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Fire History of Douglas-fir Forests in the Morse Creek Drainage of Olympic National Park, Washington

Abstract

In the Morse Creek drainage of the northeastern Olympic Mountains, montane forests dominated by Douglas-fir owe their prominence to a complex fire regime that incorporates high severity stand-replacing fires and low/moderate severity ground fires. We quantified the fire history of these forests to determine the role played by wildfire to favor dominance of Douglas-fir rather than late-successional western hemlock. Three matrix forest types reflect the influence of past wildfires. The youngest matrix type was <150 yr old, next was a matrix type 150-300 yr old, and the oldest was >300 yr old. Germination dates and fire release markers were identified on increment cores from 318 Douglas-firs, and used to date past fire events. A 600-yr fire history was developed for this 2500 ha area. Periods characterized by many small-scale, low and moderate severity fires were interrupted by two high severity, stand-replacing burning periods in 1687-1720 and 1897-1904. Mean fire return intervals (FRI) were calculated for various land units. The most informative size was 200 ha, the approximate mean size of lateral tributaries to Morse Creek. FRI was 21 yr at this spatial scale. For the entire 2500 ha drainage, mean FRI was estimated at 3 yr. Similar to Douglas-fir forests in central Oregon and northern California, small patchy fires were much more common in the eastern Olympics than previously thought. Instead of fire exclusion, a policy that uses management fires to burn many small patches of forest each year would approach the kind of fire regime typical of these forests.

Introduction

Forests in the Pacific Northwest support three different fire regimes, based on fire severity (Agee 1993). Low severity fires are surface fires that kill a small percentage of the tree species on the site. High severity fires are canopy fires that kill a high percentage of species. Moderate severity fires define a broad range between these two extremes, such that some of the species are killed by a fire whereas others survive. Authors writing about western fire regimes often simplify the discussion by contrasting low severity fire regimes with high severity fire regimes (Kilgore and Taylor 1979, Arno 1980, Swetnam and Dieterich 1983, Schullery 1989, Greenlee and Langenheim 1990, Stephenson et al. 1991, Swetnam 1993, Agee 1997), but all three fire types can burn in Pacific Northwest forests (Agee et al. 1990, Morrison and Swanson 1990, Wallin et al. 1996, Cissel et al. 1998, Taylor and Skinner 1998). The proportions accounted for by each fire type vary depending on the vegetation type under consideration, climate, fire weather, and fuel accumulation (Agee 1993). Over several centuries, the combined differences in fire severity have created a mosaic forest structure at the landscape level, with patches of forest reflecting low, moderate, and high severity fires (Morrison and Swanson 1990, Stephenson et al. 1991).

Mean fire return interval (FRI) is the mean time span between fires, specific to a given unit of land, vegetation type, or region. FRI have been studied by many workers in the western United States, using units of land varying in size from a single tree (<0.001 ha) to entire watersheds (>600 ha)(Kilgore and Taylor 1979, Madany and West 1980, Arno and Peterson 1983, Swetnam and Dieterich 1983, Cooper et al. 1987, Barrett and Arno 1988, Agee et al. 1990, Morrison and Swanson 1990, Taylor and Skinner 1998, Brown et al. 1999, Taylor 2000). FRI provide fundamental information about the fire history of a region, and fire severity can be inferred from FRI. Communities with shorter FRI generally are characterized by low and moderate severity fires, because fuel loads accumulated between fires are insufficient to support crown fires, even under extreme fire weather. Communities with longer FRI generally are characterized by high severity fires during extreme fire weather, which are supported by the high fuel loads accumulated between infrequent fires.

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Douglas-fir (*Pseudotsuga menziesii*) dominates montane forests west of the crest of the Cascade Range from northern California to Washington. Fire has been an important environmental factor throughout this region, and the widespread dominance of Douglas-fir is testimony to its ability to respond positively to low, moderate, and high severity fire regimes. When mature, Douglas-fir is a resister to low and moderate intensity fires (Agee 1993). Since Douglas-fir commonly repopulates sites cleared by stand-replacement fires, it is an invader in high intensity fire regimes. When young, Douglas-fir is sensitive to fire, and is classified as an avoider (Agee 1993).

For over half a century, Douglas-fir forests on the Pacific slope have been understood to support infrequent, high intensity, stand-replacement fires (Munger 1940, Fonda and Bliss 1969, Hemstrom and Franklin 1982, Henderson et al. 1989, Agee 1997). FRI of 200-400 or more years were commonly estimated for Douglas-fir forests in the Pacific Northwest, largely based on dates of stand establishment after high severity fire. Research in Douglas-fir forests since 1990, however, has revealed that fire frequency is much shorter, and fire severity is much less, than previously thought. The central Cascade Range, Oregon, has been the most intensively studied region, and Douglas-fir forests there support low, moderate, and high severity fire regimes (Morrison and Swanson 1990, Wallin et al. 1996, Cissel et al. 1998). In this region, the well-known 200-400 yr FRI resulted in large, stand-replacement fires, however, many old growth stands in the study area resulted from multiple, patchy fires of varying severity, with 20-100 yr FRI (Morrison and Swanson 1990). Data from Wallin et al. (1996) and Cissel et al. (1998) agree with this general pattern. Forests in the Klamath Mountains, California, support a complex fire regime characterized by frequent, less severe fires, with FRI ranging from 13-22 yr (Taylor and Skinner 1998). These forests differ from the northern Douglas-fir forests, however, because a mixture of overstory conifers with a more flammable understory characterize the stands. Both the central Cascades and the Klamath Mountains support multi-aged stands, products of low and moderate severity fires, and even-aged stands, products of high severity, stand-replacement fires (Morrison and Swanson 1990, Taylor and Skinner 1998). Mean FRI of 7-9 yr at Point Reyes, California, are the shortest yet reported for Douglas-fir forests (Brown et al. 1999). Clearly, the fire regime associated with forests dominated by Douglas-fir is much more complex than originally reported.

The northeastern Olympic Mountains lie in a rain shadow that produces some of the driest conditions north of California. In this region, montane forests are dominated by Douglas-fir stands initiated after past fire events (Fonda and Bliss 1969). Even-aged stands grow where high severity crown fires burned; uneven-aged stands with multi-story structure remain where low severity fires burned (Pickford et al. 1977, Franklin and Dyrness 1988), and they contain occasional fire survivors >1000 yr old (Henderson et al. 1989). Fire weather, lightning patterns, and fuel loading govern fire size in Olympic National Park (Pickford et al. 1980). Ignitions are governed primarily by fire weather and fuel moisture, secondarily by available fuel. If extreme fire weather dominates the region, and fuel moisture is low, ignition causes high severity crown fires (Agee 1997) that burn uniformly through the forest. Fuel moisture, however, is rarely low enough to support stand-replacement fires. If fires start under less than extreme conditions, ignitions cause low severity surface fires that burn in patchy patterns. Of the five fire regimes described by Stephenson et al. (1991), two apply to the general fire regime of the eastern Olympics: 1) high intensity fire with patchy low intensity fire, for which groups of canopy trees survive within a matrix of dead trees; 2) uniform high intensity fire, for which the majority of the canopy trees are killed. For eastern Olympic montane forests, FRI has been estimated at 270-300 yr (Fonda and Bliss 1969), 200-300 yr (Fonda 1979), and 130-250 yr (Henderson et al. 1989). These estimates, applied specifically to high severity fire episodes in the montane zone, were derived from stand establishment dates. Each reflects the common clusters of postfire establishment dates, and possibly maximum tree ages, associated with the forests studied, but none specified the units of land to which FRI applied.

No fire history studies in the eastern Olympics have investigated the possibility of a complex fire regime of low, moderate, and high severity fires, nor have any studies related FRI values of Douglas-fir forests to specific units of land. In this study, we quantified the fire history of the Maiden Creek tributary of Morse Creek in the northeastern Olympics. We wanted to calculate FRI to determine the relative proportion of frequent, low/moderate severity fires and infrequent, high severity fires. We asked four research questions: 1) has fire favored dominance of Douglas-fir in this drainage, rather than the late-successional western hemlock (*Tsuga heterophylla*), as occurs elsewhere on the Olympic Peninsula (e.g., Fonda and Bliss 1969, Henderson et al. 1989)? 2) what are the age and structure of stands in the Morse Creek drainage? 3) when did widespread, high severity fires burn compared to smaller low and moderate intensity fires? 4) what are the modal characteristics and ranges of the fire regime in this region?

Methods

The study site was in the Morse Creek drainage, south of Port Angeles, Washington. We concentrated on the section of the drainage defined by Maiden Creek and by Morse Creek near the confluence with Maiden Creek. Topographically, the area is characterized by steep slopes falling 350-750 m from the forested ridge lines to Maiden Creek and Morse Creek (Fig. 1). Morse Creek's lowest elevation in the study area is ~325 m. Maiden Creek's upper elevation in the study area is ~1050 m. Forest stands in the montane zone of the drainage are dominated by Douglas-fir, with various amounts of western hemlock (Fonda and Bliss 1969). High severity fires in the montane zone of the Olympics kill nearly all trees (Fonda and Bliss 1969, Henderson et al. 1989), although a few trees may survive (Fig. 2). In this paper, we apply the term matrix forest types to stands that develop after the fire, but which can contain a few survivor trees. The age of the matrix type is defined by the ages of the postfire trees, not the older survivor trees. Our study identified matrix types and survivor trees in the montane zone. Above this zone, at ~1200 m, is the subalpine forest zone, characterized by stands dominated by subalpine fir (*Abies lasiocarpa*), and a few localized stands of lodgepole pine (*Pinus contorta*) dating from fires near 1900 (Fonda and Bliss 1969, Zolbrod and Peterson 1999).

We constructed the fire history of this drainage from two databases: 1) age classes of matrix types established after a high severity fire, based on germination dates of trees assumed to have germinated in response to that fire (Figs. 1, 2); and 2) fire release markers (Fig. 3) in cores taken from trees that germinated in response to high severity fires 250-500 or more years ago, and that survived subsequent fires (Fig. 2).

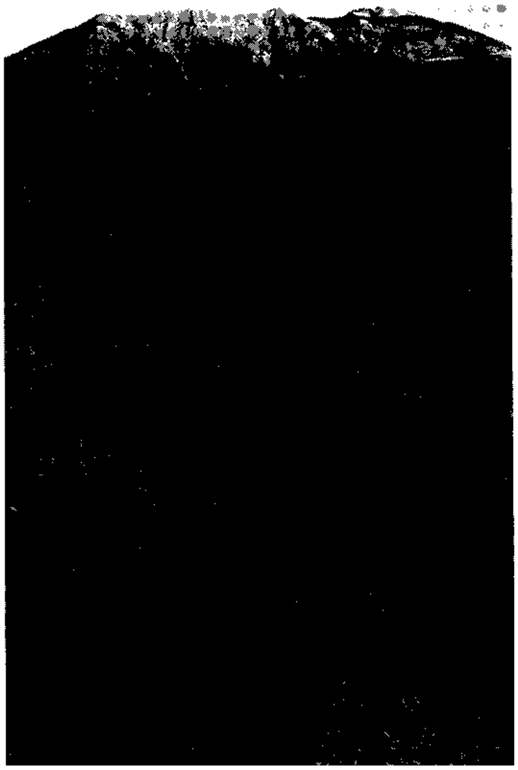


Figure 1. View south from Mt. Angeles into the eastern portion of the study area and Maiden Creek. Forests responding to fires within the past century have smooth, fine-grained-appearing canopies. Forests responding to older fires have rough, coarse-grained canopies.

All trees were bored ~1.4 m above the root collar on the upslope side of the tree during summer 1994. Diameters of trees within 38 groves were measured at 1.4 m (i.e., dbh), the trees were bored, and the cores were stored in labeled straws. We bored >700 living trees. Many of the Douglas-firs sampled were at least 250 yr old, but various fungal pathogens made more than half the cores extracted unusable for this study. All trees used for analysis were alive when bored, and we assumed that the outer ring was from 1994.

Increment cores were mounted on boards, then sanded smooth with progressively finer grit to expose annual growth rings. Abrupt and sustained increases in ring width (Fig. 3) were determined with an ocular micrometer integrated into a 6-40X

Figure 2. Two survivor Douglas-fir trees, >300 yr old, in a 90-yr Douglas-fir stand (DF1). The high tree density and mortality are typical of the DF1 matrix type.

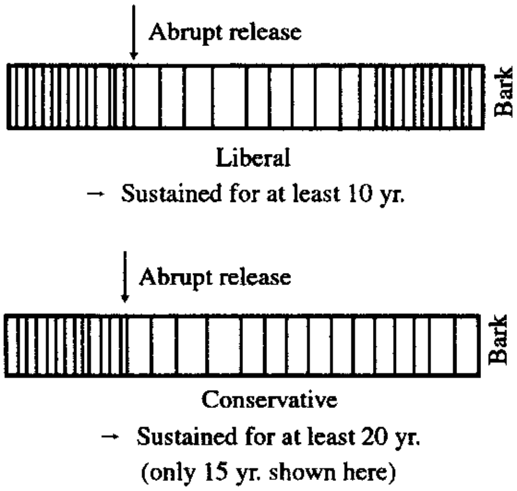


Figure 3. Examples of fire release markers. Liberal releases are based on 10 yr of sustained growth, as shown. Conservative releases are based on 20 yr of sustained growth, although only 15 yr are shown in this example.

stereoscope. These growth releases were associated with past fires, and they were judged on each core according to liberal and conservative criteria (Fig. 3). A release classified as meeting the liberal criterion showed an abrupt increase in ring width, with subsequent growth sustained for over 10 yr. Conservative releases showed at least a fivefold increase in measured ring width over the previous year, with subsequent growth sustained for at least 20 yr.

All increment cores in this study were scored separately by two people. Each person evaluated each core twice, first to identify liberal release patterns and again to identify conservative release patterns (Fig. 3). Cores with dates about which the two disagreed were completely reevaluated until the disagreement was resolved. Ultimately the pith age at 1.4 m of every tree core was accurately determined, and accurate dates were assigned to the growth releases.

We ensured that the dates associated with events recorded in our tree cores were visually accurate, but we did not attempt to match ring patterns among the 318 cores we obtained. We sampled trees from the forest interior, and they had the characteristics of the complacent tree-ring series (Fritts 1966, 1971; Stokes and Smiley 1968). In contrast to the sensitive series, tree-rings in the complacent series are uniformly wide, with low correlation among trees. The standard deviation associated with ring widths on individual cores is low (Fritts 1966, 1971), and the lack of variation is unlikely to produce useful sequences (Stokes and Smiley 1968). Brown et al. (1999) faced exactly this situation with fire scar data from Douglas-fir in California. In the forest interior, precipitation is effective from year to year, there is less variability in annual precipitation, and fewer days when moisture is limiting (Fritts 1966, 1971). Thus, the trees are unlikely to have missing rings, especially in northern climates (Fritts 1971). Missing rings in Douglas-fir are uncommon west of the Cascade Mountains in Washington, and are a negligible source of error in establishing the age of the tree and fire events (Morrison and Swanson 1990). We assumed the trees in the study area had no missing rings and they presented a complete record of the age and history of the trees.

In drier mountainous regions, Douglas-fir and ponderosa pine (*Pinus ponderosa*) are resisters to low intensity fires (Agee 1993), and both exhibit visible injuries in the form of cat-faces with associated fire scars. Douglas-fir that survive fires in the Olympic Mountains lack cat-faces and visible fire scars, however, their responses to fire can be recognized by release markers in the growth rings (Fig. 3). Fires that kill neighboring trees open the canopy of the stand, providing an improved growing environment for surviving trees (Stephenson et al. 1991). The improved growth is recorded in tree-rings in years subsequent to the fire event (Morrison and Swanson 1990, Stephenson et al. 1991, Swetnam 1993, Mutch and Swetnam 1995). We assumed that the wood of trees recording fires by growth release markers was uninjured by the fire. Still, fire may scorch foliage and bark (Mutch and Swetnam 1995), and injure fine roots (Swezy and Agee 1991). Damaged trees might respond to high severity fires initially with decreased growth for up to 2 yr (Morrison and Swanson 1990, Mutch and Swetnam 1995), although subsequent growth increases are possible beginning in the third year (Mutch and Swetnam 1995). To account for possible lags between fire and the growth release, we adjusted fire dates for cohort trees within the same grove and likely fire perimeter that had markers within 3 yr of each other to the earliest fire date within the period in question.

Conversely, it is possible that a larger growth ring could be the result of a canopy gap created by wind throw. Morrison and Swanson (1990) acknowledged this relationship, but discounted the importance of wind relative to fire. They noted that stands disturbed by wind were locally small, and had a low abundance of early seral tree species in these areas. In our study area, the Douglas-fir matrix surrounding any witness tree was more extensive than could be accounted for by wind throw. Furthermore, the 460 growth releases recorded by the 318 trees bored in this study, the repeat releases registered by most of the older trees, the extent of the surrounding matrix stands, and the frequency of documented fires (Pickford et al. 1980) argue that only fire as a repeatable disturbance could have contributed the growth releases we documented.

All fire event data in this study were derived from usable increment cores taken from 318 living Douglas-fir trees. We were most interested in Douglas-fir >300 yr old, because they presumably had survived and recorded the one or two high severity fires noted by Fonda and Bliss (1969). Because the size of the study area encompassed more than 25 km^2, topographic maps, aerial photos, and ground reconnaissance were used to identify candidate trees and groves. Groves containing older trees were easily identified, because the canopy of the forest appears rough and coarse-grained (Fig. 1). We identified matrix forest types that delimited the physical borders of different fire events, and worked with candidate trees within smaller groves. Trees >300 yr old, however, often occurred as single survivors in younger forest types. Even when groves of a few >300 yr old trees were located, their area was ~1-2 ha. Because we worked in a wilderness, access was an important consideration. All sites had to be within 5 hr cross-country travel from roads and trails in the study area. We targeted multi-layered, uneven-aged, older groves, because they had the best chance to contain the fire event data we sought. We also worked in single-layered, even-aged younger groves, many of which contained survivor trees. The younger trees in these groves lacked fire release markers, but we used their germination dates as evidence of fires near 1900.

We analyzed 15 cut saplings to determine the number of years required for trees to reach 1.4 m tall. We determined this value on naturally germinated saplings ~15-30 yr old growing in open, previously forested sites and on downed trees ~60-70 yr old that had grown in stands that had originated in the open. We dated the cut trees at the root collar and at 1.4 m. The mean age difference between the two markers was 11.7 ± 0.5 yr. The low standard error associated with this sample indicated that the 12 yr factor was accurate for our estimates, with a possible difference of ±1 yr from the germination dates we present. This 12 yr value was added to the pith age of each tree at 1.4 m to obtain a closer estimate of year of germination and stand establishment.

Mean FRI based on fire release markers was calculated for each individual tree core. The bulk of the data came from Douglas-fir >250 yr old. Trees with the longest record of fire history were invariably the oldest and largest trees, which had survived and recorded one to six fire events in their lifetimes. Survivor trees >250 yr old, growing in matrix types <150 yr old (Fig. 2), carried the best long-term evidence of fire events in this drainage. Survivor trees in separated groves often recorded separate fires. We also located trees >300 yr old in small groups of up to five trees, all of which had survived past fires. We built our FRI database from 318 single-point samples into progressively larger units of land, working with the fire intervals represented by the trees specific to the unit of land in question. Documented 20th century wildfires in the eastern Olympics commonly burned small areas (Pickford et al. 1977), leading us to assume the same relationship for presettlement fires. Although our FRI data progress from point fire frequencies to area frequencies (Agee 1993), we intend to focus our discussion on ~200 ha units because that is the general area of the tributary drainages to Maiden Creek in the study area.

Although trees were bored in groves throughout the drainage, we selected 23 sites to characterize the matrix forest types. Data on tree species (density and diameter class) and understory species (percent cover) were gathered on one 16-m radius macroplot per selected site. We chose this size primarily because the area of groves comprising trees >300 yr old commonly was ~1000 m^2. Data for downed and dead fuel weights were gathered on six 15.3 m transects at each of these selected sites using the methods of Brown (1974). Fuels <2.54 cm diameter were tallied along 182 cm of line (10.9 m total length per site), fuels 2.55-7.62 cm diameter were tallied along 364 cm of line (21.8 m total length per site), and fuels >7.62 cm diameter were tallied along the full length of the line (91.8 m total per site). Mass of standing dead elevated fuels (>2 m above the top of the organic soil horizon) was calculated using density values obtained from the macroplots and an equation derived from commercial harvest weights for each species and size class. These values were combined for each plot for total standing dead mass.

The research was designed so that FRI among various sized units and fuel loads among forest types could be analyzed by completely randomized design ANOVA. Significant differences among the treatments were determined by Newman-Keuls multiple range test (Zar 1999). Significance level was set at 5% for all tests before the data were collected.

Results

Matrix forest types

Three matrix forest types were present in the Morse Creek drainage, among which age, composition, structure, and fire history differed. These types are named according to the age of the trees that form the matrix forest, so that the Douglas-fir 1 type (DF1) is <150 yr old, the DF2 type is 150-300 yr old, and the DF3 type is >300 yr old. In actuality, few stands in the study area were 150-200 yr old, so that the effective age range of the DF2 type is 200-300 yr. Every DF1 and DF2 matrix type contained a few trees much older than the given age limits. These older, large diameter trees survived the fire that destroyed the previous matrix stand, and occurred only as widely scattered individuals or in small groups, often near the limits of the fire (Fig. 2). Presumably, they were the parent trees of the postfire matrix forest.

The data in Table 1 speak to density and diameter class, and provide information on dominant and subordinate positions within the forest. Trees with smaller diameters formed a fragmented, intermediate layer below the canopy. Douglas-fir dominated all three matrix forest types, with the greatest density and basal area among all trees >14 cm diameter (Table 1). For DF1 and DF2 types, there were considerably more western hemlock than Douglas-fir <14 cm diameter. Only in the DF3 type were there more small Douglas-fir than western hemlock.

In the DF1 matrix type, shade tolerant western hemlock and western redcedar (*Thuja plicata*) were well represented in diameter classes <25 cm, but were virtually absent in the larger size classes. Standing dead stems were a mixture of Douglas-fir and western hemlock. A mean of 38% of the standing stems in the DF1 matrix type were dead. Although the DF1 type was the youngest of the three matrix types, Douglas-fir trees >64 cm diameter and >250 yr old always were present (Fig. 2; Table 1). The understory was depauperate. Step moss (*Hylocomium splendens*) and Oregon beaked moss (*Kindbergia oregana*) combined for 25% cover. More than 12 herbaceous understory species grew in infrequent openings, but never attained 2% cover. Rocks and bare ground together accounted for 64% of the forest floor, and tree litter was a prominent component of the forest floor.

The DF2 matrix type was characterized by large Douglas-fir 200-300 yr old, with western hemlock and western redcedar well represented in the smaller diameter classes (Table 1). Trees >300 yr old, with records of past fire events, were

TABLE 1. Size class distribution (trees/ha) of the three matrix forest types in the study area. The DF1 type was <150 yr old, the DF2 type was 150-300 yr old, and the DF3 type was >300 yr old. The category "other species" includes all species present in small sizes and densities: western white pine (*Pinus monticola*), Pacific yew (*Taxus brevifolia*), red alder (*Alnus rubra*), Pacific silver fir (*Abies amabilis*), and subalpine fir (*A. lasiocarpa*).

	Diameter class (cm)								
Species	<3	3-13	14-25	26-38	39-51	52-64	65-76	>76	Total
				DF1 matrix type					
Douglas-fir	–	384	471	105	74	25	1	21	1081
Western hemlock	–	1560	125	19	5	1	17	–	1727
Western redcedar	–	268	31	7	28	–	–	–	334
Other species	–	69	51	6	27	–	–	1	154
				DF2 matrix type					
Douglas-fir	25	116	146	277	52	40	10	10	676
Western hemlock	99	178	7	17	22	–	–	–	323
Western redcedar	–	161	–	5	2	–	–	–	168
Other species	–	29	12	–	–	–	–	–	41
				DF3 matrix type					
Douglas-fir	113	507	267	103	62	23	11	11	1097
Western hemlock	128	366	219	142	28	–	–	–	883
Western redcedar	88	176	158	9	–	–	–	–	431
Other species	49	10	19	–	15	–	–	–	93

common in this type. Overall stand density was less than the DF1 type, as 51% of the standing trees were dead. The dead trees were mainly Douglas-fir and western hemlock from the smaller diameter classes, similar to mortality in the DF1 type.

Unlike the DF1 type, understory species were more common in the DF2 type. Step moss (48%) and Oregon beaked moss (9%) accounted for well over half of the understory cover. The DF2 type supported a strong shrub component. Salal (*Gaultheria shallon*) averaged 9% cover; red huckleberry (*Vaccinium parvifolium*), kinnikinnick (*Arctostaphylos uva-ursi*), and dull Oregongrape (*Berberis nervosa*) combined for another 10% cover. The only noteworthy herbaceous species was pipsissewa (*Chimaphila umbellata*), with 5% cover. Six other species averaged <2% cover each. Rocks and bare ground averaged 13% cover, and tree litter was abundant.

The DF3 matrix type had few dead standing trees, and a higher tree density of Douglas-fir and western hemlock than the DF2 type (Table 1). Although Douglas-fir was the dominant tree species, western hemlock and western redcedar accounted for many more 14-51 cm diameter stems than in the DF2 type. Large, evenly-spaced Douglas-firs that had survived numerous fire events formed an open crown layer. The older age classes of Douglas-fir and western hemlock had evidence of common pathogens and decreased vigor. The 620 Douglas-firs <13 cm diameter are an interesting characteristic of the DF3 types, because they address replacement potential for the future. These diameter class distributions indicate that populations of Douglas-fir in DF3 types are more stable than in DF1 and DF2 types.

The DF3 type had the best developed understory structure of the three stand types. Cover of step moss and Oregon beaked moss was 48%, but cover of the vascular species exceeded 70%. Salal (45%) and kinnikinnick (14%) dominated. Pipsissewa (4%), red huckleberry (3%), and dull Oregongrape (2%) were the other prominent species. Rocks and bare ground averaged <2% in the DF3 forests, and tree litter was less prominent than in the other two forest types.

Fire History

Wildfire is the common disturbance agent in the Morse Creek drainage. Wind, snow avalanches, and mass wasting can create small disturbances,

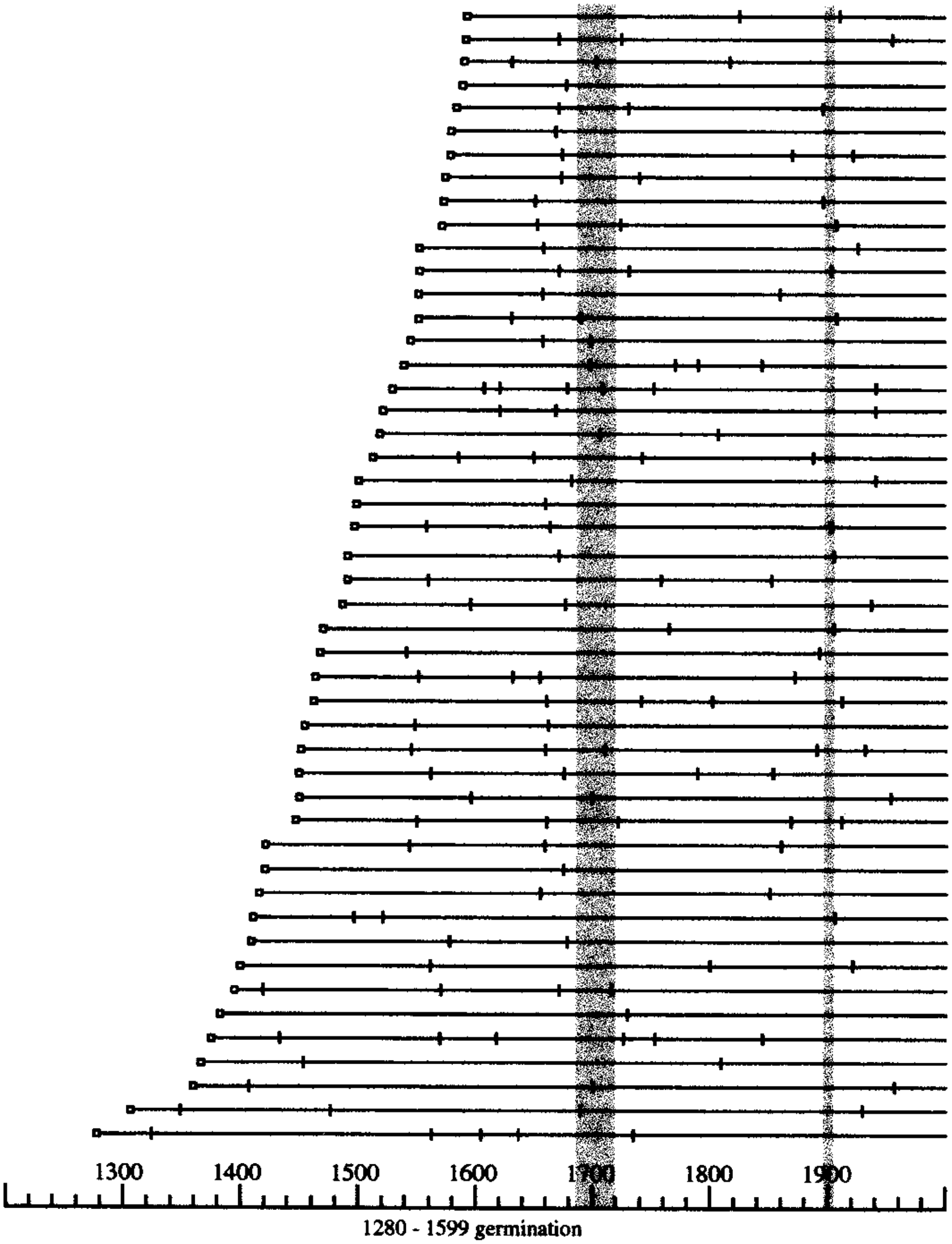


Figure 4. Fire records for trees that germinated before 1600. Germination dates are indicated by ┘, fire releases by I. The wide gray band marks the 1687-1720 burning period; the narrow gray band marks the 1897-1904 burning period. All trees were alive in 1994.

but these agents are infrequent and localized. The database of fire release markers and germination dates contains evidence of periods of widespread, high severity fires and smaller, low and moderate severity fires (Figs. 4-7). A series of fire years from 1687-1720 is indicated by the wide gray band

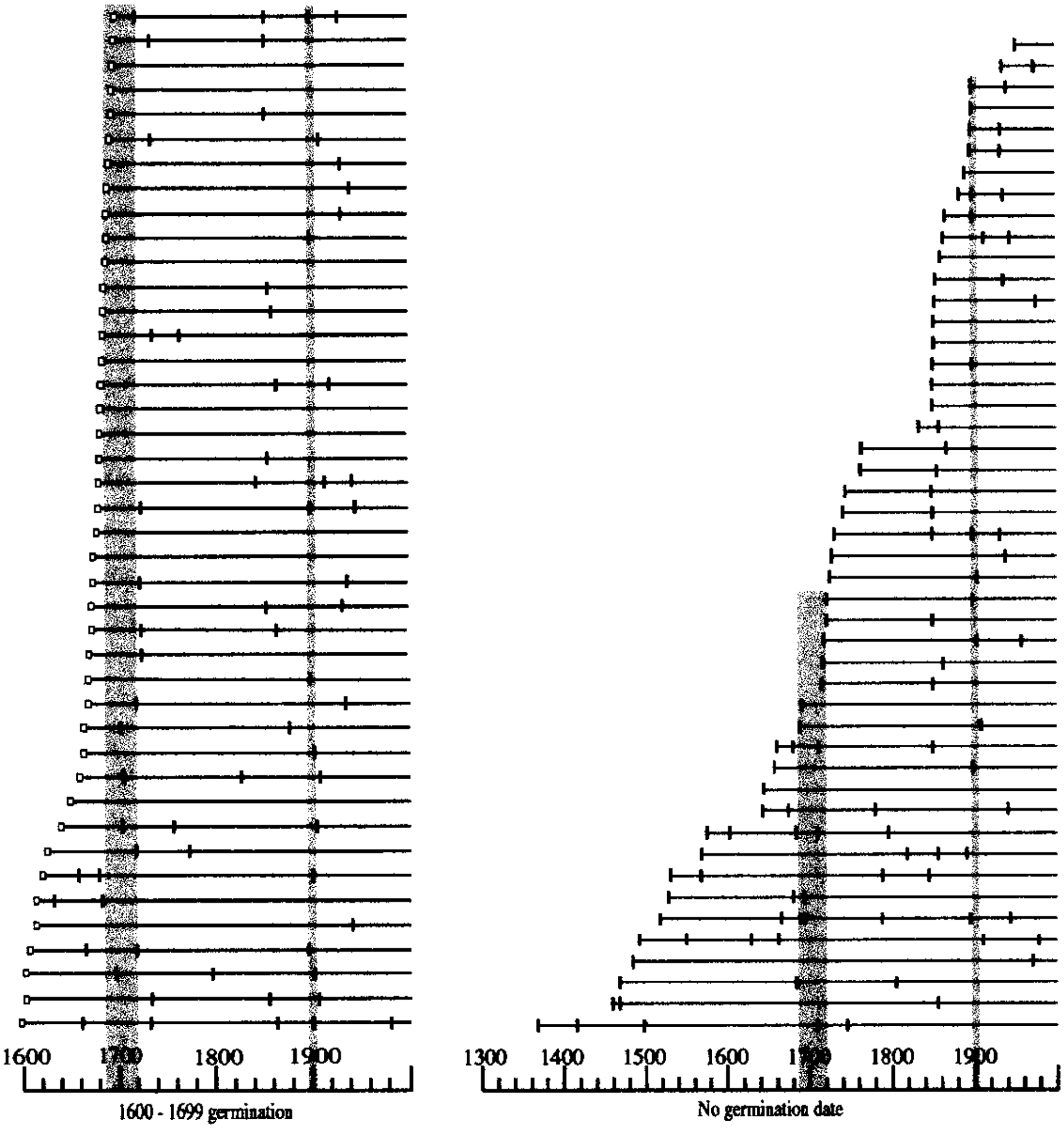
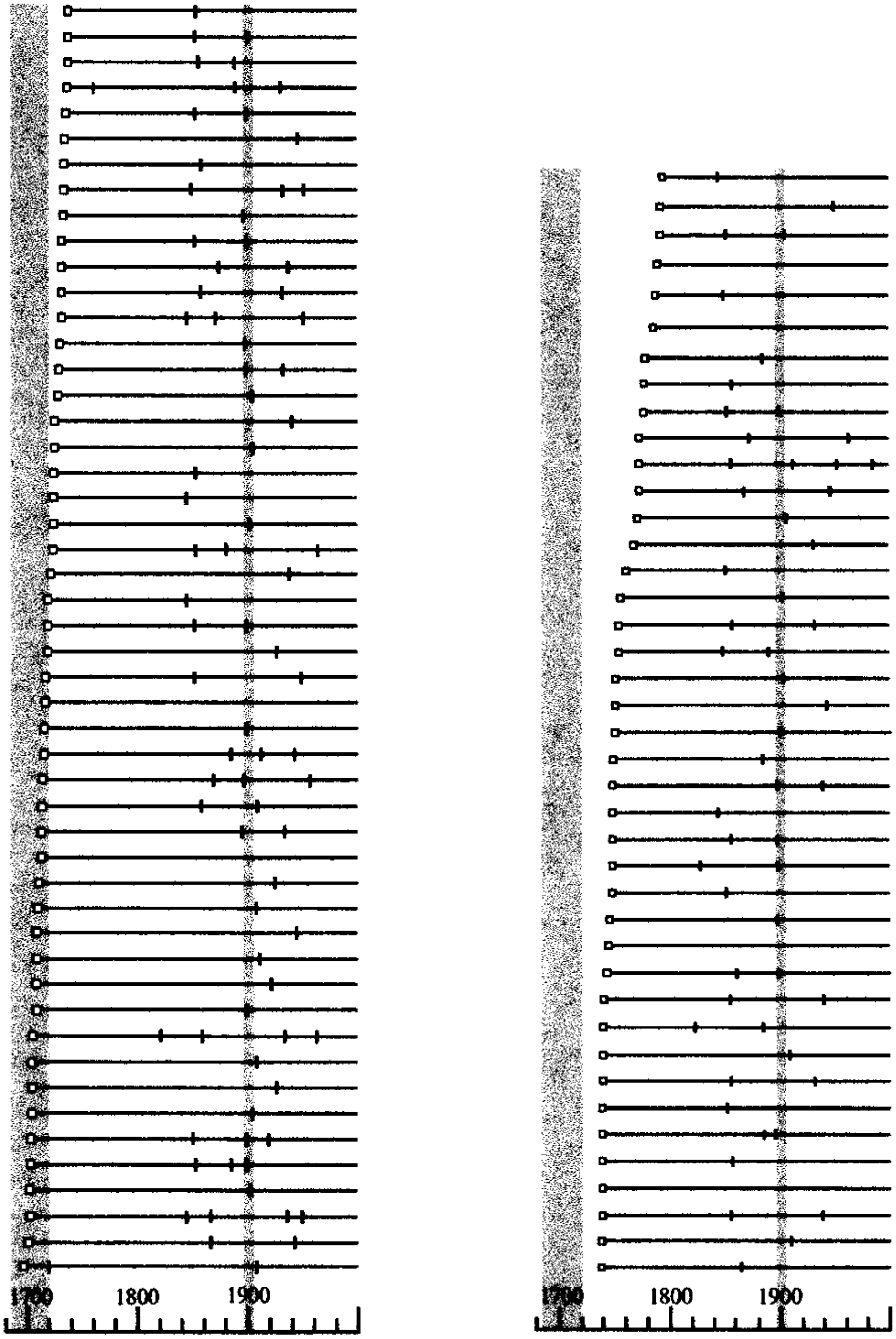


Figure 5. Fire records for trees that germinated 1600-1699 (left) and for trees with unknown germination dates (right). Germination dates are indicated by ⊐. Lines for trees with unknown germination dates begin with the first fire event (I). All trees were alive in 1994.

in Figures 4 and 5. The database contained 74 mature trees alive in 1700, of which 30 (41%) carried a fire release marker for 1687-1720. Germination in response to these fire years appears to extend from 1690 to 1740, when 59 of the trees in the database germinated (Fig 6). The trees that responded to this series of fire years now constitute the DF2 matrix type.

The narrow gray band in Figs. 4-7 marks a burning period from 1896-1904. The database contains 168 mature trees alive at this time, of which 43 (26%) carried a fire release marker for 1896-1904. Thousands of Douglas-firs in this drainage date from this burning period, and they form the DF1 matrix type. The forests formed by these trees are easily visible in the drainage (Fig. 1). Our



1700 - 1740 germination

1741 - 1799 germination

Figure 6. Fire records for trees that germinated 1700-1740 (left) and 1741-1799 (right). Germination dates are indicated by ⅃, fire releases by I. The wide gray band marks the 1687-1720 burning period; the narrow gray band marks the 1897-1904 burning period. All trees were alive in 1994.

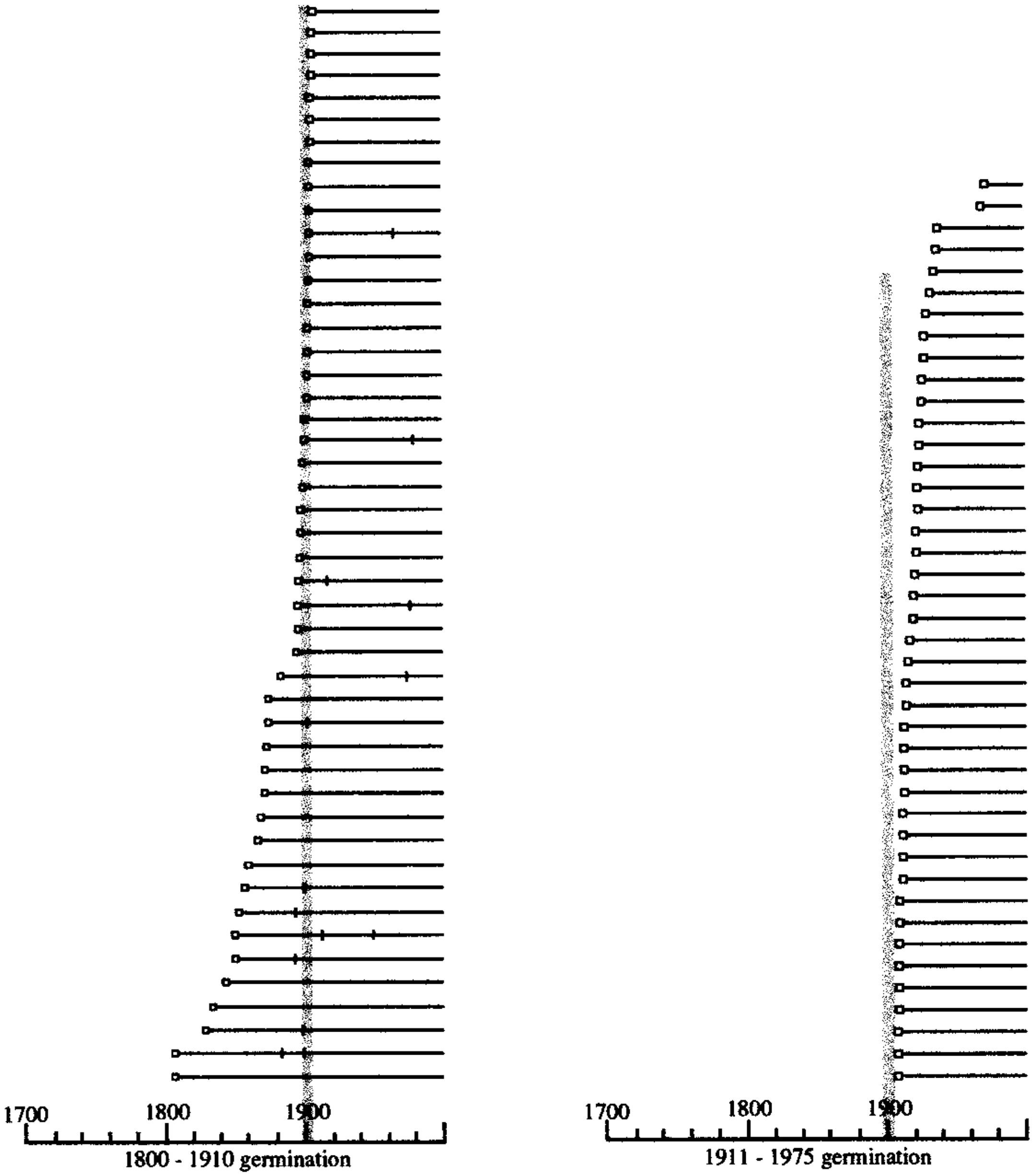


Figure 7. Fire records for trees that germinated 1800-1910 (left) and 1911-1975 (right). Germination dates are indicated by ⊔, fire releases by **I**. The narrow gray band marks the 1897-1904 burning period. All trees were alive in 1994.

database contains 44 trees that germinated between 1898 and 1919 in response to these fires (Fig. 7).

The two major burning periods, during which widespread fires burned in the Morse Creek drainage, identified by the combination of fire release markers and germination dates have been known for many years. The forests that have developed in response to the two burning periods characterize the landscape in the Morse Creek drainage (Fig. 1). Additionally, many small fires were discovered in this research, and the evidence is not visually obvious across the landscape. Based on fire release markers, unrelated fires burned throughout the drainage over the last 650 yr (Figs. 4-7). The earliest fire event recorded by release markers was in 1323, by a tree that germinated in 1280, the oldest tree in the sample (Fig. 4). Trees in the study area responded to the effects of a fire event on an individual basis. The variability among the release markers is high; few trees in the study area recorded the same fire event via growth releases. Only cohort trees in the same grove matched growth releases. Even then, differences of a few years remained in the actual record, depending on whether the growth increases came immediately after the fire, or after 1-2 yr of lower growth.

Decades during which at least 12 living trees recorded fire events by release markers are shown in Table 2. Few decades had <5 fires, and only during periods of above-average fire incidence did the number of recorded fires exceed 15. Some time periods were relatively free from fires, such as the early and mid-1600s (Fig. 8) and 1760-1840 (Table 2), whereas many trees recorded fire events 1841-1870 and 1880-1920 (Table 2, Fig. 8). There were, however, no decades when fire was completely nonexistent in the study area. Fires did burn somewhere in the drainage during each decade, even into the 1980s (Table 2, Figs. 4-8). The four decades from 1800 to 1839 had the fewest trees (12) with fire records, although other decades earlier than 1640 had fewer trees with recorded fires (Fig. 8). For example, fires were recorded by only seven trees during 1580-1620. Data from pre-1640 must be interpreted with caution, however, because fewer trees alive then survived until 1994.

TABLE 2. Decades in which at least 12 trees recorded fires, by release markers only, in the Morse Creek drainage.

Decade	Number of fires
1670-1679	15
1710-1719	12
1720-1729	14
1840-1849	13
1850-1859	56
1860-1869	15
1880-1889	12
1890-1899	46
1900-1909	33
1910-1919	14
1930-1939	28
1940-1949	20

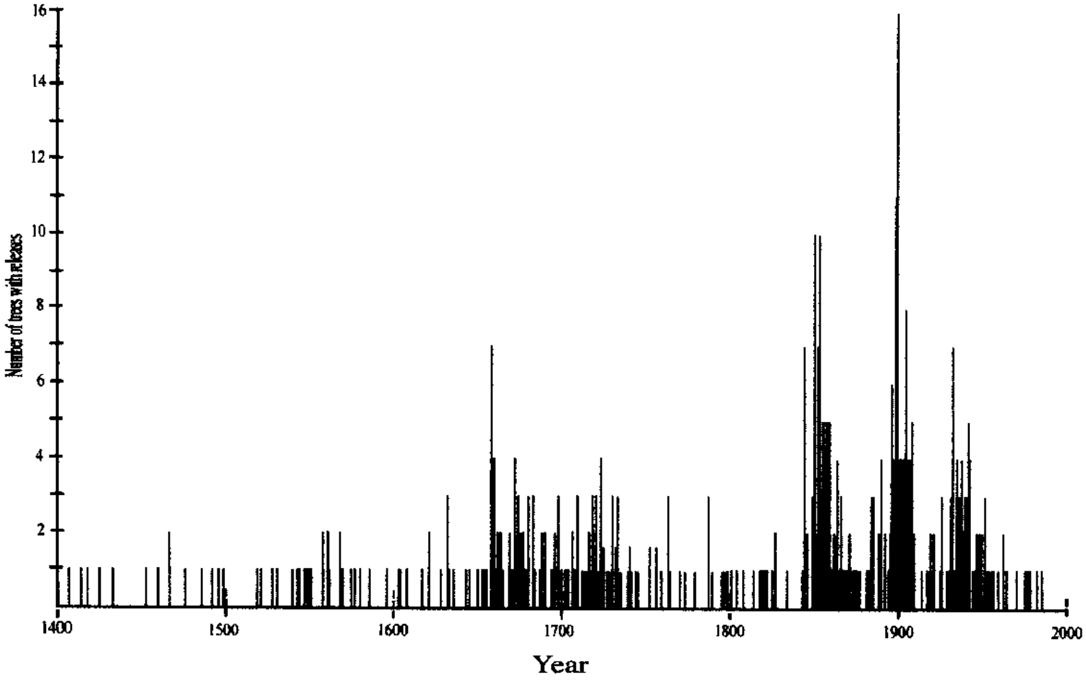


Figure 8. Number of living trees recording fire events 1400-1985.

Fire release markers from survivor trees in DF1 stands (Fig. 2) matched the ages of the younger trees in the postfire matrix stand (Figs. 4-8). Fire release markers were common in DF3 stands. Most trees >38 cm dbh had at least one release, and many 26-38 cm dbh trees also had fire release markers. Past fire events have favored shade-intolerant and fire resistant Douglas-fir over shade-tolerant, fire sensitive western hemlock and western redcedar.

Fire Return Intervals

Although we constructed separate FRI based on liberal and conservative growth criteria to reveal differences in tree responses to fire events, no significant FRI differences between liberal and conservative databases emerged for any landscape unit. We choose to present the liberal estimates, however, because we are convinced that definite fire events were excluded using the conservative criteria.

We calculated mean FRI at four spatial scales in the study area (Table 3). As the size of the unit increased, intervals between fires decreased. Tributary drainages in mountains are important fire ecology features, because wildfires often are confined by the ridges separating adjacent tributaries. Mean area for the lateral tributaries in the study area is ~200 ha, a size we believe yielded the most appropriate estimate of fire intervals in the forests of the Morse Creek drainage. At this spatial scale, mean FRI was 21 yr, with a median of 15 yr (Table 3). Of the 12 tributaries in which we gathered data, mean FRI for all but three was 11-22 yr. Two tributaries exceeded 40 yr. A confidence interval constructed from these data shows that the true mean FRI value on the tributary spatial scale lies between 13 and 30 yr, with a 5% probability of error.

Many groves on smaller units of land were distributed throughout the study area. Of the groves studied, 38 contributed to the mean FRI calculation. Each had at least three trees that carried multiple fire release markers, except for one grove in which two trees combined for seven fire release markers. Mean FRI for these 38 groves was about twice as long as the tributary level, and the median was about 17 yr longer (Table 3). Of the 38 groves, 20 had mean FRI between 20 and 40 yr, and fire returned to three of the groves on average <20 yr. All but two groves had mean FRI <100 yr.

TABLE 3. Fire return intervals (FRI) on four landscape unit sizes in the Morse Creek drainage, based on liberal criteria for growth release markers (Fig. 3).

Unit	Size (ha)	FRI ± SE (yr)	Median (yr)
One tree	<0.001	105.5 ± 6.1	91
Grove	0.1 - 1	44.3 ± 4.8	32
Tributary	200	21.3 ± 3.7	15
Morse Creek	2500	2.9 ± 0.3	–

Of the 318 Douglas-firs contributing to this study, 142 had multiple fire release markers, from which we could calculate FRI on the individual level (point frequency). Mean FRI was 106 yr, with a median of 91 yr (Table 3). Of the 142 trees, 37 had mean FRI of 50 yr or less, 80 had FRI <100 yr, 14 had FRI >200 yr, three of which had FRI >300 yr.

The entire drainage experienced a fire event on the average of once every 3 yr (Table 3). Pre-1650 mean FRI was 5 yr, somewhat longer than the overall mean because of fewer trees in the database. The longest time span without fire between 1400 and 1650 was 10 yr. From 1650-1985, the longest fire free interval was 8 yr (1780-1788), and post-1940 it was 6 yr (1964-1970). The longest interval during which at least one fire burned per year in the Morse Creek drainage was 1849-1862. If a fire had burned in 1863, this interval would have extended to 1871.

Standard errors generally were small, and declined as unit size increased. Individual trees were the most variable unit; the entire drainage was the least variable. These low standard errors indicate that fire is a regular environmental factor for these forests. It is noteworthy that standard error for the point frequency of fire on individual trees is merely 6 yr. Fire has returned often to the Morse Creek drainage, and few trees live their entire lives without experiencing one or two fires.

Fuel Loading

Surface woody fuels were significantly lower in the DF3 matrix type, and there were no significant differences between the DF1 and DF2 types (Table 4). Percent fine fuels (0.1-2.54 cm diameter) in the surface woody fuel component differed significantly across all three matrix types. Fine fuels represented a significantly smaller percentage of the surface fuels in DF1, and a

TABLE 4. Woody fuel loads (tons/ha) in DF1, DF2, and DF3 stands in the Morse Creek drainage. Like superscripts indicate no significant difference between the stand types. Percent fine fuels (0.1-2.5 cm diameter) were transformed by arcsin before statistical analysis.

	DF1	DF2	DF3
Surface fuels	48.5^{a}	50.2^{a}	31.0^{b}
Percent fine fuels	22^{a}	45^{b}	56^{c}
Elevated fuels	9.1^{a}	1.9^{b}	8.3^{a}
Total fuel load	57.6^{a}	52.1^{b}	39.3^{c}

significantly higher percentage in DF3. Elevated fuel mass did not differ significantly between DF1 and DF3, and both had significantly greater elevated fuel mass than DF2. Total woody fuel load was significantly different among all three types. DF1 had significantly higher total woody fuels, and DF3 had significantly lower total woody fuels. These fuel categories relate to the ages of the matrix stand types. In the DF1 type, for which 38% of the standing stems were dead and many more had fallen to the ground, coarse (>2.54 cm diameter) woody debris accounted for >27 kg/ha of the fuel component. The DF2 type had fewer total standing dead stems, but many decades of branch and twig fall contributed to the heavy surface fuels and high percentage of fine fuels. Standing dead stems were common in the DF3 type, but <14 kg/ha of coarse woody fuels characterized the sparse surface fuel component.

Discussion

The Morse Creek drainage supported a fine-grain mosaic of three matrix forest types (Table 1, Fig. 1) that reflect a mixed fire regime. The DF1 matrix type originated after stand-replacement fires. The DF2 and DF3 matrix types probably originated after high severity fires, but for the past three to five centuries have experienced only low to moderate severity surface fires. Any DF2 or DF3 units that had experienced high severity fires have been replaced by the postfire DF1 type.

The differences in woody fuels relate to the structural characteristics of the matrix types and to fire history. The younger DF1 type included small, standing dead trees, which contributed high amounts of elevated fuels. Abundant woody litter on the ground provides the fuel continuity to sustain fire and lift it to the canopy. The significantly lower percentage of fine fuels, however, argues that surface fires would be difficult to start and sustain to the point of igniting the large woody fuel loads. Thus, the DF1 type is unlikely to sustain low severity surface fires, but it could sustain high severity fires during extreme fire weather. Pickford et al. (1980) noted that the probability of crown fire was higher in these young stands. This relationship is reflected in the fire release data. Few trees that germinated in response to the 1896-1904 burning period carried fire release markers (Fig. 7).

The DF2 matrix type could support low, moderate, or high severity fires, depending on fire weather. Fires are more likely to be supported once ignited by lightning in this forest type. The significantly lower mass of elevated fuels argues that stand-replacement fires in DF2 would burn most probably under extreme fire weather conditions, which was the case in the two major fire episodes in 1687-1720 and 1897-1904. When low and moderate severity surface fires burn in DF2, the gaps in the downed woody fuel bed must be bridged by dead salal leaves and live mosses, salal, and kinnikinnick. Fire release data (Figs. 4-6) indicate that such low and moderate severity fires have started many times in the past in DF2, but low fuel continuity limited the spread to small areas. These fires probably were intense enough to kill western hemlock and western redcedar, leading to the growth releases in Douglas-fir.

The DF3 matrix type is likely to support low and moderate severity surface fires, largely because of the significantly lighter total fuel load. Although elevated fuel mass was significantly higher than in DF2, the lower surface fuel loads, coupled with higher densities of less-flammable western hemlock and western redcedar, argue against fires running into the canopy and developing into stand-replacement fires.

At any spatial scale from individual tree to the entire drainage (Table 3), all FRI estimates were shorter than FRI previously estimated for the eastern Olympic Mountains (Fonda and Bliss 1969, Fonda 1979, Henderson et al. 1989). Fires in the study area have burned more frequently and with more variable severity than the earlier 130-300 yr estimates. The fire regime is characterized by periods of 50-70 low and moderate severity fires, interrupted by infrequent, large-scale, high severity burning episodes (Figs. 4-8).

Based on date of stand establishment, Fonda (1979) and Henderson et al. (1989) identified two widespread, major fire episodes that burned in the area ca. 300 and 500 yr ago. Henderson et al. (1989) estimated FRI of 130-259 yr in large (>200 ha) Douglas-fir stands of the eastern Olympics, and stated that stand-replacement fires were common. In contrast to the data of Henderson et al. (1989), mean FRI based on fire release markers in this study equaled 21 yr on the 200 ha level (Table 3). Our germination and fire release data yielded no conclusive evidence of high severity fires earlier than 1680.

Fire history has been studied in other Douglas-fir forests on the Pacific slope. Since 1990, it has become clear that Douglas-fir forests ranging from northern California (Brown et al. 1999), through the Klamath Mountains (Taylor and Skinner 1998), the central Oregon Cascades (Morrison and Swanson 1990, Wallin et al. 1996, Cissel et al. 1998), to the North Cascades in Washington (Agee et al. 1990) have supported combinations of frequent low and moderate severity fires, and infrequent, high severity fires. Now the eastern Olympics can be added to the list, and the estimated FRI for northern forests dominated by Douglas-fir can be shortened considerably. Even at the level of individual trees, mean FRI was only 106 yr. These studies ranging from California to Washington demonstrated that low severity fires, presumably started by lightning, burned more frequently than high severity fires. The longest FRI was 94-137 yr in the North Cascades (Agee et al. 1990); the shortest was 13-22 yr in the Klamath Mountains (Taylor and Skinner 1998). Douglas-fir forests at Point Reyes actually supported 7-9 yr FRI (Brown et al. 1999). Although many of the fires were attributed to Native American burning, the short FRI establishes that Douglas-fir forests are capable of supporting frequent, low severity fires.

Fires throughout western North America have been less frequent since 1900 because of fire exclusion and changing land use patterns (Fonda and Bliss, 1969; Habeck and Mutch, 1973; Arno, 1976; Madany and West, 1980; Swetnam and Dieterich, 1983, Morrison and Swanson 1990, Brown et al. 1999). In the Morse Creek study area, the number of trees recording fires changed from 168 between 1841-1900 to 125 from 1901 to 1960 (Table 3), a decrease of ~25%. Most of the documented fires in this region were small (Pickford et al. 1977). Of the 140 fires documented by Pickford et al. (1977) for the eastern montane zone between 1916 and 1975, 76% burned <1 ha. Only 6% burned >20 ha, and the two largest burned 348 ha in 1924 and 121 ha in 1930. Nevertheless, in contrast to almost all other western regions, fires continued to burn in the Morse Creek drainage throughout the 1900s to the present (Table 3, Fig. 9).

The Little Ice Age extended from ~1600 to 1850 (Peterson et al. 1999). The fire record from the Morse Creek drainage appears to reflect the end of the Little Ice Age (Table 2, Fig. 8). Fire incidence during the Little Ice Age was low, and only four decades had a dozen or more trees that recorded fire (Table 2). The marked increase in 1850-1859 in the number of trees carrying fire release scars (Table 2, Fig. 8) appears to signal the drier and warmer conditions when the Little Ice Age closed. Of the 56 trees that recorded fires from 1850 to 1859 (Table 2), 10 recorded fires in 1850. Of the 71 trees recording fires 1850-1869 (Table 2), 52% recorded fires 1850-1855. Clearly, a long period of low fire activity ended dramatically as post-Little Ice Age weather became drier and warmer. One possible consequence of global climate change is a higher incidence of wildfires (Lenihan et al. 1998), presumably because extreme fire weather could be more common under drier and warmer conditions. Fires in the Douglas-fir forests in this region are governed primarily by fire weather, rather than by fuels (Agee 1997). If the climate in the eastern Olympics changes toward drier and warmer, so that the incidence and length of fire weather increase, fire events could increase suddenly, similar to the end of the Little Ice Age.

The fire history of the Morse Creek drainage provides a framework within which recommendations for managing fire in Douglas-fir forests in the eastern Olympics can be suggested. Lighting-ignited wildfires continued to burn in this area during the 20th Century, and they should continue into the future. Given the previous scenario of high intensity, stand-replacement fires every two to three centuries when extreme fire weather coincided with sufficient fuel loadings (Fonda 1979, Henderson et al. 1989, Agee 1997), fire exclusion and suppression were reasonable fire management strategies. This scenario no longer accurately describes the fire regime, however. Low to moderate severity fires have been common in the Morse Creek drainage, but they have been small, not widespread. Management fires that burn many small patches of forest each year would approach the kind of fire regime typical of these forests. Such fires would perpetuate DF2 and DF3 matrix forest types, rather than allowing the fire avoider western hemlock to dominate the forests in the absence of fire. Furthermore, such fires would reduce fuel loadings, so that extreme fire weather would be less likely to cause high intensity, stand-replacement fires.

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