# BIOMASS AND PRODUCTIVITY IN AN OLD-GROWTH DOUGLAS-FIR /WESTERN HEMLOCK STAND IN THE WESTERN CASCADES OF OREGON

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## ABSTRACT

Annual bole productivity was determined for a 0.25-ha old-growth Douglas-fir (*Pseudotsuga menziesii*)/western hemlock (*Tsuga heterophylla*) stand in western Oregon for a 29-year period using increment cores, repetitive stem diameter remeasurement and mortality monitoring. Annual values for fine and coarse litterfall were estimated for an 18-year period. These data were analyzed to investigate changes in standing bole biomass with time, annual variation in bole productivity, monthly and annual patterns of litterfall, and the correlation between bole productivity and litterfall. The effects of climatic variables (precipitation, maximum and minimum temperature), treefall, and atmospheric carbon dioxide on bole productivity were also examined.

Standing bole biomass increased from 543 Mg/ha in 1971 to 587 Mg/ha in 1999, with mortality accounting for 1.1 Mg/ha/yr. Annual bole productivity averaged 2.7 Mg/ha/yr and followed an upward trend of 0.0125 Mg/ha/yr. Fine litterfall ranged from 2.2 Mg/ha/yr to 3.3 Mg/ha/yr. No relationship was apparent between bole productivity and litterfall.

The critical time period for cumulative precipitation in predicting annual bole productivity was from mid-May to mid-July. Annual bole productivity was best predicted by mean maximum temperature during this same time period, with higher temperatures projecting lower productivity for the year. When using mean minimum temperature as a predictor for bole productivity, the critical period extended from mid-April to mid-August.

Because it has been shown in earlier studies that productivity in old-growth forests either reaches a "steady state" or declines over time (Grier & Logan 1977, DeBell & Franklin 1987), it could be argued that the upward trend in productivity in this stand corresponds to the similar trend in atmospheric carbon dioxide. However, a closer analysis of the available long-term data indicates that it is likely that some trees within the stand experienced accelerated growth following treefalls on the edge of the stand, and that this growth response accounts for the upward trend in productivity for the stand as a whole.

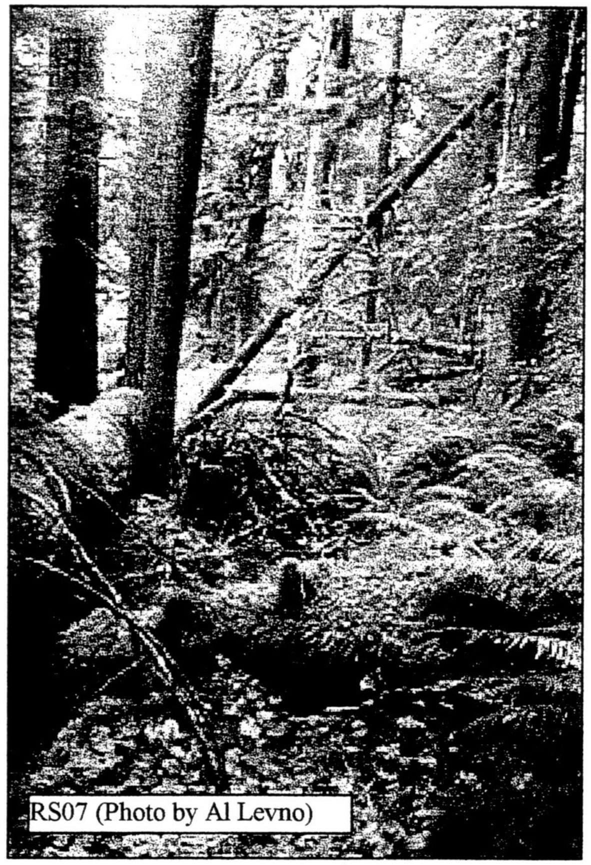
These results illustrate 1) the value of long-term data sets in this line of research and 2) the importance of examining local effects before applying results on an expanded scale. Because this long-term reference stand is only one of many in an extensive network, an excellent opportunity exists to examine productivity trends on larger spatial and temporal scales.

## INTRODUCTION

Increasing attention has been given to forests as a means of offsetting anthropogenic carbon dioxide ($CO_2$) inputs to the atmosphere. There is no question that old-growth forests in the Pacific Northwest store large amounts of carbon (Harmon *et al.* 1990). However, the rate at which these forests accumulate carbon over time is not entirely clear. Some studies have suggested that productivity in old-growth forests is equally balanced, or even exceeded, by mortality (Grier & Logan 1977, DeBell & Franklin 1987, Ryan *et al.* 1997). Research stations such as HJ Andrews Experimental Forest (AEF) are addressing a series of questions relating to carbon dioxide fluxes in forests. The purpose of this study was to gather data on one old-growth stand in the HJ Andrews Experimental Forest and analyze the carbon dynamics of this stand.

For the purposes of this study, two components of annual productivity in an old-growth Douglas-fir (*Pseudotsuga menziesii*) forest were calculated: bole production (wood plus bark) and litterfall. Base estimates of annual bole productivity were determined for a period of 29 years (1971 – 1999) using radial growth rings from increment cores. The long-term data sets available at AEF allowed a unique opportunity to adjust these estimates to account for all trees present over the course of the study, including ingrowth and those trees that died before increment cores were taken. Litterfall was collected at AEF for 18 years and thus provided another source of long-term productivity data.

Using these data sets, changes in standing bole biomass with time, annual variation in bole productivity, temporal patterns of litterfall, and the effects of treefall on productivity were analyzed. In addition,



RS07 (Photo by Al Levno)

bole productivity and litterfall estimates were compared to look for a possible correlation. The relationship between bole productivity and climatic variables was also investigated. Finally, the potential link between bole productivity and $CO_2$ in the atmosphere was examined.

## DESCRIPTION OF STUDY AREA

The study area, Reference Stand 7 (RS07), lies within the 6,400-ha H.J. Andrews Experimental Forest, in the central-western Cascade Range of Oregon, approximately 65 km east of Eugene. RS07 is located at 44°21' north latitude and 122°25' west longitude in Watershed 2 (WS02), one of AEF's control watersheds. The stand is 0.25-ha in size (50 m x 50 m square) and is situated on a 50-60% slope of north-facing aspect, at 490 m elevation. It is classified as an old-growth forest, with dominant trees $400^+$ years in age. The canopy is dominated by Douglas-fir (*Pseudotsuga menziesii*) of 50-70 m in height, with western hemlock (*Tsuga heterophylla*) and western redcedar (*Thuja plicata*) comprising a large portion of the canopy, though at lesser heights. The latter two species also make up a substantial proportion of the subcanopy and tall shrub strata, with vine maple (*Acer circinatum*), Pacific yew (*Taxus brevifolia*), and Pacific dogwood (*Cornus nuttallii*) also contributing to the tall shrub layer.

RS07, established in 1971, is one of 38 reference stands located in and around AEF, selected to represent a typical regional forest community type. Under this system it is classified as a *Tsuga heterophylla / Polystichum munitum – Oxalis oregana* plant association (the latter two species are herbaceous). As part of this network of permanent plots, periodic data has been collected on the trees of this stand (Dyrness & Acker 1999). In addition, long-term litterfall, meteorological, and hydrologic data are available for the study area.

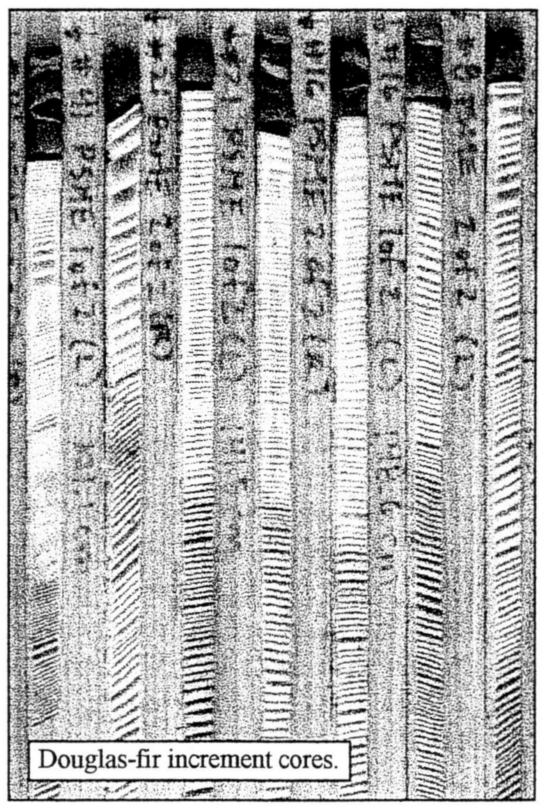
## METHODS

### Bole Biomass & Productivity Estimation

When RS07 was established in 1971, all trees ≥ 5 cm in diameter at breast height (dbh, 1.37 m) were tagged and mapped. Data recorded for each of these trees included species, dbh, vigor, and crown and bole condition. Trees were remeasured in 1976, 1981, 1986, 1990, and 1996. During these remeasurements, ingrowth trees were tagged and added to the data set. For most of this time period, annual mortality counts were also conducted. Heights of selected trees were measured in 1972 and 1986 (Dyrness & Acker 1999).

Based upon the 1996 remeasurement data for dbh, a sampling protocol was established for taking increment cores in June and July of 2000. Smaller trees were sampled less intensively than larger trees in order to protect the long-term health and integrity of the stand. Two cores were taken from all trees ≥ 15 cm dbh (in 1996), with a minimum of 90 degrees separating the cores. One core was taken from all trees ≥ 8 and < 15 cm dbh, and no cores from trees < 8 cm dbh. Seventy-four of the 101 tagged trees were cored. The dbh of all tagged trees was also recorded in 2000.

The cores were dried, mounted, and sanded. The ring widths from 1971-1999 were measured using a microscope with movable stage, video monitor, and tree ring computer program. Of the 128 cores taken, 124 were in a condition adequate for measurement and 4 were damaged or too difficult to read. Three cores had > 15, but less than a full set of rings. For these cores,



Douglas-fir increment cores.

Table 1: Variables for Allometric Equations (Acker, 2001)

| Species | $b_0$ | $b_1$ | Bark volume to wood volume ratio | Bark density ($Mg/m^3$) | Wood density ($Mg/m^3$) |
|---|---|---|---|---|---|
| PSME | 0.0003381500 | 2.240783 | 0.290 | 0.438 | 0.452 |
| THPL | 0.0003339420 | 2.197256 | 0.082 | 0.333 | 0.312 |
| TSHE | 0.0003720880 | 2.259720 | 0.124 | 0.415 | 0.421 |
| *Where wood volume = $b_0$*($dbh$^$b_1$). Wood volume is in $m^3$, dbh in cm, and biomass in Mg.* | | | | | |

the average ring width was calculated and that average attributed across the remaining years. The 2000 ring, if present, was measured but recorded as an incomplete year of growth. Average ring widths were then calculated for trees with multiple cores. Using allometric equations for the three dominant species (PSME--*Pseudotsuga menziesii*, TSHE--*Tsuga heterophylla*, and THPL--*Thuja plicata*), bole biomass and annual bole productivity were calculated for each tree for each year (Table 1).

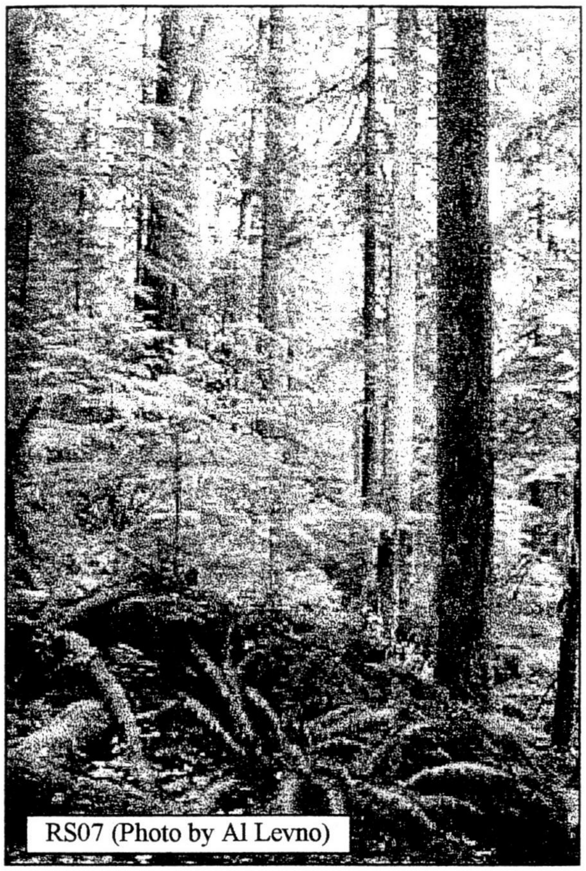
These values were summed to generate base estimates of annual bole productivity and standing biomass for the total stand and by species. A regression line was fit through the annual productivity data points to determine to what extent each year's growth varied from the trend.

The base estimate was then adjusted to account for mortality, damaged cores, and tagged trees less than 8 cm dbh. An initial diameter was available (in the HJ Andrews database) for each of the trees unaccounted for in the base estimate. For those trees present in 1971, the initial diameter was ascribed to that year. For ingrowth, the initial diameter was attributed to the first year in which it was recorded in the remeasurement data (1976, 1981, 1986, 1990, or 1996). A final diameter and the year of mortality were available from annual mortality counts. For those trees still alive in 2000, the 2000 diameter was the final diameter. Nine trees were recorded as having a decreasing diameter over time (likely due to measurement error). In these instances, the smaller of the diameters was used for both the initial and final diameter growth (i.e. diameter increase was zero).

Based on the initial and final diameter values, a net diameter increase was calculated. This increase was evenly distributed over the years between 1971 and 2000 during which each tree was alive. Using the same allometric equations, standing bole biomass and annual bole productivity were calculated for each of these trees. Two other species were present, Pacific dogwood *(Cornus nuttallii)* and Pacific yew (*Taxus brevifolia)*. The allometric equation for western hemlock was used to make the calculations for these species. Annual productivity sums from these added trees were adjusted based upon the regression data to reflect differences in growth from year to year. The two data sets were merged to obtain annual values of standing bole biomass and annual bole productivity for the entire stand on a per hectare basis.

**Estimation of Monthly and Annual Litterfall**

Litterfall was collected in RS07 from 1977 to 1995, between 6 and 15 times per year. Between 1977 and 1992, litterfall in the stand was collected in six 1-$m^2$ traps. Between 1990 and 1995, litter was collected in six plastic buckets, each with a cross-sectional area of 0.0661 $m^2$. After collection litterfall was oven-dried and stored. In the early 1980's, the litterfall from 1977 to mid-




1981 was finely sorted into 15 different categories. In July 2000, the litterfall collected from mid-1981 to 1995 was sorted into two categories: fine and coarse. The coarse litterfall included twigs, bark, cones, and deciduous leaves. The fine litterfall consisted primarily of needles and cedar scales. The litterfall was then oven-dried and weighed.

The 1977-81 litterfall data set was consolidated into coarse and fine categories and added to the 2000 data set. Average litterfall amounts were calculated for each collection date, and those amounts were evenly apportioned over the preceding collection period. Estimates of average monthly litterfall were determined over the 18-year collection period. Annual estimates for fine and coarse litterfall were also calculated, based upon the litter year, March 1 – February 28. For example, litterfall attributed to the 1990-91 season fell between March 1, 1990 and February 28, 1991. Selection of the litter year was based upon an analysis of litterfall patterns throughout the year, knowledge of the onset of the leaf and wood production in the region, and monthly rainfall patterns.

## Comparisons Within and Among Data Sets

*Annual Bole Productivity and Litterfall*

In order to look for a relationship between annual bole productivity and litterfall, the correlation coefficient was calculated between the yearly estimates for each. Because conifers retain their needles for more than one year, the correlation coefficients were also calculated for one, two, three, four, and five-year time lags in litterfall. For example, a one-year time lag would consider the 1977-1978 bole productivity estimate versus the 1978-1979 litterfall estimate.

*Annual Bole Productivity versus Temperature and Precipitation*

Similarly, the relationships between annual bole productivity and precipitation, and bole productivity and temperature (both maximum and minimum) were examined. The purpose of this exercise was to optimize the predictability of bole productivity using climatic data. Rather than using the standard procedure of comparing bole productivity estimates to yearly or monthly values of precipitation and temperature, they were instead compared to various blocks of time within the growing season.

In order to do this for maximum temperature, the approximate middle of the growing season was used as a start date, and the mean maximum temperature calculated including 5 days on either side of that date (10 days total) for each year. These values were compared to annual productivity values by calculating a simple correlation coefficient. Next, this 10-day period was expanded to include ± 5 more days (20 days total), the correlation coefficient calculated, and so on. This process was repeated using different start dates to achieve higher levels of predictability. The period of time associated with the maximum correlation coefficient represents the most critical period of the growing season in influencing bole productivity for the year. This procedure was also applied to minimum temperature values.

The same methodology was used to compare cumulative precipitation to bole productivity in different time periods, but with a second, added approach. In addition to expanding the time period from the middle of the growing season outward, it was also expanded in a linear fashion. That is, bole productivity was compared to precipitation in the first days of the growing season, and the period of time was gradually extended to include more and more of the days that followed. The start date was then shifted and the correlation coefficients recalculated.

*Annual Bole Productivity versus $CO_2$*

Annual bole productivity was also compared against $CO_2$ levels in the atmosphere recorded at Mauna Loa, Hawaii (Keeling 2000) by calculating the correlation coefficient between the two measures.

*Effects of Disturbance on Bole Productivity*

In the course of collecting data, it was observed that recent disturbances due to treefalls had occurred near and within the stand. Because it was suspected that the canopy gaps created by these treefalls enhanced productivity for nearby trees, a comparison of bole productivity was made between trees on the edge of the gap and trees in the stand interior. Average productivity per year per tree was calculated for edge and interior trees for three time periods (1971-1999, 1971-1985, and 1986-1999) and regression lines fit through these estimates.

**Figure 1: Standing Bole Biomass**

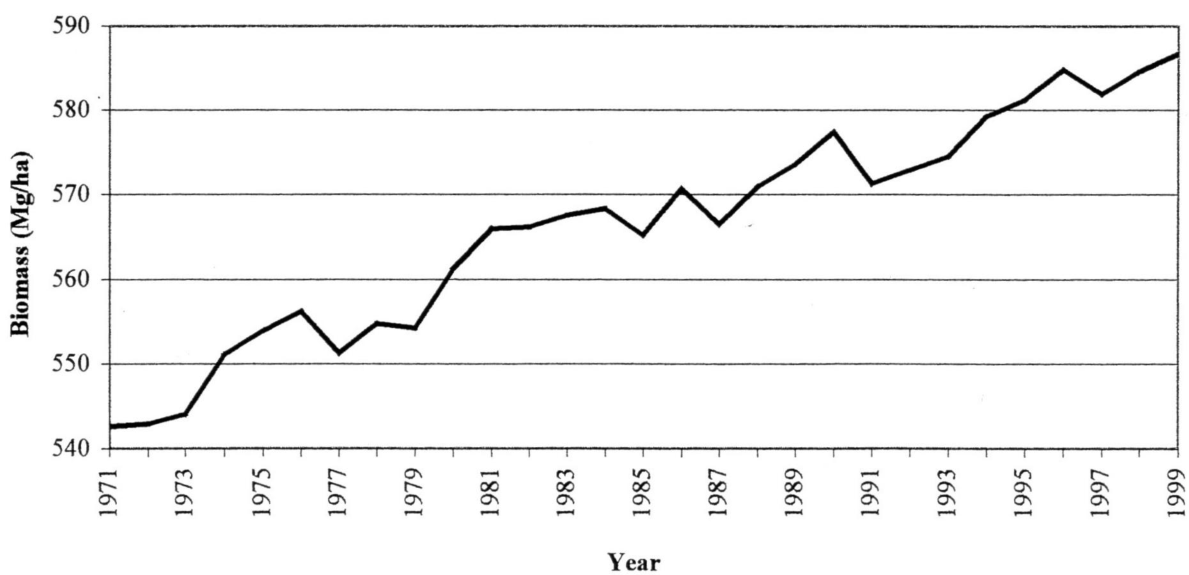


**Figure 2:**
**Contribution to Standing Bole Biomass**
(average from 1971-1999)

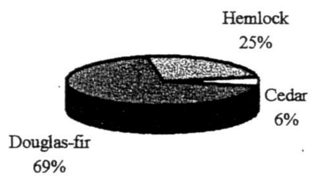
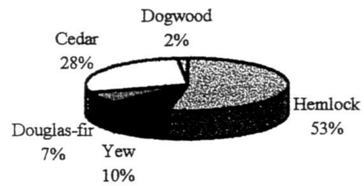



**Figure 3:**
**Contribution to Stem Density**
(including all individuals from 1971-1999)




## RESULTS & DISCUSSION

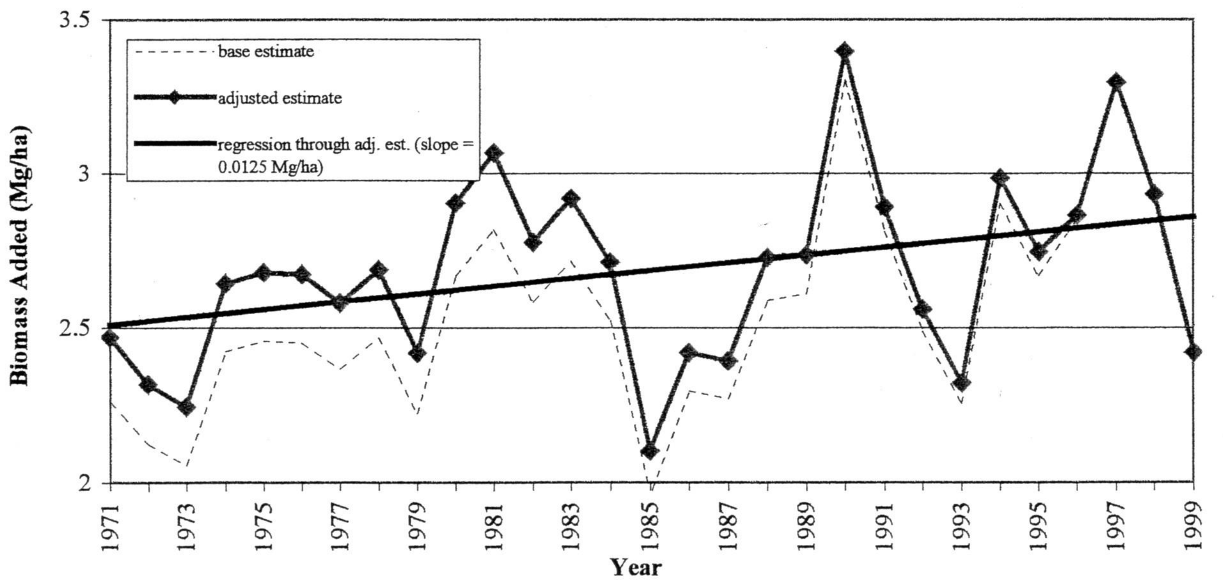
### Standing Bole Biomass & Stem Density

The annual estimates for standing bole biomass are presented in Figure 1. According to these estimates, the standing bole biomass in RS07 has been steadily increasing with time--from 543 Mg/ha in 1971 to 587 Mg/ha in 1999. Even in years following the mortality of large trees in the stand (evident in the short-term declines of the curve), the biomass level recovered quickly and continued its upward trend.

Assuming that carbon accounts for roughly 50% of the wood and bark composition, this equates to the stand sequestering 760 kg/ha of carbon in bole biomass each year. As it does not include branches and belowground biomass, this is a conservative estimate of carbon sequestration in the stand. These results differ from those found in other related studies. DeBell & Franklin (1987) analyzed a 36-year record of growth in a similar stand and found that increase in net timber volume was essentially zero, with gross volume growth balanced by mortality over the course of the study. Their results indicated a net volume gain of 1-2%, while the stand in this study showed an 8% net increase in bole biomass over a 30-year period.

Figures 2 & 3 illustrate contribution by species to standing bole biomass and stem density within the stand. The total number of individuals contributing to the standing bole biomass over the course of the study was

**Figure 4: Annual Bole Productivity**



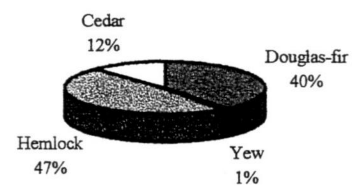
121, with approximately 100 live stems at any given time. Twenty-two individuals died between 1971 and 1999, representing a loss of 1.1 Mg/ha of standing bole biomass per year.

At 69%, Douglas-fir accounted for the largest proportion of standing bole biomass, even though it only represented 7% of individuals in the stand. All Douglas-fir trees were greater than one meter in diameter. Hemlock contributed 25% of the standing bole biomass and 53% of the stems, while cedar 6% of biomass and 28% of stems. These two species were represented by trees in both the large and small diameter classes. Individuals of yew and dogwood each contributed less than 1% of biomass but 10% and 2% of stems, respectively. Between 1971 and 1999, significant mortality of yew was balanced by ingrowth of cedar.

**Annual Bole Productivity**

Figure 4 shows annual estimates of bole productivity from 1971-1999. The base estimate reflects the annual productivity of all trees with readable cores. The adjusted estimate also includes 1) trees with unreadable cores, 2) trees that were too small to core, and 3) trees which died before 1999. The large difference in the earlier years can be attributed to the mortality of several large individuals of hemlock in the 1970's and 1980's. Before dying they contributed measurably to annual productivity in the stand.

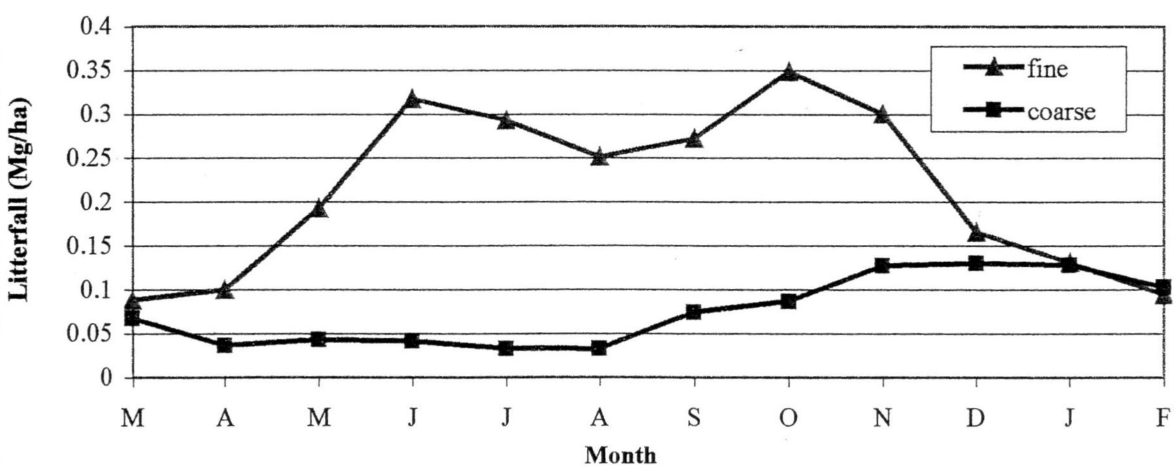
**Figure 5:**
**Contribution to Annual Bole Productivity**
(average from 1971-1999)

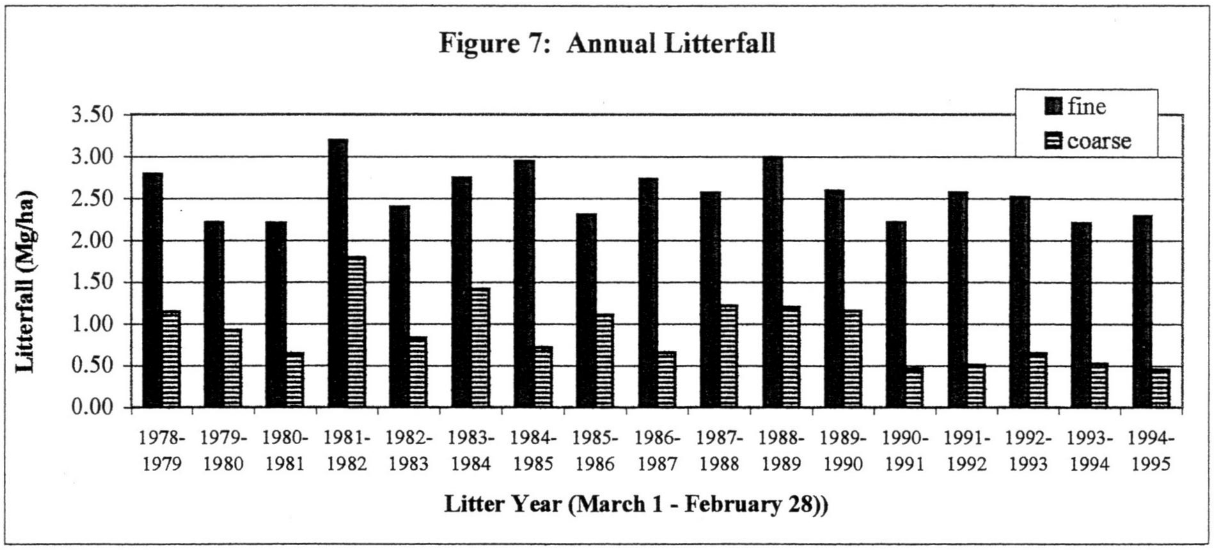



Annual bole productivity values ranged from 2.2 Mg/ha/yr to 3.4 Mg/ha/yr. The average bole productivity from 1971-1999 was 2.7 Mg/ha/yr with a slight upward trend (0.0125 Mg/ha/yr). This upward trend is not consistent with the general contention that old growth forests are in a "steady state" in terms of production (Ryan *et al.* 1997).

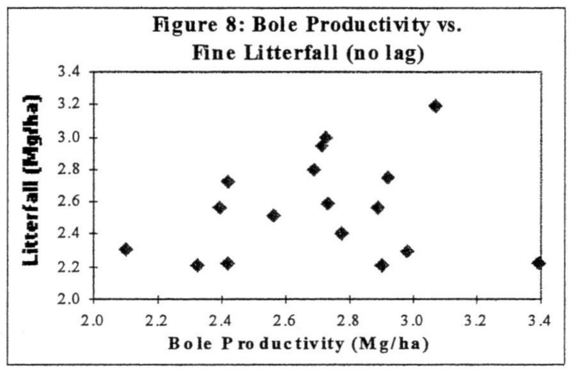
During the time period under consideration, Douglas-fir accounted for 40%, hemlock for 47%, and cedar for 12% of total annual productivity (Figure 5). Thus, while Douglas-fir comprised the

**Figure 6: Monthly Litterfall**
(Average from 1977-1994)



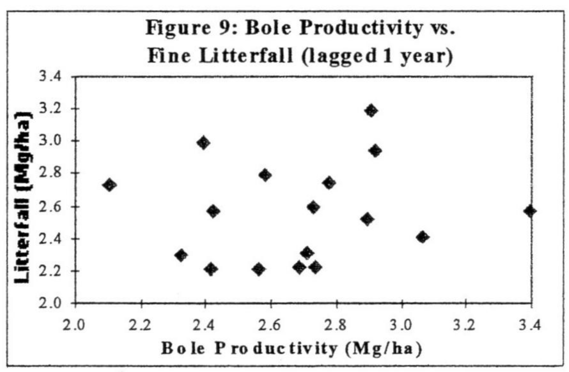



majority of standing bole biomass, it ranked second after hemlock in annual bole productivity. Within other stands at AEF, Grier & Logan (1977) found similar trends in contribution by species to biomass and productivity. With mortality of the dominant Douglas-fir individuals, and the lack of Douglas-fir in the subcanopy and understory, we would expect hemlock and cedar to account for larger and larger proportions of annual bole productivity and biomass over time.




## Monthly and Annual Litterfall Estimates

Figure 6 illustrates the temporal distribution of litterfall, based upon averages over 18 years. Fine litterfall was relatively low between the months of January and April, and increased with the onset of spring. There were pulses of fine litterfall in June and October, with high amounts of litterfall throughout the summer months.




The pattern of coarse litterfall was distinctly different than that for fine litterfall, with the heaviest litterfall months in late fall and winter. This coincides with damage that would be expected from snow and ice during the cold months (Grier 1988).

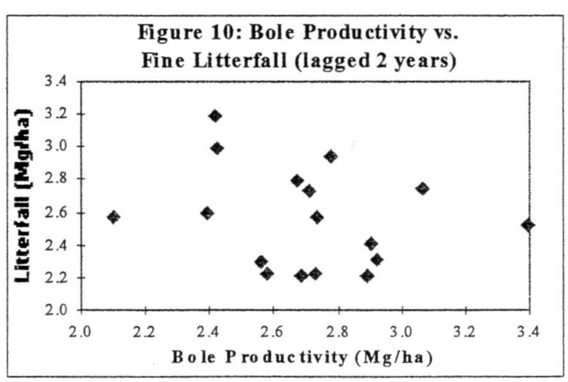
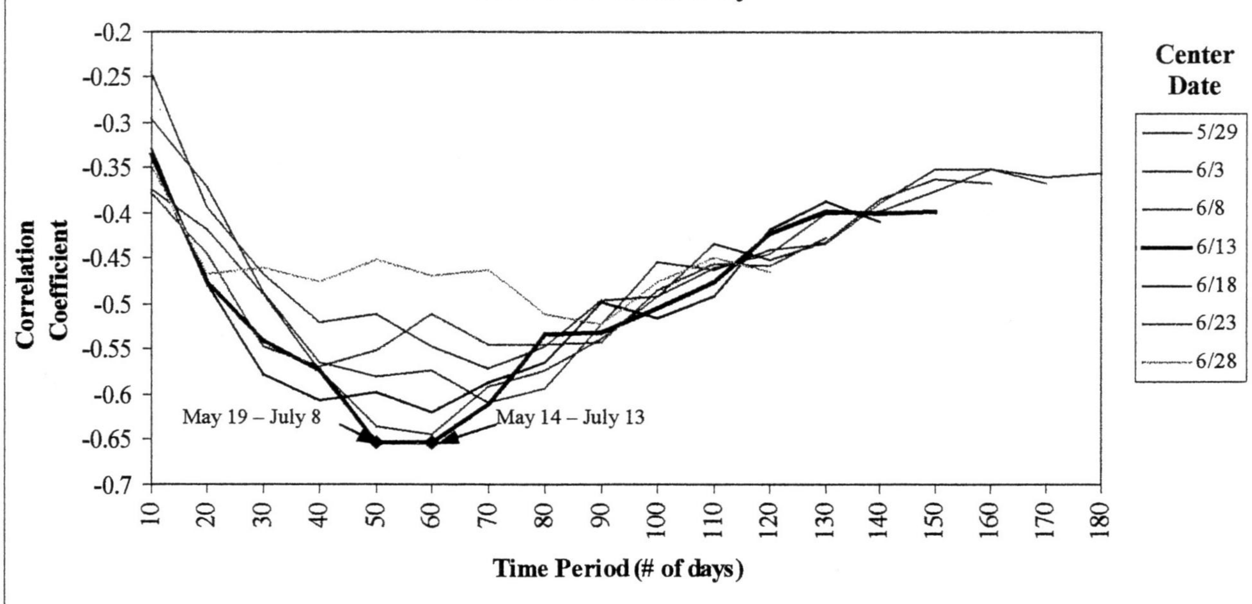



Figure 7 is a graph of annual litterfall, based upon the litter year March 1 –

**Figure 11 : Mean Maximum Temperature vs. Bole Productivity**




February 28, which encompasses both the June and October pulses of litterfall. Annual values of fine litterfall ranged from 2.2 Mg/ha to 3.3 Mg/ha, with an average of 2.6 Mg/ha. Coarse litterfall averaged 0.9 Mg/ha, and had a range of 0.5 Mg/ha to 2.0 Mg/ha.

## Comparisons Among Data Sets

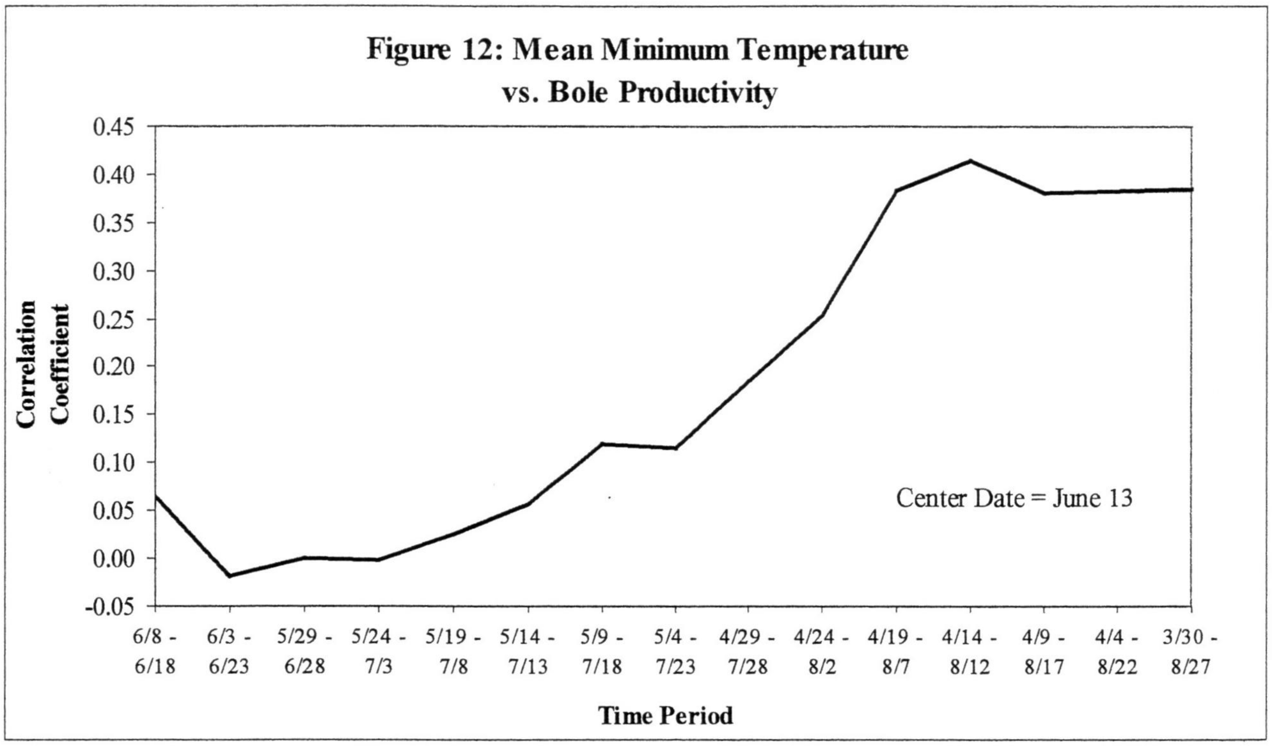
*Bole Productivity and Litterfall*

In comparing annual bole productivity and litterfall, no strong relationship was apparent between the two measures, with or without an included lag in litterfall. Figures 8-10 illustrate some of these comparisons.

*Annual Bole Productivity versus Temperature and Precipitation*

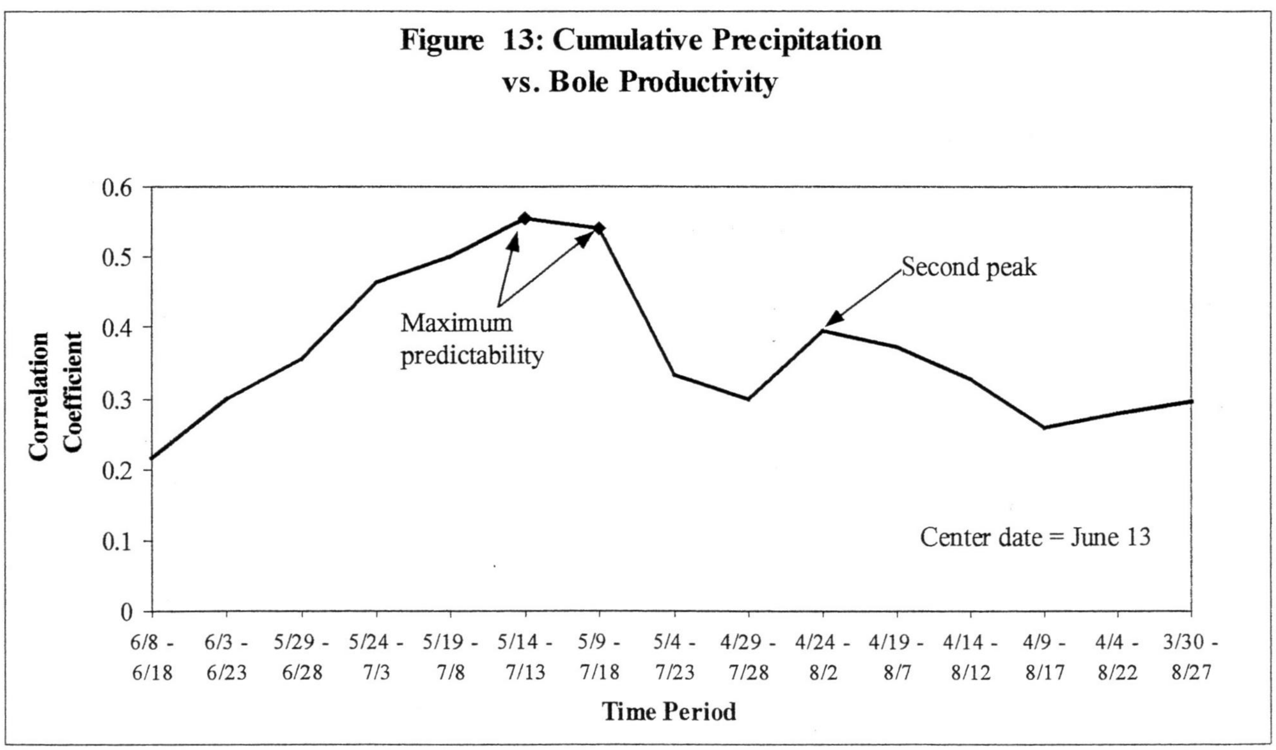
Figure 11 shows not only the results of comparing mean maximum temperature and bole productivity, but it also illustrates the process by which they were compared. Each line shows the correlation coefficients generated using a different starting point. The x-axis represents the length of the time period over which the mean maximum temperature was calculated (10 days = 5 days on either side of the center date). Bole productivity was best predicted by using June 13 as the center date, and by calculating the mean maximum temperature from May 19 - July 8 or May 14 - July 13. The negative correlation suggests that a higher average temperature over this time period leads to lower levels of bole productivity for the year.

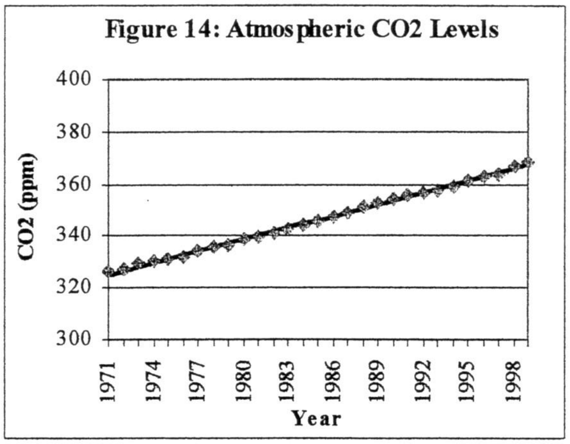
Figure 12 demonstrates that the critical period of time for mean minimum temperature in predicting bole productivity is different than that for mean maximum temperature. The correlation between mean temperature was weak when only temperatures in the middle of the growing season were used. The relationship strengthened when temperatures in the earlier and latter parts of the growing season were included. The positive correlation suggests that annual bole productivity can be best predicted using the mean minimum temperature between mid-April and mid-August.

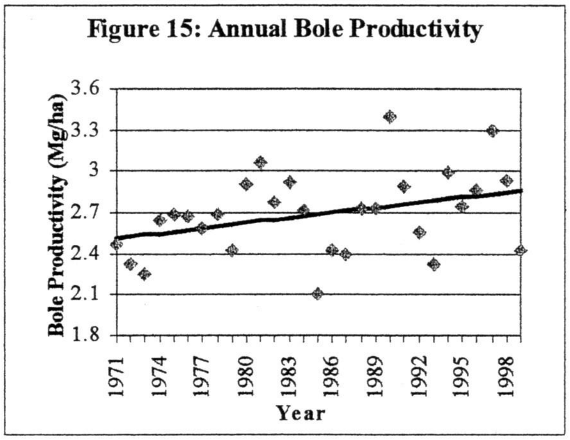



In analyzing the relationship between precipitation and annual bole productivity, the critical period of time was similar to that for maximum temperature. Cumulative precipitation from May 14 - July 13 or May 9 - July 18 was the best predictor of annual productivity. High cumulative precipitation during these time periods forecasts high bole productivity for the year.

The second peak indicates that there is another critical period of precipitation,






which spans a broader period of time. However, it was not possible by the first method to determine whether it was precipitation in the spring or late summer which caused this second peak. By calculating cumulative precipitation from the start of the growing season on (the first 10 days, the first 20 days, etc.) and successively shifting the start date, it became evident that the second peak was driven by the latter half of the summer. Because the latter part of July and August are typically very dry in Oregon, this indicates that precipitation during this time gives an extra boost to the year's productivity.

*Annual Bole Productivity versus $CO_2$*

Figures 14 and 15 show trends in annual bole productivity on RS07 and $CO_2$ levels in the atmosphere between 1971 and 1999. Enhanced $CO_2$ concentrations present one possible explanation for the increasing productivity in a supposedly "steady state" old-growth ecosystem.

*Effects of Disturbance and Topography on Bole Productivity*

Analyzing the effects of canopy openings provides another means of accounting for the stand's increasing productivity. Two dominant Douglas-fir individuals fell on the north edge of the stand, creating significant openings. One individual fell just outside the stand, parallel to the northern edge, while the other fell into the stand from the northeast corner, killing and/or damaging several individuals. The latter treefall probably occurred on or around 1986, when the mortality data indicates the death of two large hemlock stems that were in the path of the fallen tree.

Figures 16 - 18 show regression lines fit through the average bole productivity values for the edge, interior, and all individuals in the stand. The edge group had higher growth on average than the interior group, both before and after the disturbance. This higher productivity is likely due to the position of the edge trees at the base of the slope, in closer proximity to the stream.

In comparing productivity pre- and post-1986, the average productivity of edge trees clearly increased during the latter period. The average bole productivity of the interior trees, on the other hand, was generally constant over time. This suggests that productivity of the edge trees was enhanced by canopy gaps. The productivity of the stand as a whole increased over time, but it is possible that in the absence of this disturbance, productivity would have been constant between 1971 and 1999.

**Figure 16: Average Bole Productivity for Edge Trees** (regression line)

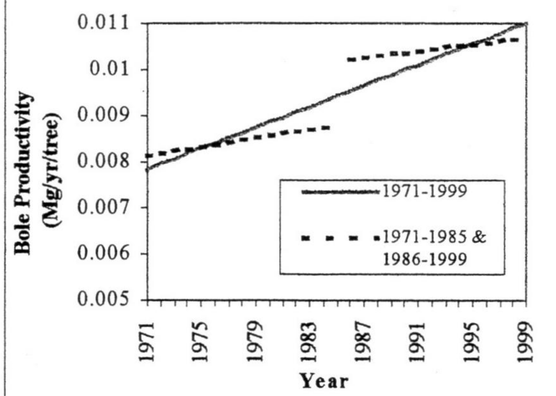



**Figure 17: Average Bole Productivity for Interior Trees** (regression line)

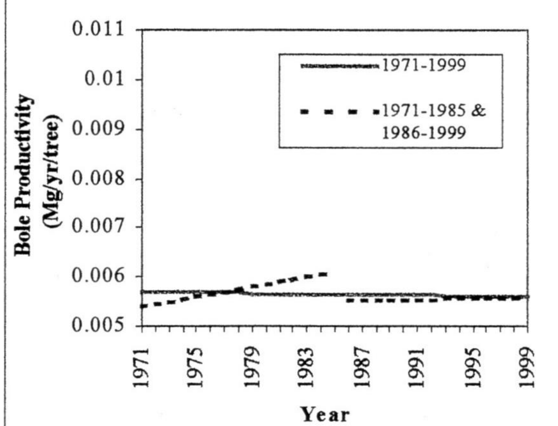
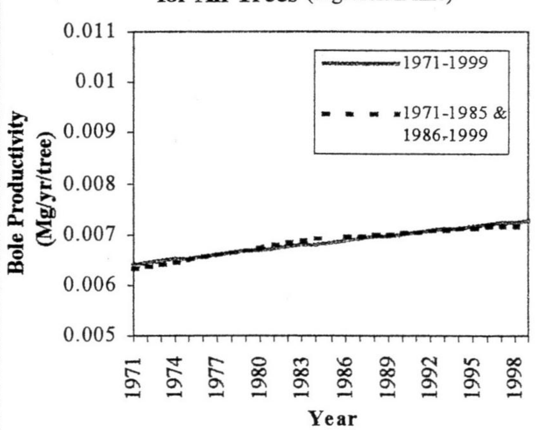



**Figure 18: Average Bole Productivity for All Trees** (regression line)




## CONCLUSION

Perhaps the most significant finding of this study is that RS07 had a net increase in carbon storage in bole biomass over the past 29 years. Standing bole biomass increased by 8%, from 543 Mg/ha in 1971 to 587 Mg/ha in 1999. Annual bole productivity exceeded mortality (2.7 Mg/ha/yr and 1.1 Mg/ha/yr, respectively). These findings are contrary to past findings indicating that mortality is equal to or greater than annual productivity in similar old-growth forests.

However, if examined on a larger scale, both spatially and temporally, the findings might have been very different. For example, if the study area had been larger in size, the treefalls on the edge of the stand would likely have been *within* the stand. The mortality of these very large individuals might have cancelled out or diminished any productivity gains within the stand. Further, if the study period were extended for any length of time, even a few years, it is inevitable that one of the Douglas-fir trees would die. The Douglas-fir trees within the stand are currently 11.3 Mg on average, and the stand is 0.25-ha, so this would represent 45 Mg on a per hectare basis. Mortality of this one individual would reduce the standing bole biomass to 542 Mg/ha--virtually identical to the standing bole biomass at the beginning of the study.

This thought exercise argues for the importance of conducting similar studies before applying findings to a larger context. Fortunately, the network of permanent plots already established within AEF and across the Pacific Northwest provide the long-term data sets necessary for pursuing these research questions on larger, and multiple, scales.

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1) LTER Reference Stand System (PI--McKee, W. Arthur; Franklin, Jerry F.; Greene, Sarah E.; Acker, Steven A.)
2) HJ Andrews Meteorological Data (PI--McKee, W. Arthur; Greenland, D.; Daly, C.; Grant, G.)
3) H.J. Andrews Reference Stand Component Litterfall Study (PI--McKee, W. Arthur; Harmon, Mark)

Photographs of Reference Stand 07 included in this paper were taken by Al Levno of the US Forest Service.

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