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Forest Fire Regime of the Bull Run Watershed, Oregon

Abstract

Forest fire history of the Bull Run watershed in northwestern Oregon was evaluated using the natural fire rotation technique. The average NFR over the last 500 years is 347 years, but the record is heavily influenced by a few large events. Fire severity is generally high, with most large fires occurring in summer to fall. Fires that appear to have entered the watershed from its edge significantly influence the historic record. Because the Bull Run receives much more precipitation than watersheds directly north or south, its high-severity fire regime contrasts with the moderate-severity fire regime observed in these adjacent areas.

Introduction

In 1891, the Bull Run watershed (Figure 1) in northwestern Oregon was included as part of a national system of forest reserves in the United States and the next year was established as a water source for the Portland metropolitan area. The 26,000 ha watershed has almost twice the precipitation of watersheds directly north and south (Figures 1 and 2). Quantity and quality of water has varied over past millennia, due to long-term climate change, shorter-term periods of wetter and drier weather, and natural disturbances such as fire and wind. Water balance data from Luchin (1973) suggest that runoff in the Bull Run could possibly increase by as much as 90 cm (40%) if a stand replacement disturbance affected the entire watershed. Swanson (1981) summarizes the effects of large-scale disturbance by fire on geo-

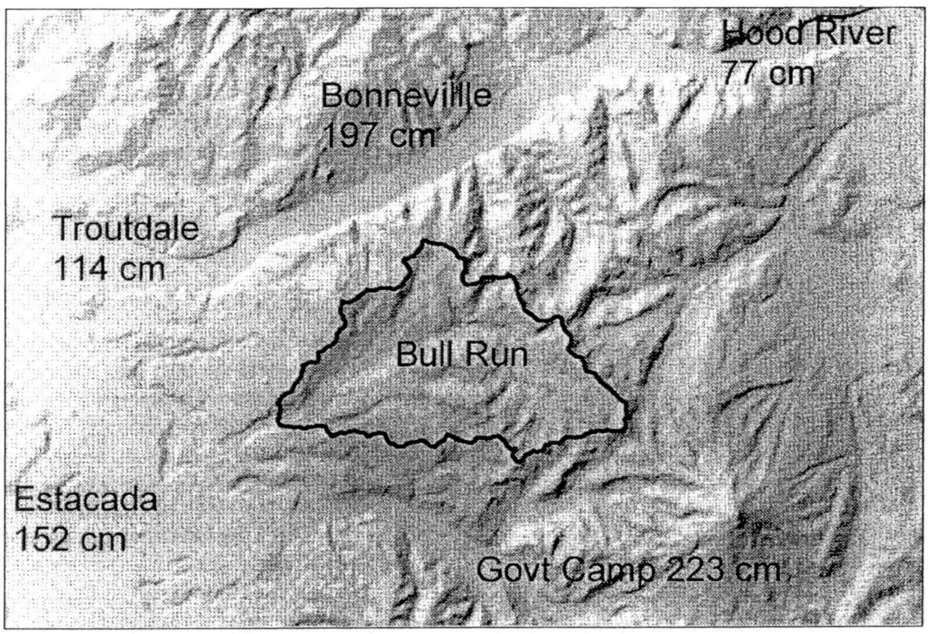

Figure 1. Location of Bull Run watershed in northwest Oregon. The Bull Run is located just south of the Columbia River, flowing in this figure from Hood River west to Bonneville and Troutdale. Annual precipitation for neighboring weather stations shown (Website http://www.wrcc.dri.edu/summary/climsmor.html). Mount Hood is the obvious peak in the southeast corner of the frame. Data for figure supplied by Diana Sinton.

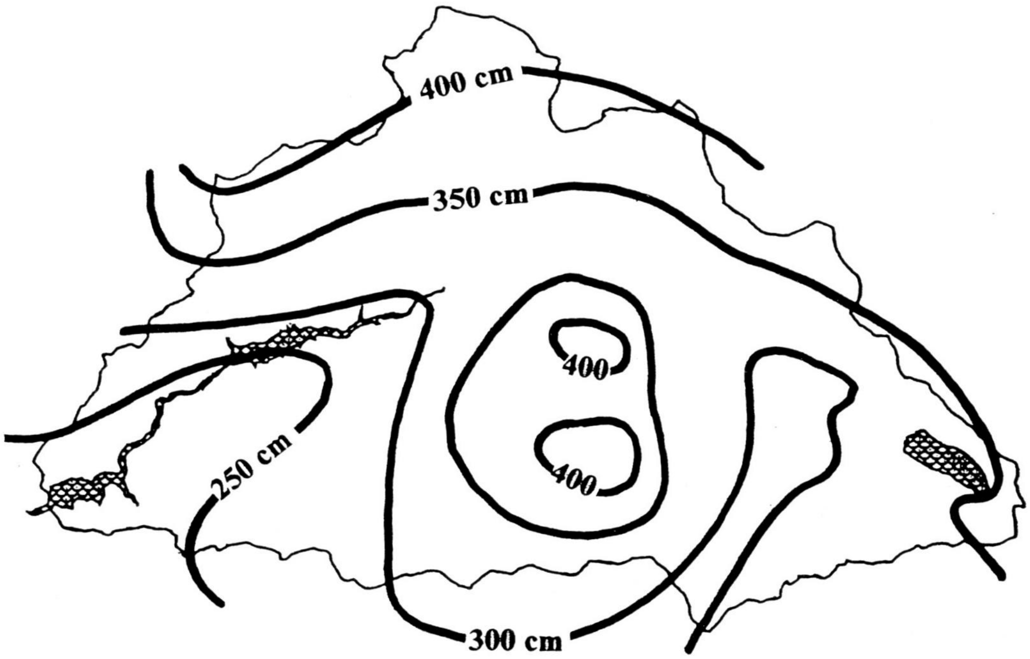

Figure 2. Annual precipitation within the Bull Run (data from City of Portland, Oregon, Bureau of Water Works).

morphic processes, and sediment production could increase several-fold after stand replacement fires in watersheds such as the Bull Run.

In 1983, a major windstorm entered the watershed and about 10 percent of the existing forest area had a significant number of trees blown down (Sinton 1996). Salvage logging was conducted on about 675 ha of the area affected by the 1983 windstorm. In 1994, about 90 percent of the watershed became designated as a Late Successional Reserve (LSR) as part of the Northwest Forest Plan (Thomas 1994). Timber harvest and salvage operations are restricted under the LSR designation of the Forest Plan such that future water quality impacts will largely be due to natural disturbance patterns.

The potential for natural events to adversely affect water quality in the watershed raised interest in defining the natural disturbance regimes of the watershed. Forest fires in the western Cascades have usually been described as infrequent, high intensity events that kill almost all the trees within the fire boundaries. Large-scale events such as the Yacolt burn (1902) and the Tillamook burn (1933) served as archetypes for all forest fires in the western Cascades prior to the 1980's (Morrison and Swanson 1990). However, fire can operate at a variety of scales and severities, and it can range over a spectrum of severities known as high-, moderate-, and low-severity fire regimes (Agee 1993). Small portions of the landscape in high-severity fire regimes may burn with moderate- or low-severity. Near Mount St. Helens, about 100 km north of the Bull Run, Yamaguchi (1993) found 3-4 fires occurring in the first 150 years of stand development after high-severity fire. However, these fires were of low-severity, scarring occasional trees but not resulting in any Douglas-fir establishment. High-severity fire was important in the Siouxon watershed of southwestern Washington, with multiple reburns on some sites after the Yacolt fire of 1902 (Gray and Franklin 1997).

There are locally variant forests west of the Cascades crest where a moderate-severity fire regime is the dominant fire regime, represented by more frequent (return intervals of less than 100 years) and less intense fires leaving substantial residual forest: the San Juan Islands (Agee and Dunwiddie 1984), the Ross Lake area of the North Cascades (Agee et al. 1990), and the northeastern Olympic Mountains (Wetzel and Fonda 2000). A gradient of fire severity from high, in the Olympic Mountains and northern Washington Cascades, to moderate in the central Oregon Cascades is well-established (Means 1982, Teensma 1987, Morrison and Swanson 1990, Agee 1991, Van Norman 1998, Olson 2000).

The objectives of this study were to define the historical frequency, severity, and seasonality of fire in the watershed using tree-ring reconstructions and archival records. There are four archival sources that identify historical fires for the Bull Run and vicinity. In 1900, a forest type map of Oregon was produced by the U.S. Geological Survey (Gannett 1902). It showed substantial burned land in and around the Bull Run. A larger scale but anonymously authored map of burned lands in the Bull Run was produced early in the 20th century and it is fairly consistent with the USGS map. Another age class map of the watershed (Pincha 1979) is fairly consistent but has more recent (post-1900) age classes northwest of the Bull Run River in the vicinity of two dams on the river. A compilation of 20th century fires (USDA Forest Service, Mount Hood National Forest, unpublished data) lists location, source, and size of recent fires with map locations of most of them. Some recent fires north and south of the Bull Run appear to have been of moderate-severity, prompting speculation that the fire regime of the Bull Run is also of moderate-severity.

Study Area

The forests of the Bull Run Watershed are similar to those elsewhere west of the Cascade Crest. There are two major forest zones (Franklin and Dyrness 1973) defined on the basis of potential vegetation that might eventually dominate that type in the long-term absence of disturbance (we use the phrase "forest zone" as equivalent to "forest series"). The most widespread is the western hemlock (*Tsuga heterophylla*) zone, occupying the lowest elevations in the watershed and covering the most area, particularly in the western half of the watershed. The major species in this zone include Douglas-fir (*Pseudotsuga menziesii*) and western hemlock, with western redcedar (*Thuja plicata*) and other species more locally important (Franklin and Dyrness 1973). Douglas-fir in this area is considered shade-intolerant, so it usually becomes established only on disturbed sites where considerable growing space has been opened. It tends to be a widespread dominant after forest fires along with western hemlock (Agee 1993). Because Douglas-fir can live over 750 years (Waring and Franklin 1979), forest age classes that have Douglas-fir as a dominant serve as temporal markers of past forest disturbance. Western hemlock, as a shade-tolerant species, can become established after fires, but may also establish well in small gaps locally created by individual tree falls.

At higher elevations, the Pacific silver fir (*Abies amabilis*) zone is present. Shade-tolerant species like western hemlock and Pacific silver fir will eventually dominate these sites if they are undisturbed for many centuries. Douglas-fir plays an ecological role similar to its role at lower elevations, but is usually less dominant because of frost, cold soils, snow breakage as saplings, and generally cooler conditions favoring other species. Noble fir (*Abies procera*) may be an early seral codominant along with Douglas-fir (Minore 1979, Stewart 1986). Alaska yellow-cedar (*Chamaecyparis nootkatensis*) is occasionally found on wetter sites and tends to be a shade-tolerant, late-successional codominant along with Pacific silver fir. The Pacific silver fir zone covers most of the higher elevation area in the eastern portion of the watershed, with the highest elevation mountain hemlock (*Tsuga mertensiana*) zone almost absent in the Bull Run.

Methods

Defining Fire Regimes

Age classes of Douglas-fir are important in establishing fire frequency and severity. Temporal distance between age classes helps to establish fire return intervals, and the dominance of the different age classes helps to establish what proportion of older age classes was killed by one or more previous fires. In high-severity fire regimes, a single age class of Douglas-fir will be found at any single site, but it can have a wide age range (up to 75 years [Hemstrom and Franklin 1982]) on marginal sites, where brush competition exists after disturbance, where reburns have occurred, or where seed sources are absent (Franklin and Hemstrom 1981). Residual Douglas-firs can be found after high-severity fires, but they are usually found in protected microsites and represent only a small proportion of the pre-fire basal area.

In moderate-severity fire regimes, one or more significant residual age classes will be present. High-severity patches occur, but many places on the landscape are only thinned by fire, opening substantial growing space for Douglas-fir between the residual trees. Other places underburn with low-severity fire, and those patches may have so few large trees killed that post-fire establishment of Douglas-fir does not occur. Instead, either no regeneration, or a post-fire cohort of more shade tolerant species, such as western hemlock or Pacific silver fir, creates a new understory layer. The presence of Douglas-fir in one or more age cohorts usually is reliable as a fire indicator, but reliance on establishment of Douglas-fir to indicate a fire may underestimate the presence of very low intensity fires that might not be severe enough to open the canopy and result in successful Douglas-fir establishment.

Other disturbance events also occur and may be confused with the effects of fire. Wind tends to be an important episodic event in the western Cascades area. Unlike fire, which tends to thin from below (e.g., kills smallest trees first, largest last), wind tends to thin from above, removing larger, exposed trees, and leaving smaller, protected ones. Often intermediate crown class trees are preferentially windthrown, but as the intensity of the event increases, it is the understory that is left (Edmonds et al. 2000). Usually these trees are shade-tolerant (e.g., western hemlock and Pacific silver fir locally), and will show a substantial growth release when the overstory is removed, so that wind can be differentiated from fire in stand reconstructions (Sinton 1996, Sinton et al. 2000).

Fire Frequency Models

Methods to evaluate fire frequency include two general types: point frequencies and area frequencies (Agee 1993). Area frequencies are used in moderate- to high-severity fire regimes where fire-scarred trees are uncommon, but discrete forest age classes likely to have regenerated after fire will exist. Preliminary observations suggested that the Bull Run clearly fits in this latter category. Two types of area frequencies may be applied when forest age class data are available. The first is natural fire rotation (NFR). From the age class data and assumptions about reconstruction of past fire events, the area of individual past fire events is determined as a proportion of the total watershed area (Heinselman 1973). The NFR is then determined by the quotient of any time period and the proportion of study area burned in that time period. A separate NFR can be calculated by plant community type, century, aspect, or any other temporal or geographic subset of the watershed. The NFR is a simple, easily understood technique, but has the major disadvantage of requiring the reconstruction of all past fire events. Fire events more than 200-300 yr old, particularly if they were small, may have been partially, or sometimes wholly, erased from the landscape by subsequent fires. Therefore, the NFR technique becomes more conservative as one moves back in time.

The second area frequency technique is based on statistical distributions such as the Weibull or the negative exponential. This method assumes a stationary population of stands that are unlikely to actually exist on the landscape. Initial field surveys showed that the Bull Run had more old than young stands. Since no stationary population can have more old than young stands (Huggard and Arsenault 1999), the natural fire rotation technique was used in place of the negative exponential, similar to the way it has been applied in other Pacific Northwest forests (Hemstrom and Franklin 1982, Teensma 1987, Agee et al. 1990, Morrison and Swanson 1990, Agee 1991).

Fire regimes for the Bull Run watershed were reconstructed by determining stand establishment dates from tree cores and stump ages and delineating stand boundaries from aerial photographs. A total of 208 plots were established, with size cohorts of Douglas-fir visually identified and an average of 4 trees (S.D. 1.89) sampled per plot (832 trees total). In units previously harvested that are scattered throughout the watershed, and along roads, large stumps could be aged in the field or removed with chain saws and returned to the lab for sanding and counting. Most logged units were in the oldest age classes because they had contained the highest volume. Most unlogged stands were sampled with increment borers, and we could obtain samples close to the pith at core heights of 30-50 cm in stands up to 250 years old with increment borers up to 75 cm long. These samples were placed in straws and returned to the lab where they were mounted in routed grooves and sanded until ring widths were clearly countable. Some cores did not reach the pith due to the large size of the trees (e.g., in stands over 250 years old trees might be >2 m diameter) and core age corrections were necessary.

Estimates for correction on large standing trees where increment borers could not reach the pith were based on 25 cores selected from five sites across the watershed. Ring widths for these trees were measured with a zoom microscope with an attached video monitor and a staging table accurate to 0.01 mm. The cores were measured to 140 mm out from the pith or 70 years, well beyond the corrections actually needed for sample cores. Individual curves for the 25 cores were grouped into five curve groups representing categories of annual increment growth from low to high. The five curves were graphed with distance to pith on the abscissa and years to pith on the ordinate. Selection of the curve to be used for a given core was determined by defining the missing distance to pith from core length and field measured tree diameter, matching the average annual increment for the oldest 10 years on the core to the closest fit curve, and then graphically determining the age adjustment to be applied to that core. This methodology was used to substantiate the presence of an age cohort at a site but was not used independently as evidence of a cohort because of potential estimation error.

Estimated germination dates were calculated by adding several years to pith dates calculated or counted for stump or increment core samples based on sample height and data on seedling height by age from McArdle and Meyer (1930). Because of the necessary age adjustments, not every sample was as reliable as the next. Age cohorts were defined on the basis of the best samples at each site: where the fewest years had to be added to obtain an origin date and where consistent origin dates were obtained on multiple samples (Table 1).

Stands were then assigned cohort origin dates (one or more per site) based on reliable tree ages, primarily of the Douglas-fir cohorts if they were present on the site, and together with the stand boundary delineations, fire events were reconstructed. Aerial photographs from 1957-58 and 1972 were used to delineate many stand boundaries, and used in conjunction with topographic maps to evaluate effects of slope and aspect on color and texture variation within an age class patch. The data allowed reconstructions back to roughly 750 years before present and calculations of natural fire rotations. Due to the spatial extent of one large event about 500 years B.P., NFR calculations were not extended back beyond that date. Variability in natural fire rotation was expressed in two ways. First, natural fire rotations were calculated by aspect, elevation, and by century, to account for topographic and temporal variability. Another estimate of variability in fire return interval is to fit the number of fires in each cell of a grid placed over the landscape to a Poisson distribution (Agee 1993). A grid representing 250 ha cells was placed over the landscape, and the

TABLE 1. Examples of tree ages collected from several sites with brief interpretations of identified cohorts (age groups).

Site	Species	Tree Ages	Interpretation
104	Psme	91, 91, 91, 86, 86	This is a young, single-aged cohort. Very common here at various ages.
190	Psme Psme Tshe	499, 498 242 102, 101, 100, 97	This is a three-aged cohort, with the most recent fire of low-severity, leaving enough residual canopy that only western hemlock could regenerate. Unusual here.
233	Abam Psme	249, 241, 232 94, 91, 90, 86	This is a two-aged cohort with Pacific silver fir forming the older cohort and an apparent patchy, low-severity fire allowing a second cohort of Douglas-fir to establish. Unusual.
240	Psme Abpr Psme Abgr Psme	410 336, 297 308 232, 142, 101 89, 88	This appears to be a stand with multiple, confounding disturbances most likely involving wind and fire. Interpretation requires matching with adjacent sites, and use of the most reliable core ages. Very uncommon.

Psme = Douglas-fir, Tshe = western hemlock, Abam = Pacific silver fir, Abgr = grand fir, Abpr = noble fir.

number of fires over time per cell were recorded. The fit of the data to a Poisson distribution was tested with a Kolgomorov-Smirnov goodness-of-fit test (Zar 1996).

Fire Severity

Historical fire severity was analyzed using three independent sets of data. High-severity plots were defined as those with one age cohort, and low- or moderate-severity plots were those with multiple cohorts (Table 1). If more than one Douglas-fir age class, or a discrete shade-tolerant age class beneath Douglas-fir overstory was present (see Table 1 site 190), a multiple age cohort was assumed to exist, representing a moderate-severity fire regime. The first data set was age class information from Forest Service "FS" ecology plots (N. Diaz, USFS, unpublished data). Of the 33 plots, 23 had clearly identifiable single or multiple cohort age classes. Ten of the 33 plots had unusual tree age distributions and were field checked; a total of 7 were added to the single cohort category and 3 were added to the multiple cohort category. Plots were then stratified to forest series. The second data set consisted of the age class information collected for this project ("UW"). The age class data were evaluated similarly to the Forest Service ecology plots.

The third data set was photo-interpreted fire severity from three large fires that burned in the watershed after 1850 and before 1915: the Camp Creek fire, the Falls Creek fire, and the Hickman Butte fire. For the Camp Creek fire, only those portions south of the Bull Run River were analyzed, as reservoirs have filled in some of the burned area. For the Falls Creek and Hickman Butte fires, only those sections of the fires within the Bull Run drainage were analyzed. These fires were outlined and the three fire severity levels (low = 0-20 percent young (post-fire) forest in older matrix; moderate = 20-70 percent young forest in older matrix; high = > 70 percent young forest) were photo-interpreted by placing a 2.25 ha cell grid over orthophotos and using proportions of canopy coverage of younger/older forest to determine fire severity level. The photo-interpretation of the Camp Creek fire was independently analyzed by three interpreters to check consistency of classification, and the maximum difference between any two observers for the percentage of land area in a fire severity category was 3 percent, 7 percent, and 7 percent.

Historical fires were naturally extinguished when they no longer spread. We hypothesized that fire severity should be less in the transitional area ("edge") between unburned forest and the interior of the burn. Possible changes in fire severity in the edge of historic burns were analyzed by defining a 150 m edge (roughly 2 tree lengths) along the boundary of each of the three sample fires. The fire severity data were then re-aggregated by "edge" or "interior" to evaluate whether the proportions of fire severity levels differed by location. The interaction of edge and fire severity was tested with a Chi-square analysis. The 1480 ha Camp Creek fire was intensively field-checked around its edges for the occurrence of low-intensity fire. A series of 15 transects was placed normal to the edge of the high-severity fire zone, and the occurrence of residual trees and/or charcoal was measured away from the edge of the high-severity fire zone. The area of the moderate/low-severity fire zone was then compared to the total fire area.

Fire Seasonality

Where fire events are identified from tree ages, the seasonality of fires of previous centuries cannot be determined as it can for low-severity fire regimes (Baisan and Swetnam 1990). Two methods were employed to enable inferences about the seasonality of fire in this study. The first was to evaluate the 20th century record, which was compiled by the Forest Service (Pincha 1979, C. Smith [USDA Forest Service, Mt. Hood National Forest, Gresham, OR] unpublished data). Fires that could be identified to month were recorded. The second method of evaluating fire seasonality was to use a fire cycle model based on climate (Agee and Flewelling 1983) applied to a weather set from the Bull Run vicinity. This model was originally built for the Olympic Mountains but has been applied on a regional basis (Agee 1991, 1993) using 20th century weather records for local weather stations. Based on 10-day increments from June 1 - September 30, the model predicts the probability of lightning ignitions based on long and short-term drought, thunderstorm activity, and east winds. The omission of fires starting in October probably underestimates fire activity in that month. The model does not provide a quantitative estimate of fire activity, but does allocate ignitions between months, and has been used effectively at a regional scale to evaluate fire regimes and seasonality (Agee 1991). The proportions of fires by month that were likely to grow >1 ha in size were compared to the 20th century record of fires by month as a way to evaluate the seasonality of historic fires in the Bull Run.

Results

Fire Frequency

The Bull Run has burned infrequently, and contains a large proportion of old growth forest as a result. Major fire events (Figure 3 A-F) are summarized below, and dates listed are approximate rather than precise to the year, particularly for those events 200 years or more B.P. Generally they will tend to be conservative, as years may have passed between the event and the first documented regeneration.

1243 A.D.

The two remnant stands (130 ha) from this event (Figure 3, A) have large Douglas-fir, along with Pacific silver fir, Alaska yellow-cedar, and western hemlock. Many of the trees have candelabra (multiple) tops, representing minor wind damage on the tops of very old trees. The two stands are separated by about 4 km, and if they represent a single large event 750 years ago, most of the evidence has been erased by more recent fires. This event could have been large, but can only be shown as two small inclusions within the large 1493 event. This event was not used in reconstruction of natural fire rotation calculations because its extent could not be accurately reconstructed, and events between then and the 1493 fire were also erased. The presence of these oldest stands on ridgetops rather than in valleys is unusual, in that ridgetops tend to be less common as topographic refugia than valley bottoms.

1493 A.D.

This reconstructed event (Figure 3, A) is the largest single fire event to burn in the watershed, covering over 26,000 ha. Occurring about 500 years ago, it now forms the single largest age class in the watershed, and is usually the remnant age class in multiple-aged stands. It occurs from the head of the watershed to the east all the way across down to the lowlands on the west. The only portions of the watershed that did not burn are the remnant 750 year-old stands. Most of the more recent fire events are etched into a matrix of this 500 year-old set of forest age classes.

1663 A.D.

After the 1493 A.D. event, there appears to have been little severe fire activity for the next 150 years. The next large fire (>2800 ha) occurred in 1663 A.D. in the eastern portion of the watershed (Figure 3, B), and most of the stands burned were contiguous to the watershed boundary to the northeast or to the south.

1693 A.D.

The 1693 fire (Figure 3, C) burned in the western portion of the watershed, and much of this area has reburned between then and the present. It was identified by the presence of scattered residuals over most of this landscape.

1873 A.D.

Almost two centuries passed before evidence of the next large fire event (>2700 ha). We believe that two different fires occurred, one burning the western lowland in the vicinity of Reservoir 2, and the other burning the boundary area in the vicinity of Hickman Butte and Thimble Mountain (Figure 3, D). The latter fire is further analyzed for fire severity as the Hickman Butte fire. The long east-west burned area on the west end of the watershed and south side of the reservoir is called the Camp Creek fire and is one of the sites analyzed for fire severity. The USGS map shows these areas to be contiguously burned, as much of the area south of the watershed was burned in the same time period.

1881 A.D.

A rather patchy fire burned in the north portion of the watershed in 1881 (Figure 3, E). This fire has been named the Falls Creek fire and is further analyzed in the fire severity section of the report.

20th Century fires

A number of smaller, human-caused fire events (primarily escaped slash fires) could be identified in the 20th century (Figure 3, F). Together they burned less than 2000 ha. They tend to be clustered in the northern portion of the watershed.

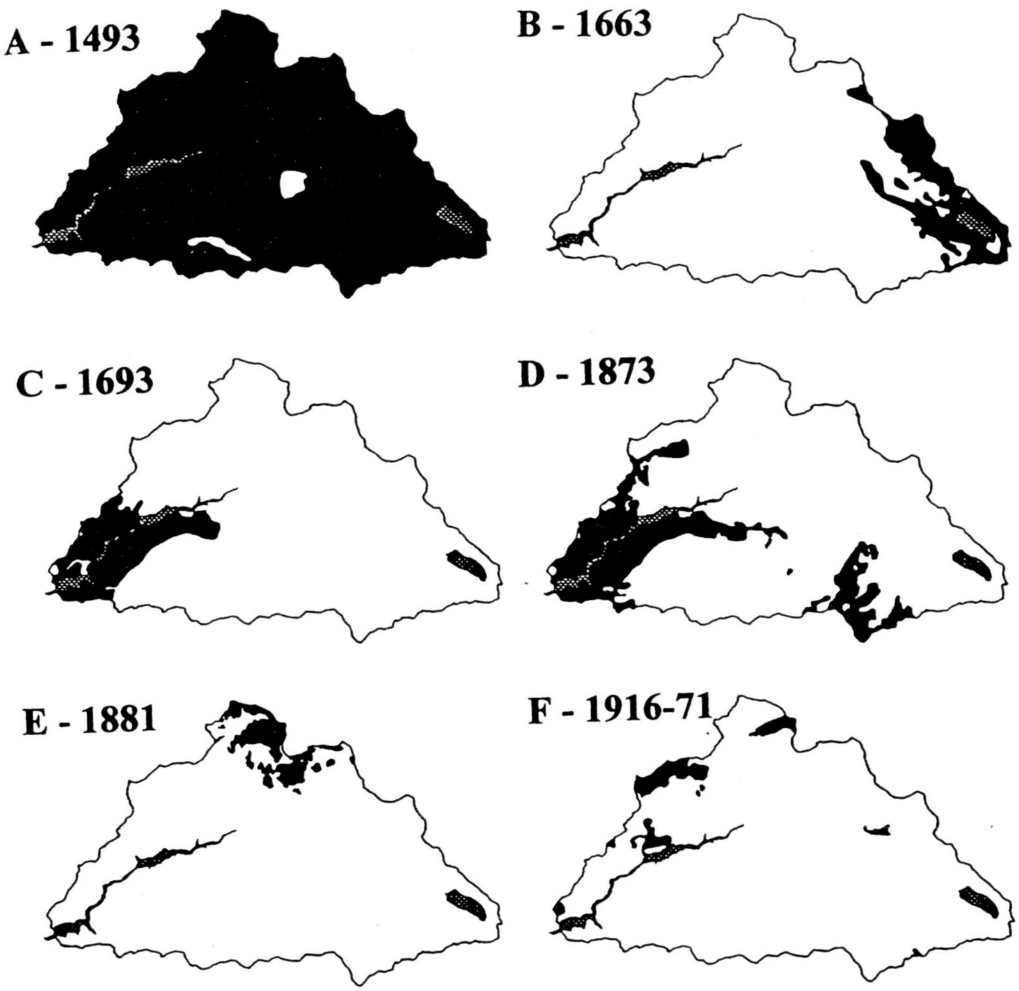

Figure 3. Reconstructed extent of historic fires in the Bull Run watershed. A. 1493 A.D. fire. The ca. 1243 A.D. fire is shown as two small white polygons. B. 1663 A.D. fire appears to have entered the watershed from the east. C. 1693 A.D. fire is in the lower western portion of the watershed. D. 1873 A.D. fire covers much of the same area as the 1693 fire plus a separate area on the southern edge of the watershed. E. 1881 A.D. fire is a patchy fire at the northern edge of the watershed. F. Twentieth century fires (1916 A.D. through 1971 A.D.) are small and scattered.

The overall NFR for the Bull Run watershed is 347 years (Table 2). The literal interpretation of this number means that roughly every 350 years, an area equal in size to the watershed has burned. Obviously there is considerable variation in this number: NFR's calculated by century show a range from roughly 100 years for the century encompassing the 1493 fire event to centuries for which NFR's could not be calculated because of the apparent absence of large fire activity (Figure 4). The 1493 event erased possible fire evidence earlier in that century, and the NFR calculation for that century assumes no earlier fire activity from 1400-1492. Areas above 1000 m elevation generally burned more frequently than areas below 1000 m elevation. This elevation boundary is roughly

TABLE 2. Natural fire rotation (NFR) for the Bull Run watershed. Individual NFR's are calculated by elevation, roughly at the break between the western hemlock and Pacific silver fir zones, and by time period.

Time Period	Natural Fire Rotation (years) Below 1000 m Elevation	Above 1000 m Elevation	All Elevations
Total (1493-1993)	**369**	**289**	**347**
15th Century	99	102	101
16th Century	—	—	—
17th Century	1371	219	667
18th Century	—	—	—
19th Century	431	601	462
20th Century	1660	805	1328
Before 1900	312	253	296
Before 1800	286	212	267

equivalent to the boundary of the western hemlock/Pacific silver fir zones, and indicates that the Pacific silver fir zone in the Bull Run can burn more often than the western hemlock zone.

The natural fire rotation calculations are heavily weighted to fires of antiquity, which appear to have been very widespread across the watershed. The overall NFR of 350 years becomes 296 years if the time period only before 1900 is considered, and 267 years if the period only before 1800 is considered. The NFR's are so closely tied to individual fire events of these past centuries that it is not possible to consider these past centuries as examples of different equilibrium fire regimes. Rather, they appear to be centuries where somewhat aberrant, unusual conditions coalesced to produce widespread burning in a watershed that is typically not very flammable.

Natural fire rotations were also calculated for topographic aspects, but NFR did not differ significantly by aspect. In the post-1800 era, south and west aspects have burned slightly more frequently than north and east aspects (NFR of 734 vs. 827 years), probably because the areas burned have generally been concentrated in the northern portion of the watershed that has a generally south aspect. This difference is small enough that as-

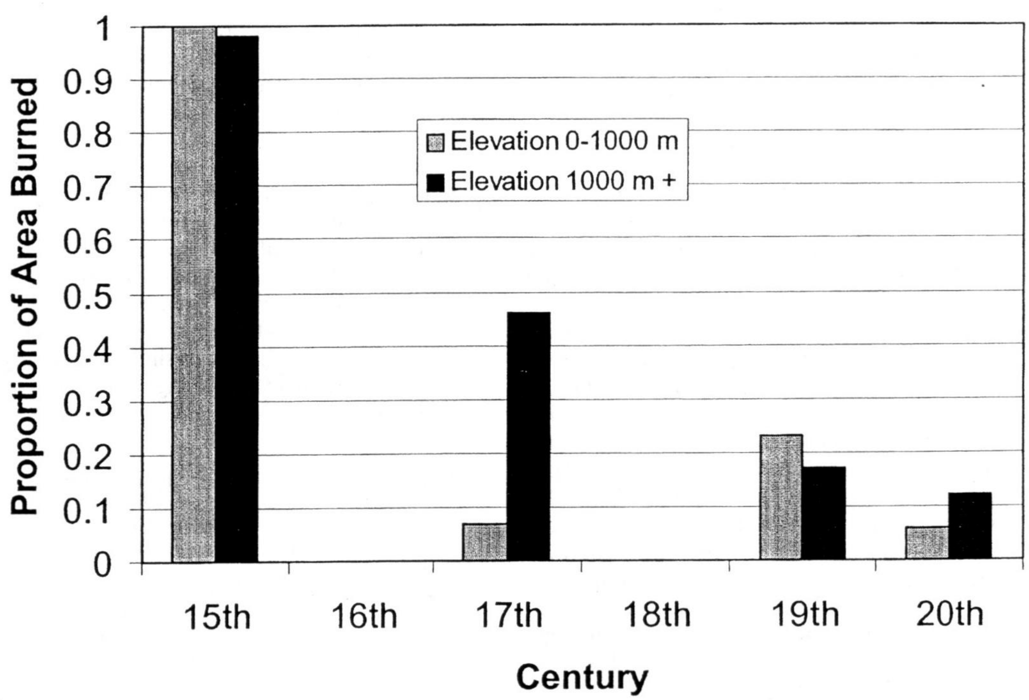

Figure 4. The proportion of the watershed burned by century by elevation zone. There is a decreasing proportion over time, and no apparent trend by elevation zone.

pect does not appear to be a controlling factor in fire spread in the Bull Run watershed.

The Poisson parameter calculated for these data was 1.438. This parameter divided into the time period is equivalent to the NFR. A comparison of actual fire occurrence per cell and Poisson estimations (Table 3) indicated that the Poisson overestimates unburned cells, because in the Bull Run almost the entire watershed burned in the 500 year old event. Results of the Kolgomorov-Smirnov test showed that the field data do not fit a Poisson distribution. In last 500 years, most of the watershed has burned only once, but it almost all burned then, and only about 10 percent has burned at a fire return interval of 150 years or less (3 times or more in the 500 yr period). The watershed therefore contains a large proportion of old growth forest.

TABLE 3. The proportion of 250 ha cells that have burned over the Bull Run watershed over the last 500 years.

Source of Data	Number of Times Burned in 500 years 0	1	2	3	4	5	6
Field Data	0.01[1]	0.66	0.21	0.11	0.01	0	0
Poisson estimates	0.24	0.34	0.24	0.11	0.04	.0.01	<0.01

[1]There are probably small refugia in riparian zones, among cliffs, etc., that did not burn but were missed at the scale of this analysis.

Fire Severity

Fire severity is inferred to be primarily high, as 75-90 percent of the stands have a single early seral cohort of Douglas-fir, with remaining stands having two or more early seral cohorts. The FS database had only two samples from the mountain hemlock zone, because of its limited extent in the watershed, and neither one had multiple age cohorts. In the Pacific silver fir zone (Table 4), tree ages in 5 of the 6 plots indicated single cohort stands. The single multiple-aged stand had some 250-year-old Douglas-fir (now 750 years old) survive the fire of 500 years ago. The western hemlock zone, which is more widespread in the western lowland portion of the Bull Run, had the most plots and the most evidence of multiple cohort stands. Of the 33 plots evaluated in the FS database (Table 4), 85 percent were single-aged. The UW database showed slightly lower proportions of single-aged stands than the FS database.

TABLE 4. Number of plots with single or multiple age classes in the Forest Service Ecology Plot (FS) database, the plot database of this study (UW), and photo-interpreted fire severity portion (pixels) of the current study. In the photo-interpreted study, low- and moderate-severity classes are combined in the "multiple" age class category. Figures in parentheses are percents.

Database	Western hemlock zone Single	Multiple	Pacific silver fir zone Single	Multiple	Total Single	Multiple
FS	28 (88)	4 (12)	5 (83)	1 (17)	33 (87)	5 (13)
UW	101 (78)	30 (22)	46 (74)	16 (26)	147[1] (76)	46[1] (24)
Photo-Interpretation[2]					1130 (69)	508 (31)

[1]total does not sum to 208 because several plots had only one usable tree age.

[2]not differentiated by forest zone.

Between 74-78 percent of the plots in both forest series had single age cohorts, with the remainder in two-aged cohorts, with a few three-aged cohorts. Douglas-fir was the residual tree species in both forest zones as it has much higher fire resistance than western hemlock or Pacific silver fir.

Photo-interpreted fire severity from late 19th century fires suggests that high-severity fire is the most common pattern experienced (Table 5): 62-73 percent of the area of these fires appeared to be a single age-class with a canopy of uniform texture. Roughly 18-31 percent of the area had a substantial residual component, and this was most evident on the Falls Creek fire, particularly in its western portion. Only 7-9 percent of the land area was photo-identified as low-severity fire in these three fires. Comparison with the two Bull Run age-class databases (Table 4) indicates that these photo-interpreted fires had a slightly lower high-severity component than the age-class databases. This may be due to the age class data collection

TABLE 5. Proportions of selected Bull Run watershed fires in high (>70 percent), moderate (20-70 percent), and low (<20 percent) fire severity classes, based on residual canopy measured by photo-interpretation.

Fire	Date of Fire	Fire Severity Level High	Mod	Low
Camp Creek	1873	73	19	8
Falls Creek	1881	62	31	7
Hickman Butte	1873	73	18	9

being biased to the interiors of well-defined patches, so that edge effects were underrepresented in the age class databases.

All three of the approaches to evaluate fire severity produced consistent results, although each of the approaches has bias. The FS, UW, and photo-interpreted fires from the late 1800's indicated that high-severity fire was the dominant type of fire affecting the Bull Run watershed. Estimates of high-severity fire based on these three data sources ranged from 62-90 percent of the area affected. Moderate-severity fire accounted for much of the remaining area (18-31 percent), with low-severity fire accounting for less than 10 percent of the burned areas.

The spatial distribution of low- and moderate-severity fire suggests it is most common at the edges (150 m, or two tree lengths) of the fires. At the Camp Creek fire, 86 percent of the low- and moderate-severity fire occurred within the edge zone. At the Hickman and Falls Creek fires, the percentages of low- and moderate-severity within 150 m of the fire edge were 58 percent and 52 percent, respectively. The proportions of low/moderate and high fire severity differed significantly between the fire area as a whole and the 150 m edge zone ($P < .005$) for each of the three fires, indicating that low- and moderate-severity fire is more common at the edge between high-severity fire and unburned forest. However, while low- to moderate-severity fire is largely an edge phenomenon, it also is found in the interior of the fires in the vicinity of drainages and rocky areas. Even within areas of high-severity fire, occasional residuals can be present, so the presence of a high-severity fire regime does not mean residual trees are totally absent from the landscape.

Field checks at the Camp Creek Fire suggest that proportions of low-severity fire were not misidentified or unidentified by photo-interpretation. The perimeter area of low-severity fire based on intensive field searches for surface charcoal was calculated to be 3 percent of the area of the high-severity fire, suggesting that the photo-interpreted proportions are not highly biased against the identification of low-severity burn areas. The largest area of low-severity fire was on the southwest edge of the fire. This may be the result of lowered fire spread and intensity after winds from the east or northeast moderate.

Fire Seasonality

From the 20th century record, there are similar numbers of human-caused and lightning-caused fires (42 human-caused, 31 lightning, and 5 unknown). The largest number of fires (55) are in the Class A size (0-.1 ha), with 7 Class B (0.1-4 ha), 5 Class C (4-40 ha), 5 Class D (40-120 ha) and 6 Class E (120-400 ha). There are no fires exceeding 500 ha in the record for this century. A total of 1920 ha are known to have burned, and most of the area burned in 12 escaped slash fires. The fires are confined to summer and autumn months (Figure 5). The big fires (Class B-E) are skewed somewhat to the late summer, probably because slash burns were historically ignited in the autumn. Of the 16 lightning fires dated to month and day, 10 occurred in July, with one in June, 3 in August, and 2 in September, so that the mode of the distribution of ignition is in mid-summer. Although none of the 20th century lightning ignitions grew exceptionally large, fires previous to that time may have smoldered for weeks before a severe fire weather event (east winds) allowed them to grow to considerable size. Based on these data, a 4-month fire season (July, August, September, and October) appears to occur in the Bull Run watershed.

The fire cycle model produced results comparable to earlier simulation results found by Agee (1991) for the Wind River (Figure 5) across the Columbia Gorge from Bull Run, although the Bull

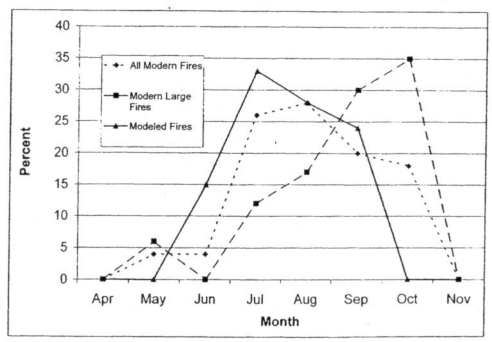

Figure 5. Proportional seasonal distribution of twentieth century fires. Modern fires are those within the watershed, and large modern fires are those exceeding 0.1 ha in size. Modeled fires are for the Wind River area (just north of Bonneville in Figure 1) and are for fires exceeding 1 ha in size.

Run had slightly fewer ignitions. The model runs on 20th century weather records, and results roughly parallel the actual seasonal distribution of lightning fires for the Bull Run. As this model does not simulate weather for October, no fires were generated for that month, but lightning and ignition could occur then. With favorable burning conditions known to occur, given the number of debris burn-caused fires in October, this month should also be considered part of the significant fire season. These results apply to the 20th century record, although it is likely that similar patterns of mid- to late-summer fires occurred in past centuries, as had been documented farther south in the Oregon Cascades (Olson 2000).

Discussion

The Bull Run watershed appears to have a high-severity fire regime characterized by infrequent fires that are largely stand replacement events. As the events are identified from interpretation of age classes, several closely-spaced fires could be interpreted as one fire. From the standpoint of current issues, whether each identified event is one fire, or perhaps more than one fire clustered at nearly the same time, is not of paramount importance.

The overall natural fire rotation for the Bull Run (347 years) is quite long, although shorter than the 465 year NFR calculated for the Mount Rainier area (Hemstrom and Franklin 1982). The Mount Rainier forests are primarily in the Pacific silver fir zone, in contrast to the predominantly western hemlock zone forests of the Bull Run. The periods of large fire events (particularly the ca. 1493 event) corresponds to similar periods identified elsewhere in the coastal wetter portions of western Oregon and Washington as times of large fires (Franklin and Hemstrom 1981, Yamaguchi 1993, Agee 1993, Gray and Franklin 1997). One hypothesis for these clustered dates (Agee 1993) is that these were times of sunspot minima associated with periods of lower than normal solar activity (Stuiver and Quay 1980). These global cooling periods may be linked to changes in the factors associated with large fire events in more recent times in the wetter portions of the Pacific Northwest: drought, lightning activity, the occurrence of east winds, or less summer onshore flow of moist air. We do not understand these linkages well, or linkages between fires and other episodic but potentially catastrophic disturbances.

To date, there is no evidence that the major fire events in the Bull Run are closely linked to wind, earthquake or volcanic activity. A massive forest fire ca. 1700 AD has been identified in the eastern Olympic Mountains of Washington (Fonda and Bliss 1969, Henderson et al. 1989) and was previously attributed to unusual lightning activity, east winds, or other such phenomena (Agee and Flewelling 1983, Agee 1993). Recently, a major historical earthquake that occurred between the growing seasons of 1699 and 1700 has been documented along the Oregon-Washington coastline from tree-ring records (Yamaguchi et al. 1997), and it corresponds to a major tsunami that hit the coast of Japan on January 26, 1700. Substantial "quakethrow" of timber may have been associated with this estimated magnitude 9 earthquake occurring at a time when low elevation soils were wet. Subsequent drying of the leaf and branch debris might have created continuous fuel over portions of the Olympic Mountains, which subsequently may have ignited.

Mount St. Helens, roughly 100 km to the north of Bull Run, had a major eruption in 1480, but this appears to have killed forest primarily to the northeast of the volcano (Yamaguchi 1993). Although the eruption year is close in age to the single largest fire event in the Bull Run, heat or wind effects from this eruption are unlikely to have affected forests so far to the south. A massive windthrow from strong east winds channeled down the Columbia Gorge during winter might also create additional fuels that might drive a watershed-wide fire. Sinton (1996) noted a 3 yr occurrence frequency of winter winds and temperatures that are associated with windthrow in the Bull Run, but all of the events of the last century affected isolated patches of forest averaging 5-10 ha in size. At least four fire study plots provided evidence that historical windthrow was followed by a small, patchy burn some years later, allowing shade-intolerant Douglas-fir to establish amidst a canopy of Pacific silver fir or western hemlock. The true fir and hemlock showed growth releases after the windthrow and these trees were missed by the subsequent patchy fire.

The forest ecosystems of the Bull Run appear to be good examples of nonequilibrium landscapes, where ecosystems in "normal" times do not exhibit much fire activity. Although the "abnormal" times may be widely separated in time and perhaps of short duration, they have major impacts on the forests we see today. The legacy effects enabled by the long life of Douglas-fir allow species composition and structural effects of a disturbance to be recognizable over much of a millennium. The vast majority of forests in the Bull Run have been produced by a handful of past fires that range back to 750 years before present, and the current species composition and structure are still very much influenced by the trees that established after these events of antiquity. Although some of the watershed in the lower elevation west end has burned multiple times over the last 500 years, about two-thirds of the watershed has avoided fire for the last 500 years.

Across the Pacific Northwest, the Pacific silver fir zone, as a cooler, moister forest type, has longer fire return intervals than the western hemlock zone (Agee 1993). Yet in the Bull Run, the Pacific silver fir zone has a shorter natural fire rotation. This pattern appears to be linked to the spatial distribution of the higher elevation Pacific silver fir forests around the rim of the watershed, which appears to be susceptible to incursion of fires from drier, low elevation areas on the surrounding landscape. The fire season tends to concentrate in late summer, and as in other regional areas, large fires tend to be associated with east winds of low humidity and sometimes high velocity (Cramer 1957). September and October are the dry season months with the highest frequency of east winds.

When fires occur in the Bull Run, they tend to be high-severity events. The three independent sources of data analyzed (age classes and aerial photographs) consistently identified the major fire severity class as "high"; nevertheless, some residuals can be found within high-severity portions of past fires. Moderate- and low-severity burning that leave significant residual tree canopy occurred primarily around the margins of the burns, and in riparian zones within the burn. Farther south, in a moderate-severity fire regime, Morrison and Swanson (1990) showed less that one-third of the landscape burned with high-severity fire, in contrast to the roughly two-thirds or more of the landscape at the Bull Run.

The fire regime of the Bull Run differs from those north and south. To the north in the Columbia Gorge, moderate-severity fire regimes are more common. The 1991 Falls fire near Multnomah Falls, several km north of the Bull Run watershed, shows a classic moderate-severity fire pattern (personal observation, J.K. Agee). The Bull Run has a fire regime more similar to the wetter forests at Mount Rainier and in the Olympic Mountains because of its precipitation regime. Major storm tracks drop two to three times as much precipitation in the Bull Run as in the Columbia Gorge directly to the north or in portions of the Clackamas River drainage directly to the south of the Bull Run (Figure 1, Figure 2). This high precipitation affects the moisture content of dead fuels and live foliar moisture through the dry season, often enough to extinguish fires that may enter these areas. It is not surprising that the two oldest patches of forest are in the wetter central portion of the watershed that receive >300 cm of annual precipitation. The gradient in fire severity in the west Cascade Mountains from northern Washington to southern Oregon is not a monotonic gradient.

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