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Interannual Variability in Aboveground Tree Growth in Stehekin River Watershed, North Cascade Range, Washington

Abstract

Many forests in the Pacific Northwest region of North America are both highly productive and sensitive to climate. The combination of productivity and sensitivity makes forests vulnerable to changes in future climate and most likely to feed back to the regional carbon cycle. We reconstructed basal area increment (BAI) for 20 yr using tree-ring increments and diameter to identify species-specific responses of 14 forested vegetation types in the Stehekin River watershed in the North Cascade Range, to interannual climatic variability. Mean basal area increment (MBAI) for the 20-yr period is low when the standard error is low, but as MBAI increases, the standard error (SE) is more variable. Growth at sites with both low SE and MBAI may be related to climatic variables, however, some forest types dominated by Douglas-fir and mountain hemlock are both productive and responsive to climatic variability. Many forests in the Pacific Northwest are dominated by Douglas-fir, a commercially important timber species, and as a result, may play a major role in the regional carbon balance. Douglas-fir and mountain hemlock forests in the eastern portion of the North Cascades should be carefully monitored and managed in the context of both changing climatic conditions and regional carbon budgets.

Introduction

The United States carbon budget has been the subject of intense scientific focus in the last two decades (Turner et al. 1995, Fan et al. 1998, Pacala et al. 2001, Gurney et al. 2002). Forest ecosystems in the United States remove a considerable amount of carbon from the atmosphere resulting in a net gain of carbon to the terrestrial pool (Schimel et al. 2000, Pacala et al. 2001), which compensates for loss of forest cover during the last two centuries (Houghton 1995). Much attention has been paid to Southeastern forests where land cover changes have been dramatic and models identify the largest sinks (Schimel et al. 2000). Western forests may be a significant carbon sink, as a result of changes in forest structure due to fire exclusion and high rates of productivity in some ecosystems (Hessl et al. In press).

Approximately 70% of the carbon sink in the western United States may occur at elevations >750 m (Schimel et al. 2002). The complex geography of the West creates two problems for studies of carbon flux. First, measuring carbon flux in mountainous terrain is difficult. Ground-based eddy correlation towers require relatively flat terrain to make accurate measurements. Similarly, methods that use remotely sensed data to model productivity or carbon flux are difficult to use in steep terrain because of the effects of shadows from terrain and cloud cover. Second, species composition and productivity in mountainous forests are heterogeneous (Hessl et al. In press). For example in the Pacific Northwest, aboveground annual productivity varies between 10 Mg $m^{-2} yr^{-1}$ for western larch (*Larix occidentalis*) on Chumstick Mountain, Washington (Gower et al. 1989) and 1050 Mg $m^{-2} yr^{-1}$ for Douglas-fir (*Pseudotsuga menziesii*) in the interior Coast Range of Oregon (Gholz 1982). Thus, estimating carbon budgets from eddy flux sites, remotely sensed data, or modeling requires species-specific information. In addition to variability between species, variability within species can be great. For Douglas-fir, aboveground productivity varies between 51 Mg $m^{-2} yr^{-1}$ for a natural stand on the west side of the Cascade Range, Washington (Turner and Long 1975) and the aforementioned 1050 Mg $m^{-2} yr^{-1}$ in the interior coast range, Oregon. The difficulties of terrain and heterogeneity demonstrate the need for extensive

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empirical sampling to support regional estimates of carbon flux in mountainous ecosystems.

In addition to the spatial heterogeneity of mountainous ecosystems, temporal changes in climate are likely to affect regional carbon dynamics via changes in productivity and respiration (Dai and Fung 1993). Modeled predictions of an enhanced greenhouse climate in the Pacific Northwest generally agree that by the year 2050 winters will be warmer and wetter, with average annual temperatures rising by 2-4°C (Climate Impacts Group 1999). Forest ecosystems in the Pacific Northwest may be affected by these changes in climate either directly through changes in productivity, or indirectly through changes in fire regimes or insect outbreaks (Climate Impacts Group 1999). Coupled with long-term predictions of climatic change, climatic variability operating on interannual-to-decadal time scales may be superimposed upon the variability in productivity over space in the Pacific Northwest.

Extensive data exist on tree growth responses to climatic variability over time (Fritts 2001). Because these measures are often taken from dominant trees growing at the extremes of their range, they do not represent the diversity of environmental conditions in which a species may grow. Furthermore these measures of dominant trees cannot be extrapolated to stand-level measures of productivity. Annual variability in temperature and precipitation has been correlated with annual aboveground net primary productivity at a few sites in the Pacific Northwest (Graumlich et al. 1989), but little is known about the effect of interannual climate variability on growth and productivity over environmental gradients for multiple species. Interdecadal climatic variability is closely linked to radial growth patterns in mountain hemlock (*Tsuga mertensiana*) (Peterson and Peterson 2001) and subalpine fir (*Abies lasiocarpa*) (Peterson et al. 2002), although responses are heterogeneous and depend on the factors limiting tree growth at different sites. For example, mountain hemlock growth at low elevation is limited by low soil water supply, whereas growth at high elevation is limited by late lying snow. This observed variability in tree growth makes uniform responses to climatic change unlikely and necessitates extensive fieldwork to support predictions of ecosystem responses to climate change (Fagre and Peterson 2002, Fagre et al. 2003).

Some Pacific Northwest forests are productive and sensitive to climate, are potentially vulnerable to changes in climate, and are, as a result, likely to feed back to the regional carbon cycle. In this study, we reconstructed basal area increment (BAI) for 20 yr using tree-ring increments to identify species-specific growth responses of forests of the North Cascade Range to interannual climatic variability. Specifically, we address the following questions: (1) Which forest types in the North Cascades are most productive, in terms of their basal area increment? and (2) Which climatic variables account for variability in patterns of aboveground growth?

Study Area

The study area is located on the east side of the crest of the North Cascades, in the Stehekin River watershed (Figure 1). The North Cascades are a north-south trending range that block maritime air masses and create a strong rain-shadow effect on the east side. The 83,900 ha watershed is a topographically varied region between 330 and 2900 m in elevation. Valleys are deep and steep sided. The substrate is composed of partially metamorphosed sedimentary rocks and intrusions of granite batholiths. Many ridges and peaks have glacial features, and several small mountain glaciers exist at the highest elevations.

Forested vegetation in the watershed is highly varied as a result of the dramatic elevation gradient and the strong rain shadow effect. At least 14 coniferous and 4 broadleaf tree species are present in the watershed (Table 1). Ponderosa pine (*Pinus ponderosa*) and Douglas-fir dominate the lowest elevations (300-500 m), located farthest to the east of the crest. Riparian areas at low elevations are dominated by grand fir (*Abies grandis*) and several hardwood species. At slightly higher elevations, (500-1000 m) these forests give way to a mixed-conifer zone dominated by Douglas-fir and western hemlock (*Tsuga heterophylla*). Pacific silver fir (*Abies amabilis*), subalpine fir and mountain hemlock dominate the highest elevations (1000-2000 m), just below alpine meadows and permanent snowfields.

Methods

Data were collected in North Cascades National Park, North Cascades National Recreation Area

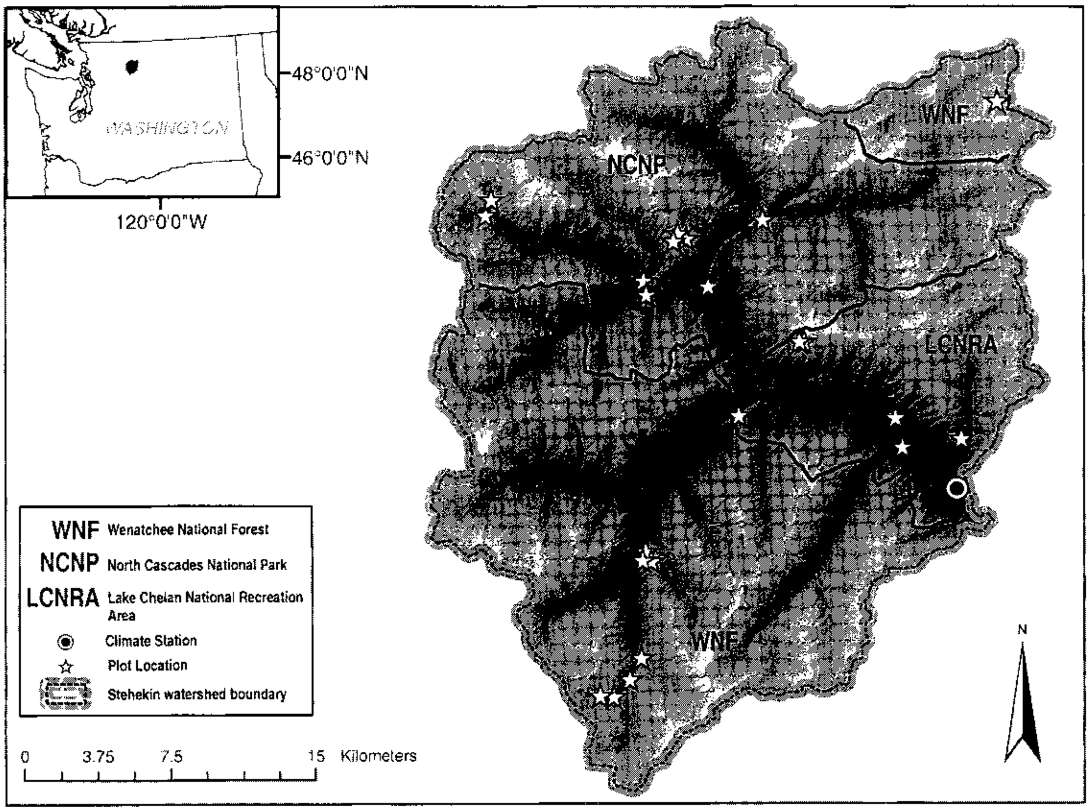

Figure 1. Location of the Stehekin River Watershed and the location of the sampled sites used for this analysis.

TABLE 1. Tree species observed in the Stehekin River Watershed.

Latin name	Common name
Conifers	
Abies amabilis	Pacific silver fir
Abies grandis	Grand fir
Abies lasiocarpa	Subalpine fir
Chamaecyparis nootkatensis	Yellow cedar
Larix lyallii	Alpine larch
Picea engelmanii	Engelmann spruce
Pinus albicaulis	Whitebark pine
Pinus contorta var. latifolia	Lodgepole pine
Pinus monticola	Western white pine
Pinus ponderosa	Ponderosa pine
Pseudotsuga menziesii	Douglas-fir
Thuja plicata	Western redcedar
Tsuga heterophylla	Western hemlock
Tsuga mertensiana	Mountain hemlock
Broadleaf deciduous	
Acer macrophyllum	Bigleaf maple
Cornus nuttallii	Pacific dogwood
Populus trichocarpa	Black cottonwood
Salix sitchensis	Sitka willow

and Wenatchee National Forest (Figure 1). Twenty-three circular 0.05 ha plots were located across the largest ecological gradients in elevation and aspect. For maximum efficiency, plots were located in portions of the study area that best represented these ecological gradients and also had trail access. We sampled 14 forested vegetation types (Williams and Lillybridge 1983, Williams et al. 1990, Lillybridge et al. 1995) from low-elevation Douglas-fir to high-elevation subalpine fir (Table 2). If possible, we located plots in two age classes (<150 yr and >150 yr) within each forest type. Plots were located in stands with no obvious evidence of recent disturbance (charcoal, windthrow, mistletoe, bark beetles) and at least 20 m from any trails.

In each plot, we first measured the diameter at breast height (dbh) of all trees and then identified the three most abundant and dominant species with at least one individual >20 cm dbh inside the plot. We then randomly selected 1-2 trees of each species in each 10-cm size class. For each tree, we collected two cores on opposite sides of

TABLE 2. Plot summary and description of each plot including the plant association (Williams and Lillybridge 1983, Williams et al. 1990, Lillybridge et al. 1995), dominant species, number of trees per plot, number cored trees used in this analysis, mean basal area increment (MBAI) from 1978 to 1989, climatic variables and correlation coefficient. All correlations are significant at the 0.05 level. Data are in ascending order of MBAI.

Plot no.	Dominant species	Mean BAI	Elevation (m)	Trees (no.)	Trees Cored	Tree density (ha-1)	Climatic variable	Correlation
127	Mountain hemlock	15	919	6	3	120	Summer precipitation	-0.665
135	Subalpine fir	20	1001	4	2	80	Summer temperature	0.466
129	Alpine larch	53	2047	24	4	480	Annual precipitation	0.599
201	Alpine larch	65	1915	14	8	280		
156	Whitebark pine	66	1820	22	4	440		
155	Alpine larch	72	1925	8	6	160		
136	Yellow cedar	75	1031	21	3	420		
105	Lodgepole pine	94	696	23	6	460		
47	Douglas-fir	122	1077	10	4	200	Annual precipitation	-0.476
130	Subalpine fir	123	2048	44	8	880		
148	Douglas-fir	153	624	9	3	180		
114	Western hemlock	164	944	31	10	620		
113	Western hemlock	167	843	30	9	600		
116	Subalpine fir	184	1070	32	5	640		
132	Douglas-fir	191	652	24	8	480		
58	Douglas-fir	293	439	23	7	460		
20	Douglas-fir	324	965	20	7	400		
120	Pacific silver fir	331	1285	42	4	840		
115	Engelmann spruce	347	851	12	9	240		
104	Douglas-fir	402	777	16	6	320		
121	Mountain hemlock	473	1375	42	9	840	Total annual snow	0.562
64	Douglas-fir	615	421	33	5	660	Annual temperature	-0.466
119	Engelmann spruce	754	1242	17	8	340		

the tree at dbh. Samples were processed according to standard dendrochronological methods (Fritts 2001). Cores were mounted on wooden boards and sanded with increasingly fine grades of sandpaper. Cores were measured using a Velmex measuring system beginning with the ring created in 1850 (or if trees established after 1850, we used the first ring present in the core). We used a combination of skeleton plots and COFECHA (Grissino-Mayer 2001) to crossdate the cores when possible. Because we sampled in a variety of environments, including closed canopy stands, many cores were difficult to crossdate. In these cases, rings were counted and notes were taken describing the confidence in dating based on ring widths and wood quality. Only those cores dated with high confidence were included in this analysis (279 out of 359 total cores taken). Though only 45% of these cores were crossdated, we were interested in only the last 20 yr of growth (1978-1997). We are confident that this period is accurately dated.

Ring-width data were translated into annual diameter increments using the dbh measured in the field and a bark coefficient (Table 3) to estimate the decrease in bark thickness on successively smaller diameter trees:

$$D_{t-1} = \frac{[D_t - ((1-B_s) * D_t)] - R_t}{B_s}$$

where B_s is the bark coefficient for species s, D_t is the dbh at year t, D_{t-1} is the dbh at year t-1, and R_t is two times the ring width during year t. Annual dbh increments were then translated into basal area increments (BAI). This method is similar to that of Runyon et al. (1994). These values were then converted into annual BAIs using the equation:

$$\mathrm{BAI} = \pi * (D_t/2)^2 - \pi * (D_{t-1}/2)^2$$

The end product is an annual estimate (1978-1997) of BAI for each tree for which we collected an increment core. Aboveground biomass is typically estimated from dbh and allometric equations (Clark et al. 2001). We used annual estimates of BAI as a proxy for aboveground productivity. But because BAI does not include mortality, litterfall or branchfall it will overestimate productivity in

TABLE 3. Bark thickness coefficients and references used to estimate dbh given annual ring-width increments.

Species	Bark coefficient	Reference
Big leaf maple	0.961	Smith and Kozak 1967
Black cottonwood	0.935	Smith and Kozak 1967
Douglas-fir	0.830	Smith and Kozak 1967
Engelmann spruce	0.956	Smith and Kozak 1967
Grand fir	0.914	Finch 1948
Lodgepole pine	0.961	Smith and Kozak 1967
Ponderosa pine	0.897	Smith and Kozak 1967
Subalpine fir	0.970	Finch 1948
Western hemlock	0.914	Smith and Kozak 1967
Western red cedar	0.959	Smith and Kozak 1967
Western white pine	0.951	Smith and Kozak 1967
Yellow cedar	0.970	Smith and Kozak 1967

stands with high rates of mortality or recent disturbance (disturbed stands were avoided in this study). We also chose a recent and short period of analysis (1978-1997) because the frequency of mortality and decay (data lost to this analysis) increases as longer time periods are analyzed. BAI is a more accurate estimate of tree growth than ring width (Visser 1995), but unlike ring widths, BAI is not subject to an age related growth trend. Therefore time series of BAI do not need detrending to remove this age related trend. Our analysis focuses on relative differences in growth rather than absolute values, so that small errors derived from variability in bark thickness and mortality should not affect the interpretation of our results.

To expand the analysis to a whole plot, we applied the annual BAI time series of each tree in a given size class to all the other trees of the same species and the same size class, producing a weighted mean BAI for each size class for each species (weighted by the number of individuals in each group). Data were summarized by plot, with all trees and all species combined. By analyzing data by size class and applying these results to uncored trees we were able to core fewer trees per plot and include a larger number of forest types in our analysis.

Mean annual BAI for the period of record was compared to climatic data and to standard error to identify which forest types are most likely to be both sensitive to interannual climatic variability and productive. Temperature and precipitation data were derived from divisional data (Washington State division 6, East Cascades, National Climatic Data Center 2003), and total snow depth was derived from the Stehekin cooperative weather station (#458059), located within the sampled watershed (Figure 1). Data were summarized into annual values, based on the growing season (October-September) and into seasonal values, based on a two-season year reflecting the wet season (October-May) and the dry season (June-September). Annual and seasonal climatic variables were compared to the BAI series for each plot using Pearson correlation coefficients (significance level set at $P = 0.05$).

Results

Twenty-three plots contained sufficient tree cores (minimum four trees cored) to represent the range of species and diameter classes necessary for this analysis. Plots were distributed across a range of elevations and vegetation classes (Table 2). Mean number of trees (>10 cm dbh) per plot was 22, and an average of 13 cores was collected and analyzed per plot. Mean BAI (MBAI) for the period of analysis (1978-1997) ranged from 15 to 754 $cm^2/0.05$ ha. Plots with low MBAI were in middle to high elevation, subalpine forest types with moderate to low tree density (Table 2). Plots with high MBAI were located at low to middle elevation sites with moderate to high tree density. Plot 119 had the highest MBAI but had relatively low tree density relative to other sites.

MBAI and standard error (SE) of BAI were positively associated at low values of MBAI (Figure 2). At high values of MBAI (>300 $cm^2/0.05$ha), SE of BAI was highly variable. With the exception of two plots (64 and 121), plots that correlated well with climatic variables tended to have low MBAI and low SE (Table 2, Figure 2). These plots represent typical dendroclimatic reconstruction sites in which species growing at the extremes of their environmental limits have low productivity but are sensitive to climate (Fritts 2001). However, two sites with moderate to high MBAI also had annual BAI correlated with climate. Plot 121, dominated by mountain hemlock had moderate MBAI and was correlated with total annual snow depth ($P = 0.01$). Plot 64, dominated by Douglas-fir, had high MBAI and was negatively correlated with annual temperature ($P = 0.038$).

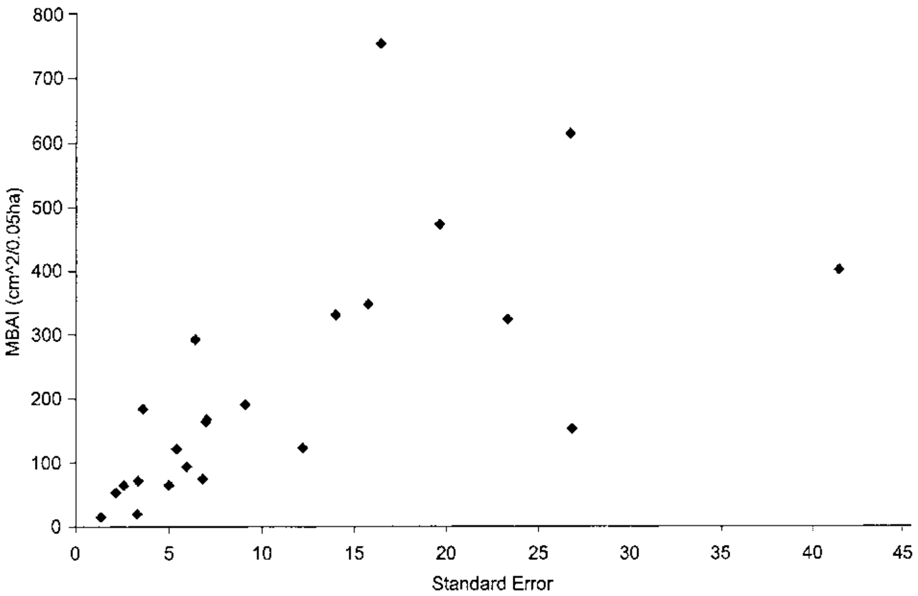

Figure 2. Mean basal area increment for the period of analysis (1978-1997) versus standard error for the same period.

These two plots, located in interior forest locations, indicate that some stands can be both sensitive to climate and highly productive.

Seven middle elevation plots (430-900m) show no relationship with any of the climate variables examined (Table 2) and have a wide range of MBAI. Trees in these plots are located above the elevation at which moisture stress is common but below the elevation at which the length of the growing season (determined in the Cascades by temperature and snow depth) is limiting (Peterson and Peterson 2001). At these locations the physiologically active period is relatively long and no clear climatic factor is limiting, resulting in complacent series (Fritts 2001). Low MBAI values may also indicate other limiting factors, such as soil nutrient status (plot 105) or intraspecific competition (plot 113), while high MBAI may represent more mesic or riparian conditions (plot 115).

Comparing plots dominated by the same species highlights site-specific differences. Plots 127 and 121 were both located at high elevation sites dominated by mountain hemlock but the two plots were associated with different climatic variables and had different rates of growth. Plot 127 was negatively correlated ($P = 0.001$) with summer precipitation and had low MBAI. Plot 121 was positively correlated ($P = 0.01$) with total annual snow depth and had high MBAI. Similarly, though two plots dominated by Douglas-fir had annual BAI correlated with climatic variables (plots 47 and 64) not all sites with Douglas-fir responded to climate. These results indicate the relative importance of site-specific variables versus species in affecting both climatic response and rates of productivity.

Plots with high MBAI had at least one tree >100 cm dbh present (Figure 3a-e). This pattern contrasts with the dbh distribution for all sites combined (Figure 3f) that indicates that most trees had dbh <100 cm. Individual tree data within plots also suggest that large trees contribute disproportionately to MBAI. For example, the plot with the highest MBAI shows a strong relationship between tree size and MBAI (Figure 4). Similarly, plots 135, 136, 47 and 116 have similar elevations (~1000m) but have a range of MBAI values (Table 2). Though differences in species dominance may explain some of this variability, dbh of trees appears more important. Plots 47 and 116 have several trees >50 cm dbh and have relatively high MBAI while plots 135 and 136 have

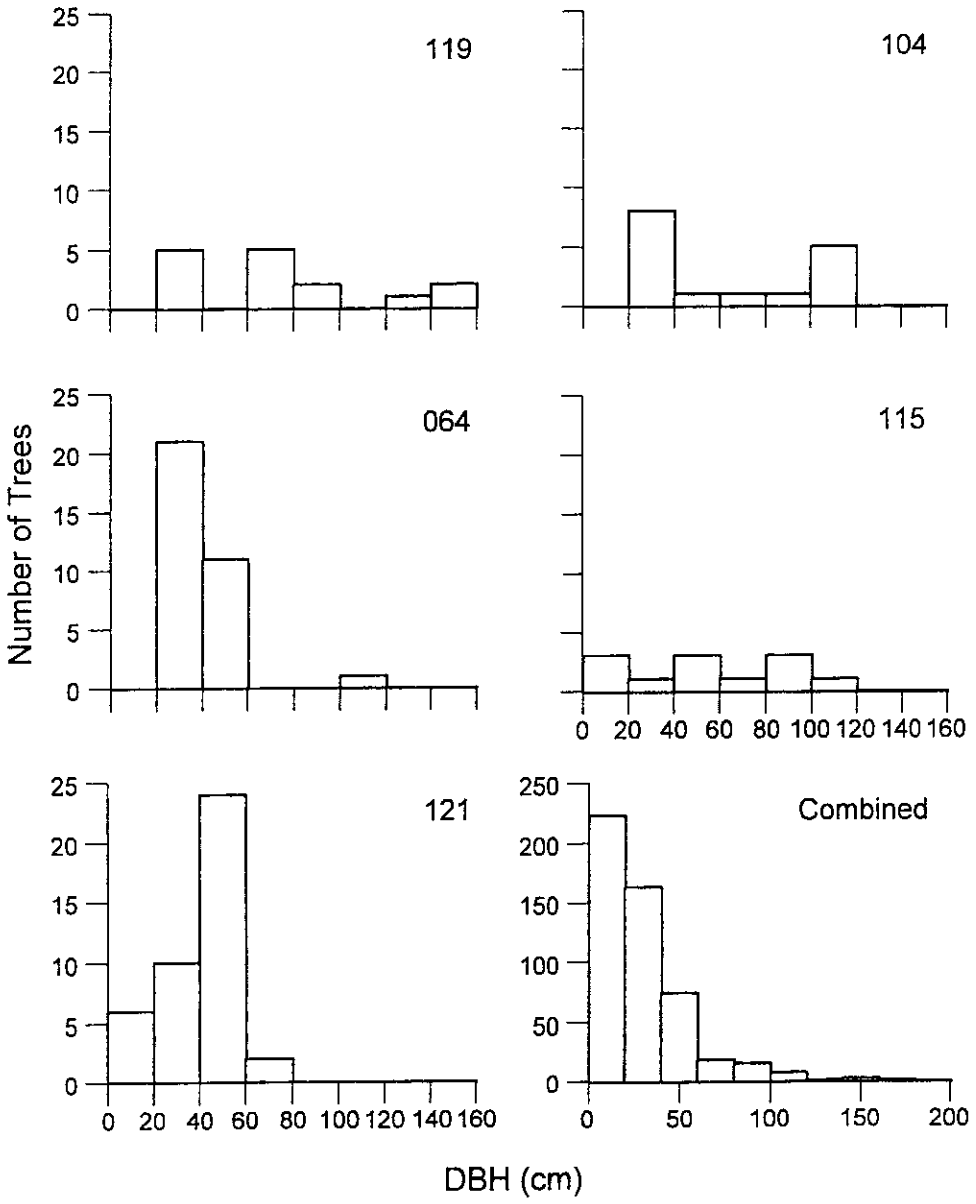

Figure 3. Diameter distributions of five plots with the highest mean annual basal area increment. The diameter distribution of all plots combined suggests that among all plots, few trees are large.

no trees above 30cm dbh and exhibit relatively low MBAI.

Discussion

The relationship between interannual climatic variability and tree growth has been well documented for many tree species growing at the extremes of their range (Fritts 2001). However, because these forests typically have low productivity, it is unlikely that they serve as significant sinks or sources of carbon. We observed four stands with low productivity and sensitivity to climate typical of dendroclimatic reconstruction sites.

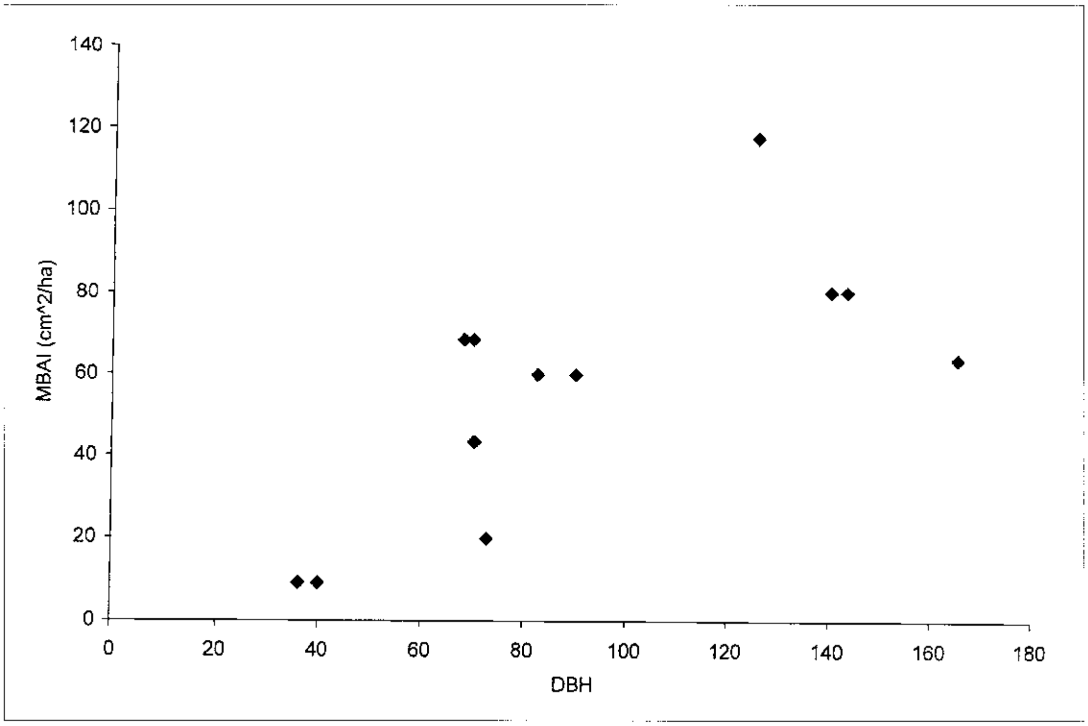

Figure 4. Mean basal area increment (1978-1997) plotted against diameter for plot ST119, the plot with the highest mean basal area increment.

Unlike the highly productive stands, relatively small diameter trees dominated these plots and plots maintained low tree density. Schimel et al. (2002) suggest that the greatest carbon sink in the intermountain west probably occurs above 750 m. Based on our results, we expect that the largest carbon sink should be between approximately 400-1400 m. Above 1400 m, MBAI is extremely low and though rates of decomposition are likely lower due to a short growing season, we expect that this does not compensate for the low rates of productivity we observed. High MBAI does occur at elevations below 750 m, but locations with high productivity may be restricted to moist microclimates where high rates of productivity are offset by high rates of decomposition due to a longer growing season.

Forests with high productivity and sensitivity to climate may be of the most interest in the context of climate change and carbon cycling. Of 23 forested plots, we observed only two stands with high productivity and sensitivity to climate. Though site-specific variability, including variability in tree size, may influence rates of productivity and sensitivity to climate, we suggest that mountain hemlock and Douglas-fir forests of moderate elevation in the North Cascade Range should be further monitored for their potential as carbon sinks (and sources). Some of these forests are productive, responsive to climatic variability, and relatively widespread in mountainous portions of the Pacific Northwest. However, five of seven sites dominated by Douglas-fir at middle elevation (430-900 m) show no sensitivity to climate. Similar studies performed in the Olympic Mountains also demonstrate that Douglas-fir is moderately productive and responsive to climate, though extensive variability exists there as well (Holman 2004).

These conclusions are tempered because BAI is only a proxy measure of past productivity. By failing to measure mortality and litterfall, we have likely overestimated productivity, especially for species with short leaf longevity, stands affected by insect infestations, or other disturbances. However, estimates of aboveground productivity in coniferous forests are commonly based on increment cores and allometric equations (Clark et al. 2001), the most practical and cost-efficient way to estimate aboveground productivity of diverse forest ecosystems in mountainous terrain. Our consistent estimates of MBAI for three alpine larch plots at similar elevations (Table 2) serve to validate our approach. We were interested in relative differences in productivity between forest types, so that small errors resulting from bark thickness and branch mortality should be inconsequential. We also applied productivity estimates from one tree in a size class to all other individuals in that size class. This method affects the accuracy of estimates, but is unbiased. In addition, coring all trees in a plot would have reduced the number of plots and the environmental variability sampled. Monitoring productivity of multiple forest types on an annual basis for two decades would be enormously expensive. Despite the shortcomings mentioned here, all measures of productivity are only estimates. This method is an efficient and cost effective technique that provides an unbiased estimate appropriate for comparing productivity and sensitivity between forest types in mountainous environments, and allows one to evaluate sensitivity to climate over time.

This study has demonstrated that focused research on biogeographic patterns of tree growth and sensitivity can provide insight on how forest productivity is affected by climatic variability, which in turn facilitates inferences on how forest systems will respond to the greenhouse climate of the future. Though several studies have addressed the responsiveness of individual species to climate throughout their range (Peterson and Peterson 1994, Kusnierczyk and Ettl 2002), this study addressed multiple forest types across a range of elevations and aspects. Resource managers have neither the time nor budget to monitor many sites continuously across complex mountainous landscapes. However, a one-time effort that quantifies the range of responses by forest systems to climatic variability can target a small subset of species and locations that serve as biomonitors of trends in productivity related to climatic change and other environmental factors. This approach, currently being evaluated in other areas of the Cascade Range and Olympic Mountains (Fagre and Peterson 2002, Fagre et al. 2003, Nakawatase 2003, Holman 2004), may prove valuable in quantifying trends in forest productivity at regional and subcontinental scales.

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