A method for estimating vulnerability of Douglas-fir growth to climate change in the northwestern U.S.

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ABSTRACT

Borrowing from landscape ecology, atmospheric science, and integrated assessment, we aim to understand the complex interactions that determine productivity in montane forests and utilize such relationships to forecast montane forest vulnerability under global climate change. Specifically, we identify relationships for precipitation and temperature that govern the spatiotemporal variability in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) growth by seeking similarities in patterns of growth/climate models across a significant portion of the climatological range of the species. In the 21st century and beyond, sustainable forestry will depend on successful adaptation to the impacts of climate change and climate variability on forest structure and function. The combination of these foci will allow improved prediction of the fate of montane forests over a wide range of biogeoclimatic conditions in western North America and thus allow improved management strategies for adapting to climate change. We describe a multi-disciplinary strategy for analyzing growth variability as a function of climate over a broad range of local-to-regional influences and demonstrate the efficacy of this sampling method in defining regional gradients of growth-limiting factors.

Key words: Douglas-fir, *Pseudotsuga menziesii*, climate variability, climate impacts, mechanism-response, tree rings, growth-climate relationships

RÉSUMÉ

En empruntant à l'écologie écosystémique, aux sciences atmosphériques et à l'évaluation intégrée, nous cherchons à comprendre les interactions complexes qui déterminent la productivité des forêts de montagne et à utiliser ces relations pour prévoir la vulnérabilité des forêts de montagne en fonction des changements climatiques. Plus précisément, nous identifions les relations portant sur les précipitations et les températures qui gouvernent la variabilité spatio-temporelle de la croissance du sapin Douglas (*Pseudotsuga menziesii* (Mirb.) Franco) en cherchant les similitudes dans les tendances des modèles de croissance en fonction du climat pour une portion significative du domaine climacique de l'espèce. Au cours du XXI^e^ siècle et des années qui suivront, la foresterie durable dépendra de l'adaptation réussie face aux incidences des changements et de la variabilité climatiques sur la structure et les fonctions des forêts. La combinaison des centres d'intérêts permettra une prévision améliorée du devenir des forêts de montagne en fonction d'une grande diversité de conditions biogéoclimatiques rencontrée dans l'ouest de l'Amérique du Nord et ainsi permettra d'améliorer les stratégies d'aménagement pour faire face aux changements climatiques. Nous décrivons une stratégie multidisciplinaire d'analyse de la variabilité de la croissance en fonction du climat pour un large éventail d'influences allant de locales à régionales et démontrons l'efficacité de la méthode d'échantillonnage en définissant les gradients régionaux des facteurs limitant la croissance.

Mots clés : sapin Douglas, *Pseudotsuga menziesii*, variabilité climatique, incidences climatiques, mécanisme de réponse, anneaux de croissance, relations entre la croissance et le climat

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Introduction: Background and Rationale

Forest ecosystems have the potential to provide ecological, cultural, and sustainable economic services at time scales of decades to millennia. In the 21st century and beyond, ecosystems will be influenced in novel ways by climate change, and managers of ecosystem goods and services will be challenged to mitigate and/or adapt to new conditions. For example, climate change is predicted to produce a warmer and wetter climate in much of the northwestern United States (Mote *et al.* 2003). However, significant changes in the seasonality of precipitation and snowpack duration are also predicted (Mote *et al.* 2003). In the western United States, climate is additionally modulated by ocean/atmosphere interactions that exert

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strong influence on precipitation and temperature regimes (McCabe *et al.* 2004, Wang and Schimel 2003). The El Niño Southern Oscillation (ENSO) (e.g., McCabe and Dettinger 1999) and Pacific Decadal Oscillation (PDO) (Mantua *et al.* 1997) are implicated in climate variability. The combination of climate change and climate variability will present novel combinations of mean and extreme conditions in the mountainous terrain of western North America.

Montane forests have a complex relationship with climate because they are limited as much by water availability as by temperature, and are often subject to frequent disturbances (fire and insects) that are in turn partially controlled by climate. Given this complexity, it is likely that relatively small shifts in climate will have profound influence on the structure and function of montane forests over large areas of the western United States (Zolbrod and Peterson 1999).

The effects of global climate change on regional precipitation seasonality, snowpack and climate variability may be more critical to forests than temperature increase alone because forest ecosystems are fundamentally structured around the distribution and flow of both water and energy (Stephenson 1990). In the 21st century and beyond, sustainable forestry will depend on successful adaptation to the impacts of climate change and climate variability on forest structure and function. Because no single discipline possesses all the concepts and techniques to evaluate such a complex suite of nested drivers and responses, adaptation depends critically on trans-disciplinary research that integrates the drivers of forest ecosystem processes at different scales to identify vulnerable processes.

As an example, we set out to determine the likely impact of future climate change to Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) growth along a gradient of climate conditions where the species occurs in the northwestern United States. Such a question is of interest to both ecologists and silviculturalists because growth is an estimate of species viability, net primary productivity, and resource sustainability. An appropriate sampling methodology would necessarily capture a large portion of the gradient of climate variability experienced by Douglas-fir across its biogeographical range. In this paper, we explain the rationale and interdisciplinary approach leading to a novel sampling effort designed to capture multiple, hierarchical gradients required to answer the above question by assessing the relationship between water (precipitation), energy (temperature), and tree growth.

Models of climate change impacts to ecosystems often focus on potential changes in the spatial distribution of species (Shafer *et al.* 2001), communities, or processes (Hansen *et al.* 2001). Due to the long time scale of forest population processes, these changes may take centuries to manifest in montane forests unless disturbance intervenes. Growth rates are alternative indicators of climate-mediated ecosystem performance that are readily re-sampled and analyzed through time. Annual radial growth of trees expresses the spatial and temporal variability in primary productivity and climate sensitivity (Graumlich *et al.* 1989). Much as niche dimension boundaries can be defined by the zero net-growth isoclines for populations (e.g., Chase and Leibold 2004), growth rates should approach very low standardized values near the climatological limits of a species distribution, but should also provide information about inter-annual departures (i.e., growth releases or suppressions) from mean conditions. We emphasize a mechanism-response approach and focus on developing a biophysical range of growth responses to limiting climatic factors.

The approach we describe below is the first step in constructing a mechanism-response statistical model of growth that accounts for the spatial and temporal variability of climate. A key assumption is that trees experience climate change, climate variability, physiography, topography, and competition only as the local (tens of meters) integration of available moisture, light and heat. In contrast, the drivers of these limiting variables occur at multiple scales. The chief difference in our approach from a process-modeling approach is that, instead of explicitly considering a host of nested driving variables, we attempt to find a scaleable response unit common to all drivers. Climatic influence on variability in tree growth must be considered at local watershed, physiographic, and sub-continental scales (Peterson and Parker 1998) to correctly attribute variability to different drivers. For example, growth is only loosely tied to regional climate in stands where local conditions mediate climate variability, but climate variability can exert strong controls on growth in other locations (Bunn *et al.* 2005) that are not buffered by their position on the landscape. The vulnerability of an ecological process to climate change can be hypothesized to be directly proportional to the sensitivity of its most limiting factors to climate, and our approach seeks to identify and map that sensitivity.

In the example that follows, we invoke principles and techniques from landscape ecology, atmospheric science, and integrated assessment. Landscape ecology provides the principles of hierarchy, scale, and the influence of pattern on process (Allen and Hoekstra 1992). This set of concepts suggests partitioning influences on tree growth into extrinsic (ocean basin/continental), regional (physiographic), and local (aspect, elevation, and within-plot). It also provides the analytical basis for developing sampling gradients in complex topography. From atmospheric science, we incorporate ocean/atmosphere drivers of inter-annual to decadal climate variability (Wang and Schimel 2003). This identifies important time scales of climate variability as well as the expected statistical properties of growth response. Finally, we use integrated assessment to guide interpretation of how our findings are likely to be linked to other contexts that are themselves interdisciplinary. We blend these principles into a strategy designed to yield a sampling design likely to identify important sources of variability in the species' growth response to climate change. The strategy follows:

1. Identify the fundamental ecological unit of the study and an appropriate spatial scale for sampling.
2. Identify the spatiotemporal scale of extrinsic or top-down drivers as well as local or bottom-up variables that amplify or dampen the role of extrinsic variables.
3. Identify scaleable physical units that link extrinsic and local drivers.
4. Sample regional limits of the identified response by bracketing the identified gradients.

This approach substitutes a diagnostic identification of controls at a variety of scales for a classical treatment/control approach.

Table 1. Hierarchical sampling scheme for measuring Douglas-fir growth response to climate variability

Hierarchy level	Specific gradient domain	Range of Sampled Climate	
		Ann. Precipitation (cm)	July Temperature (C°)
Continentality: 1 transect	Latitude 48/49 transect	Maritime – continental	Maritime – continental
	Olympic Mountains: Olympic National Park	244 – 533	11.6 – 16.1
Physiography: Four mountain ranges, each with west/east rainshadow	Cascade Mountains: North Cascades National Park	92 – 219	12.4 – 19.8
	Selkirk Mountains: Idaho Panhandle National Forest	71 – 128	14.0 – 18.6
	Northern Rocky Mountains: Glacier National Park	68 – 190	9.2 – 17.5
Watershed topography: Aspect and elevation Two aspects* three elevations	North and south aspects Lowest, mid, highest local elevation	Approx. Same Low Mid High	Less north More south High Mid Low
Stand: trees within plot Ten trees per plot, one core per tree		None: Fundamental Sampling Unit	

Methods

Tree growth varies locally through time and spatially at any given time, so we targeted sampling to the largest possible spatiotemporal domain. The fundamental sampling unit of the study must be useful to all potential end users and also retain the specific local factors influencing the effect of climate. A stand, despite its lack of a true "scale," is probably the best compromise between replication (individual trees) and local topographic homogeneity (elevation, aspect, and soils). We defined a stand as all the trees within a 100-m radius of a center point within a landscape facet of relatively homogeneous elevation, aspect, slope to keep local influences on growth as equal as possible between samples.

Extrinsic drivers of variability in tree growth are often climatic. Inter-annual and decadal patterns of Pacific basin atmosphere/ocean interactions are known to exert an important control on the climate of the western United States (Wang and Schimel 2003) and tree growth (Peterson and Peterson 2000). In addition, the warming trend evident in many late twentieth-century instrumental temperature (Hansen *et al.* 1999) and snowpack (Mote *et al.* 2003) records encompasses at least the last fifty years of growth. It is therefore imperative to have annual resolution for as long as possible, at the very least for the multi-decadal observed trends in 20th century climate.

Our sampling design was informed by four gradients that serve to bracket variability in growth as a function of climate. First, the relative maritime or continental environment of a stand influences the seasonal distribution and intensity of climate variables such as winter snowpack, growing degree-days, and summer drought. The CLIMET project transect (Fagre and Peterson 2000), from the maritime Olympic Peninsula in Washington to the continental eastern slope of the central Rocky Mountains in Montana, provided a prototype for this gradient. Second, the mountainous terrain in western North America greatly influences climate, especially precipitation, via orographic rain shadows. We focused on a few watersheds on each side of four mountain ranges to bracket this physiographic variability. Third, within a watershed, aspect influences stand climate by modulating the daily and seasonal distribution of light and temperature and, as a consequence, moisture through evapotranspiration. We sampled generally north- and south-facing slopes within each watershed to provide maximum contrast in topographic influence on climate. Finally, elevation along a given aspect gradient determines the seasonal distribution of degree-days, precipitation, and snowpack duration (e.g., Running *et al.* 1987). We bracketed local Douglas-fir elevation ranges from valley floors to the local maximum elevation of the species.

We incorporated these factors into a hierarchical sampling scheme (Table 1). We used geostatistical analysis of the watershed topography (slope, aspect, elevation) and 1980–1997 climate normals (DAYMET, 1-km resolution, Thornton *et al.* 1997) to evaluate the watershed, rainshadow, and physiographic distributions of a soil moisture proxy (topographic relative moisture index, TRMI). We then used these to prioritize sampling plot locations by identifying areas with maximum contrast (e.g., low, middle, and high elevations on both north and south aspects, west and east sides of mountain ranges). In each plot, 10 to 15 canopy-dominant Douglas-firs were cored at approximately 140 cm above ground. Since our goal is not reconstructing climate per se but concentrating on

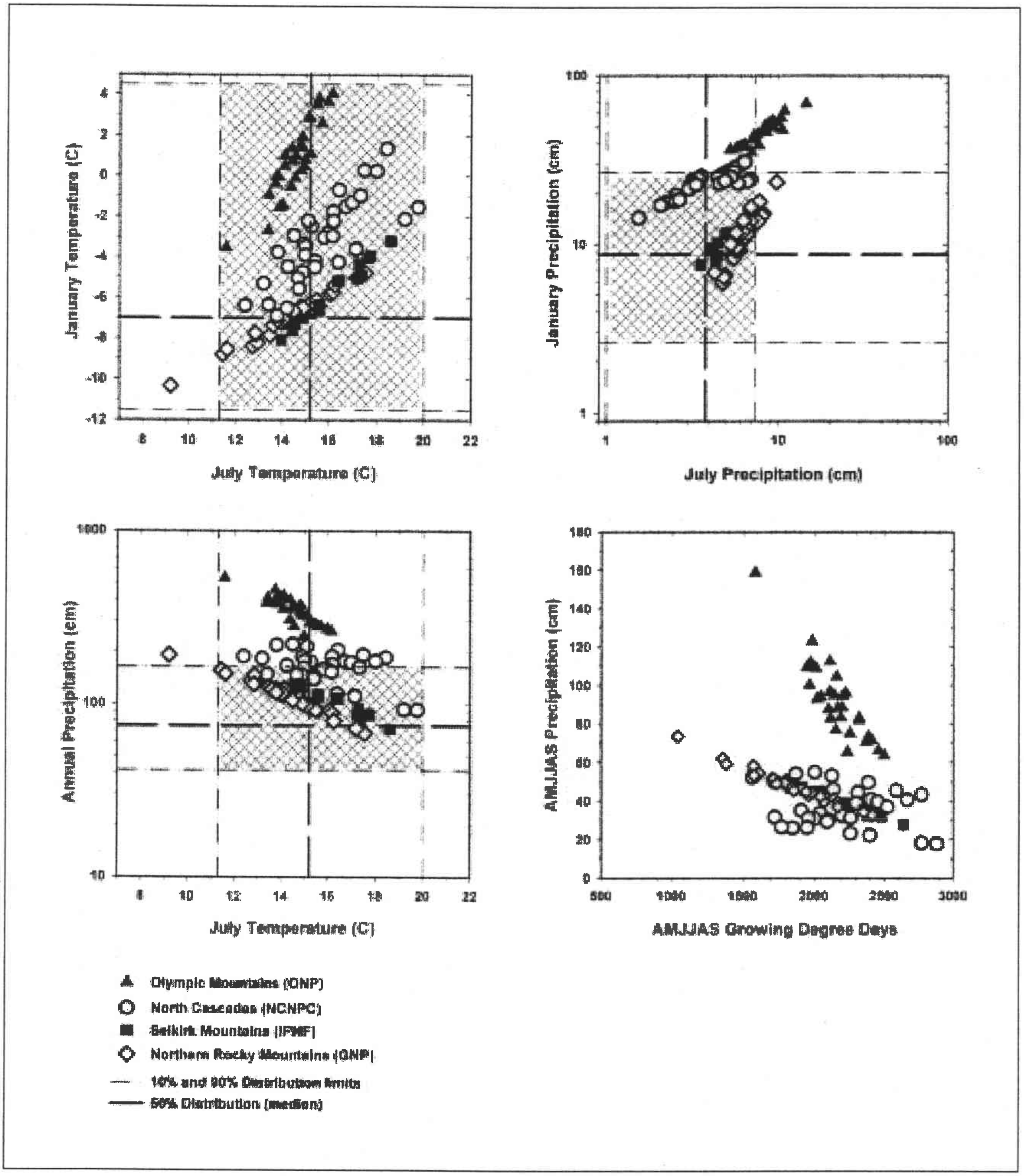

Fig. 1. Climate sampling space for Douglas-fir (this study) along a transect from the maritime western Olympic Peninsula, Washington to the continental eastern slope of the Northern Rockies, Montana. Shaded boxes indicate the two-dimensional climate niche for Douglas-fir for the North American continent. Values of plot locator points were determined from DAYMET maps of the indicated climate variables for the period 1980–1997*.

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*Sampled plots are depicted in two dimensional climate space for Olympic National Park (filled triangles), North Cascades National Park Complex (circles), Idaho Panhandle National Forest (filled squares) and Glacier National Park (diamonds). Dash/dot (10th and 90th percentile limits) and bold dashed lines (50th percentile median) indicate continent-wide climatic limits for Douglas-fir described in Thompson *et al.* (2000).

robust growth/climate relationships derived from 20th century data, we sampled stands if they were greater than or equal to about 150 years old. Using standard dendrochronological techniques (Cook and Kairiukstis 1990), we produced standardized tree ring chronologies for each level of elevation and both aspects within each watershed for six total plot chronologies per watershed. Using response function analysis, we developed diagnostic regression-based growth/climate models (Littell and Peterson, unpublished data) to determine the monthly climate variables (National Climatic Data Center 2004: climate division temperature, precipitation, and Palmer Drought Severity Index (PDSI)) most limiting to tree growth. We then developed a full set of 132 sampling locations using the hierarchical scheme in Table 1 and compared the resulting sampled range of climate to the range of climate across the range of Douglas-fir derived from an independent estimate (Thompson *et al.* 2000) to evaluate whether the sampling method produced acceptable gradients of limiting factors.

Results

For each plot in a preliminary survey (36 plots in six north/south paired transects, two in Olympic National Park, three in North Cascades National Park, and one in Glacier National Park), combinations of precipitation and temperature and/or PDSI in April, May, June, July, August, and September figured prominently in growth/climate regression models, with key months and climate variables varying with elevation, aspect, and physiography. The sign of these regression relationships was generally positive for precipitation and PDSI while negative for temperature. We interpreted this as an ecophysiological sensitivity to water balance deficit, and considered the diagnostic regressions to be sensitive to either summer or growing season hydrological deficit. Current summer (June, July, August, and September) hydrological deficit was indicated as an important growth-limiting variable in 25% of plots whereas prior summer hydrological deficit was indicated in 47% of plots. Current growing season (April through September) deficit was important to 33% of the plots, while only one plot was sensitive to the prior growing season deficit. Prior winter snowpack was included as a positive term in 31% of the models while only 8% of plots were most limited by current (immediately prior to growth) winter snowpack. About 25% of plots, especially those at low elevations, seemed to exhibit marginal April, October, or November temperature relationships, suggesting length of growing season is limiting in some locations. These plots also tended not to exhibit important water deficit indicators. Winter precipitation was less important overall, but explained significant variance in higher elevation plots where the sign of winter precipitation relationships with growth was negative.

Plotting the DAYMET estimates of climate variables identified as limiting in Thompson *et al.* (2000) for the full set of plots (Fig. 1) reveals strong linear gradients.

Discussion

Combinations of climate warming and climate variability may result in stronger lag relationships for severe conditions during some phases of Pacific basin oscillations (e.g., warm PDO or ENSO). A wider range of growth responses is therefore possible in the future at a given location depending on the shifts in climate. Simple substitution of equilibrium climate constraints on biogeography will fail to capture growth relationships in the future. The key differences in Douglas-fir sensitivity along elevation and aspect gradients allow locally specific (scale of 100 m) parameterization of growth/climate models. This illustrates the potential to use growth/climate relationships to refine understanding of how interannual and decadal fluctuations in climate will impact key ecophysiological processes and perhaps species distribution.

The climate space sampled by our transect approach (Fig. 1) suggests excellent potential for building the statistical predictive models described above. Ordinating the plots in a space defined by (1) growing season (AMJJAS) growing-degree-days and (2) growing-season-precipitation illustrates the energy and water supply gradients sampled in the study. The southern portion of Douglas-fir's range in the United States and Mexico represents warmer, drier portions of the realized niche to which we cannot extrapolate with confidence, and these gaps are evident in Fig. 1. Similarly, the most continental sites (probably in interior British Columbia and Alberta, Canada and in Wyoming, USA) are poorly represented. Eventually, it would be particularly useful to consider the specific adaptations of each local sample to account for the different varieties we sampled.

Assessing the vulnerability of each stand is crudely possible by evaluating its proximity to the edge of the climate niche of the species identified in Thompson *et al.* (2000). Generally, the North Cascades, Selkirk Mountains, and Northern Rockies portions of our distribution have some plots (usually lower elevation, south facing) within 1.5–3.0° C of the ninetieth percentile of temperature for Douglas-fir. This is well within the range of climate model-predicted temperature increases during the 21st century (IPCC 2001). Most plots in these areas are close enough to the median precipitation that the combination of precipitation and temperature observed in the next century is more important to determining local vulnerability than precipitation alone. This further underscores the importance of developing a common set of physical, units that are well correlated with annual tree growth.

Conclusion

Managers can use this information to decide which strategies to employ in adapting to new conditions. For example, provenances with more specific adaptations and known climatic tolerances can be chosen for seed sources despite the genetic variability in the original sample. Integrated assessment of socioeconomic vulnerability to climate impacts to forests could similarly benefit from a locally specific, ecological vulnerability assessment.

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References

Allen, T. F. H. and T. Hoekstra. 1992. Toward a unified ecology. Columbia University Press, NY. 384 p.

Bunn, A.G., L.A. Waggoner and L.J. Graumlich. 2005. Topographic mediation of growth in high elevation foxtail pine (*Pinus balfouriana* Grev. et Balf.) forests in Sierra Nevada, USA. Global Ecology and Biogeography 14: 103–114.

Chase, J.M. and M.A. Leibold. 2004. Ecological niches: Linking classical and contemporary approaches. Biodiversity and Conservation 13: 1791–1793.

Cook, E.R. and L.A. Kairiukstis. 1990. Methods of dendrochronology. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Fagre, D.B. and D.L. Peterson. 2000. Ecosystem dynamics and disturbance in mountain wildernesses: assessing vulnerability of natural resources to change. *In* D.N. Cole and S.F. McCool (eds.). Wilderness Science in a Time of Change. USDA Forest Service Proceedings RMRS-P-015. Rocky Mountain Research Station, Ogden, UT.

Graumlich, L.J., L.B. Brubaker and C.C. Grier. 1989. Long-term trends in forest net primary productivity — Cascade Mountains, Washington. Ecology 70: 405–410.

Hansen, A.J., R.R. Neilson, V.H. Dale, C.H. Flather, L.R. Iverson, D.J. Currie, S. Shafer, R. Cook and P.J. Bartlein. 2001. Global change in forests: Responses of species, communities, and biomes. BioScience 51: 765–779.

Hansen, J., R. Ruedy, J. Glascoe and M. Sato. 1999. GISS analysis of surface temperature change. Journal of Geophysical Research 104: 30997–31022.

Intergovernmental Panel on Climate Change (IPCC). 2001. Climate Change 2001: The scientific basis-Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change. eds. J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. vander Linden, *et al.*. Cambridge University Press, New York.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace and R.C. Francis 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78: 1069–1079.

McCabe, G.J. and M.D. Dettinger. 1999. Decadal variations in the strength of ENSO teleconnections with precipitation in the western United States. International Journal of Climatology 19: 1399–1410.

McCabe, G.J., M.A. Palecki and J.L. Betancourt. 2004. Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States. Proceedings of the National Academy of Sciences 101: 4136–4141.

Mote, P.W., E.A. Parson, A.F. Hamlet, K.N. Ideker, W.S. Keeton, D.P. Lettenmaier, N.J. Mantua, E.L. Miles, D.W. Peterson, D.L. Peterson, R. Slaughter and A.K. Snover. 2003. Preparing for climate change: The water, salmon, and forests of the Pacific Northwest. Climatic Change 61:45–88.

National Climatic Data Center. 2004. Online. http://www.ncdc.noaa.gov/oa/climate/onlineprod/drought/ftppage.html. Accessed 22 December 2003.

Peterson, D.L. and V.T. Parker. 1998. Dimensions of scale in ecology, resource management and society. *In* D.L. Peterson and V.T. Parker (eds.). Ecological Scale: Theory and Applications. Columbia University Press, New York, NY.

Peterson, D.W. and D.L. Peterson. 2000. Regional growth responses and climatic limitations of mountain hemlock (*Tsuga mertensiana*). Ecology 82: 3330–3345.

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

Running, S.W., R.R. Nemani and R.D. Hungerford. 1987. Extrapolation of synoptic meteorological data in mountainous terrain and its use for simulating forest evaporation and photosynthesis. Canadian Journal of Forest Research 17: 472–483.

Shafer, S.L., P.J. Bartlein and R.S. Thompson. 2001. Potential changes in the distributions of western North America tree and shrub taxa under future climate scenarios. Ecosystems 4: 200-215.

Stephenson, N.L. 1990. Climatic control of vegetation distribution – the role of the water balance. American Naturalist 135: 649–670.

Thompson, R.S., K.H. Anderson and P.J. Bartlein. 2000. Atlas of relations between climatic parameters and distributions of important trees and shrubs in North America – introduction and conifers. U.S. Geological Survey Professional Paper 1650-A. 269 p.

Thornton, P.E., S.W. Running and M.A. White. 1997. Generating surfaces of daily meteorology variables over large regions of complex terrain. Journal of Hydrology 190: 214–251.

Wang, G. and D. Schimel. 2003. Climate change, climate modes, and climate impacts. Annual Review of Environment and Resources 28: 1–28.

Zolbrod, A.N. and D.L. Peterson. 1999. Response of high-elevation forests in the Olympic Mountains to climatic change. Canadian Journal of Forest Research 29: 1966–1978.