ABSTRACT--Tree age distributions, fire history, tree age patterns, and gap-phase replacement were investigated in two, dry coniferous forest stands in the Willamette National Forest, Oregon. The fire history of 73 vegetation plots was also investigated. Natural stands burned at approximately 100-yr intervals before effective fire suppression. These fires generally destroyed only a portion of the canopy and were followed by periods of tree establishment (attainment of breast height) which spanned 60 to 150 yr. Repeated fires resulted in reverse-J shape diameter distributions and all-aged stands. The fires make regeneration by gap-phase replacement unimportant. The surviving trees generally occur in 0.1- to 0.3-ha patches. Managers can expect regeneration to be slow on the more severe sites. Based on this understanding of natural stand development, the selection silvicultural system is appropriate, but current regulations and ignorance of uneven-aged stand yields and appropriate logging systems currently limit the practice of selection silviculture.

KEYWORDS--Fire history, gap-phase replacement, age distribution, tree age map, selection silviculture, regeneration, Pseudotsuga menziesii, Libocedrus decurrens.

INTRODUCTION

Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) and its occasional associate Incense-cedar (Libocedrus decurrens Torr.) are apparently climax species (in the sense of Daubenmire 1968) on hot, dry sites in the central western Cascade Range of Oregon (Dyrness et al. 1974). These sites are generally restricted to low elevation, southeast- to west-facing slopes with shallow to deep, often gravelly Entisols, Inceptisols, and Alfisols (Means 1980). An understanding of stand development in these dry, coniferous forests has been lacking. Specifically, stand age distributions and disturbance histories have not been investigated. In contrast, stand development on the more widespread, moister sites--where Douglas-fir functions as a long-lived seral dominant--has been understood for some time (Munger 1930, 1940, Thornburgh 1969).


Tree size distribution of dry coniferous forests is characterized by many small, overtopped trees in the reproductive size classes and an exponential decline to few individuals in the larger size classes (Means 1980). This distribution contrasts with the typically bell-shaped diameter distribution of Douglas-fir on mesic sites (Means 1980). Possible causes of this size distribution in dry coniferous forests include: (1) continuous mortality of individual trees or groups of
trees followed by the establishment of trees in the resultant gaps and eventual growth to the canopy; (2) slow restocking of the site following destruction of the previous stand; (3) regeneration during several distinct periods in the history of the stand; (4) widely differing rates of tree growth.

The work reported here is part of a larger study of dry coniferous forests in the Willamette National Forest. Descriptions of the plant communities and height growth patterns of Douglas-fir are reported elsewhere (Means 1980). In the study area, dry coniferous forests are defined as forests usually over 100 yr old, within the Tsuga heterophylla zone (Franklin and Dyrness 1973), with fewer than 10 western hemlock (Tsuga heterophylla (Raf.) Sarg.) per hectare, and more similar to the Pseudotsuga menziesii/Holodiscus discolor association than to any others of Dyrness et al. (1974). The sites on which these communities occur are called dry sites in this paper. Dry coniferous forest with Douglas-fir as the only major conifer is also called dry-site Douglas-fir.

Much of the inspiration for this study came from Stephens (1955, 1956, also see Oliver and Stephens 1977) and Henry and Swan (1974) who showed that close examination of old, undisturbed, temperate forest stands can reveal much of their history.

OBJECTIVES AND HYPOTHESES

This study examined site history and successional trends and mechanisms. The objectives of the study were:

1. Examine the age distribution of each tree species to investigate tree establishment through time.

2. Examine the spatial distribution of tree ages and evidence of fire and windthrow to investigate stand history, particularly regeneration patterns.

3. Look for evidence of a previous stands such as logs, stumps, charcoal, and rootthrow mounds and pits--to investigate site history.

In addition, the following hypotheses guided work not covered by the objectives or focused on particular questions.

1. Trees require more than 50 yr to reoccupy these dry sites fully after a major disturbance. The conventional wisdom (based on typical, more mesic Douglas-fir stands) is that dense Douglas-fir regeneration occupies a disturbed site quickly (within 20 to 30 yr) (Isaac 1943). Recent studies in this area have indicated, however, that 60 yr (Fig. 1) to 150 yr (Franklin and Waring 1980, Franklin and Henstridge 1981) were required for full occupancy on some mesic sites in past centuries. Regeneration may take even longer on the severe sites of this study. A basis for rejecting this hypothesis would be age cohorts that span less than 50 yr because full stocking limits additional regeneration.

2. Douglas-fir and incense-cedar replace themselves when openings occur in the canopy so they are climax in dry coniferous forests (Whittaker 1975). A basis for rejecting this hypothesis would be evidence that other species become more common as stands develop.

3. Gap-phase replacement (Watt 1947, Bray 1956, Runke 1981) is an important mechanism for regeneration in mature, dry coniferous forest stands. Although the study type is called climax Douglas-fir (Dyrness et al. 1974), the successional mechanism of Douglas-fir and its associates have not been investigated. The key to its successional status is the success of its reproduction in competition with other trees in gaps created by tree mortality in the canopy. Only relatively old stands that have had significant natural mortality and resultant regeneration can be used to test this hypothesis. A basis for rejecting this hypothesis would be evidence that an insignificant number of trees had reached the canopy in gaps created by the death of one to several (e.g., five) canopy trees.

This study was designed to examine the importance of reproduction in gaps caused by the death of 1 to perhaps 10 trees as described by Bray (1956) and Runke (1981). Watt (1947), in the article that first proposed the gap-phase mechanism of plant replacement, allows that "there are exceptional factors of rare or sporadic occurrence, such as storms, fire, drought, epidemics, which create a gap-phase of exceptional dimension" (Watt 1947, p. 13). This very broad definition of the gap phase easily includes all regeneration of dry sites (and most other forests) and so is not an interesting basis for a hypothesis.

4. Dry coniferous forests are first generation forests on the sites studied. It is possible that some of these stands may be first generation forests on sites that previously supported more xerophilic vegetation such as oak savanna. Evidence for rejecting this hypothesis would be the presence of stumps, logs, charcoal or rootthrow mounds older than the oldest trees in the stand.

METHODS

Data for this study came primarily from two intensively studied plots, and secondarily from 73 extensive vegetation plots. Intensive plot 1 is 0.75 ha (75 x 100 m) added during 1976 to reference stand 1 in the H. J. Andrews Experimental Forest (Hawk et al. 1978) (Table 1). This plot is primarily in the Pseudotsuga/Holodiscus/Acer community type but also
TABLE 1.
TOPOGRAPHY, BEDROCK, AND SOILS ON THE INTENSIVE PLOTS.a

<table>
<thead>
<tr>
<th>Item</th>
<th>Intensive plot 1</th>
<th>Intensive plot 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>H. J. Andrews Experimental Forest</td>
<td>7 km north of Oakridge, Oregon</td>
</tr>
<tr>
<td>Elevation (m)</td>
<td>500</td>
<td>930</td>
</tr>
<tr>
<td>Slope (percent)</td>
<td>72 (45-92)</td>
<td>55 (45-65)</td>
</tr>
<tr>
<td>Aspect (degrees)</td>
<td>200 (160-237)</td>
<td>230 (195-260)</td>
</tr>
<tr>
<td>Bedrock</td>
<td>Andesite, Breccia</td>
<td>Andesite (Breccia)</td>
</tr>
<tr>
<td>Soils characteristics:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil ordersb</td>
<td>Inceptisols (Alfisols, Entisols)</td>
<td>Alfisols, Inceptisols, Entisols</td>
</tr>
<tr>
<td>Depth (cm)</td>
<td>132 (11 to approx. 250)</td>
<td>90 (8 to approx. 250)</td>
</tr>
<tr>
<td>Coarse particles (percent)</td>
<td>54 (43-64)</td>
<td>25 (11-59)</td>
</tr>
<tr>
<td>Textures:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A horizon</td>
<td>Silt loam (loam, sandy loam)</td>
<td>Loam, silt loam</td>
</tr>
<tr>
<td>B horizon</td>
<td>Silt loam, (loam, sandy loam, silty clay loam, clay loam)</td>
<td>Clay loam, silt loam</td>
</tr>
<tr>
<td>Estimated available</td>
<td></td>
<td></td>
</tr>
<tr>
<td>water-holding capacity</td>
<td>6.3 (1.1-9.9)</td>
<td>7.8 (1.3-15.8)</td>
</tr>
<tr>
<td>to 100 cm (cm)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

aNumbers in parentheses are ranges or minor inclusions.

bSoil taxonomy follows Soil Survey Staff (1975).

includes some areas of both phases of the Pseudotsuga/Holodiscus/grass type (Means 1980) and possible minor areas of wooster habitat types of Dyrness et al. (1974). This intensive plot sweeps around a side ridge that has steep slopes.

Intensive plot 2 is 0.5 ha (50 x 100 m), located 7 km north of Oakridge, Oregon (Table 1). The plot was chosen because it showed little sign of major disturbance since the oldest trees were initiated. (This assumption was subsequently proved wrong). Intensive plot 2 includes areas of Libocedrus/Whipplea and Pseudotsuga/Berberis/Disporum types with lesser amounts of the Pseudotsuga/Holodiscus-Acer type (Means 1980). It is on moderate slopes (Table 1) with three small side ridges running through it, increasing its variability.

Vegetation plots provided data on the disturbance histories of 56 dry-site communities and 17 climax western hemlock communities. The plots were distributed throughout all but the Sweet Home and Lowell Ranger Districts of the Willamette National Forest in the western Cascade Range of Oregon (Means 1980).

Field Methods on the Intensive Plots

A grid system, corrected for slope, was installed with metal stakes at 25-m intervals. String was placed at 5-m intervals to facilitate mapping objects at a scale of 5 m = 1 in. Probably accuracy was within 1.0 m for two-thirds of all objects mapped. Species, d.b.h., and crown class (Smith 1962) were then determined. Trees larger than 10 cm d.b.h. (15 cm for plot 1) and taller than 137 cm were mapped. Trees smaller than this but taller than 137 cm (greater than 5 cm for plot 1) were mapped and inventoried on one-fourth of the 25 x 25-m grid sections, randomly selected. Diameter limits on intensive plot 1 were slightly different because the original mapping and measuring of trees was done by the vegetation crew of H. J. Andrews Experimental Forest. Numbered metal tags identified each mapped tree. The areal extent of all rootthrow mounds and pits was also mapped.

The importance of regeneration in canopy gaps was investigated using a paired-plot technique in both intensive plots. All canopy gaps created by death of identifable trees were mapped and young trees occurring in these gaps were tallied. Near each gap I selected a live tree or group of trees that matched in size and microenvironment (indicated by vegetation and
topography) those that died. A similar tally of smaller trees was conducted under these selected canopies.

Evidence of fires, such as charcoal on tree bark, was recorded. Fire scars were increment-cored and counted in the field with a hand lens or in the laboratory under a binocular microscope. Often several attempts were necessary to find a reliable age of faint shock rings or rings obscured by heart rot that often develops behind scars. Typically at least four cores were required to determine the age of a scar; 12 cores were taken in one. Heart rot prevented determining the age of some scars.

All trees greater than 50 cm d.b.h. and 35 percent of the tagged trees that were smaller were cored at breast height to construct the age distribution. Thus the age distribution of intensive plot 1 is based on trees larger than 5 cm d.b.h. and that of intensive plot 2 is based on trees taller than breast height. Sampled trees were increment-cored at breast height and information for determining height was collected using an abney level. Core length to the pith, when present in the core, or to where the core passed the pith, bark thickness, sapwood thickness, and current incremental growth (in rings/cm) were recorded. Cores were then sealed in plastic straws, transported to the lab, and rings were counted under a binocular microscope. Recorded for cores not passing the pith were the angle between the core and the perpendicular to the rings at the end of the core, or to where the core passed the pith, bark thickness, sapwood thickness, and current incremental growth rate (rings/cm) along the perpendicular. Occasionally, easily read cores were counted and measured in the field. Bark thickness, sapwood thickness, and current incremental growth were also determined on a second core taken on the opposite side of the tree. Ages determined for trees and fire scars on the intensive plots include growth rings through 1978, the year increment cores were taken.

Increment coring was used to determine the ages of trees and scars because it is faster and less destructive than other methods of investigating intact stands. Cutting wedges out of fire scars, falling trees to determine the age of cross-sections, and cross dating and verifying sequences of tree rings would have given more reliable ages (Stokes 1980) but would have reduced the sample size. Fire danger in the field was often too great to operate chain saws away from roads, and hand-sawing would have been too slow.

The intensive plots were thoroughly searched for evidence of a previous stand. Evidence included old stumps, logs, rootthrow mounds and pits, and charcoal in soil pits.

Seven soil pits were described in intensive plot 1; eight in plot 2. They were located to cover the range of point basal areas estimated with a 40-Factor (ft²/acre) prism (Husch et al. 1972). Methods for describing soil pits are given elsewhere (Means 1980).

Laboratory Methods for the Intensive Plots

Increment cores with rings too narrow to count in the field with a 10x hand lens were counted in the laboratory under a binocular microscope. Ages were estimated by program AGEHT (Means 1980) when extrapolation beyond the end of the core (up to 20% of total age) was needed. Heights were also estimated by program AGEHT (Means 1980).

Site index was estimated using the curves from McAriddle et al. (1961) instead of King (1966). Although King's curves are almost certainly more accurate for young dry-site Douglas-fir, they cannot be used on trees older than 120 yr.

Regeneration density was calculated from the tree counts in canopy gaps and under the mapped tree canopies on a per-100-m² basis for each condition (gaps and canopies), then on a per-hectare-of-forest basis. The regeneration density was combined with the diameter tally of larger trees to give the diameter distribution. Stocking of trees 0.0-5.0 cm d.b.h. in intensive plot 1 was taken from the regeneration tallies and the tree tally on vegetation plot 48 (see Means 1980 for vegetation plot descriptions).

Ideally, age distributions are obtained by determining the ages of all trees. To save time, however, I increment cored only a sample of trees 0-50 cm d.b.h., which were relatively numerous. I wanted to estimate ages for the other trees so that the relative magnitudes of peaks in the age distribution would reflect conditions in the field. When only a sample of trees are aged, and when ages of the remainder are estimated from regressions of age on diameter, the detail in the age distribution is reduced because the relationship between diameter and age is generally quite poor (Harper 1977, Blum 1961). To illustrate, ages of uncored Douglas-fir in plot 2 could have been estimated by the regression of age on diameter shown in Figure 2. Then all trees 50 to 80 cm d.b.h. would have been assigned ages between 170 and 220 yr; the ages of most trees that size, however, are not in this range.

![Figure 2](image-url)

**FIGURE 2.** Diameter versus age of Douglas-fir on intensive plot 2. The regression line was fit by least squares (n = 50, R² = .59, standard error of age = 6.6).

The method used here to construct the age distribution preserves detail in the distribution of the available ages by assigning each uncored tree the age of an aged tree of similar diameter. All trees, aged and unaged, were grouped by 10-cm d.b.h. classes. Then each unaged tree was assigned the age of an aged tree in its diameter class. All ages in a d.b.h. class were assigned the same number of times when possible. Otherwise, a sufficient number of randomly selected ages was used one more time.
Methods for the Extensive Vegetation Plots

Investigating the disturbance history on the 73 vegetation plots included noting charcoal on tree bark and determining the age of the fire scars as on the intensive plots. One or two trees of the oldest-appearing cohort were cored to estimate the stand age. Larger trees were aged with less accuracy because greater extrapolations were necessary in program AGEHT (Means 1980). Ages of fires occurring since stand initiation were usually determined from fire scars; 10 stands, however, had trees with charred bark, indicating a fire had occurred, but had no datable scars associated with that fire. In these stands, that fire age was estimated as half the age of the previous fire but not greater than 120 yr. I assumed charcoal rarely lasts longer than this. Fire ages in eight stands were based on marked diameter cohorts (strikingly evident in the diameter distribution) and the relationships of these cohorts to diameters of aged trees. Three of these fire ages were for the initiation of large, old-growth cohorts undatable because of heart rot.

Fire ages based on charred bark and marked diameter cohorts are less accurate, but their use was generally not necessary. Only 10 of the 135 fire ages are based on char and 8 on marked diameter cohorts, whereas 89 and 28 fire ages are more accurately based on increment-cored trees and fire scars, respectively.

Several terms need definition. A major fire was defined as a fire estimated to have reinitiated 50 percent or more of the canopy based on field observations of stand structure and the diameter distributions (Means 1980). The effects of disturbances of this size were usually obvious, so major fires were usually easily determined. A fire interval was defined as the time between two consecutive fires on one plot. The mean interval between fires for a community was the arithmetic average of all fire intervals on plots in the community. All ages on the vegetation plots have been corrected for sampling year; the ages are as of 1980.

RESULTS AND DISCUSSION

Basal Area and Diameter Distribution

The greater basal area of incense-cedar and greater total basal area on intensive plot 2 (Table 2) are consistent with the average values for the community types represented (Means 1980). Both these features are probably due, in part, to the greater average age of plot 2. Site index is substantially higher on plot 2 than on plot 1, although it is variable on both plots (Table 2). This difference in site index can be attributed, in part, to greater overestimates of site index using the curves from McArdle et al. (1961) for the older trees of plot 2 (Means 1980).

Diameter distributions on both intensive plots closely approach the classical reverse-J shape (Figs. 3 and 4), characteristic, although not indicative, of an all-aged stand (Whittaker 1975, Harper 1977). Overstories of both plots 1 and 2 are dominated by Douglas-fir. Understories are dominated by Douglas-fir on plot 1 and incense-cedar on plot 2. The numerous, small western yew (Taxus brevifolia Nutt.) on plot 1 are not atypical for a Pseudotsuga/Holodiscus-Acer stand (Means 1980).

Age Distribution and Stand History

There are three major age cohorts in intensive plot 1 (Fig. 5). A broad age cohort, or perhaps several indistinguishable cohorts, became established 230 to 410 yr ago. These trees are now the large diameter, rounded- or broken-topped dominants. A more distant age cohort (133 to 195 yr old) became established following a fire 195 yr ago (Fig. 5). This fire age is based on only one scar. The youngest cohort is 50 to 133 yr old. It followed a fire approximately 133 yr ago dated by 17 scars spanning a range of only 3 yr. This fire correlates with the period of initiation of the widespread 135-yr-old age class in the Pacific Northwest (Jerry F. Franklin 1980, personal communication).

The younger age cohorts in intensive plot 2 are broader than those in intensive plot 1 but can also be interpreted with knowledge of past fires (Fig. 6). This plot has more dominants over 200 yr old than intensive plot 1. The oldest cohort consists of only three trees 420 to 470 yr old (Fig. 6). Although older than the oldest trees aged in intensive plot 1, it is still within the 450-yr-old age class of the oldest trees identified in the H. J. Andrews Experimental Forest (Fig. 1) (Franklin and Waring 1980). The next cohort was established 140 to 300 yr ago following two or more fires (Fig. 6). Both of the fire ages between 300 and 340 yr old are from a large incense-cedar with a rotten center. Problems in finding shock rings and determining the age of the scar make these fire ages questionable. The date of initiation of this cohort corresponds approximately to the ca. 1688 fire episode at Mount Rainier National Park (Hemstrom 1979). The youngest cohort is 40 to 140 yr old (Fig. 6) and apparently established following a fire 138 yr ago. Only one scar is dated at 138 yr, but the occurrence of this fire is supported by charcoal on tree trunks.

The significance of charcoal on tree bark must be interpreted carefully. Eleven trees aged at 217 to 289 yr old have charcoal on their bark (the only other live trees with charred bark are the three over 400 yr old). These trees must have been fairly large and thus fairly old to have survived a fire that charred their bark; the fire must have occurred within approximately the last 150 yr. But the fire is not recent--it is probably more than 50 yr old--because the char extends less than half way into the 2-in-deep fissures, and 30 trees aged at over 189 yr old do not now show charring even though they are intermixed with the charred trees. Presumably some of these trees were charred in the fire but the char has weathered off. The charred trees occur in two areas in the stand where there are very few trees younger than 200 yr; therefore one cannot use the presence of many young trees less than 140 yr old to help determine the age of the fire. This disjunction, however, does not indicate that this fire did not burn areas now occupied by young trees before their establishment. In summary, the certainty of a fire approximately 50 to 150 yr ago (as indicated by the charred trees) supports the occurrence of a fire 138 yr ago (as indicated by the scar).

The hypothesis that trees require more than 50 yr to fully reoccupy these dry sites after a major disturbance is accepted. All the age cohorts span more than 50 yr and the narrowest (the 133- to 195-yr-old cohort in intensive plot 1) would probably be broader had a fire not occurred.
The hypothesis that Douglas-fir and incense-cedar replace themselves and so are climax is accepted. These species dominate the pre-fire and post-fire cohorts, and fire maintains the diameter and age structures; thus these are fire-climax communities (in the sense of Daubenmire 1968). The lack of more mesic species such as western hemlock 133 and 138 yr after fire indicates that succession to these species in the absence of fire will be very slow, if it occurs at all. The apparent increase of incense-cedar in the youngest cohort in intensive plot 2 (Fig. 6) does not necessarily indicate it is replacing Douglas-fir. A future fire might favor Douglas-fir, especially if it is more resistant to fire than incense-cedar (Minore 1979, Martin and Johnson 1979).

The methods used here have several limitations; for this reason, I have attempted to interpret only broad age cohorts. The first limitation is that historical information is lost with time as tree centers rot out (especially behind scars) and old fire scars are covered with thick bark. Second, past mortality is unknown, a common problem in plant population studies (Harper 1977). The older age cohorts only contain trees that have survived competition, past fires, and other causes of mortality, so these cohorts are greatly reduced from when they were established. Yet it is often the establishment period that we seek to understand. Third, all the ages on the intensive plots are breast height ages. It seemed reasonable to count a tree as established when it reaches breast height for silvicultural purposes, but this can cause problems in stand history studies: regeneration periods may be artificially lengthened if competition is greater later in the period and trees that germinate at that time reach breast height more slowly. Also, ages of species that grow relatively slowly in height will be less than those of more rapidly growing species germinated at the same time. Fourth, not all trees were aged; so, for example, incense-cedar 140 to 170 yr old may be present though not shown in the age distribution. These problems make interpretation of fine-scale features in the age distribution infeasible, but they should not affect interpretation of the broad age cohorts.

Tree Age Maps.

The oldest age cohort in intensive plot 1 is concentrated in the upper right and lower left portions of the stand (Fig. 7). The two fires that occurred subsequent to its establishment have probably reduced its abundance in the rest of the stand. Alternatively, it may never have been present in portions of the stand originally occupied by still older trees. The 140- to 195-yr-old cohort occurs in two well-defined clumps (Fig. 7), probably because the fire 195 yr ago opened growing space in the oldest cohort and the fire 133 yr ago opened very little growing space in the then 60-yr-old cohort. Members of the youngest cohort are most common in a band going from top left to bottom right and avoiding the clusters of other cohorts.

Patterning also occurs in the distribution of age cohorts in intensive plot 2 (Fig. 8). The oldest cohort is represented by only three individuals grouped at the upper plot boundary. Most individuals of this cohort were probably killed by the fire occurring about 300 yr ago, which resulted in initiation of the 140- to 300-yr-old cohort. Most members of the 140- to 300-yr-old cohort now occur in two clusters, one near the plot center and one near the right edge where the fire 138 yr ago killed few of this cohort. The youngest cohort occurs primarily in the left side of the stand and in a strip from top to bottom in the right portion of the stand.

TABLE 2.

BASAL AREA AND DOUGLAS-FIR SITE INDEX ON THE INTENSIVE PLOTS. 

<table>
<thead>
<tr>
<th></th>
<th>Intensive plot 1</th>
<th>Intensive plot 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basal area (m²/ha):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pseudotsuga menziesii</td>
<td>59.4</td>
<td>66.7</td>
</tr>
<tr>
<td>Libocedrus decurrens</td>
<td>0.0</td>
<td>24.1</td>
</tr>
<tr>
<td>Acer macrophyllum</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Other speciesb</td>
<td>0.7</td>
<td>0.0</td>
</tr>
<tr>
<td>Total</td>
<td>61.4</td>
<td>92.1</td>
</tr>
<tr>
<td>Site index, base age 100 (m)</td>
<td>34 (23-42)</td>
<td>43 (33-52)</td>
</tr>
</tbody>
</table>

*The site index curves used were from McArdle et al. (1961).

bOn plot 1 only, the order of decreasing basal area was Taxus brevifolia, Tsuga heterophylla, and Arbutus menziesii.
FIGURE 3. Diameter distribution in intensive plot 1, including regeneration.

FIGURE 4. Diameter distribution in intensive plot 2, including regeneration.
FIGURE 5. Age distribution of Douglas-fir and dates of fire scars in intensive plot 1. Ages of all trees above the dashed lines, when present, are estimated as described in the text.

FIGURE 6. Age distributions of Douglas-fir and incense cedar and dates of fires scars in intensive plot 2. Ages of all trees above the dashed lines, when present are estimated as described in the text. The term "fire?" is used when fire scars were difficult to count.
partially on an area of thin soils, indicated by solid symbols. Topographic lines are drawn by hand from memory for the purpose of relating age cohort patches to the description in the text, so elevations are not indicated.

Trees that survived the fires generally occurred in 0.1- to 0.3-ha patches in both intensive plots, although trees also survived as relatively isolated individuals and small groups.

It is important to note that none of the four fires dated with scars on the intensive plots destroyed the stand. They opened a portion of the canopy, providing room for subsequent, nearly continuous regeneration and creating an all-aged stand (in the sense of Smith 1962).

Reasonable interpretations of some of the causes of these age cohort patterns can be made from topography and soils, but these are certainly not the only possible interpretations. Microtopography and soil characteristics are correlated with several indices of tree stocking on these plots (Means 1980) and probably also with regeneration rates, both of which influence tree age pattern. The cluster of the oldest age cohort on the right side of intensive plot 1 (Fig. 7) is partially on an area of thin soils, indicated by a cliff at the top and a soil pit at the bottom that hit bedrock at 11 cm. If this thin-soiled portion of the stand had lower productivity and therefore lower fuel loading, the 1785 fire (Fig. 5) may have burned more lightly here. The cluster of the 140- to 195-yr-old cohort in the lower left of intensive plot 1 is on thin soils (two soil pits are 25 and 53 cm deep) on the main side ridge in the plot. Thus, low fuel accumulations may also have helped spare it during the 1845 fire (Fig. 5). The bottom right corner of the plot is moister (western hilllock is present), resulting in denser vegetation, especially within 10 m of the ground. Relatively dense vegetation in 1845 might have resulted in greater fire intensity and tree mortality, opening space for establishment of the youngest cohort.

Most portions of the clusters of 140- to 300-yr-old trees near the middle and at the extreme right side of intensive plot 2 (Fig. 8) are on areas of deeper soils (soil pits 160 and 153 cm deep did not reach bedrock), thus they may have been too moist to burn hot enough to kill trees in 1840. In contrast, the area between them on a side ridge with thin soils (28 cm to bedrock) and the area in the left third of the stand on generally thin soils (depths to bedrock in five pits are 8, 12, 13, 125, and 140 cm) support most members of the youngest age class. The occurrence of younger trees on thinner soils could be caused by drier conditions on these sites resulting in greater mortality in the 1840 fire, or by continued tree establishment in openings existing before the 1840 fire. The middle age cohort is quite broad (160 yr) indicating that establishment of trees 137 cm tall can take a long time.

The tree age maps provide greater understanding of stand development processes than do age distributions alone. They do not, however, answer all the questions. Several elements of the age cohort patterns in both intensive plots are not easily explained. In intensive plot 1, for example, these include the cluster of the oldest cohort on the left side and the cluster of the middle-aged cohort near the top (Fig. 7). To understand the effects of a fire on a stand, one must know about weather during the fire and even watch the fire move through the stand. Fire intensity can vary from minute to minute as wind changes and the fire interacts with itself (Robert E. Martin, January 1982, personal communication), creating spatial variability in tree survival. The factors governing these effects must be complex; for example, tree clusters apparently survived better on thin soil on intensive plot 1 but they survived better on deep soil on intensive plot 2.

Evidence from Vegetation Plots

Data from the vegetation plots on fire frequency indicate that noncatastrophic fires are common in all dry coniferous forest community types encountered in the study area. The average interval between fires on all dry-site vegetation plots was 103 yr (Table 3). This does not include intervals based, in part, on an estimated age of a marked diameter cohort, but does include fires that may have had little impact on stand structure. Also, 45 percent of the dry-site plots had experienced a major fire (initiating at least half the current canopy cover) since initiation of the oldest cohort, and 64 percent had burned at least once since that time (Table 3). This relatively extensive data confirms the conclusion from the intensive plots that noncatastrophic (non-stand-destroying) wildfires were a common occurrence in dry coniferous forests before effective fire control.

The mean interval between fires, an index of fire frequency, has three primary sources of error. First, time and subsequent fires undoubtedly obliterated evidence of some fires, probably causing an overestimate of mean interval between fires. Second,
Tree age map for intensive plot 2. These age cohorts correspond to those identified from the tree age distribution and fire history (Fig. 6). Solid symbols indicate trees whose ages were determined. Open symbols indicate unaged trees assigned to an age cohort, when possible, based primarily on diameter. Several increment-cored trees known to be in a given age cohort, but not aged precisely because of heart rot, are indicated by solid symbols. Topographic lines are drawn by hand from memory for the purpose of relating age cohort patches to the description in the text, so elevations are not indicated.
TABLE 3.
SUMMARY OF FIRE DATA ON THE VEGETATION PLOTS BY COMMUNITY TYPE.

<table>
<thead>
<tr>
<th>Community type</th>
<th>Number of plots</th>
<th>Number of fire intervals</th>
<th>Stand age (age of oldest cohort)</th>
<th>Time since last major fire</th>
<th>Mean interval between fires&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Plots experiencing a major fire since initiation of oldest cohort</th>
<th>Plots burned since initiation of oldest cohort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pseudotsuga/</td>
<td>4</td>
<td>6</td>
<td>196 (104)</td>
<td>128 (52)</td>
<td>72 (41)</td>
<td>50</td>
<td>75</td>
</tr>
<tr>
<td>Holodiscus/grass--</td>
<td></td>
<td></td>
<td>94-330</td>
<td>82-197</td>
<td>26-131</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aspidotis</td>
<td>19</td>
<td>12</td>
<td>198 (84)</td>
<td>133 (51)</td>
<td>107 (65)</td>
<td>47</td>
<td>58</td>
</tr>
<tr>
<td>phase</td>
<td></td>
<td></td>
<td>75-337</td>
<td>63-266</td>
<td>34-217</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collomia</td>
<td>23</td>
<td>18</td>
<td>198 (84)</td>
<td>132 (51)</td>
<td>96 (59)</td>
<td>48</td>
<td>61</td>
</tr>
<tr>
<td>phase</td>
<td></td>
<td></td>
<td>75-337</td>
<td>63-266</td>
<td>26-217</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Both phases</td>
<td></td>
<td></td>
<td>198 (84)</td>
<td>132 (51)</td>
<td>96 (59)</td>
<td>48</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>11</td>
<td>294 (151)</td>
<td>162 (69)</td>
<td>111 (68)</td>
<td>50</td>
<td>58</td>
</tr>
<tr>
<td>Pseudotsuga/</td>
<td></td>
<td></td>
<td>89-450</td>
<td>89-420</td>
<td>41-232</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Holodiscus/Acer</td>
<td></td>
<td></td>
<td>96-323</td>
<td>96-322</td>
<td>27-207</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pseudotsuga/</td>
<td>9</td>
<td>9</td>
<td>226 (85)</td>
<td>184 (88)</td>
<td>118 (59)</td>
<td>33</td>
<td>78</td>
</tr>
<tr>
<td>Berberis/Disporum</td>
<td></td>
<td></td>
<td>96-323</td>
<td>96-322</td>
<td>27-207</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Libocedrus/</td>
<td>7</td>
<td>7</td>
<td>244 (92)</td>
<td>194 (52)</td>
<td>94 (46)</td>
<td>29</td>
<td>71</td>
</tr>
<tr>
<td>Whipplea</td>
<td></td>
<td></td>
<td>135-414</td>
<td>135-294</td>
<td>53-186</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Libocedrus/</td>
<td>5</td>
<td>4</td>
<td>239 (95)</td>
<td>155 (57)</td>
<td>104 (86)</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Chimaphila</td>
<td></td>
<td></td>
<td>144-399</td>
<td>98-220</td>
<td>14-216</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All dry-site</td>
<td>56</td>
<td>50</td>
<td>232 (105)</td>
<td>156 (69)</td>
<td>103 (60)</td>
<td>45</td>
<td>64</td>
</tr>
<tr>
<td>plots</td>
<td></td>
<td></td>
<td>75-450</td>
<td>63-420</td>
<td>14-232</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All western</td>
<td>14</td>
<td>5</td>
<td>221 (136)</td>
<td>150 (86)</td>
<td>144 (122)</td>
<td>21</td>
<td>43</td>
</tr>
<tr>
<td>hemlock climax</td>
<td></td>
<td></td>
<td>74-450</td>
<td>74-401</td>
<td>40-284</td>
<td></td>
<td></td>
</tr>
<tr>
<td>plots</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>These communities are described in Means (1980).

<sup>b</sup>Intervals based on estimated ages of marked diameter cohorts (for example, unaged, large old-growth trees) are not included.
these 0.1-ha vegetation plots probably excluded evidence of other fires that would have been included in a 0.5- or 0.75-ha plot. This probably also causes an overestimate of mean interval between fires. Third, necessary omission of stands that have not had a second fire (but which, given enough time and no fire suppression) probably causes an underestimate of mean interval between fires. Since the effect of the third error is opposite that of the first two, the overall interpretations are probably not significantly affected. If there is a significant bias, it is probably that fires were more frequent than indicated in Table 3.

The temporal distribution of fires on the dry-site vegetation plots (Fig. 9) illustrates several points. Older fires are more difficult to detect because their traces are erased by subsequent fires and time. The lack of fires on the vegetation plots during the last 60 yr probably reflects initiation of a policy of fire suppression in 1915 (Burke 1979) as well as my attempts to sample only relatively mature stands. A marked peak in dated fires occurs between 110 and 140 yr ago (Fig. 9) which coincides with fires on both intensive plots. Also, the 135-yr-old forests on Wildcat Mountain in the Willamette National Forest, in Cascade Head Experimental Forest in the Coast Ranges (personal observations), and in the Mount Hood National Forest (Jerry F. Franklin 1979, personal communication) were initiated during this period. The concentration of fire ages between 260 and 275 yr coincides with the ca. 1703 fire episode of Mount Rainier National Park (Hemstrom 1979) and a drier-than-normal Pacific Northwest winter identified by Blassing and Fritz (1976) based on interpretation of tree ring records. The peak in fire scar dates between 60 and 75 yr ago corresponds with the 1914 and 1919-1921 peaks in lightning-caused fires in the central portion of the Willamette National Forest (Burke 1979).

These dry coniferous forests apparently burn naturally at intermediate intervals and intermediate intensities compared to other Pacific Northwest forests. Ponderosa pine (Pinus ponderosa Doug. ex Laws.)-white fir (Abies concolor [Gord. & Glend. Lindl. ex Hildebr.]) forests on the eastern slope of the Oregon Cascades have a mean interval between fires of 9 to 42 yr and contain evidence of many fires (mean 10 per plot), indicating that most fires killed a small portion of the stand (McNeil 1976). A similar fire regime existed (fire frequency 5 to 15 yr) in ponderosa pine forests of Lava Beds National Monument before fire suppression (Martin and Johnson 1979). In contrast, Hemstrom (1979) estimated the natural fire rotation in the relatively moist forest surrounding Mount Rainier to be 465 yr (range 213 to 1,033) and characterized the fires as catastrophic (stand-destroying). The mean interval between fires of 103 yr on dry sites (Table 3) is intermediate by comparison. Most dry-site stands have had at least one noncatastrophic fire since initiation of the oldest cohort (Table 3). So, although fires on dry sites are more likely to be catastrophic than those in east-side ponderosa pine-white fir forests, they are less likely to be catastrophic than those at Mount Rainier.

Fire frequency in dry coniferous forests in the study area is probably influenced by the surrounding, relatively mesic forest mosaic in which dry sites occur as islands. Other fire history studies, in contrast to this one, have included all the forest in a geographic area. To the extent that the mesic forest ignites less readily and retards fire spread, its dominance of the landscape decreases fire frequency on dry sites.

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**FIGURE 9.** Histogram of dates of fires on dry-site vegetation plots by 5-yr age classes.
Regeneration

Regeneration density is much greater in canopy gaps than under canopies (Table 4). Gaps, however, cover very little of the area in the intensive plots so regeneration under tree canopies is much more common in the forest as a whole (Table 4). Most gaps were created by the death of only one or two trees.

The tallest trees found in gaps were 60 cm in intensive plot 1 and 130 cm in intensive plot 2. The tallest trees found under the canopies were less than 35 cm in both plots. The lack of trees between 35 and 137 cm in height in areas sampled beneath canopies was also observed generally in the stands. This indicates that these seedlings rarely reach breast height and probably attain canopy height much more rarely than seedlings occurring in gaps despite the larger number of the former.

The hypothesis that gap-phase replacement is important in these stands is rejected, based on this data. Two factors limit the importance of reproduction in small canopy gaps. Fires generally open much more of the stand, allowing many more trees to reach the canopy. Also, growing space created by death of one or two trees is probably effectively occupied by neighboring trees, when these trees are less than 100 to 150 years-old.

Evidence of a Previous Stand

Charcoal in soil pits indicates that the stands on the intensive plots are not first generation forests, but the evidence is weak. Also, all rootthrow wounds and pits and logs could probably have come from the present 400-plus-year-old stands. Thus a definitive test of the hypothesis that dry coniferous forests are first generation forests on the intensive plots is not possible. Charcoal was found well within the mineral soil (10 to 130 cm) in 1 of 7 soil pits in intensive plot 1 and in 2 of 8 pits in plot 2. Only the face of each pit was examined for charcoal, corresponding to a horizontal projected area of about 20 x 50 cm.

Assuming a conservative conversion factor (for example, one piece of charcoal per two square meters), there are certainly hundreds, and probably thousands of deeply buried pieces of charcoal in both intensive plots. This indicates that trees were probably burned on these sites previous to initiation of the oldest trees, assuming it takes that long to bury charcoal deeply (all soil pits with charcoal had some below 40 cm), and that all of it may not be from roots burned since stand establishment.

TABLE 4.

REGENERATION IN GAPS AND UNDER CANOPIES ON THE INTENSIVE PLOTS.

<table>
<thead>
<tr>
<th>Species</th>
<th>Number per 100 m² of gap</th>
<th>Number per 100 m² of canopy</th>
<th>Number per hectare of forest in gaps</th>
<th>Number per hectare of forest under canopy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensive plot 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(based on 7 gap-canopy pairs):</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pseudotsuga menziesii</td>
<td>8.4</td>
<td>1.7</td>
<td>32</td>
<td>191</td>
</tr>
<tr>
<td>Taxus brevifolia</td>
<td>0.4</td>
<td>1.0</td>
<td>1</td>
<td>115</td>
</tr>
<tr>
<td>Arbutus menziesii</td>
<td>0.4</td>
<td>0.0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>All species</td>
<td>9.1</td>
<td>2.7</td>
<td>35</td>
<td>306</td>
</tr>
<tr>
<td>Intensive plot 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(based on 2 gap-canopy pairs):</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pseudotsuga menziesii</td>
<td>13.6</td>
<td>0.8</td>
<td>22</td>
<td>76</td>
</tr>
<tr>
<td>Libocedrus decurrens</td>
<td>1.2</td>
<td>1.2</td>
<td>2</td>
<td>114</td>
</tr>
<tr>
<td>All species</td>
<td>14.8</td>
<td>1.9</td>
<td>24</td>
<td>190</td>
</tr>
</tbody>
</table>
The logs and rootthrow mounds and pits cannot help test the hypothesis that these are first-generation stands since these stands are so old. Mounds and pits are present in all stages of deterioration, from fresh, with a decay class 1 log (Fogel et al. 1973), to those with decay class 5 logs or no log at all. The most deteriorated mounds and pits could probably have been made by uprooting of trees in the oldest age cohorts many years ago, considering the steep slopes will help speed their deterioration.

Though major fires burned both intensive plots about 135 yr ago, observations indicate very little dead wood remains. Many trees probably died in these fires to allow establishment of the large number of younger trees now present. This implies that decomposition of tree boles on these warm sites is probably quite rapid. Temperatures are relatively warm on these sites all year (Zobel et al. 1976), and large logs probably retain enough water to allow rapid decomposition well into the warm summer. The ability of rotten wood to retain moisture is indicated by the predominant occurrence of western hemlock on this substrate when this species is found on dry sites (Means 1980). In contrast to the possible rapid decay of logs, Douglas-fir needles decay more slowly on dry sites than mesic sites (Fogel and Crouack 1977). Part of the reason for this is certainly that needles desiccate quite rapidly on dry sites.

SYNTHESIS AND CONCLUSIONS

Based on the intensive plot data, a general pattern of development of dry coniferous forests can now be synthesized for the pre-fire-suppression period in the study area. The first process is occurrence of a fire that kills a portion of the canopy trees. This fire may be limited to less than 0.1 ha or may cover many hectares, and may kill from very few trees to a majority of the canopy. Trees generally survive in 0.1- to 0.3-ha patches, but survival of smaller groups and relatively isolated individuals is also common. Intervals between these disturbances (Table 3), and several closely spaced fires may initiate a single age cohort. These fires probably kill a higher portion of the smaller trees because they have thinner bark and lower crowns. Some trees are probably killed immediately (generally the smaller ones), whereas others (generally larger trees) are weakened by decay behind fire scars and die from rootthrow, stem break and other causes.

The second process is tree establishment in the newly available growing space. This may proceed for over 150 yr after the fire, although the probability of younger trees reaching the canopy decreases with time. The narrowest age cohort spans 60 yr between two fires in intensive plot 1; but judging by the continuity of tree ages, this period was truncated by the 133-yr-old fire. These processes may repeat one or more times as fires are followed by long periods of tree establishment. This regime of recurring disturbances is similar to that described by Loucks (1970) who maintains that periodic disturbances help maintain diversity and community productivity. Observations on the intensive plots and vegetation plots indicate fires vary widely in intensity; some kill a small proportion of the stand while others destroy whole stands. Most fires in dry coniferous forests, however, do not kill all the trees in the stand.

Extrapolation of this general pattern of dry-site stand development from the intensive plots to the study area as a whole appears reasonable given the available data. Data from the 56 dry-site vegetation plots indicate the two processes in this general pattern are widespread. First, fires which destroy only a portion of the canopy are common on dry sites in the study area (Table 3). Second, almost all dry coniferous forests have reverse-J shaped diameter distributions (Means 1980) which are probably caused by long regeneration periods as well as periodic, noncatastrophic fires.

Diameter distributions of dry coniferous forests are reverse-J shaped (Figs. 3 and 4, Means 1980) because of the pattern of stand development described above. The trees that become established following periodic fire grow under different degrees of competition and vary widely in age. Subsequent fires may release or kill them, or they may continue growing in competition with other trees until a poor relationship between age and diameter (Fig. 2), and the diameter distribution is reverse-J shaped.

Dry coniferous forests are all-aged, with a reverse-J-shaped age distribution (Figs. 5 and 6) because of the recurring pattern in which a fire leaves some canopy trees alive is followed by long periods of tree establishment.

Silvicultural Implications

Natural regeneration these stands in a manner resembling a partial cut and then establishes trees over the next 60 to 150 yr. This scenario has two main implications for management. First, shelterwood or selection silvicultural systems (Smith 1962) will most closely mimic the natural system. Currently, the silvicultural system used most commonly for Douglas-fir includes clearcutting as the regeneration cut (Williamson 1973). Continuous canopy cover will have beneficial effects on many dry sites. For example, the overstory will probably retard soil loss on steep sites with thin soils, and its shade may speed regeneration.

Second, on some sites successful regeneration may require a considerable length of time no matter what silvicultural system is used, and artificial regeneration may not be cost effective. Clearcutting will result in different regeneration potential on many of these hot, dry sites. Foresters in the Blue River, Oakridge, and Ridgdon districts of the Willamette National Forest indicated that slow regeneration is common on some of these sites, and the most extreme sites are not restocked after five or more plantings. Under the selection system, the site is continually occupied with growing stock, and rapid regeneration is not as critical. Shade from the overstory will probably reduce temperature and evaporative demand in the seedlings' environment, facilitating tree establishment.

Slow regeneration in a selection silvicultural system results in a lower level of growing stock, but yields may not be significantly reduced. Increased volume growth on fewer trees provides a comparable level of stand growth. In an even-aged silvicultural system, however, a regeneration delay results in the site being unoccupied and thus nonproductive; the delay creates a reduction in the maintainable harvest (Brodie and Tedder 1982). Thus in a selection system, planting costs—often increased by the need for shade cards and
failure of initial attempts—could be reduced. On the more extreme and unproductive dry sites, low-intensity management such as use of a selection system without artificial regeneration is probably the most appropriate. Unfortunately, very little is known about yield of natural, uneven-aged stands of Douglas-fir, and less is known about their yield when managed selectively. Also, implementation of such a system is hindered primarily by two factors. First, regulations formulated pursuant to the National Forest Management Act now require that USDA Forest Service lands be adequately restocked within 5 yr of a selection cut (U.S. Department of Agriculture, Forest Service 1979). Second, selection logging will probably be difficult on the steep slopes common to dry coniferous forests in the study area.

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While I was a student in New Haven, David M. Smith aroused my interest to look at the development of Douglas-fir stands in the Pacific Northwest. Kevin Short provided valuable field and laboratory assistance. Financial support was provided by National Science Foundation grants DEB-8004562, DEB-7925939, and DEB-7708075 to Oregon State University. Jerry Franklin, Chad Oliver, Bill Killinghain, and Mark Harmon, among others, provided valuable reviews.

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