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Reconstructed Old-Growth Forest Stand Structure and Composition of Two Stands on the Olympic Peninsula, Washington State

David H. Peter and Constance A. Harrington

Authors

David H. Peter is an ecologist and **Constance A. Harrington** is a research forester, Forestry Sciences Laboratory, 3625 93rd Avenue SW, Olympia, WA 98512-9193.

Cover photo: A large Douglas-fir stump in a predominantly western hemlock stand in the study area suggests both structural and compositional differences between the previous and current stands.

Abstract

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We reconstructed the stand structure and composition for two western Washington old-growth forest stands harvested around 1930 (named Fresca and Rail) from field and historical data. Both old-growth stands had a codominant or dominant 250-year-old Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) overstory with a few scattered older Douglas-fir. Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) was codominant at Rail but was predominantly in the mid-story and understory at Fresca. The Fresca site is now dominated by Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and western hemlock, whereas Rail has a composition similar to the previous old-growth stand. Events taking place early in succession are probably responsible for the differences between the modern and historical stands. Accelerated restoration of old-growth structural diversity may be possible at both sites through repeated creation of artificial gaps, but Fresca will remain different from its historical composition.

Keywords: Old growth, stand history, stand reconstruction, Douglas-fir, succession, tree stumps, restoration.

Summary

Finding relict stands to suggest an appropriate site-specific model for restoration of old-growth structure and composition can be difficult. However, stand legacies and historical information may indicate structural and compositional features of a previous stand. We used site vegetation, local fire history and General Land Office survey information with measurements and identifications of legacy stumps from two sites to reconstruct old-growth stands that had been clearcut 70 years before our measurements. We also described the modern stands using tree measurements made on 5.6-ha plots in each study area. These stands, named Fresca and Rail, are 15 km apart and are on similar landforms located on the northwestern Olympic Peninsula in western Washington. Each stand followed a different successional pathway to an old-growth condition, and both modern stands are following different pathways. We suggest that the former stands were initiated by a stand-replacement fire, and that postfire Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) dominance was limited by competition with other tree species. Stump diameter class frequency curves at Rail are similar for western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Douglas-fir suggesting coestablishment after the fire, but at Fresca, differing curves for these species suggest western hemlock entered the stand later than Douglas-fir. The stand at Fresca may have developed from initial codominance of red alder (*Alnus rubra* Bong.) and Douglas-fir. Later senescence of the red alder permitted entry of western hemlock. Fresca is now dominated by western hemlock and Sitka spruce with little Douglas-fir, so it would be impractical to restore the old-growth composition there. The composition at Rail is similar to that of the old-growth stand, so a more complete restoration of the old-growth character would be possible there. Our reconstructions suggest that old-growth restoration options are limited by events taking place early in succession.

Contents

Introduction

Some forest managers are interested in accelerating development of old-growth characteristics in young stands. Although old-growth forests are unique products of historical events and not entirely reproducible (Franklin and Spies 1991), restoration based on an understanding of old-growth structures and their developmental processes is more likely to be successful than restoration based on more limited information (Franklin et al. 2002). But, old-growth forests suitable for site-specific management models often no longer exist.

North Pacific coast old-growth forests are distinguished from second-growth forests by large trees, snags, down logs, deep irregular crowns, and multiple canopy layers (Franklin and Spies 1991). These older forests are habitat for unique assemblages of plant and animal species. Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) trees typically dominate these forests after fire, but gradually give ground to more shade-tolerant species during long fire-free intervals. The development of canopy-dominant Douglas-fir trees in many forest types and the relationship of the dominant Douglas-fir to associated shade-tolerant trees drive major changes in live and dead structures and the habitats they create for at least 500 years (Spies and Franklin 1988).

Old tree stumps are ubiquitous in western Washington, providing clues to former stand structure.

Owing to more recent disturbances, the historical stand structure may not be obvious, but there are several potentially useful sources of information. Information based on forest type or plant association is widely available but is not site specific. Such information suggests the combinations of species that are possible on a site, their likely growth rates, and thus size, at a given age. Early land survey records are often the best information available on premanagement forest structure and composition, but may be biased owing to individual surveyors and differences in intended use (Schulte and Mladenoff 2001). Old tree stumps are ubiquitous in western Washington, providing clues to former stand structure. Large Douglas-fir logs may take more than 300 years to decay (Means and Cromack 1985), but distinctive bark allows identification of even very old specimens. Slow decay rates permit fairly accurate estimates of diameter. Thus, structural and compositional insight can be obtained from historical records, knowledge of community successional potential, an understanding of past disturbance, and structural legacies including old stumps from prior stands.

We used historical records and measurements of legacy stumps to reconstruct the former structure and composition of two stands clearcut around 1930. We asked if it was possible with silvicultural manipulation for the two modern young stands to produce the kind of old-growth stand they replaced.

We used historical records and measurements of legacy stumps to reconstruct the former structure and composition of two stands clearcut around 1930. The stand legacies (stumps, logs, and snags) suggested important differences from current stands. We asked if it was possible with silvicultural manipulation for the two modern young stands to produce the kind of old-growth stand they replaced.

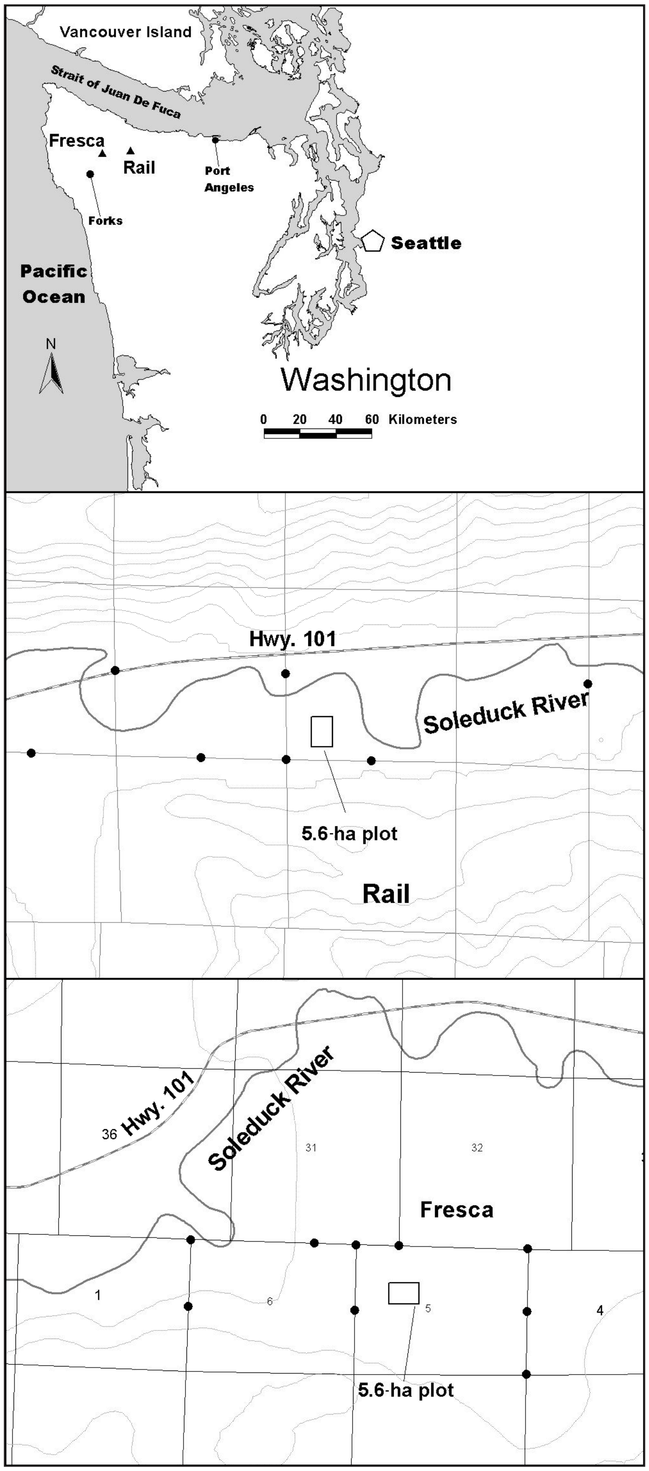

Figure 1—Location of study areas: (A) Rail and Fresca in western Washington; (B) General Land Office (GLO) survey locations and 5.6-ha measurement plot at Rail; (C) GLO survey location and 5.6-ha measurement plot at Fresca. In B and C, scale is indicated by square sections, which are 1.6 km on a side. (Universal Transverse Mercator coordinates for 5.6-ha plot centers: Rail—420493, 5322709; Fresca—404576, 5321997).

Methods

Study Area

The Olympic Habitat Development Study is a project of the U.S. Forest Service Pacific Northwest Research Station and the Olympic National Forest on the Olympic Peninsula in western Washington. Established in 1994, its purpose is to evaluate the use of variable-density thinning and management of coarse woody debris to accelerate the development of stand structures and plant and animal communities associated with late-successional forests (Reutebuch et. al 2002). Two 5.6-ha plots established for the larger study were used for this analysis; these sites, named Fresca and Rail, are 15 km apart in the Soleduck River Valley on the Olympic Peninsula (fig. 1).

Fresca receives about 2670 mm and Rail about 2410 mm of precipitation falling mostly as rain (USDA NRCS and OSU 2005). Both sites are on a flat gravelly glacial outwash plain derived from the continental glacial retreat about 13,000 to 14,000 years ago (Mosher and Hewitt 2004). Elevation above sea level is 150 m at Fresca and 290 m at Rail. The soil at Fresca is a very deep moderately well-drained Pachic Fulvudand in the Emmiott Series. The soil at Rail is a very deep, well- to somewhat excessively well-drained Typic Udivitrand in a complex of the Bogachiel and Ishmael Series (series descriptions available at: http://soils.usda.gov/technical/classification/osd/index.html). The entire area was mapped as a "recent cutover" in 1931 (Harrington 2003).

Both sites appear to have originated after a stand-replacing fire around 1700, and both may also have been burned by fires around 1500 and 1300 (Henderson et al. 1989). A 160-cm legacy stump from the circa 1930 clearcutting near Fresca had 250 to 270 rings (Peter, unpublished data; uncertainty owing to decomposition; counted in 1995) suggesting a date of origin in the late 1600s.

Dodwell and Rixon (1902) reported forest statistics by township from the General Land Office (GLO) and other surveys on the Olympic Peninsula (see below). According to this report, most merchantable timber in the 1890s in the Rail area was Douglas-fir (217 yr, 104 cm diameter), and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) (145 yr, 53 cm diameter). They indicated that most of the timber in the Fresca area was western hemlock (151 yr, 66 cm diameter) followed by Douglas-fir (235 yr, 107 cm diameter), with small amounts of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) (200 yr, 135 cm diameter) and western redcedar (*Thuja plicata* Donn ex D. Don). Thus, a late 1600s origin is also indicated by their data.

Plant Communities

The sites straddle the ecotone between the Sitka Spruce Zone and the Western Hemlock Zone (Henderson et al. 1989). In general, the Sitka Spruce Zone receives more precipitation and fog than the Western Hemlock Zone; however, in this ecotonal area, these differences are probably slight. Vegetation at Fresca is in the Sitka spruce/Oregon oxalis (*Oxalis oregana*) plant association (Henderson et al. 1989). The most common plant association at Rail was western hemlock/salal-swordfern (*Gaultheria shallon–Polystichum munitum*) (80 percent of the area), but western hemlock/swordfern–foamflower (*Tiarella trifoliata* L.) and western hemlock/Oregon oxalis associations (Henderson et al. 1989) are also present. In all of the associations at these sites, red alder is a potentially common seral species with a lifespan of 70 to 100 years; Douglas-fir is a common long-lived seral species; and western hemlock fills both seral and climax roles. Sitka spruce is a seral and climax species only in the Sitka Spruce Zone (Henderson et al. 1989).

General Land Office Survey Data

The GLO Survey, which was begun in 1812, covered most of the land area of the United States with a surveyed 1-mi (1.6-km) grid including maps and notes of major land features, settlements, and vegetation (available from: U.S. Department of the Interior, Bureau of Land Management, http://www.glorecords.blm.gov/). The GLO surveyors referenced survey monuments at grid (section) corners to witness trees, which were usually the closest trees to the survey monument. Witness-tree data from GLO surveys from 1891 and 1894 and descriptive information from the 1879 township survey were extracted for our study sites. Most of the survey data we used came from 1891 and was the work of the same surveyor at both sites. Data were used from surrounding section-corners and quarter corners, which were similar in soils and topography to the Rail and Fresca 5.6-ha plots (described below). Species

Witness-tree data from GLO surveys from 1891 and 1894 and descriptive information from the 1879 township survey were extracted for our study sites.

identifications and lower bole diameters were obtained for trees around seven section and quarter-section-corners surrounding Rail and from nine section and quarter-section-corners surrounding Fresca (fig. 1).

The number of trees per hectare (tph) by species was calculated from the witness tree data using the distance from the monument to each tree with the point-quarter method (Krebs 1999) and averaged across all points. Surveyors were instructed to witness section-corners with four trees and quarter-section-corners with two trees. When only two trees are available, each tree is given twice the weight in the calculation of density, so quarter-section samples are less likely to provide an accurate description of the surrounding stand than section-corner samples. Accurate stand reconstruction based on witness trees assumes that the trees selected by the surveyors were the closest trees to the corner and that there was no size or species bias. Potential biases are discussed later.

We surveyed legacy stumps around each of the 16 section or quarter-section points from which General Land Office data had been obtained.

Stump Survey at GLO Points

To provide a more complete picture of the larger trees in the historical stand, we supplemented the GLO survey data with recent interpretations of remaining legacy stumps. We surveyed legacy stumps around each of the 16 section or quarter-section points from which GLO data had been obtained. The area around each point was quartered along cardinal directions. The closest legacy stump in each quarter was located. Then a plot radius was established, which completely included all four stumps. The radius of the average plot was 21.5 m (standard deviation = 7.0 m) at Rail and 19.5 m (standard deviation = 13.2 m) at Fresca. This method was an efficient way to sample widely varying stump densities from point to point. A single small plot size might not sample any stumps at the wider spaced locations, whereas a single large plot size would require sampling large numbers of stumps at closer spaced locations. The negative relationship between plot size and the log of stumps per hectare had an $r^2 = 0.83$. We recognize that our smaller plots might miss much of the spatial variation included in our larger plots, but our objectives were to produce a diameter distribution representative of the stand around each point and from general observations from each site, we believe that this was accomplished.

All legacy stumps in the plot were measured for height and diameter. It was not difficult to discern which stumps were from the stand harvested around 1930, but the certainty of identification to species differed. Douglas-fir stumps were easily identified based on their thick bark with its characteristic color and texture. Identification of western hemlock and Sitka spruce stumps was difficult because their thinner bark sloughs and decomposes more rapidly than Douglas-fir bark. We believe the unidentified stumps were mostly western hemlock because much western hemlock was found by the GLO surveyors, and it is still common in the modern stands. We were also sometimes able to identify western hemlock from bark on stumps, and it is the primary shade-tolerant tree expected on these sites (Henderson et al. 1989). We lumped the western hemlock and unidentified stumps into a group that we refer to as "western hemlock+" for analysis and discussion.

Stump Survey From 5.6-ha Plots

Stump and snag data were collected from one previously established Olympic Habitat Development Study 5.6-ha plot at each site (fig. 1). Stumps and snags of decay class 3 or higher were considered legacies of the previous stand (see Maser et al. 1979 for descriptions of decay classes). For each legacy stump or snag, we recorded species, diameter, height at the point of the diameter measurement, decay class, and estimated bark and wood erosion. Inside-bark diameter was measured if possible, otherwise it was estimated using portions of the stump that were complete, or nearly so. Diameters were recorded at 1.3 m or near the top for stumps shorter than 1.3 m. Species were identified by remnants of bark adhering to the stump (see discussion above).

Stump Diameter Calculations

Measurements of stump diameter from both stump surveys were converted to diameter at breast height (d.b.h. = 1.3 m). We used an equation for Douglas-fir, which accounts for lower bole taper and bark thickness (Kozak and Omule 1992). For all other stumps, we used an equation for calculating breast-height diameter for western hemlock (Demaerschalk and Omule 1982). This formula does not account for bark thickness, and none of the unidentified stumps had bark on them so we estimated it based on observations of live trees. Our estimates of bark thickness for western hemlock ranged from 2 cm for 40-cm stumps to 6 cm for stumps ≥ 200 cm. We used a bark thickness of 3 to 5 cm for four Sitka spruce stumps.

Modern Stand

The current stands at Rail and Fresca originated around 1930 after clearcut logging, slash burning, and natural seeding. Postclearcutting aerial photos (from 1939) show that clearcutting was complete with no residual trees visible in either area. Rail was lightly thinned in 1986 to salvage mortality from a recent bark beetle (*Dendroctonus pseudotsugae*) attack and increase tree growth; stand basal area was about 70 m^2/ha before thinning and about 60 m^2/ha after thinning. Following thinning, a two-layered stand developed with a mature Douglas-fir overstory and a dense, patchy western hemlock understory. Fresca had not been thinned prior to

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its inclusion in the Olympic Habitat Development Study; it had a western hemlock-Sitka spruce overstory with almost no understory or midstory present.

A variable-density thinning prescription was implemented in 1997 at Rail and Fresca. The prescription called for thinning from below (leaving larger trees) to remove 20 to 25 percent of the mature stand basal area in the matrix, with areas in the stand designated as “skips” (no thinning, 10 percent of area) and “gaps” (removal of all merchantable trees of the dominant species, 15 percent of area). Hardwoods and less common conifers were retained in the gaps when present. The amount of basal area removed was low, and the size of the gaps was small to minimize the potential for windthrow. In the matrix, Douglas-fir and Sitka spruce were preferentially retained over western hemlock. One square 1.44-ha stem-mapped subplot was established within each of the 5.6-ha plots at each site such that proportions of skips, gaps, and matrix were closely similar to the 5.6-ha plot as a whole. Trees in the 1.44-ha subplots were measured prior to (1996) and following (1997) thinning. All trees on the subplot large enough to have a diameter at breast height (1.3 m) were measured and species recorded. There was a large response of western hemlock regeneration following the thinnings. Field counts of trees taller than 1.3 m and less than 5 cm diameter in 2002 at Rail included 32,494 tph in the thinned matrix, 28,190 tph in gaps and 60,205 tph in skips. At Fresca the respective numbers were 829, 7,472, and 3,781.

Results

GLO Data

At Rail, the GLO surveyor’s notes for the section-corner nearest (265 m) to the plot include, “Timber a heavy growth of fir, hemlock, spruce, and alder, with a dense undergrowth of same and huckleberry, salmonberry, and devil’s club.” There was no mention of fire or other disturbance along section lines or corners near the plot. Although “fir” (Douglas-fir) was frequently the first tree mentioned in the section-corner descriptions, 17 of the 18 witness trees in the vicinity of Rail were western hemlock, and only 1 was Douglas-fir. The average tree density was 147 tph (table 1). The lone Douglas-fir (representing ~1 tph) had a d.b.h. of 183 cm, and the western hemlock ranged from 10 to 122 cm (mean = 66 cm). Based on the stand descriptions, Sitka spruce was a minor species. The Rail diameter distribution (fig. 2) was dominated by trees in the 100- to 120-cm diameter size class but was nearly one-sided with most trees smaller than the dominant class.

Table 1—Sample sizes, mean diameters, and mean tree (or stump) densities for each site and survey method (± one standard deviation)

	Rail			Fresca		
		Stump surveys			Stump surveys	
Variable	Witness trees	GLO points	5.6-ha plot	Witness trees	GLO points	5.6-ha plot
Total number of trees (or stumps)	18	65	415	25	55	513
Number of points or plots sampled	7	7		9	9	
Percentage Douglas-fir[a]	1 ± 32	55 ± 27	53 ± 20	27 ± 43	69 ± 22	68 ± 10
Tree nearest the survey point:						
Distance (m)	5.2 ± 2.3	8.4 ± 7.1		5.6 ± 3.4	6.4 ± 6.0	
Diameter (cm)	70 ± 37	98 ± 32		65 ± 43	113 ± 60	
Mean tree diameters from plots (cm):						
All trees on plot	73 ± 43	110 ± 25	113 ± 16	60 ± 33	135 ± 25	134 ± 13
Douglas-fir	183	153 ± 32	130 ± 32	108 ± 30	168 ± 27	151 ± 17
Western hemlock+	66 ± 35	65 ± 19	95 ± 21	46 ± 19	66 ± 23	99 ± 22
Density (trees per hectare)	147 ± 152	75 ± 35	74 ± 24	150 ± 139	93 ± 65	92 ± 24

Note: GLO = General Land Office.
[a] Percentage of the sample trees that were Douglas-fir.

At Fresca, the nearest section-corner was 407 m from the 5.6-ha plot. The GLO survey has the following description: "Timber a heavy growth of fir, hemlock, spruce and alder with a dense undergrowth of same and vine maple, salmonberry, huckleberry, currant and devils club." No mention of fire was made for any of the nearest section lines or corners. Another section-corner (342 m) description from an 1879 township survey says: "Timber hemlock and fir of good quality...undergrowth; salal, huckleberry, salmonberry and briars."

In the vicinity of Fresca, 5 Douglas-fir, 19 western hemlock and 1 Sitka spruce were used for a total of 25 witness trees (table 1). The average tree density was 150 tph (Douglas-fir 58 tph). The average diameter of the Fresca witness trees was 60 cm, and the average diameter of the trees nearest the survey points was 65 cm. All the Douglas-fir, but only two of the western hemlocks were larger than 53 cm. The only Sitka spruce measured had a diameter of 76 cm. The diameter distribution of trees at Fresca peaked in the 20- to 80-cm range (fig. 2).

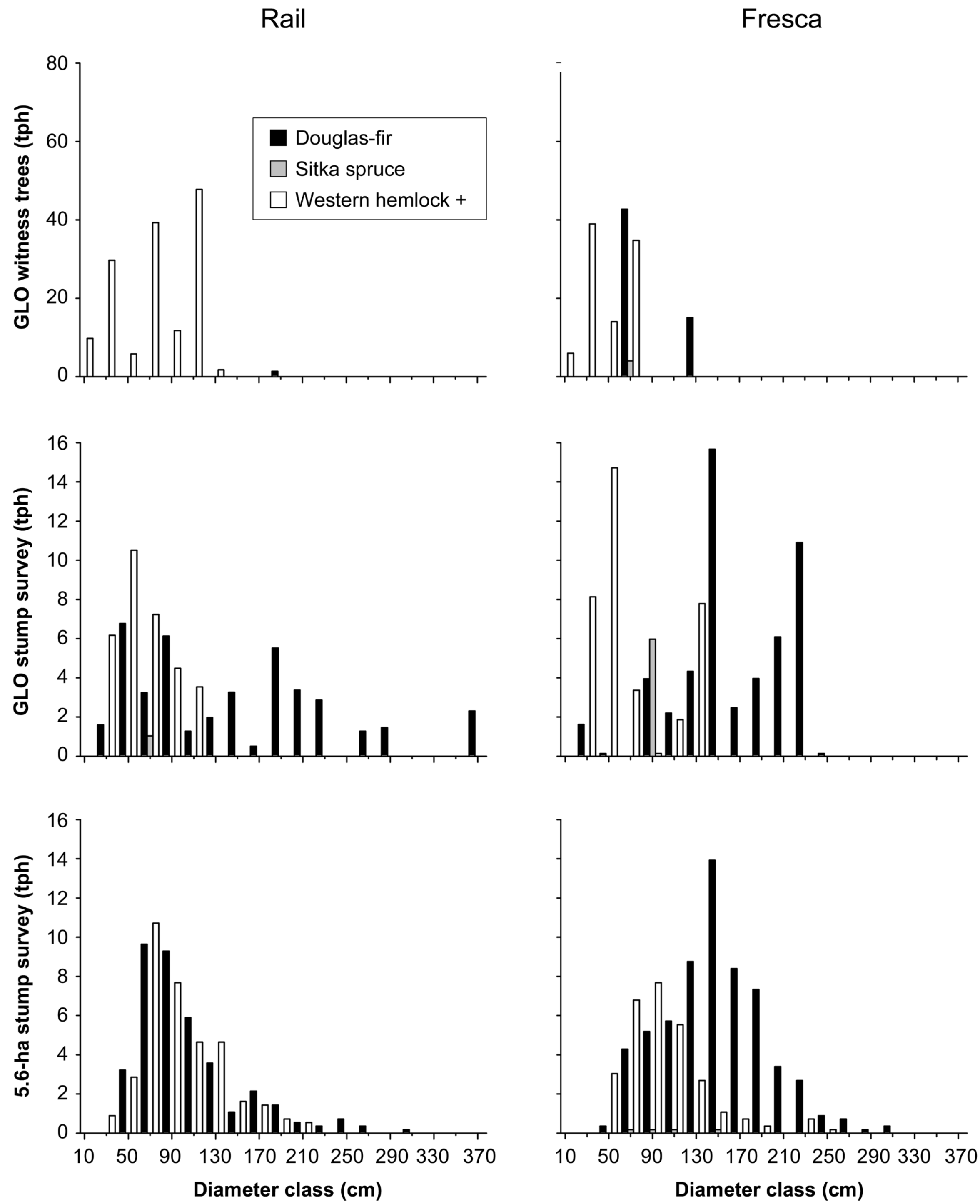

Figure 2—Diameter-class distribution by species for Fresca and Rail based on stand reconstructions from General Land Office (GLO) surveys (1890s), and modern stump surveys. Note: the y axis varies. The x axis labels denote the center of 20-cm diameter-classes. tph = trees per hectare.

Stump Surveys Around GLO Corners

The stump survey plots at the GLO points near Rail included 32 Douglas-fir, 21 unknown, 11 western hemlock, and 1 Sitka spruce stump representing an average of 75 tph (Douglas-fir 42 tph) (table 1). The average diameter of stumps on the Rail plots was 110 cm, and the mean diameter of the nearest stump to the plot center was 98 cm. The diameter distribution peaked in the 40- to 60-cm diameter class, and was skewed to larger sizes up to about 360 cm (fig. 2). The western hemlock+ group dominated most size classes smaller than 130 cm, although Douglas-fir stumps were common in these classes. All stumps larger than 130 cm were Douglas-fir, and most stumps with residual bark had bark char from slash burning.

The nine survey plots near Fresca included 39 Douglas-fir, 10 western hemlock, 5 unknown, and 1 Sitka spruce stump for a total of 55 stumps representing an average of 93 tph (Douglas-fir 51 tph) (table 1). The stump diameter distribution did not have a single clear peak (fig. 2). Douglas-fir stumps at Fresca were found in size classes from 20 to 260 cm in diameter, but were generally larger than those in the western hemlock+ group. There were very few trees in the western hemlock+ group in the upper half of the diameter distribution, and very few Douglas-firs in the lower half. Most stumps with residual bark were charred from slash burning.

Stump Surveys From 5.6-ha Plots

There were 216 Douglas-fir, 198 unknown, and 1 western hemlock stump at Rail representing 74 stumps/ha (Douglas-fir 46 tph) (table 1). Douglas-fir, and the western hemlock+ group had similar stump size distributions that were skewed toward the larger size classes, but Douglas-fir extended furthest into the large size classes (fig. 2). The peak of the distribution was at 60 to 100 cm d.b.h. for both Douglas-fir, and the western hemlock+ group.

There were 348 Douglas-fir, 151 unknown, 10 western hemlock, and 4 Sitka spruce stumps at Fresca representing 92 stumps/ha (Douglas-fir 62 tph) (table 1). Douglas-fir diameters were symmetrically distributed about a peak in the 140- to 160-cm size class with a mean of 151 cm. The western hemlock+ group was distributed around an 80- to 100-cm peak with a mean of 99 cm and was skewed to the larger size classes.

The main effect of the variable-density thinning was to create small canopy gaps and to remove intermediate and smaller codominant western hemlocks and a few Douglas-fir.

Modern Stand Structure and Composition

At Rail prior to the 1997 thinning, Douglas-fir were 33 cm larger in diameter on average than western hemlock (table 2). Douglas-fir was primarily in dominant or codominant crown positions, but western hemlock was mostly in lower crown class positions with most stems less than 20 cm d.b.h. The main effect of the variable-density thinning was to create small canopy gaps and to remove intermediate and smaller codominant western hemlocks and a few Douglas-fir; the thinning did not appreciably change the shape of the diameter distribution. After thinning, the average Douglas-fir was 35 cm larger in diameter than the average western hemlock (table 2). The percentage of all trees > 40 cm d.b.h. went from 22 percent before thinning to 30 percent after thinning.

Table 2—Sample sizes, mean diameters and mean tree densities for each 1.44-ha subplot at Rail and Fresca before and after thinning

	Rail		Fresca	
Variable	**Prethinning**	**Postthinning**	**Prethinning**	**Postthinning**
Total number of trees	1,129	846	787	500
Mean diameter of all trees (cm)	20	22	36	42
Diameter of Douglas-fir	42	44	50	51
Diameter of western hemlock (cm)	9	9	32	36
Diameter of Sitka spruce (cm)	—	—	49	52
Tree density (trees per hectare)	784	588	546	347
Douglas-fir density (trees per hectare)	260	211	12	11
Percentage Douglas-fir	33	36	2	3
Percentage Sitka spruce	0	0	29	36
Tree density >40 cm diameter at breast height	173	176	239	197
Percentage Douglas-fir >40 cm diameter at breast height	82	82	4	5

— = none present.

At Fresca prior to the 1997 thinning, the diameter distributions of Sitka spruce and western hemlock were approximately bell-shaped with Sitka spruce centered at 40 to 60 cm and western hemlock at 20 to 40 cm. There was very little Douglas-fir, and that which was present was similar in size to the Sitka spruce (table 2). Overall, the 1997 thinning reduced the stand density by 36 percent, but tree density >40 cm only decreased by 18 percent (table 2). Because thinning was from below and Sitka spruce were favored as leave trees, the peak of the western hemlock distribution shifted from 20 to 40 cm to 40 to 60 cm, while the Sitka spruce distribution changed little. The percentage of all trees >40 cm d.b.h. went from 44 percent before thinning to 57 percent after thinning.

Discussion

Among several important characteristics of Pacific Northwest old-growth stands is a negative exponential distribution of shade-tolerant species with many small trees and fewer large trees (Huff 1995, Van Pelt and Nadkarni 2004, Winter et al. 2002). However, this distribution is not shown by the GLO survey or stump data that we used in our old-growth stand reconstruction. The most likely explanation in the case of the GLO survey lies in the needs of the surveyors for certain qualities in witness trees. The GLO witness trees were marked by chopping through the bark and inscribing reference information on the wood. We suspect that on these sites, surveyors avoided small trees (< ~10 cm diameter) that were impractical to inscribe or might not last as long as larger witness trees. A bias in favor of medium-sized trees has been reported in GLO data elsewhere (Bourdo 1956). Thus, we would not expect many small witness trees even though the GLO surveyors noted a "dense undergrowth" of trees and shrubs was present at both sites. It therefore seems likely that the historical stand had something resembling a negative exponential distribution of shade-tolerant trees at the time of the GLO survey.

The stump data also has relatively few small stumps, probably because most of the smaller stumps were from shade-tolerant western hemlocks, which decay more rapidly than larger Douglas-fir stumps (Aho and Cahill 1984, Harmon et al. 1986). Also, slash burning after cutting in the 1930s would have burned small stumps more completely than large stumps. Thus, because we surveyed stumps ~70 years after clearcutting and slash burning, we did not expect to find many small stumps even if, as the surveyors suggested, they had been there.

The GLO witness-tree data are apparently also biased against large Douglas-fir trees, resulting in underestimating this species abundance in the Rail and Fresca old-growth stands by 40 to 60 percentage points (when compared with the stump surveys, table 1). We suspect that on these sites surveyors avoided large Douglas-fir trees (> 130 cm) that were difficult to mark owing to the difficulty of chopping through the very thick bark, leaving mostly medium-sized western hemlocks. Had we not collected stump data around the same points surveyed in the late 1800s, we might erroneously assume from the witness tree data that these stands were dominated by small to medium-sized western hemlock trees. The stump data clearly show that larger Douglas-fir and western hemlock trees were common. We believe the stump and witness tree data are complementary based on our understanding of the biases of each data set, and also from the site potential (which suggests these species are often found together), successional theory (which suggest that western hemlock can grow in the shade of Douglas-fir trees, but not vice versa), and from

We believe the stump and witness tree data are complementary based on our understanding of the biases of each data set.

other regional studies that consistently have found shade-tolerant trees in the understory of older Douglas-fir-dominated stands (Spies et al. 1990, Van Pelt and Nadkarni 2004, Winter et al. 2002).

Taken together, the surveys suggest that both stands had overstories dominated by large, widely spaced Douglas-fir trees. A large component of western hemlock in the mid- to understory was apparently present in both stands.

Taken together, the surveys (GLO witness, GLO stump, 5.6-ha stump) suggest that both stands had overstories dominated by large, widely spaced Douglas-fir trees. The somewhat skewed bell-shaped Douglas-fir distributions from both stands suggest a single dominant age class (Agee 1993). The skewed tails of the Douglas-fir distributions suggest a smaller component of older trees with larger diameters was also present (especially visible in the 5.6-ha stump survey data of fig. 2). A large component of western hemlock in the mid- to understory was apparently present in both stands and, although not visible in our data, may have had a negative exponential distribution as previously discussed. Western hemlock was also codominant in the overstory at Rail, but not at Fresca. These reconstructions compare favorably with regional descriptions of lowland old growth. For example, coastal Douglas-fir old growth typically includes widely spaced dominant Douglas-fir and smaller western hemlock trees (Bailey 1996, Spies and Franklin 1991) with high age and size variation (Franklin and Spies 1991, Tappeiner et al. 1997).

Conceptual models attempting to explain how the Rail and Fresca old-growth stands formed must include (1) low density of large overstory dominant conifers, (2) Douglas-fir canopy dominance, and (3) coestablishment of western hemlock at Rail. Tree establishment can be rapid on moist sites like those at Rail and especially at Fresca. Harcombe (1986) found that 83 percent of Sitka spruce and 68 percent of larger western hemlocks established within 20 years after fire. Given this possibility, the Fresca model must also explain (4) why western hemlock established mainly after the Douglas-fir.

The diversity in Douglas-fir stump sizes at our sites suggests that our historical stands included larger diameter trees, which survived the fires of the late 1600s or early 1700s.

Forest species composition and stand structure has been profoundly influenced by fire in this region (Agee 1993). Large, stand-replacement fires burned in this portion of the Olympic Peninsula around 1500 and 1700 (Henderson et al. 1989). Two large fires on the Olympic Peninsula that burned around the time that the Rail and Fresca old growth established were dated to 1668 and 1701 by Henderson et al. (1989). Scattered tall and thick-barked Douglas-fir trees often survive fires providing a seed source for recolonization (Huff 1995). The diversity in Douglas-fir stump sizes at our sites suggests that our historical stands included larger diameter trees, which survived the fires of the late 1600s or early 1700s. For example, it is unlikely that the scattered Douglas-fir trees greater than 3 m in diameter originated after the same fire as the majority of trees that were 70- to 170-cm in diameter, so the larger diameter trees are likely to have originated after an earlier event such as the fire that occurred ~1500. These scattered larger diameter Douglas-fir would have functioned as seed trees for the Douglas-fir in the stand following the late 1600s or early 1700s.

Tappeiner et al. (1997) suggested that many Douglas-fir old-growth stands were sparsely stocked and diverse in size owing to repeated partial burning rather than starting out densely and self-thinning as modern stands do. The age of a stump in the vicinity of Fresca (Peter, unpublished data) and ages provided by Dodwell and Rixon (1902) suggest stand origination in the late 1600s, but Douglas-fir trees in the northern Olympic Peninsula commonly date to the early 1700s (Henderson et al. 1989). A mixed-severity reburn in the early 1700s after a late 1600s fire might have extended the regeneration period similar to what Tappeiner et al. (1997) found in western Oregon, but this does not explain the coestablishment of fire-sensitive western hemlock with Douglas-fir at Rail. Also, Douglas-fir diameters in single-aged stands regenerating from fire usually form a bell-shaped curve (Agee 1993) similar to that at both sites. Thus, multiple fires around 1700 probably did not occur at Rail or Fresca.

Douglas-fir establishment after fire can require 10 to 100 years (Franklin and Hemstrom 1981, Huff 1984, Munger 1940, Tappeiner et al. 1997, Yamaguchi 1986) owing to seed availability, site conditions (Huff 1995), and periodic reburns (Tappeiner et al. 1997). However, in the moist Sitka Spruce Zone and wetter parts of the Western Hemlock Zone, establishment tends to be rapid (Harcombe 1986) and often includes shade-tolerant species and shade-intolerant red alder (*Alnus rubra* Bong.). Douglas-fir is less common than in drier parts of the Western Hemlock Zone because fires are smaller; fire-free intervals are longer; and red alder, western hemlock, and Sitka spruce establish more aggressively (Agee 1993, Henderson et al. 1989). However, once established, Douglas-fir can remain for centuries (Munger 1940). Owing to its tolerance of shade and the lengthy fire cycle in these areas, western hemlock (and Sitka spruce at Fresca) will increase over time at the expense of shade-intolerant Douglas-fir or red alder (Franklin and Dyrness 1988, Henderson et al. 1989). Thus, fire and site interact to determine the initial stand stocking and composition with centuries-long consequences.

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Old-growth characteristics often accrue through multiple local disturbances that open single to multitree canopy gaps from windthrow, disease, or age-related senescence (Spies et al. 1990, van Pelt and Nadkarni 2004, Winter et al. 2002). Thus, an initially dense and uniform Douglas-fir forest can become more open and also more diverse as shade-tolerant trees are recruited into the canopy gaps. Windstorms produce pulses of regeneration in scattered patches. Western

Washington has a history of large windstorms such as the relatively recent 1921 Blow and the Columbus Day Storm of 1962 capable of extensive gap formation (Boyce 1929, Henderson et al. 1989, Morganroth 1991, Orr 1963). Winter et al. (2002) documented how structural diversity accrued in pulses (interpreted as windstorms) in a Western Hemlock Zone stand in the southern Washington Cascade Mountains resulting in a structurally diverse 500-year-old stand. The stand described by Winter et al. (2002), although older than our Rail and Fresca stands, had a similar overall stand density (91 tph), but only had 14 Douglas-fir tph. Our stump data indicated that there were 43 to 46 Douglas-fir tph at Rail and 51 to 62 tph at Fresca. However, compared to a 280-year-old lowland old-growth stand near Mount Rainier in western Washington, which had 105 Douglas-fir tph (van Pelt and Nadkarni 2004), the Douglas-fir tree density at Rail and Fresca is quite low. Also, there is no evidence of repeated pulses of conifer regeneration, so we think it likely that another (or additional) mechanism contributed to gap formation and the evolution of stand structure at Fresca and Rail.

It is important to recognize that some successional pathways are more likely than others owing to climate and site potential. For example, early red alder recruitment is only possible on moister sites in the Pacific Northwest where red alder aggressively competes with conifers after fires (Henderson et al. 1989) and multiple fire-mediated pathways are unlikely in many of these same areas, as fire tends to occur rarely in them (Agee 1993). Rail and Fresca are both moist maritime sites where early seral recruitment of red alder is likely (Henderson et al. 1989). Red alder has light seed capable of widespread wind dissemination (Harrington 2006) from small refugia, such as riparian stands, so it is able to access considerable areas of landscape as it becomes available for colonization after disturbances such as fire. When established simultaneously with red alder on moist sites, Douglas-fir is often overtopped and killed (Newton et al. 1968), but mixed stands result when some Douglas-fir establishes a few years before most of the red alder (Stubblefield and Oliver 1978). Henderson et al. (1989) suggested that initial canopy codominance by red alder in the plant associations present on these sites may commonly be responsible for an initial low density of conifers. After 60 to 80 years, red alder dies, which creates gaps that permit recruitment of shade-tolerant species such as western hemlock.

The species distributions of stumps at our two sites suggest somewhat different stand histories. Douglas-fir was not only widely spaced, but western hemlock entry lagged behind that of Douglas-fir at Fresca. At Rail, however, Douglas-fir and western hemlock coestablished.

The species distributions of stumps at our two sites suggest somewhat different stand histories. Douglas-fir was not only widely spaced, but western hemlock entry lagged behind that of Douglas-fir at Fresca. At Rail, however, Douglas-fir and western hemlock coestablished. This would seem to indicate that a considerable gap-forming event occurred sometime after the establishment of the Douglas-fir stand at Fresca, but not at Rail. Two likely candidates for this gap-forming event are a large windstorm or senescence of coestablished red alder. Either of these processes could account for the wide Douglas-fir spacing and the lag in western hemlock regeneration.

At Rail, which appears to date from the same stand-initiation fire as Fresca, the strong overlap of the Douglas-fir and western hemlock size distributions and low stand density suggest that Douglas-fir and western hemlock coestablished. Western hemlock also has light seed capable of widespread wind dissemination (Packee 1990), which may have facilitated its establishment. Having started from codominance, this stand probably continued to gradually open and diversify from local gap-forming processes. Both the GLO surveyors and Dodwell and Rixon (1902) mentioned smaller and younger western hemlocks, so we assume that some established later in response to disease, wind disturbance, or red alder/conifer senescence.

Because the distribution of western hemlock diameters at Rail is essentially the same as for Douglas-fir and certainly not bimodal, we do not believe a large windstorm affected the development of the stand at Rail. At this site, low Douglas-fir density is explicable by partial exclusion of Douglas-fir by western hemlock during stand establishment. Because Rail is only 15 km from Fresca over flat land and Rail does not appear to have been affected by a windstorm, we think a partial competitive exclusion by red alder is a better explanation for the low Douglas-fir tree density at Fresca than a windstorm.

The modern 70-year-old stands at Fresca and Rail are younger, denser, have smaller diameter trees, and less size variation than the historical stands had, and because of shade suppression also have sparse herb and shrub understories. They are similar to other densely stocked modern stands with low age and size variation (Bailey 1996, Curtis et al. 2004, Franklin and Spies 1991, Oliver and Larson 1990). We believe the uniformity of Fresca and Rail is due to four factors: (1) the area was uniformly clearcut and slash burned, (2) progressive cutting allowed uniform and heavy seeding from remaining old-growth stands, (3) no postestablishment fires or large windstorms caused significant gap formation, and (4) there is no indication that red alder was an important species at either site in modern times. Higher modern stand densities probably limit diameter growth compared to historical stands, especially if historical stands were fertilized by red alder (Bormann 1977). A legitimate question managers have about these kinds of stands is how to change the successional trajectory to increase structural and compositional diversity for the benefit of wildlife species associated with late-successional stands.

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One way to change successional trajectory is by thinning the stand. At Fresca, where the overstory density is almost 40 percent greater than at Rail, the thinning treatments made only small changes in overstory tree density. Rail received an additional thinning in 1986 that explains much of the difference in overstory density between these two stands. The difference in density may also explain the large amount of western hemlock regeneration at Rail, but not at Fresca and possibly faster tree growth at Rail than at Fresca (contrary to what would be predicted based on their respective plant associations). Thus, differences in thinning, combined with differences in site potential have elicited different successional trajectories.

Thus far, our discussion has assumed that no change in climate has or will occur. However, this is not the case; climate changed continuously throughout development of the old-growth and modern stands, raising the possibility that species composition has been affected. Most of the succession of the old-growth stands occurred during the cooler The Little Ice Age climate, which is generally thought to have been at its greatest expression around the time these old-growth stands established (Cook et al. 2004, Gavin and Brubaker 1999, Heusser 1957). The Little Ice Age ended and a warm period began in the mid-1800s. Thus, both Fresca and Rail were initiated in a period thought to have been cooler than the present climate. Because large fires occurred on the Olympic Penisnsula in the late 1600s and early 1700s, the summer climate may have been drier at that time as well (Henderson et al. 1989). Thus, the relative lack of Sitka spruce in the old-growth Fresca stand and the abundance of it in the modern stand may relate to drier conditions during old-growth stand establishment and moister conditions during modern stand establishment. Our data do not permit a definitive statement on this matter, but it is important to consider that climate change is an ongoing phenomenon that could alter future successional trajectories making only very general restoration objectives practical.

Conclusions

Because the overstory species composition of Rail is similar to that of the previous historical stand, restoration approximating the historical stand structure and composition may yet be possible and might be accelerated by appropriate silvicultural manipulation. This would require additional thinning treatments to diversify stand structure. In addition, diversification of the shrub and herb layers would require control of western hemlock regeneration after thinning. One difference between the modern stand and historical stands not restorable with silvicultural manipulation is the older age classes of large Douglas-fir trees that were present in the historical stand.

It is not possible, even if it were desired, to reestablish the historical stand composition at Fresca since Douglas-fir is now a minor species there and of only one age class. If our reconstruction is correct and the historical conifers established at wider spacing while benefiting from red alder nitrogen fertilization, the higher stand density of the modern stand may limit diameter growth if there is no additional thinning.

The modern stands are following different successional pathways than the old-growth stands and can only be partially restored with silvicultural manipulation. However, the stand histories that we reconstructed hold keys to diversifying these and other forests.

Based on plant community potential, fire history information, and inference from our reconstructed stands, we suggest that the modern stands are following different successional pathways than the old-growth stands and can only be partially restored with silvicultural manipulation. However, the stand histories that we reconstructed hold keys to diversifying these and other forests. Thinning when the stand was younger, particularly releasing individual trees would have facilitated earlier development of large trees, while allowing the development of a variable understory. But, for the current stands, larger and more diverse tree sizes might develop more rapidly by the creation of larger openings that would reduce the overstory tree density to levels more in line with the historical overstory density and facilitate the logging operations necessary to create them. Planting these openings with red alder would delay occupation by shade-tolerant conifers. The natural fertilization from the red alder trees would further encourage conifer size diversification. Shrub and herb understory development under red alder is greater and more diverse than under conifers (Franklin and Pechanec 1968), and conifer replacement of red alder is relatively sparse and slow (Newton et al. 1968) facilitating shrub and herb retention.

These sites appear to have multiple developmental pathways determined by events early in their stand histories that affect stand structure and composition for hundreds of years. This has implications for the possibilities of, and methodologies for, restoration of old-growth structure and function. But, naturally or through silvicultural manipulation, diversification in at least these plant associations is encouraged by lower early conifer density, patchy spacing of dominant trees, and prevention of immediate conifer occupancy of openings.

Scientific name	Common name
Alnus rubra Bong.	red alder
Gaultheria shallon Pursh	salal
Oxalis oregana Nutt.	redwood-sorrel
Picea sitchensis (Bong.) Carr.	sitka spruce
Polystichum munitum (Kaulf.) C. Presl	western swordfern
Pseudotsuga menziesii (Mirb.) Franco	Douglas-fir
Tiarella trifoliata L.	threeleaf foamflower
Tsuga heterophylla (Raf.) Sarg.	western hemlock

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English Equivalents

When you know:	Multiply by:	To find:
Millimeters (mm)	0.0394	Inches
Centimeters (cm)	0.394	Inches
Meters (m)	3.28	Feet
Kilometers (km)	0.621	Miles
Hectares (ha)	2.47	Acres
Square meters per hectare (m^2/ha)	4.37	Square feet per acre
Trees per hectare (tph)	0.405	Trees per acre
Degrees Celsius (°C)	1.8 °C + 32	Degrees Fahrenheit

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