John Duff Bailey, School of Forestry, Northern Arizona University, Flagstaff, Arizona 86011-5018

and

Leon H. Liegel, USDA Forest Service, Pacific Northwest Research Station, Corvallis, Oregon 97331

Pacific Yew (*Taxus brevifolia* Nutt.) Growth and Site Factors in Western Oregon

Abstract

Conservation biologists in the Pacific Northwest have recently turned their attention to Pacific yew (*Taxus brevifolia* Nutt.), given past harvest of this species for taxol and the fragmentation of late-successional forested landscapes. Understanding yew growth and reproduction patterns is important given interest in the long-term viability of yew populations and important contributions this species makes to stand structure. Our research, based on data from 11 intensively measured 2-ha plots, confirms and quantifies some early qualitative observations of yew tree size and age distributions in three forested subregions of western Oregon. These distributions show a general lack of regeneration in the last century, which should be of some concern to land managers given Pacific yew's contribution to late-successional stand structure. Although correlations between size measurements, for example between diameter and height, are strong (coefficients > 0.61 across all plots) and consistently positive, correlations between size and site variables (e.g., aspect) are weaker (coefficients < 0.41 across all plots) and inconsistent. Most plots demonstrated a weak but consistent relationship between size and age, and yew tree size and age distributions were relatively consistent within subregions. However, there were substantial differences in diameter growth rates among subregions.

Introduction

Pacific yew is a relatively slow-growing, coniferous tree species found in the understory of undisturbed forests from northern California to central British Columbia, and inland to Idaho (Bolsinger and Jaramillo 1990). Through the early 1990s, yew bark was the only approved source of taxol, a drug used to treat several forms of cancerous tumors (Wani et al. 1971, Rowinsky et al. 1990). Demands for taxol dramatically accelerated the harvest - both legal and illegal - of yew trees growing on private and federal forests in Oregon, Washington, and California. This acceleration threatened the distribution and demographics of the species at local and regional levels, drawing the attention of scientists, federal land managers, and conservationists. Advances in taxol synthesis allowed the Bristol-Myers-Squibb Corporation to stop purchasing Pacific yew bark from federal lands in 1992. However, past and current logging practices that increase fragmentation of large late-successional forested landscapes still focus attention on the conservation biology of Taxus and other genera growing in Pacific Northwest forests (Spies et al. 1994; Busing et al. 1995).

Yew trees are extremely shade tolerant and occur as scattered individuals or clumps across diverse landscapes, being most abundant in the understory of older forests lacking recent large-scale disturbance (Busing et al. 1995). Though undocumented, yew tree growth in undisturbed forests likely follows a sigmoidal curve or related growth pattern over time. Yew trees survive and their radial growth increases following partial overstory removal associated with thinning or shelterwood treatments (Bailey and Liegel 1997). However, yew foliage is harmed by sun, wind, or cold exposure following heavy canopy removal associated with clearcut logging (Bolsinger and Jaramillo 1990; Busing et al. 1995). Vegetative reproduction from stumps is common following cutting; yew can sprout from damaged or buried stems and branches even if most of the tree is killed (Bolsinger and Jaramillo 1990; Minore and Weatherly 1996). However, clearcut logging and site burning after harvest severely limit regeneration (Busing et al. 1995). These limits on regeneration and the cutting of older individuals in the population have had major impacts on landscape demographics.

Information on specific site and stand factors that influence Pacific yew populations is limited; thus, it is difficult to build models that predict tree and regeneration locations within forests or to identify optimal environmental conditions for culturing yew for understory structure in managed stands. Busing and Spies (1995) used long-term data sets to develop a preliminary stand-level model of Pacific yew population dynamics, and they called for additional models to characterize growth dynamics and autecology of yew across diverse landscapes. Our intent in this paper is to further the understanding of yew size and age structure and potential environmental factors regulating yew populations in western Oregon.

We present results from a research effort designed to identify site and stand factors associated with yew populations. We characterized the surrounding landscape, over- and understory vegetation, site history, and reproduction in late-successional Douglas-fir stands. We also quantitatively and qualitatively compared sizes and ages of yew trees both within and across western Oregon subregions. Such information provides a basis for constructing sound hypotheses about the spatial arrangement of yew within landscapes and for predicting yew size and age structure for specific environmental conditions.

Methods and Materials

Study plots were located in three physiographic subregions of western Oregon Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) forests (Figure 1): Central Cascades (4 plots), Willamette Valley (4 plots), and Coast Range (3 plots). These are referred to as Cascade, Valley, or Coast in the rest of the text. All 11 sites had characteristics typically associated with late-successional Douglas-fir stands: large living trees >200 years old, large snags, and a multi-storied canopy (Franklin and Spies 1991). Three sites had a recent history of partial harvesting (Table 1). Two-ha square plots, 142 m per side, were established in the first 3-4 stands located per subregion in which preliminary reconnaissance indicated the presence of more than 10 yew trees/ha over a broad area (a moderate-to-high density). Plots had randomly located corners, referenced to the stand entry point. For each plot, we mapped individual tree location by diameter class for all yews with a diameter at breast height (DBH) of at least 7.5 cm. We also surveyed four 10-m fixed-radius subplots within each plot to characterize over- and understory tree composition and density in the 2 hectares (Table 1).

Within each plot, we randomly selected (proportionally to stand diameter distribution) approximately 20 yew trees for sampling. For each selected tree, we measured the site and tree variables listed in Table 2. Trees were defined as originating from a single stem at ground level; Pacific yew typically forks one or more times below breast height. Diameter at breast height was recorded for the largest fork in these cases. All measurement techniques were consistent with both the USDA Forest Service and USDI Bureau of Land Management Yew Inventory procedures (USDI Bureau of Land Management 1992). A portable data recorder was used for data collection and handling. Data were downloaded to a personal computer for analysis. Aspect was sine-converted.

From all sample trees, we collected four increment cores just above the stem collar (ground level), one in each cardinal direction. Cores were stored in paper straws for transport and were later mounted and sanded following procedures described by Swetnam et al. (1985). Cores were aged using a binocular microscope by multiple readers to increase accuracy. Readability of a tree's four cores often varied considerably, so tree age estimates were based on the highest quality cores. Cores were not cross-dated, and incremental growth was measured on only two sites (Bailey and Liegel 1997). Average radial growth over the life of the tree was calculated from age and diameter.

Data were checked for consistency using regressions of known relationships (e.g., collar diameter against diameter at 1.3 m, and total height against peelable height). One data point out of approximately 8000 was excluded after this validation procedure. For each plot, we used SAS to graph and regress all variable pairs showing correlation coefficients ≥0.3 and meeting normality assumptions (SAS institute, Inc. 1988). Trees and subplots were randomly located within 2-ha plots. However, because plot arrangement was not random either within or across regions, quantitative intra- and inter-regional analyses of these relationships were not performed. We used plot averages to qualitatively examine several variable relationship changes within and across regions. Plot means based on the sample tree readings were calculated for the tree growth and site variables listed in Table 2; stand-level data in Table 2 were also used. This aggregated data set with 11 nonrandom observations was examined graphically. Finally, for some analyses we attempted to reduce variation in the data set by selectively excluding certain classes of trees (e.g., the largest or smallest, damaged, or multiple-stem trees).

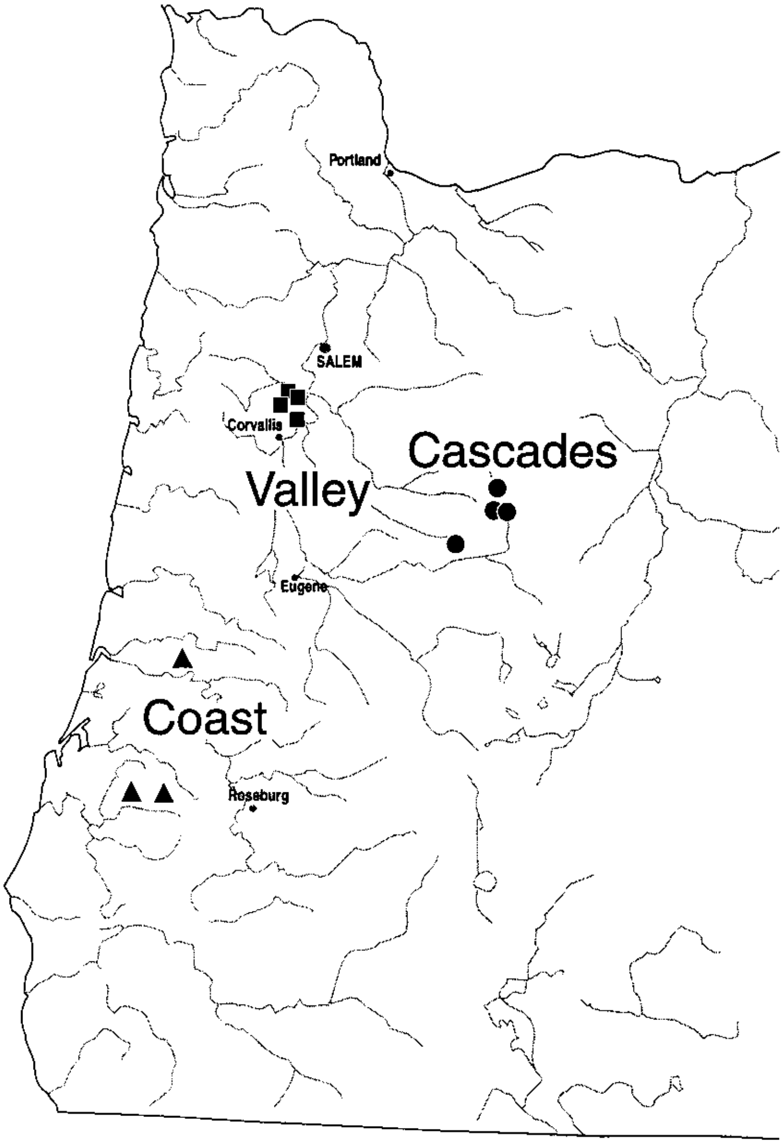


Figure 1. Study site locations in three physiographic subregions of western Oregon: western Willamette Valley (4 plots); Central Cascades (4 plots); and Coast Range (3 plots).

The intent was to improve goodness-of-fit estimates, although this data-filtering typically provided only marginal improvements.

Results and Discussion

Tree Distributions and Characteristics

Field mapping in 11 2-ha plots in late-successional western Oregon Douglas-fir forests with 15-161 Pacific yew per hectare confirmed two previous findings:

1) Pacific yew typically grows as scattered individuals or clusters within stands, supporting Bolsinger and Jaramillo (1990) and Busing et al. (1995).

2) The species primarily occurs in the understory of undisturbed stands without evidence of recent fire or other major disturbance like clearcut

TABLE 1. Site descriptions for 2-ha study plots of Pacific yew.

Region and plot	T-R-S[a]	Mean elev. (m)	Mean slope (%)	Primary aspect	Total trees/ha	Mean canopy density (%)	# yew/ha	# yew measured	Historical notes
Western Willamette *Valley*[b]									
1	10S-5W-16	180	42	–[c]	408	87	30	22	partially harvested c. 1900
2	11S-5W-7	230	56	W	323	85	30	21	
3	10S-5W-22	250	65	N	262	87	35	18	
4	11S-5W-3	230	38	W	476	92	40	22	
Central *Cascades*[b]									
5	13S-6E-36	990	25	E	228	35	72	23	thinned 1978
6	13S-6E-36	980	25	E	518	70	116	21	
7	13S-6E-25	960	25	NE	280	45	133	22	thinned 1978
8	16S-4E-25	850	45	W	289	73	98	22	
Coast[b] Range									
9	26S-9W-21	460	90	NE	185	68	17	20	
10	21S-9W-21	240	76	–[c]	271	86	15	21	
11	27S-9W-24	910	44	SE	482	73	161	18	

[a] Township, Range, and Section location.

[b] Italicized words used throughout text to identify regions.

[c] Complex terrain with no dominant aspect.

harvesting, supporting Busing et al. (1995). Recent inventory efforts by the USDA Forest Service and BLM place an actual percentage occurrence in various forest types.

In addition, we qualitatively observed that:

1) Within the Valley and Coast subregions, Pacific yew was more common on steeper slopes than on ridges, benches, or valley bottoms.

2) In all plots, Pacific yew was associated with the understory shrub species sword fern (Polystichum munitum [Kaulf.] Presl) and dwarf Oregon grape (*Berberis nervosa* Pursh).

3) Across all sites, Pacific yew seedlings were rare in these undisturbed forests, accounting for <5% of total observed regeneration, although vegetative reproduction from layering and/or stem and stump sprouts on damaged trees was common.

4) Yew growth form was quite variable across all the study plots. In 9 of the 11 plots, at least half of the sample trees had forked or multiple stems before a 3-cm diameter top (Table 3).

5) The stems of 2-5% of sampled trees were fused. Cores extracted from three single-stem trees conclusively showed two piths, and in 15 other cases multiple piths were suspected (Table 3).

6) Nearly 100% of trees in the oldest age range and largest size range sampled had pockets of rot; in >50% of the cases, they also had hollow centers.

Yew Size and Age Distributions

The distribution of collar diameters in these Pacific yew populations shows a general reverse-J pattern, particularly in Cascade plots (Figure 2). Though constructed from only the approximately 20 trees per plot, this distribution reflects that of the entire plots, since our sub-sampling was proportional across diameter classes. Age structure for these same stems, however, shows more of a broad bell-shaped, even-aged distribution. Plots were very similar within subregions; the individual plots shown are the best representatives of their subregions (Figure 2). The absence of a large number of individuals in the 10-cm size class and

TABLE 2. Yew tree site, tree growth, and stand variables and measurement techniques used in the field.

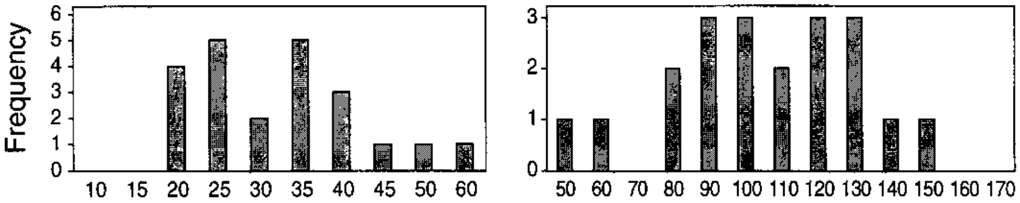
	Variable	Measurement technique
Yew tree site	Regeneration method	0 = none; 1 = stump sprout; 2 = stem sprout; 3 = seedling; 4 = unknown
	Canopy density (±4%)	Average of measurements at 4 cardinal directions at edge of yew canopy, with optical densiometer
	Slope (±1%)	Under yew canopy, with clinometer
	Slope position	0 = ridge top or bench; 1 = upper slope; 2 = side slope; 3 = bottom slope; 4 = floodplain
	Aspect (±1°)	At yew stem base, with compass
Yew tree growth		
	Diameter (±0.1 cm)	At stem collar and at breast height, with diameter tape
	Height (±0.1 m)	Total, and peelable (3-cm diameter top, with Relaskop Live crown (lowest live branch), with tape or Relaskop
	Live crown ratio	Calculated
	# peelable branches	Live branches >3 cm. diameter
	Crown width (± 0.1 m)	Average of measurements at 4 cardinal directions tape
	Fruiting	0 = none; 1 = present
	Damage to tree	0 = none; 1 = broken top; 2 = leaning; 3 = scarring 4 = essentially dead
	Growth form	0 = columnar; 1 = fork; 2 = multiple stems
	# epicormic sprouts	0 = none; 1 = 1–10; 2 = 11–30; 3 = >30
Stand		
	Total basal area/ha	Projected from tally over 4 fixed-radius subplots
	Total trees/ha	Projected from tally over 4 subplots
	Yew basal area/ha	Projected from tally over 4 subplots
	Yew trees/ha	Averaged from tally over 2 ha

TABLE 3. Summary of stem form, rot pockets, and possible and demonstrated fused stems of sample yew trees.

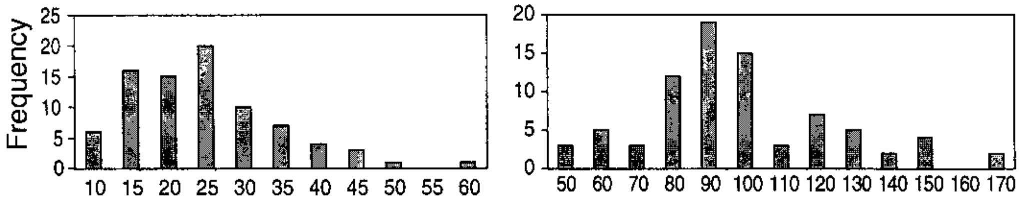
	Number of trees						
Plot #	Total # yew sampled	Single stems	Forked stems	Multi-stems	Rotten pockets	Possib. fused	Demon. fused
1	22	8	7	7	6	0	0
2	21	15	3	3	13	3	1
3	18	8	1	9	2	2	1
4	22	8	1	13	7	3	0
5	23	11	6	6	9	0	0
6	21	9	4	8	9	1	0
7	22	10	2	10	7	2	0
8	22	14	1	5	17	1	0
9	20	11	0	9	8	0	0
10	21	9	3	9	6	3	0
11	18	7	2	9	7[a]	0[a]	1[a]

[a] Figure based on observation of 16 trees, not 18 trees.

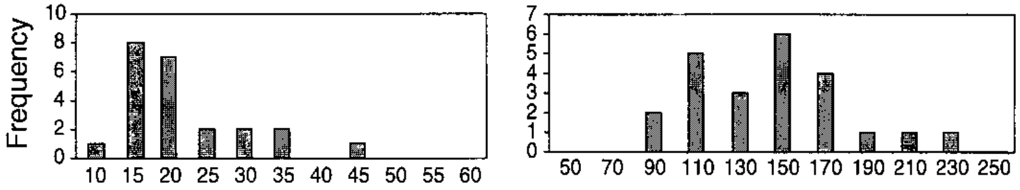
(a) Valley plot #3



(b) Valley subregion cumulative distribution



(c) Cascade plot #5



(d) Cascade subregion cumulative distribution

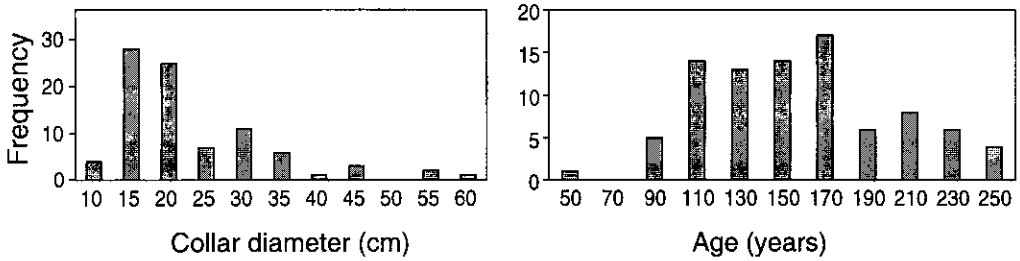


Figure 2. Collar diameter distribution and age distribution for Valley (a and b) and Cascade (c and d) plots. Cumulative distributions were constructed from >20 sampled trees per plot and 4 plots per subregion. Note the difference in age classes between the two subregions.

in age classes <100 yr demonstrates a substantial lag in yew regeneration (sprouts and/or seedlings) in the last century. This lack of smaller, younger yew trees extends well beyond our 7.5-cm minimum diameter for sampling to the general lack of reproduction noted above.

Given the difficulty of determining ages of large trees from cores (i.e., because of rotten and hollow centers), we were particularly interested in determining whether age could be predicted from collar diameter. Few plots demonstrated a strong relationship between collar diameter and age, however. Regression R^2s ranged from 0.15 to 0.75 with a median of 0.48 (average = 0.51). The maximum and minimum R^2 cases (plots) appear in Figure 3. Restricting analyses to data either for undamaged single-stem trees or for a narrower age band (80-120 yr) did not improve the collar diameter-to-age relationship.

Correlations within 2-ha Plots

Correlations between tree size variables (e.g., stem collar diameter, height, and crown variables) were consistently positive on all plots (Table 4). We

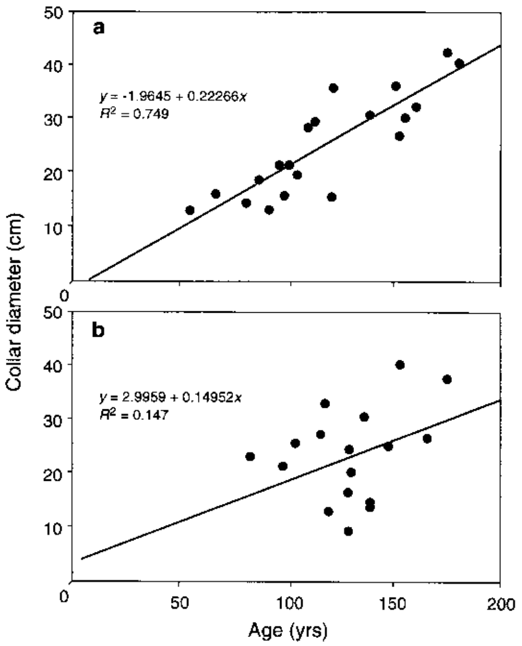


Figure 3. Yew age vs. root collar diameter in plot with (a) best R^2 (Valley plot #2) and (b) worst R^2 (Coast plot #11).

used collar height and breast height diameter even though some variability is introduced into DBH by multiple stems (Table 3). The plot 3 results shown in Figure 4 were typical for most variable pairs studied across all plots - that is, regressions demonstrated significant slopes, insignificant intercepts, and R^2s >0.6. However, correlations between site variables and tree measurements were not strong or consistent (Table 4), nor were fruiting data, given the preponderance of zeros in the data set. Likewise, correlations between tree size measurements and average radial growth were not consistent (linear or non-linear); a more complete data set supplemented with dendrochronological analysis of incremental growth is needed to determine whether yew growth follows a sigmoidal curve. Such an analysis is not possible with these data, nor is the calculation of basal area increment.

Filtering the data set for specific tree ages, sizes, and growth forms consistently improved correlations and regressions among tree variables. For example, the correlation between collar diameter and number of branches on plot 1 improved from 0.73 (based on all 22 sample trees) to 0.85 when examining only the 13 sample trees that were between 80 and 120 yr old. The correlation coefficient likewise improved to 0.93 when examining only the 6 trees with no damage and a single-stem growth form.

Ability to predict tree characteristics from site variables (e.g., slope or canopy density) was not promising; regression R^2s based on 20 trees were

TABLE 4. Correlation coefficients for pairs of yew tree size, age, incremental growth, and site variables across 11 sites.

	Valley				Cascades				Coast		
Site #:	1	2	3	4	5	6	7	8	9	10	11
Diameter (at 1.3 m) vs. total height	0.75	0.76	0.69	0.90	0.85	0.72	0.68	0.85	0.61	0.75	0.69
Collar diameter vs. crown width	0.36	0.62	0.87	0.83	0.87	0.79	0.82	0.86	0.75	0.83	0.89
Crown width vs. # of branches	0.58	0.80	0.72	0.88	0.80	0.94	0.82	0.93	0.78	0.67	0.82
Tree age vs. collar diameter	0.66	0.87	0.68	0.67	0.85	0.79	0.69	0.70	0.52	0.85	0.38
Average radial growth vs. canopy density	-0.39	-0.13	-0.22	0.18	0.08	0.06	0.00	0.08	-0.39	-0.04	-0.29
Slope vs. diameter at 1.3 m	-0.13	0.07	-0.14	-0.08	-0.20	-0.01	0.02	-0.16	0.38	0.34	-0.39
Slope vs. incremental growth	-0.22	0.25	0.00	-0.23	-0.36	-0.22	-0.11	-0.07	0.13	0.41	0.31
Sine(aspect) vs. total height	-0.02	0.22	0.09	0.02	-0.07	-0.06	0.03	0.17	-0.13	0.14	0.14
Canopy density vs. collar diameter	-0.24	-0.61	-0.32	-0.08	0.03	0.14	0.31	0.01	-0.25	0.07	-0.57

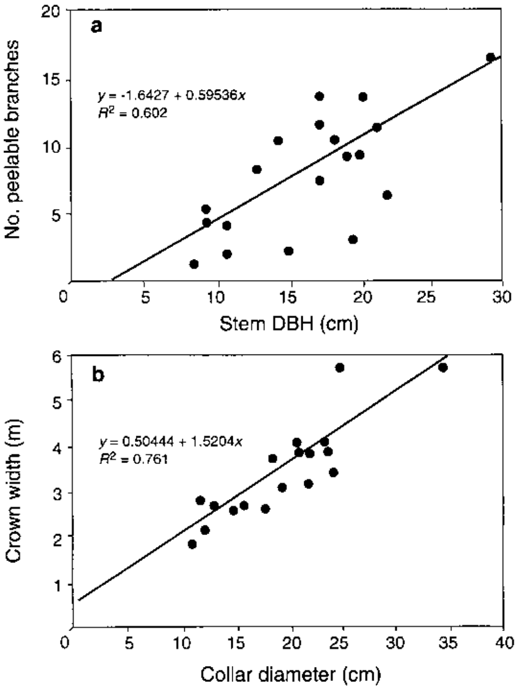


Figure 4. Relationships between pairs of yew tree growth variables in Valley plot #3: number of peelable branches vs. stem DBH (a) and crown width vs. stem collar diameter (b).

mostly <0.41. Based on Bailey and Liegel (1997), we expected canopy density to be a major correlate, but it was not. Multiple regression of site variables against tree characteristics did not significantly improve any of these correlations. Aggregating data by region also failed to improve predictive capabilities, even though significant regressions were demonstrated (e.g., with slope and aspect) based on the larger samples. Unmeasured variables, perhaps stand history attributes such as time since or distance from some disturbance, evidently have significant effects on yew growth.

Similarities among Plots, within the Same Subregion

Stand conditions and yew tree densities, sizes, and ages were most similar among Valley plots. Differences in these characteristics were larger among Cascade plots, likely due to their more diverse histories; two plots had been thinned 14 yr prior to our study. For example, average canopy density for the Cascade plots ranged from 35 to 73%, whereas canopy density of the Valley plots was 85-92%. Average canopy density for Coast plots was between these two. Within each subregion, regression patterns between pairs of tree variables and between tree and site variables typically were consistent among all plots (i.e., positive relationships on any one plot were typically positive on all plots). The statistical significance of these regressions differed among plots, however.

Similarities Across Subregions

Yew stem age ranges varied markedly across subregions (Figure 2). In Valley plots, for trees from 8.3 to 36.6 cm DBH, and readable ages ranged from 45 to 170 yr. The largest tree was 60 cm DBH; its age was estimated to be 230 yr. In the Cascade and Coast plots, trees with diameters similar to those in Valley plots (9.5-38.5 cm DBH) ranged in readable age from 80 to 260 yr, much older than those in Valley plots. The two largest trees (50.5 and 66.0 cm DBH) with rotten centers were estimated to be 350 and 400 yr. Average radial growth rates, the accumulation of diameter with time, therefore differed between Valley and Cascade plots using regressions between collar diameter and age (Figure 5). The intercepts of all eight plot lines (shown as thin lines) are not significantly different from zero; aggregated data are shown by the broad line. The regression lines for Coast plots fall between these groups, being more similar to Cascade plots and slightly above them; however, because they are not significantly different from either the Cascade or the Valley lines, we did not include them in Figure 5. Of note, Valley plot #4 and Cascade plot #8 were

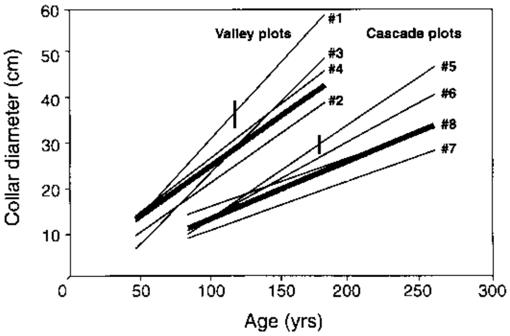


Figure 5. Regression lines for stem collar diameter vs. tree age for Valley and Cascade plots, and aggregated data regression lines (bold) for the two regions. Vertical bars on plots 1 and 5 regression lines show one standard error at mean age.

similar in all respects except for age. The direction (positive or negative) and strength of other relationships among tree variables (e.g., between collar diameter and crown width) were largely consistent among all 11 plots, with differences within any single subregion as great as those between subregions.

Stand Averages

Figure 6 shows two examples of stand averages, across all three subregions, for tree and site variables showing the strongest correlations within plots. These graphs do not prove the existence of biological relationships because these illustrated trends could be unique to the 11 plots we selected, but they nonetheless serve as hypotheses for further exploration of established correlations. Across 11 sites, yew crown width tended to increase as overstory canopy density increased (Figure 6a). Other shade-tolerant species, western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and bigleaf maple (*Acer macrophyllum* Pursh), can show such characteristic changes in form with increasing shade (Franklin and Dyrness 1984). Crown width also increased as slope increased (Figure 6b). Both these results may only reflect the fact that Coast and Valley plots, which had the largest crowns, were also located on sites with denser canopies and steeper slopes.

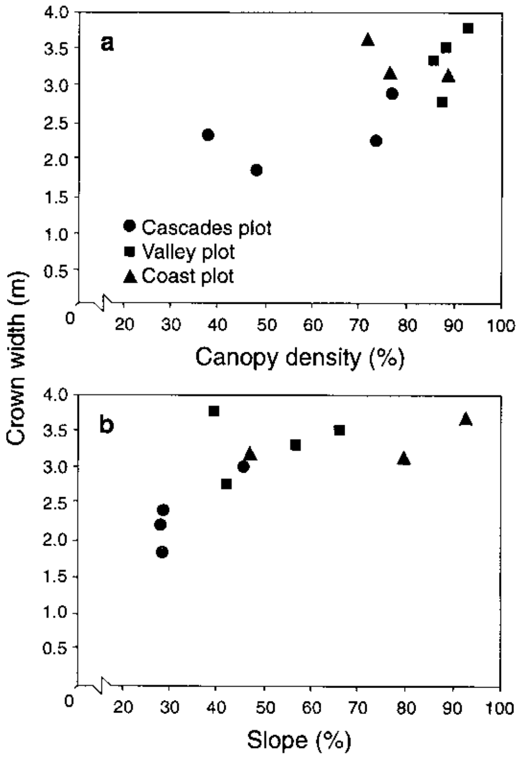


Figure 6. Tree characteristic vs. site variables for study plots: crown width vs. stand canopy density (a); and crown width vs. percent slope (b).

Conclusions

The reverse-J stem diameter distribution seen in these Pacific yew populations, in the understory of late-successional Douglas-fir forests where they are most common, suggest continual regeneration in the manner of uneven-aged populations. However, age distributions for the same stands show a dominant pulse of regeneration more than 100 years ago, resulting in a distribution more typically associated with even-aged populations with scattered older individuals. Regeneration, almost exclusively in the form of sprouts, has been low in the last century and may be explained by a reduction in low-intensity fire disturbances (which would lead to yew sprouting and/or seedbed creation), increases in seed predation and ungulate browse of young seedlings, or other changes in these forests following Euro-American settlement. This low level of recent regeneration accentuates (or perhaps creates) a bell-shaped age distribution. Additional field research specifically on Pacific yew regeneration processes will be needed to resolve this inconsistency between the expected reproductive behavior of such a shade-tolerant species (i.e., a reverse-J distribution) and the observed pattern. Other tolerant species like western hemlock reproduce more readily in the shade of an older Douglas-fir overstory.

These data also demonstrate substantial variability in yew growth trajectories among subregions, as seen in Figures 2 and 5. Yew trees are younger and grow significantly more quickly in Valley plots than in Cascade plots, although the reason for this accelerated radial growth is unclear. Valley sites were at lower elevations on average, but elevation was not significantly correlated with size or age. Valley sites had the highest overstory canopy coverage on average, but increased shading should have resulted in reduced radial growth.

We entered this study with particular interest in the relationship between overstory canopy and yew reproduction and growth rates within and among sites. Bailey and Liegel (1997) and D. Minore (pers. comm.) have suggested that yew trees, like western hemlock (Packee 1990) and bigleaf maple (Minore and Zasada 1990), grow faster or 'release' with increased light availability. Sampling along a more extensive range of stand conditions will be necessary to improve our information on this issue.

Finally, the relationships between stand characteristics and yew reproduction, survival, and growth remain largely unquantified. The stand and site variables we measured proved to be only marginally related to yew tree variables within and among our intensive plots. Percent slope and overstory density within most sites showed the best predictive capabilities, but correlation coefficients were < 0.41. Figure 6, depicting averages for plots, shows no better relationship. The lack of correlation between stand characteristics and yew characteristics suggests the strong influences of other, unsampled factors associated with soil and/or microsite variability. Understory species are sensitive to relatively small changes in light levels, available soil moisture and nutrients, and mycorrhizal associations. In addition, chance events in a stand's history (e.g., windfall or animal damage) may no longer be in evidence but may have had a large effect on yew growth or structure. We found variation among stands therefore to be high, and planning by forest managers should acknowledge this stand-to-stand variability in addition to regional variability and age structure issues raised by these plots.

Acknowledgements

Thanks to Bristol-Myers-Squibb Corporation and the USDA Forest Service for their financial support. We extend special thanks to Don Minore, Richard Busing, Pete Owston, and John Tappeiner for reviewing earlier drafts of this paper. This is Paper 3155 of the Forest Research Laboratory, Oregon State University, Corvallis.

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Received 7 March 1998
Accepted for publication 27 October 1998