*Castilleja levisecta*) on multiple sites (U.S. Fish and Wildlife Service 2010), efforts to reestablish Taylor's checkerspot butterfly populations at sites from which it had been extirpated (Linders 2006), and efforts to move Mazama pocket gophers (*Thomomys mazama*) to protected sites (Olson 2010, Knudsen 2003).

Intensive management techniques used to restore prairies and oak savannas on severely degraded sites that have been cultivated are invaluable to both increase the number of prairie habitat sites and alleviate landscape fragmentation (Bakker et al. 2010). Additionally, and maybe more controversially, managers may want to consider using prescribed fire to pre-adapt areas to projected increases in fire frequency. Prescribed fire is only now beginning to be widely utilized in prairies and oak savannas (Hamman et al. 2011). Fire managers may wish to consider higher fire frequencies on small portions of protected sites to help promote projected changes in communities, while still protecting fire-sensitive target species such as butterflies. Similarly, managers might consider altering the timing of fires to reflect the increased likelihood of summertime fires in the future.

4 – Establish new prairies and oak savannas on lands that become suitable due to climate change.

Prairies and oak savannas are likely to tolerate the impacts of climate change better than lowland Douglas-fir forest (discussed above) or floodplain agriculture (discussed below). This could create an opportunity to expand prairie and oak savanna habitat where more susceptible communities have been displaced. In fact, a climate-driven expansion of prairie habitat may reverse trends that have decreased the extent of prairie and oak savannas from the recent past.

As an example, at the Joint Base Lewis-McChord, which includes the 3rd largest U.S. Army installation, coniferous forests have expanded at the expense of historical prairie lands, especially since World War II once fire suppression was enforced on military lands. If changes in fire frequency, drought intensity, or insect outbreaks increase the mortality of mature Douglas-firs, the reestablishment of prairie habitats should be considered as an alternative to forest dieback. Moreover, altered environmental conditions may cause high tree seedling mortality and decrease recruitment, making reforestation efforts difficult. The reestablishment of prairies and oak savannas may become the best ecological alternative to maintain a well-adapted natural ecosystem and in the case of the Joint Base Lewis-McChord, consistent with the installation's primary mission of military training, since prairies are more desirable habitat for this than forests (P. Dunn).

Similar opportunities may arise in the Willamette Valley if agricultural lands become less productive. Scenarios where both drier upland fields and wetter alluvial soils become unsuitable for productive agriculture are plausible (Vynne et al. 2011). Establishing natural prairie and oak savanna habitats in these less productive areas may be an ecologically sensible alternative. Given that Willamette Valley prairies and oak savannas used to occupy what later became top quality agricultural soils (Christy and Alverson 2011), such extensions of prairie and savanna habitat may be seen as restoring some of the historical range of variability of these ecosystems. To prepare for such opportunities, conservationists should consider a) developing and demonstrating restoration techniques that will efficiently establish native species under those new conditions, and b) work to establish the regulatory framework and public awareness to ease such land use changes.

5 – Use ecosystem services from prairies and oak savannas to enhance opportunities for conservation and restoration.

Prairies and oak savannas provide a range of ecosystem services such as fire and flood buffering capacity, soil carbon sequestration, and water filtration, which may become increasingly important as climates change and human population density increases. Oak savannas ignite easily during the dry summer due to their flammable herbaceous fuels and lack of shade, but the fires are relatively easy to control and pose relatively little danger to people or structures. As long as tree canopies do not touch and ladder fuels are controlled, the oaks' partial shade helps retain higher fine fuel moisture, and the low flammability of their canopies, compared to those of conifers, reduces the likelihood of dangerous crown fires.

Grasslands are also quite efficient at sequestering carbon, an effective climate mitigation option especially when longer timeframes are considered (Hu et al. 2001). Estimating the effectiveness of carbon sequestration in WPG prairies and oak savannas has become important to prioritize the most effective sites (Table 1) . Because terrestrial carbon sequestration will be an important component of both current and future carbon markets, the restoration of prairies and savannas offers the opportunity to take advantage of financial incentives to fund conservation efforts.

Some prairies and oak savannas contribute to buffering hydrological flows. For instance, wetland prairies in the WPG ecoregion can play a role in moderating potential high-water spates that are projected for the region. In some areas such as Eugene, Oregon, they

TABLE 1. Global carbon stocks in vegetation and top 1 m of soils (based on German Advisory Council on Global Change, 2000).

Biome	Area in $10^6 km^2$	Carbon Stocks in Gt C		
		Vegetation	Soil	Total
Temperate Forests	10.4	59	100	159
Temperate Grasslands	12.5	9	295	304

are already being harnessed to the service of infiltrating peak stormwater flows from urban impervious surfaces. Since the distribution of prairies is currently limited, this strategy will likely only be one among many contributing strategies to moderate hydrological flows. However, if this service is recognized, then it may create opportunities for the creation of new prairie conservation areas.

6 – Monitor climate and threshold responses of biological communities

Monitoring climate conditions and changes to the biological communities is not a novel strategy, but the documentation of actual trends and variability over extended periods can provide critical data that will allow future conservationists to make informed decisions. Several areas within the WPG ecoregion are developing standardized monitoring systems to be used at multiple sites (e.g., Garry Oak Ecosystem Recovery Team, http://www.goert.ca; Prairie Quality, a project led by Washington Department of Fish and Wildlife) but standardized monitoring throughout the ecoregion may not be the most effective approach. Since local climate and impacts will differ, monitoring may need to be customized to particular subregions and their projected changes. For instance, extreme events such as drought may affect important plant species, such as Garry Oak or the native bunchgrass, Roemer's fescue, at the southern extent of prairies and oak savannas, whereas drought in the northern range may not have sufficient intensity to produce similar effects on core species.

Monitoring programs should include information from adjacent agricultural land and timberlands, especially those that may become susceptible to abandonment or dieback as water availability decreases during the growing season. If productivity becomes too low to be commercially viable on parts of the landscape that are currently zoned for agriculture or forestry, programs could be promoted to support conversion to prairie or oak savanna on such lands. In Oregon, lands zoned exclusively for agriculture or forestry must be maintained in their designated uses unless otherwise permitted under statewide planning policies (http://www.oregon.gov/LCD/goals.shtml). In the absence of sufficient incentives to restore and maintain native grasslands, many such areas might be released from production and abandoned, or converted to other uses such as rural residential housing through exceptions to current zoning rules or rezoning, contributing to the further loss of potential prairie habitat.

Integrating Native Grassland Conservation within a Regional Climate Adaptation Strategy

Overall, future climate change appears unlikely to disadvantage prairies and oak savannas in the WPG ecoregion in relation to forests. It is even possible that opportunities for expansion of this at-risk ecosystem will occur, should adjacent forested lands suffer from drought stress. Beyond their biodiversity values, WPG prairies and savannas also provide other services, the value of which may increase dramatically in a warmer and drier world. Their reflectivity (albedo of 0.16-0.26) contributes more to global cooling than forests (albedo of 0.5-0.15 for conifers) and they emit less water vapor than forests thus enhancing soil water storage. An increase in evapotranspiration through afforestation in temperate environments with ample water likely results in a net cooling effect through cloud formation (Anderson et al. 2011) thus the increase in surface reflectivity when grasslands replace forests may be counteracted by the lack of evaporative cooling. However, the net effect under water-limited conditions where forest trees are drought stressed and limit their transpiration is much less clear.

Prairies, like other grasslands around the world, have the potential to mitigate climate change by absorbing and storing carbon belowground (Neely et al. 2009). They represent a carbon sink if properly managed to reduce soil erosion and overgrazing (World Resources Institute 2000). Preserving and particularly restoring prairies can enhance soil carbon accumulation and in doing so, also increase soil water retention capacity. This can then buffer these systems to some extent from increased drought and help maintain healthy habitat for resident animals, plants, and soil microorganisms. While incentives were put in place to deter soil destabilization through the Conservation Reserve Program, rewarding farmers for converting highly erodible cropland to grass by earning carbon credits for grassland offsets at the Chicago Climate Exchange (http://www.chicagoclimatex.com/), the program has often been unable to compete with high agricultural land market prices. In a warmer drier world where drought-stressed agricultural land may become less productive, such programs may become substantially more effective.

Grasslands are also less subject to carbon release into the atmosphere due to logging or fire than forests (Neely et al. 2009). While forests take a long time to recover from fires, prairies are adapted to frequent fires and regrow quickly. Perennial grasses and forbs have their growth points underground where they are relatively immune to destruction from the cool fires that generally occur in grasslands (heat from grasslands fires rarely penetrates more than a few cm into the soil). Many grassland annuals either have seeds that persist through fire, seeds that are well represented in the soil seed bank, or high dispersal rates. Increases in fires due to climate change (Westerling et al. 2006, Lenihan et al. 2008) could help slow the succession of natural grasslands and old fields to forests. In this regard, grasslands may be more resilient to climate change than forests. Furthermore, even if landscape fragmentation reduces the spread of fires in the valleys of the WPG ecoregion, nearby tree plantations may experience more frequent fires or insect outbreaks that may cause forest dieback. Frelich and Reich (2010) note that remnant grasslands and savannas, even if transformed into novel communities of native species by climate warming and the northward expansion of southern species, could constitute an important seed source that would allow "forests to make a graceful transition to prairie and/or savanna" when climate conditions become too extreme to sustain forests.

Conclusion

In the context of climate change, conservation strategies for prairies and oak savannas are needed to take advantage of a suite of environmental opportunities. These may include the availability of new land for prairie restoration as timberlands and agricultural fields become less productive and are abandoned, as well as the reduction of management costs in places where prescribed fires are less essential to prevent forest expansion as drought-stressed trees dieback. We have identified a set of climate-smart strategies that do not require abandoning past management approaches, but rather reorienting them to a future that is substantially different than the recent past. These strategies focus on ways to link local and regional landscape characteristics to the emerging needs of species, including the potential for novel species assemblages, so that over time prairies and savannas are maintained in locations and conditions that remain well-suited for their persistence. At the regional scale, planning should take into account the full range of biological and environmental variability in prairies and oak savannas across the WPG. At local scales, landscape heterogeneity can be used to help support species persistence by identifying key refugia, and to identify emergent opportunities for actions such as marginal cropland or forest site conversion that expand landscape-scale ecosystem restoration. The growing importance of the services rendered by prairies and savannas may be used to secure new sources of funding and to serve broader societal needs exacerbated by climate change. Judicious monitoring of changes in the WPG ecoregion and along its boundaries can help identify biological thresholds and new restoration opportunities. In a world where climate change is but another set of doom and gloom projections, it is heartening to think that prairie and savanna protection and restoration offer opportunities for positive actions by the conservation community that have multiple benefits for society. There is little debate in the scientific community that human-induced climate change has happened and will continue to happen over this century. Conservation practitioners must develop appropriate adaptation and mitigation strategies to climate change to ensure their current and future goals are being met. To succeed in this endeavor will require enhanced communication and collaboration among conservation practitioners, academic researchers, and climate change scientists to meet the challenges and opportunities that lie ahead.

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Appendix - Table 1. Greenhouse gas emission scenarios used for AR4 (Randall et al. 2007) with information extracted and simplified from Nakicenovic et al. (2000).

SRES (special report on emission scenarios) emission scenarios used for IPCC Assessment Report 4	Description	CO_2-equiv. in ppm by 2100	Temperature change in °C 2090-99 relative to 1980-99	Sea Level Rise in meters at 2090-99 relative to 1980-99 (conservative)
A1B	Rapid economic growth, global population peaks mid-century (9 billion in 2050), rapid introduction of new and more efficient technologies: **balance across all energy sources**	~850ppm	1.7-4.4 (2.8)	0.21-0.48
A1T	Rapid economic growth, global population peaks mid-century (9 billion in 2050), rapid introduction of new and more efficient technologies: **non-fossil energy sources**	~700ppm	1.4-3.8 (2.4)	0.20-0.45
A1Fi	Rapid economic growth, global population peaks mid-century (9 billion in 2050), rapid introduction of new and more efficient technologies: **fossil-intensive**	~1550ppm	2.4-6.4 (4.0)	0.26-0.59
B1	Global environmental sustainability, global population peaks mid-century (9 billion in 2050), service and information economy, introduction of clean and resource-efficient technologies	~600ppm	1.1-2.9 (1.8)	0.18-0.38
A2	Regionally oriented economic development, continuously increasing population (15 billion people in 2100), slow technological change	~1250ppm	2.0-5.4 (3.4)	0.23-0.51
B2	Local environmental sustainability, continuously increasing global population (more than 10 billion people in 2100 and rising), slow but diverse technological change	~800ppm	1.4-3.8 (2.4)	0.2-0.43
Commitment	No change in CO_2 concentration	~380ppm		

Appendix - Table 2. Information about AR4 (Assessment Report #4) climate models (IPCC 2007) extracted and simplified from Randall et al. (2007)

GCM (general circulation model	Vintage and source	Atmosphere resolution Pixel size degree Lat x Lon L: # vertical levels	Ocean resolution Pixel size degree Lt x Lon L: # vertical levels
BCC-CM1	2005 Beijing Climate Center (China)	1.9x1.9 L16	1.9x1.9 L30
BCCR-BCM2.0	2005 Bjerknes Center for Climate Research (Norway)	1.9x1.9 L31	0.5-1.5x1.5 L35
CCSM3	2005 NCAR (USA)	1.4x1.4 L26	0.3-1.0x1.0 L40
CGCM3.1 (T47)	2005 Canadian Center for Climate Modelling and Analysis (Canada)	~2.8x2.8 L31	1.9x1.9 L29
CGCM3.1 (T63)	2005 Canadian Center for Climate Modelling and Analysis (Canada)	~2.8x2.8 L31	0.9x1.4 L29
CNRM-CM3	2004 Meteo France and CNRS (France)	~1.9x1.9 L45	0.5-2.0x2.0 L31
CSIRO-MK3.0	2001 Commonwealth Scientific and Industrial Research Organization Atmospheric Research (Australia)	~1.9x1.9 L18	0.8x1.9 L31
ECHAM5/MPI-OM	2005 Max Planck Institute for Meteorology (Germany)	~1.9x1.9 L31	1.5x1.5 L40
ECHO-G	1999 Meteorological Institute of the University of Bonn, Meteorological Research Institute of the Korea Meteorological Administration and Model and Data Group (Germany and Korea)	~3.9x3.9 L19	0.5-2.8x2.8 L20
FGOALS-g1.0	2004 National Key Laboratory of Numerical Modelling for Atmospheric Sciences and Geophysical Fluid Dynamics and Institute of Atmospheric Physics (China)	~2.8x2.8	1.0x1.0 L16
GFDL-CM2.0	2005 US Dept of Commerce and NOAA/GFDL (USA)	2.0x2.5 L24	0.3-1.0x1.0
GFDL-CM2.1	2005 US Dept of Commerce and NOAA/GFDL (USA)	2.0x2.5 L24	0.3-1.0x1.0
GISS-AOM	2004 NASA-Goddard Institute for Space Studies (USA)	3.0x4.0 L12	3.0x4.0 L16
GISS-EH	2004 NASA-GISS (USA)	4.0x5.0 L20	2.0x2.0 L16
GISS-ER	2004 NASA-GISS (USA)	4.0x5.0 L20	4.0x5.0 L13
INM-CM3.0 2004	2004 Institute for Numerical Mathematics (Russia)	4.0x5.0 L21	2.0x2.5 L33
IPSL-CM4	2005 Institut Pierre Simon Laplace (France)	2.5x3.75 L19	2.0x2.0 L31
MIROC3.2 (hires)	2004 Center for Climate System Research (U. Tokyo), National Institute of Environmental Studies, and Frontiers Research Center for Global Change (Japan)	~1.1x1.1 L56	0.2x0.3 L47
MIROC3.2 (medres)	2004 Center for Climate System Research (U. Tokyo), National Institute of Environmental Studies, and Frontiers Research Center for Global Change (Japan)	~2.8x2.8 L20	0.5-1.4x1.4 L43
MRI-CGCM2.3.2	2003 Meteorological Research Institute (Japan)	~2.8x2.8 L30	0.5-2.0x2.5 L23
PCM	1998 NCAR (USA)	~2.8x2.8 L26	0.5-0.7x1.1 L40
UKMO-HadCM3	1997 Hadley Center for Climate Prediction and Research/ Met Office (UK)	2.5x3.75 L19	1.25x1.25 L20
UKMO-HadGEM1	2004 Hadley Center for Climate Prediction and Research/ Met Office (UK)	~1.3x1.9 L38	0.3-1.0x1.0 L40

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