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Refining Mixed-Severity Fire Regimes in the Rocky Mountain Forest District

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Abstract

We have used tree rings to reconstruct the fire history of 10 stands dominated by large-diameter western larch, Douglas-fir, and ponderosa pine trees. All study sites were in the Montane Spruce (MS) and Interior Cedar Hemlock (ICH) biogeoclimatic zones in the Rocky Mountain Forest District. Each stand was structurally complex with an upper stratum of veteran trees that were >200 years old.

We developed 13 new site-specific ring-width chronologies, six for Douglas-fir, five for western larch and two for ponderosa pine and one regional chronology for each species. These chronologies were used to visually and statistically crossdate disks with fire scars to ensure fire scar dates were accurate at an annual level of resolution. The Douglas-fir, western larch and ponderosa pine chronologies were up to 323, 355 and 515 years in length, respectively. All chronologies had significant inter-annual variation and were significantly correlated over the period from 1750-2004, indicating the common influence of regional climate.

The 77 fire scar samples from nine of the 10 study sites yielded 204 fire scars and 70 unique fire dates from 1567 to 1944. Scars were recorded at only one site for 59 of 70 fire years. Notable years in the fire record occurred in years when a large number or percent of trees were scarred and fires scarred trees at more than one site. The highest scar frequencies were in 1720 and 1889, when 60% and 28% of recorder trees were scarred at three different sites. Regional fires, fires that caused scars at two or more sites, burned in 12 years from 1652 to 1922.

For individual sites, the fire scar records ranged from 177 to 470 years and included 13 to 37 fire scars, which represented four to 14 fire intervals. The Weibull median probability intervals (WMPI) ranged from 13.8 to 32.4 years and two to 102 years separated successive fires at each site. The current fire-free intervals ranged from 61 to 121 years and generally exceed the historic range of variation for the study stands, indicating a change to the fire regime during the past century. At the regional scale, only two fires scarred trees during the 65 years from 1940 and 2004. Over the last three centuries, the highest fire frequencies and shortest intervals between fires were during the settlement era from 1870 to 1939. Prior to the 1870, mean fire intervals significantly longer than fire intervals during the settlement era, likely reflecting the influence of land-use and climate variation on fire frequency.

To extrapolate results from individual stands to the surrounding landscape requires knowledge of the abundance and distribution of the forest types in which we find evidence of mixed-severity fires. Our GIS determined that structurally complex forests currently represent c. 10% of forest in the ICH and MS zones of the Invermere and Cranbrook TSAs. These results provide important background information to facilitate a statistically robust regional analysis of fire history at the landscape scale.

Refining Mixed-Severity Fire Regimes in the Rocky Mountain Forest District

Background and Introduction

Measures of ecological sustainability often include individual structural elements, such as large, green trees, snags, and downed logs or assemblages of elements, such as forest structure classes. In order to plan for long-term sustainability of these attributes predictive models are developed encompassing both spatial and temporal elements of attribute frequency, intensity, and landscape location. Improving upon the predictive capabilities of these models requires an understanding of the historic relationship between structural attributes and natural disturbances, specifically fire.

Fire regimes are described by a range of frequency, intensity, and effects metrics (Agee 1993, 1998, Brown 2000). Within the Invermere TSA, eight separate Historic Natural Fire Regimes have been described and mapped (Blackwell et al. 2003) potentially providing a useful baseline from which further analysis of the relationships between disturbances processes and resulting forest patterns can be conducted. This relationship has been quantified through studies by Gray and others (Gray 1999, Gray et al. 2002) for the dry forests dominated by ponderosa pine, Douglas-fir, and western larch.in which low-severity high-frequency fires dominated the historic fire regime. Those studies have provided interim data linking landscape-oriented stand structure characteristics to fire regime characteristics. Less research, however, has occurred in the adjacent mixed-severity fire regimes of the Invermere TSA.

A preliminary, FIA-funded project, carried out in 2004-5 provided initial statistics for describing mixed-severity fire regimes for the lower elevation and warmer portions of the ICH and MS biogeoclimatic zones in the Trench. The initial work was confounded by difficult winter field conditions. This lead to the collection of fewer fire scar samples than was initially planned and we were unable to collect any increment cores for crossdating purposes. Analysis of obtained data suggested there may be an important climate influence on the mixed-severity fire regimes that, with additional analysis, may also apply to the adjacent stand-replacement fire regimes. Additional sampling of fire scars plus the development of regional-scale, species-specific chronologies will help fill in three important aspects of the fire regime: (a) temporal range, (b) spatial extent, and (c) relationship with climate variation at annual to decadal time scales.

Purpose and Objectives

Our purpose was to refine metrics of historic fire activity in areas of 10 drainages currently modeled as mixed-severity fire regimes and to discern the influence of regional climatic patterns on the historic fire regime. This work provides the baseline required to assess the historic range of variability for a variety of stand attributes, including large old trees, snags, and downed logs. Additionally, site reconnaissance will be carried out in order to increase the geographical variability of sampling to represent montane forests at the landscape scale. This data will be used as additional input data to the predictive stand structure model being developed by Tembec and Interior Reforestation (FIA project 4389004, Stand Structure and Habitat Modeling).

The information from this project can be incorporated into Tembec and Canfor's Sustainable Forest Management Plans in the following ways:

1) Data on the historic range of variability in the abundance and distribution of stand attributes, including large old trees, snags, and downed logs, can be used to help develop and/or assess targets in the Criteria and Indicator system for these attributes. For example, current targets in Tembec's SFMP for down logs are based on data from current condition in forested stands, which may not be the same as the condition under historic disturbance regimes.

2) Data on historic fire regimes will allow an evaluation of whether current rotation ages and structural retention fall within the range of historic variability. This is especially important for stands with low and mixed severity fire regimes. In these stands, age class is not a good indicator of old growth condition, because old-growth stands were created and maintained by frequent low and moderate severity fires, interspersed with less frequent, higher severity fires, and not by infrequent high severity fires, followed by development undisturbed by fire over a period of time. Thus, in order to create or maintain old growth stands in these stand types, data on the abundance of large trees, snags, and CWD is required, so that prescriptions and stand entries can be tailored to maintain these attributes. In the higher elevation stands where frequent fires were the main disturbance regime, data on the frequency of historic fires can be used to calculate how much old growth was present under historic disturbance regimes. This can be used to assess current requirements for old growth stands under biodiversity planning, to determine if these requirements are in fact compatible with historic disturbance regimes.

3) Data on historic fire regimes can be incorporated into the Stand Structure model, which will result in more accurate predictions of historic variability in stand structure classes across large landscapes. This can be compared to current conditions, to assess how far current conditions depart from historic conditions. This in turn is one measure of ecological risk. If current conditions depart severely, it suggests that biodiversity may not be maintained under current practice, and changes are required.

Objectives

- To collect increment cores and develop regional chronologies for ponderosa pine, western larch and Douglas-fir to be used for regional climate analysis and to facilitate crossdating of fire scar samples to ensure the fire record is accurate at an annual resolution.
- To collect and analyze additional fire scar data from candidate sample sites in 10 drainages.
- To provide additional fire frequency and interval information to be incorporated into the predictive structure class model.
- To identify additional sampling sites for future sample collection.

Study Area

Our goal was to sample stands in the Montane Spruce (MS) and Interior Cedar Hemlock (ICH) biogeoclimatic zones in the Rocky Mountain Forest District for which the historical fire regime was likely of mixed severity. We identified and sampled 10 stands dominated by large-diameter western larch, Douglas-fir, and ponderosa pine trees for fire scars (**Table 1**). Each stand was structurally complex with an upper stratum of veteran trees that were >200 years old. All sites were on slopes with south-facing aspects except Bitten Lake which was a relative flat with an east aspect and the Semlin Creek site with a north aspect. Increment cores were sampled from canopy trees at seven fire history sites, plus two additional sites near Lumberton and Perry Creek.

Table 1. Fire scar disks and increment cores sampled from the 12 study sites.

Study Site	Search Area (ha)	Fire Scarred Disks (n)	Increment Cores (species, n)
Spring Creek	100	21	Douglas-fir (25), western larch (25), lodgepole pine (20)
Bittern Lake	20	9	NA
Jubilee Mountain	30	6	Douglas-fir (15)
Fenwick Creek	100	8	Douglas-fir (10)
Jack Creek	30	6	NA
Bootleg Creek	30	10	Douglas-fir (15), western larch (15), Ponderosa pine (15)
Perry Creek	NA	NA	western larch (15)
Dublin Creek	40	9	western larch (15)
Palmer Bar	100	11	Douglas-fir (10)
Semlin Creek	50	6	NA
Lumberton	NA	NA	western larch (10)
Etna Creek	50	9	Douglas-fir (20), western larch, Ponderosa pine (15)

Methods

Chronology Development

Ten to 25 dominant trees of Douglas-fir, western larch, Ponderosa pine and/or lodgepole pine at each sample site were cored to produce species-specific master ring-width chronologies. Large trees with healthy crowns and boles were selected to maximize the length of the chronology and to ensure that the information gained reflected community-level environmental effects, specifically climate influences, rather than tree-to-tree interactions. One increment core was extracted at breast height from each tree and species and dbh were recorded. All increment cores were mounted on wooden supports and sanded with a belt sander and/or palm sander using successively finer sand paper to 400 grit (Stokes and Smiley 1968).

The increment cores from canopy dominant trees were visually crossdated and the rings were measured to the nearest 0.01 mm using a Velmex bench interfaced with a computer. To ensure that calendar years were accurately assigned to each ring, the resulting ring-width series were statistically crossdated using the program COFECHA

(Holmes 1986). COFECHA compares each tree-ring series against all other series in each site to identify errors in tree-ring dates. Properly dated and highly correlated ring-width series were combined in master ring-width chronologies to represent average tree growth at each site (Fritts 1976).

The computer program ARSTAN (Cook, 1985) was used to standardize the ring-width series, then combine the series into standard and residual chronologies for each species and site. ARSTAN corrected for the age-related trend inherent to ring-width series by standardizing (or detrending) the series from individual trees by fitting either a modified negative exponential curve, a linear trend line of negative slope, or a horizontal line through the mean of the measured ring-width series. The series were then divided by the value of the curve and averaged together to produce the standard chronology for each site. Departures from the standard chronology or variability from average tree growth were represented by the residual chronology.

In this study, we used marker ring analysis and correlations to evaluate common variation among chronologies. A key element for crossdating ring-width samples from many sample sites is the degree to which chronologies from different sites exhibit common growth variability. If the chronologies in a network are similar, it indicates that tree growth is primarily controlled by a common limiting factor such as climate. If the chronologies are dissimilar, it indicates that either tree growth is not primarily controlled by a common limiting factor or that the common factor is highly variable between sites. Differences in fire history may explain potential dissimilarities among sites in this study.

Individual wide or narrow "marker" rings that are temporally synchronous within and between chronologies suggest common environmental factors influence tree growth. In this study, marker rings were defined as those years when the normalised ring-width value of the residual chronology is more than one standard deviation from the chronology mean. All positive and negative marker rings in each site- and species-specific chronology were listed. For each species we identified marker rings between 1750 and 2004 that occurred in ≥60% of chronologies. These common marker rings were compared between species as well.

In a second test comparing chronologies, correlations were calculated between the site-specific and regional chronologies for each species. All pairwise comparisons were made using the standard and residual chronologies. Correlation coefficients were calculated for the 255 years from 1750 to 2004, the period common to all chronologies.

Fire History

At each study site, we collected stem cross-sections from six to 11 trees, snags and stumps with multiple, external basal scars. The number of samples per site varied depending on the density of fire-scarred material and whether it could be sampled safely. At Spring Creek, many scarred trees were lodgepole pine that had been killed by mountain pine beetle. Preliminary assessment of the disks from Spring Creek indicated that the trees were relatively young with few tree-rings limiting the potential of successful crossdating; therefore, we sampled extra trees at this site for a total of 21 disks.

Cross-sectional discs were cut at height 5 to 160 cm from the ground. In total, we collected 77 scarred samples. Fire scars were differentiated from scars caused by mountain pine beetle or other disturbance agents based on scar morphology, presence of charcoal and fungal stains in the wood (McBride 1983, Dietrich and Swetnam 1984). Basal scars that were triangular in shape, with all bark missing from the face of the scar were considered fire scars. Often these trees had multiple scars and charcoal was present. The wood samples were examined to determine if they were stained by fungi. Red stain generally indicates fire, whereas blue stain indicates disturbance by mountain pine beetle. In this study we report only scar dates caused by fire; however some trees had been disturbed or killed by mountain pine beetle as indicated by the blue stain in the wood closest to the bark.

Samples were dried for approximately 5 to 8 weeks. Dried discs were then prepared for analysis using a planer, belt sander and/or palm sander with successively finer sand paper to 600 grit (Stokes and Smiley 1968).

Cross-sectional disks from live trees were visually crossdated by matching the negative marker rings from our site- and regional-scale species-specific chronologies. In the case of dead trees, the rings along one radius of each disc were measured to the nearest 0.01 mm using a Velmex bench interfaced with a computer. To ensure that calendar years were accurately assigned to each ring, the resulting ring-width series were statistically crossdated using the program COFECHA (Holmes 1986). COFECHA compares each tree-ring series against all other series in each site to identify errors in tree-ring dates due to false and missing rings. In the east Kootenay region, mid- to late-growing season drought may cause false rings and, during extremely dry conditions or during multiple-year droughts, rings may be incomplete or missing from the radius. The ring-width series of samples from dead trees and stumps were crossdated against the standard chronologies from live trees to determine the calendar year of the outer-most ring on the disc and estimate the year of death. Once accurate calendar years were assigned to individual rings, the date associated with each fire scar was determined.

When the tip of a fire scar is clearly visible, its position within the annual tree ring approximates the season in which the fire burned. In this study, the majority of scars were dormant-season scars, meaning the scar tips were along the boundary between two annual rings. Assigning a single year to a dormant-season scar is difficult because the scar results either from fires that burn in the fall (year x), after the annual ring has formed, or in early spring (year x+1), before the new ring begins to form. Modern fire records indicate that fires started by lightning are more common in late-summer or fall than in the spring; however fire may have been used in spring by First Nations. We used the following criteria to determine whether dormant-season scars resulted from spring or fall burns:
(a) We considered all fire scars at a given site for a given year. If the seasonality (fall or spring) of at least one scar was certain, then we reported all dormant-season scars to be consistent with that observation. For example, at Bittern Lake, earlywood scars on lodgepole pine and Douglas-fir indicated a spring fire in 1890, while the scars on adjacent larch were dormant-season scars positioned between the 1889 latewood and 1890 earlywood. Assuming the secondary growth of larch initiated after the other two species, which explains the observed discrepancy among scar positions between trees, the 1889 dormant-season scars were recorded as spring fires in 1890.

(b) If seasonality was not certain, then dormant-season scars were assigned to the calendar year of the fall, consistent with the modern fire record.

We have used fire scar dates to quantify the intervals between fires. Composite fire intervals for each site were compiled using the computer program FHX2 (Grissino-Mayer 2001). Fire intervals were analysed using all fire scars and a more conservative subset of the data that included fire years in which two or more recorder trees were scarred, representing fires of greater magnitude and impact at the site. Fire intervals were computed for scar-to-scar dates; the interval between stand initiation and the first fire scar and the interval between the last fire scar to the present were excluded. For each site, we analysed the full fire record and the period from 1828 to 2004, which was common to all study sites. The minimum, maximum and Weibull median probability interval (WMPI) was calculated from fire interval distributions. WMPI is a measure of central tendency of the Weibull distribution in which half of the fire intervals in the modelled frequency distribution are longer than WMPI and half are shorter than WMPI.

We combined the fire history data from individual sites to create a regional composite fire chronology. At the regional scale, we calculated minimum, maximum and Weibull median fire intervals for the full record and for fires that burned at least two trees and ≥10% and/or ≥25% of trees. The latter analyses identified fire years with more severe impacts on the landscape by scarring a large proportion of trees. To test for changes in the fire regime over time, we compared fire interval data over four consecutive periods: 1940-2004 (n=65 years), 1870-1939 (n=70 years), 1800-1869 (n=70 years), and 1730-1799 (n=70 years). These periods represent the fire suppression era, Euro-settlement era, and two periods of pre-settlement, respectively. Comparison of fire regimes over these periods provides a preliminary assessment of human impacts on the fire regime in the study area over the past 150 years.

Regional-Scale Forest Composition and Structure

Based on the results from this study, potential study sites are structurally complex stands with ≥2 age classes and multiple canopy strata dominated by Ponderosa pine, western larch and Douglas-fir veterans. These structurally diverse stands are most likely to have abundant coarse woody debris and evidence of past fires that can be reconstructed using dendroecological methods. To understand the spatial distribution of these types of stands, we have used a geographical information system (GIS) to stratify the landscape according to historic land use and biophysical attributes. Specifically, forest polygons were queried for the following attributes: biogeoclimatic zone (ICH and MS zone), slope aspect (south-western and north-eastern), and forest cover attributes (canopy layer 1 older than 200 years and/or presence of veteran trees). Suitable forest polygons with an area ≥3.0 ha were identified as potential study sites for landscape- to regional-scale analysis of fire history in the ICH and MS zones within the study area.

Results

Species-Specific Chronologies

Chronology Characteristics

We have developed 13 new site-specific ring-width chronologies, six for Douglas-fir, five for western larch and two for ponderosa pine (**Table 2, Figure 1**). A regional chronology was developed for each species by combining high-correlated samples from different study sites. The Douglas-fir chronologies ranged from 261 to 323 years in length (mean±standard deviation = 298±25years). The western larch chronologies were 260 to 355 years (331±36 years) and the ponderosa pine chronologies were the longest ranging from 305 to 515 years (445±121 years). We were unable to develop a chronology for lodgepole pine as the trees within our study sites were generally young with little variation in ring-widths or had been killed by mountain pine beetle, yielding poor correlations between cores within and between sites.

Mean sensitivity and standard deviation values provide a measure of the year-to-year variability in the ring-width chronologies (Fritts 1976, **Table 2**). The mean sensitivity and average standard deviation values were similar among the three species. Average first-order autocorrelation coefficients (AC(1)) were greater for the western larch chronologies than for the Douglas-fir and ponderosa pine chronologies. The greatest percentage of missing rings was for the ponderosa pine chronologies, followed by western larch. Fewer rings were missing in the Douglas-fir chronologies. This documented occurrence of missing rings indicates that visual and statistical crossdating are essential for determining the exact calendar years of individual rings and fire scars.

Table 2. Summary characteristics for tree-ring chronologies in the Rocky Mountain Trench, British Columbia. Mean length is the average number of years in each core in the chronology. Descriptive statistics include mean sensitivity (mean sens.), standard deviation (std. dev.) and first order autocorrelation coefficients (AC(1)).

Species Site	No. trees	First year	Last year	No. years	Mean length	Mean sens.	Std. dev.	AC (1)	Missing (%)
Douglas-fir									
Spring Creek	22	1727	2004	278	189	0.14	0.17	0.50	0.12
Jubilee Mountain	15	1744	2004	261	169	0.26	0.29	0.40	0.07
Fenwick Creek	10	1700	2004	305	192	0.16	0.24	0.61	0.00
Bootleg Creek	23	1690	2004	315	246	0.18	0.22	0.47	0.11
Palmer Bar	7	1723	2004	282	179	0.21	0.31	0.61	0.00
Etna Creek	18	1682	2004	323	200	0.21	0.24	0.47	0.03
Regional	76	1682	2004	323	204	0.17	0.18	0.35	0.08
Average				298	197	0.19	0.24	0.49	0.06
Western Larch									
Bootleg Creek	24	1656	2004	349	232	0.17	0.29	0.72	0.24
Perry Creek	15	1668	2004	337	244	0.14	0.21	0.67	0.16
Dublin Creek	13	1650	2004	355	216	0.15	0.21	0.62	0.09
Lumberton	11	1745	2004	260	153	0.18	0.27	0.66	0.00
Etna Creek	10	1674	2004	331	211	0.19	0.29	0.66	0.19
Regional	63	1650	2004	355	215	0.13	0.20	0.65	0.14
Average				331	212	0.16	0.25	0.66	0.14
Ponderosa Pine									
Bootleg Creek	15	1701	2004	305	245	0.17	0.19	0.43	0.05
Etna Creek	14	1490	2004	515	286	0.22	0.27	0.47	0.45
Regional	21	1490	2004	515	259	0.21	0.24	0.38	0.17
Average				445	263	0.20	0.23	0.43	0.22

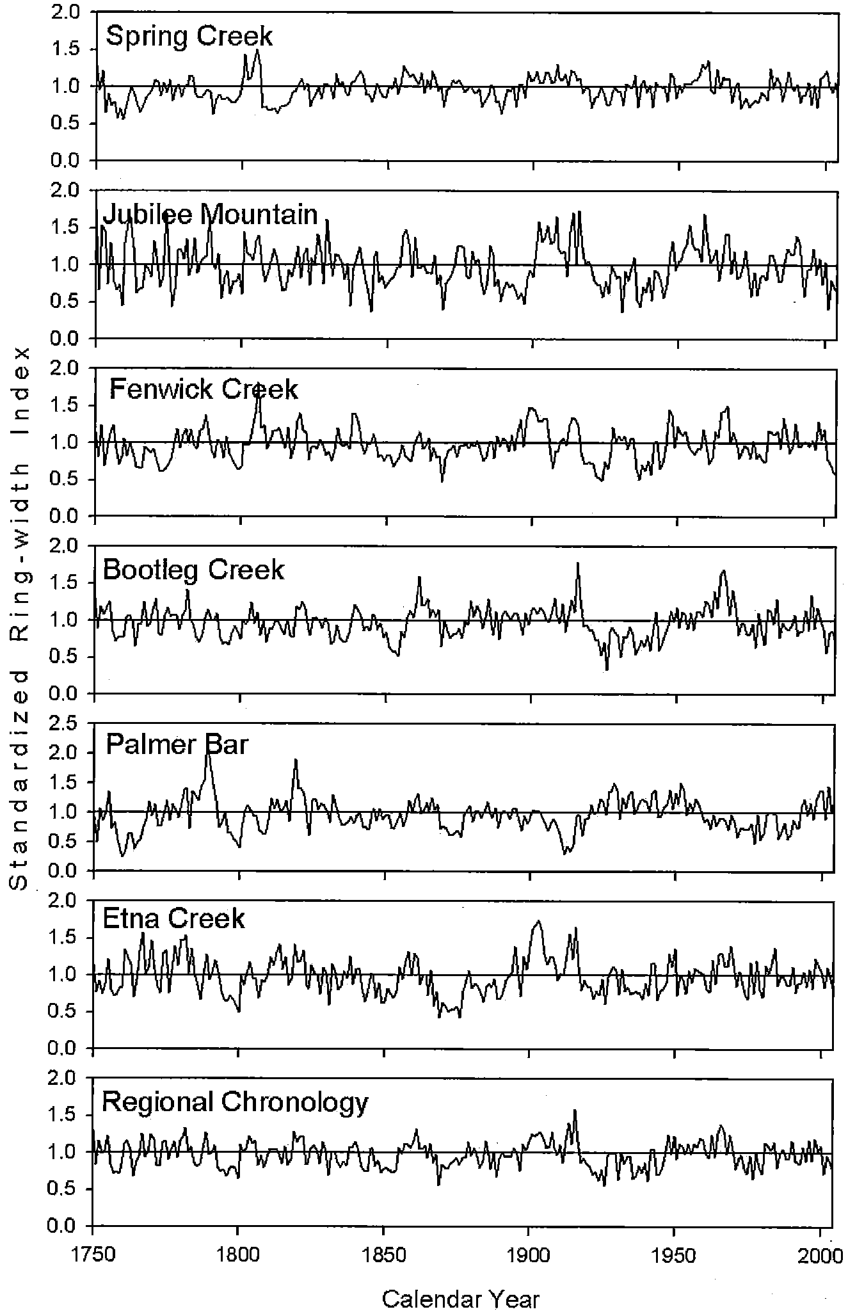

Figure 1a. Standardized Douglas-fir chronologies for six study sites and the region. Study sites are arranged from north (top) to south (bottom) in the study area. The horizontal line represents the long-term average ring-width. Departures above the line indicate years of above-average growth (wider rings) and departures below the line indicate years of below-average growth (narrower rings).

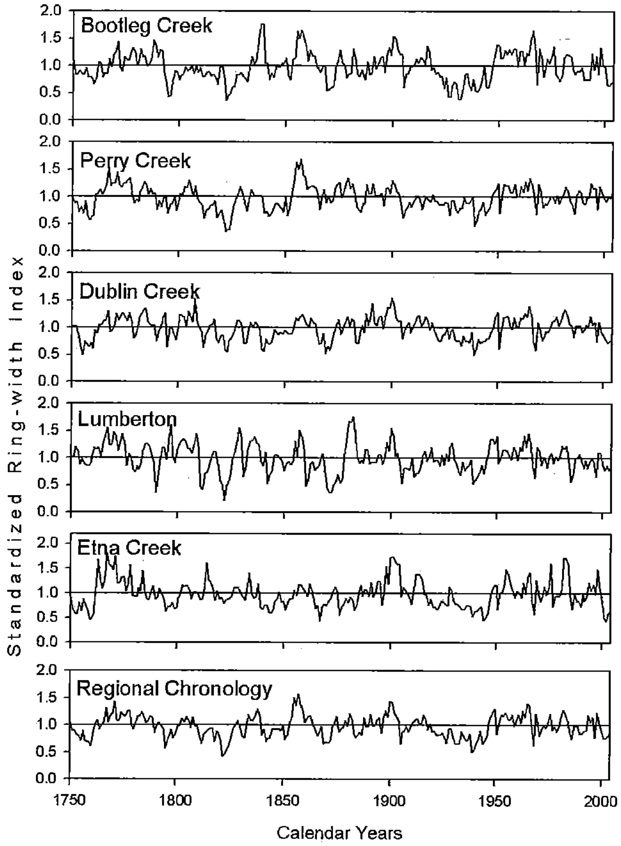

Figure 1b. Standardized western larch chronologies for six study sites and the region. Study sites are arranged from north (top) to south (bottom) in the study area. The horizontal line represents the long-term average ring-width. Departures above the line indicate years of above-average growth (wider rings) and departures below the line indicate years of below-average growth (narrower rings).

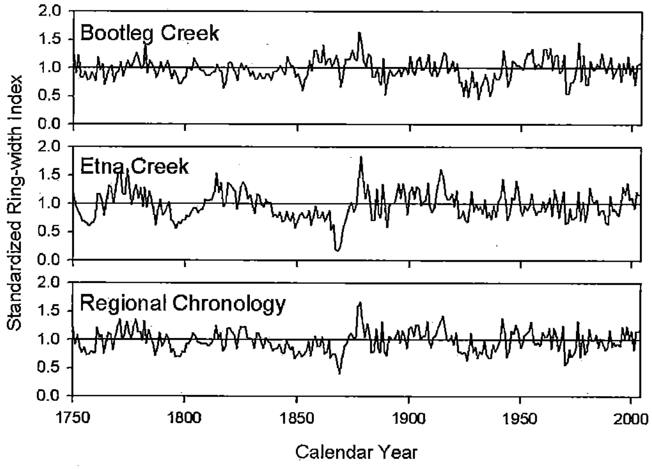

Figure 1c. Standardized ponderosa pine chronologies for six study sites and the region. Study sites are arranged from north (top) to south (bottom) in the study area. The horizontal line represents the long-term average ring-width. Departures above the line indicate years of above-average growth (wider rings) and departures below the line indicate years of below-average growth (narrower rings).

Marker Rings

Forty-nine positive and 51 negative marker rings were identified in the 13 site- and species-specific chronologies between 1750 and 2004 (**Figure 2**, **Table 3**). Western larch had more positive and negative marker rings (n = 24 for both), than Douglas-fir (n = 18 positive and 22 negative marker rings) or ponderosa pine (n = 19 positive and 17 negative marker rings). Ten positive marker rings were common to two species: 1767, 1771, 1819, 1888, 1898, 1900, 1942, 1963, 1969, and 1981. All three species had a positive marker ring in 1998. In contrast, eight negative marker rings were common to two species: 1764, 1823 1831, 1883, 1967, 1968, 1971, and 1977. All three species had negative marker rings in 1869 and 1944. Both positive and negative marker rings are essential for visually crossdating samples to ensure the ring dates, fire scar dates and tree ages are accurate at an annual level of resolution.

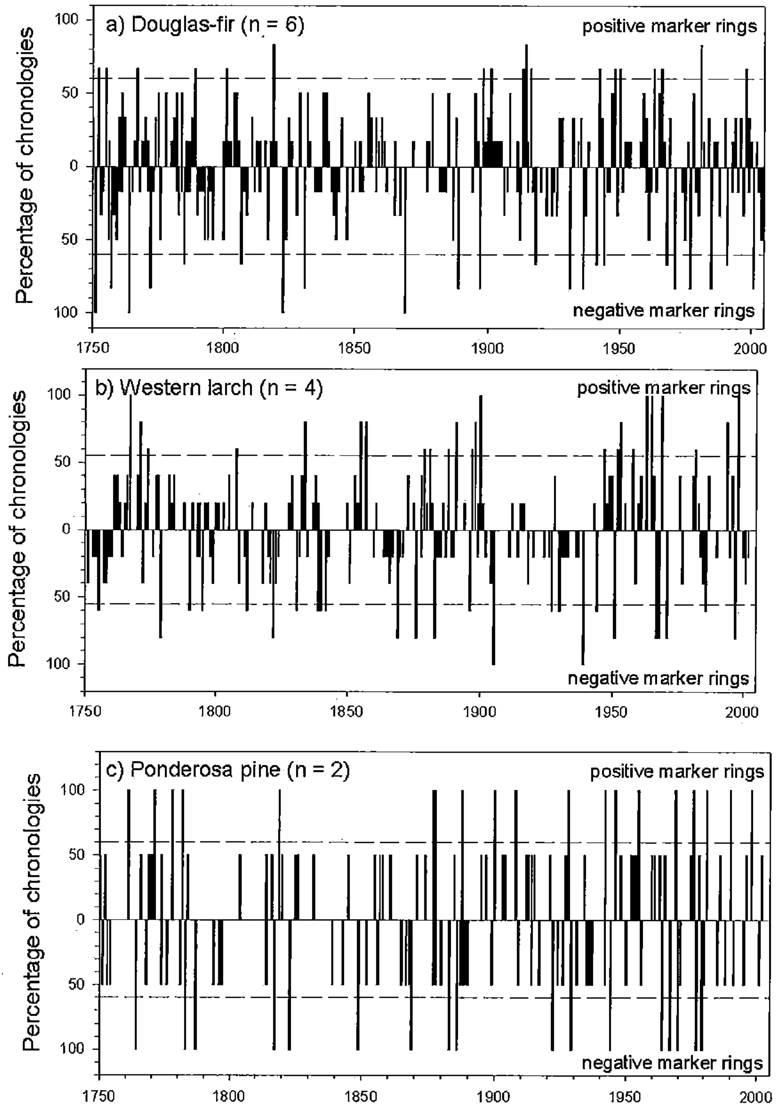

Figure 2. Percentage of the residual chronologies which show a positive (Z>1) or negative (Z<1) marker ring in each year. Years when >60% of chronologies (dashed line) have a marker ring are listed in Table 2.

Table 3. Positive and negative marker rings that were common among chronologies between 1750 and 2004. Bold years indicate years when two or three species had common marker rings. Counts of marker rings are provided in the bottom row (N = all marker years, n = each species).

Positive Marker Rings			
Year	Douglas-fir	Western larch	Ponderosa pine
1752	1752		
1755	1755		
1761			1761
1767	**1767**	**1767**	
1771		**1771**	**1771**
1774		1774	
1778			1778
1782			1782
1789	1789		
1801	1801		
1808		1808	
1819	**1819**		**1819**
1834		1834	
1855		1855	
1857		1857	
1877			1877
1878			1878
1879		1879	
1881		1881	
1888		**1888**	**1888**
1891		1891	
1897		1897	
1898	**1898**	**1898**	
1900		**1900**	**1900**
1901	1901		
1908			1908
1913	1913		
1914	1914		
1916	1916		
1928			1928
1942	**1942**		**1942**
1946			1946
1947		1947	
1948	1948		
1950	1950		
1952		1952	
1953		1953	
1955			1955
1958		1958	
1963	**1963**	**1963**	
1965		1965	
1966	1966		
1969		**1969**	**1969**
1976			1976
1981	**1981**		**1981**
1982		1982	
1990			1990
1994		1994	
1998	**1998**	**1998**	**1998**
N = 49	n = 18	n = 24	n = 19

Negative Marker Rings			
Year	Douglas-fir	Western larch	Ponderosa pine
1751	1751		
1755		1755	
1757	1757		
1764	**1764**		**1764**
1772	1772		
1779		1779	
1783			1783
1785	1785		
1787			1787
1790		1790	
1795		1795	
1807	1807		
1812		1812	
1817			1817
1822		1822	
1823	**1823**		**1823**
1831	**1831**	**1831**	
1839		1839	
1840		1840	
1842		1842	
1849			1849
1869	**1869**	**1869**	**1869**
1876		1876	
1883		**1883**	**1883**
1886			1886
1889	1889		
1896		1896	
1897	1897		
1905		1905	
1918	1918		
1922			1922
1927		1927	
1929			1929
1930		1930	
1931	1931		
1936	1936		
1939		1939	
1941	1941		
1944	**1944**	**1944**	**1944**
1951		1951	
1964			1964
1967		**1967**	**1967**
1968	**1968**	**1968**	
1970			1970
1971	**1971**	**1971**	
1977	**1977**		**1977**
1979			1979
1985	1985		
1991	1991		
1997		1997	
2001	2001		
N = 51	n = 22	n = 24	n = 17

Correlations Between Chronologies

In general, the correlations were quite high ranging from 0.34-0.91, indicating common variation between chronologies from different sites (**Table 4**). Inter-site correlations were highest for ponderosa pine, followed by western larch. The correlations for Douglas-fir were lower, but statistically significant, except the standard chronologies for Palmer Bar versus Jubilee Mountain (**Table 4a**). Low correlations between sites likely reflect the influences of unique fire histories at the sites, rather than differences in local climate.

Table 4. Comparison of the site-specific and regional chronologies for (a) Douglas-fir, (b) western larch and (c) ponderosa pine for the period from 1750 to 2004 (n = 255 years). Correlation coefficients were calculated for standard (top, right) and residual (bottom, left) chronologies. Sites are arranged according to location from north (top, left) to south (bottom, right), followed by the regional chronology. Correlation coefficients are followed by probability values in parentheses. Italics indicate correlations that were not significant at the 0.05 level.

(a) Douglas -fir	**Spring Creek**	**Jubilee Mountain**	**Fenwick Creek**	**Bootleg Creek**	**Palmer Bar**	**Etna Creek**	**Regional Chronology**
Spring Creek		0.48 (<0.001)	0.38 (<0.001)	0.42 (<0.001)	0.16 (0.013)	0.34 (<0.001)	0.57 (<0.001)
Jubilee Mountain	0.46 (<0.001)		0.41 (<0.001)	0.50 (<0.001)	*0.12* *(0.064)*	0.48 (<0.001)	0.72 (<0.001)
Fenwick Creek	0.52 (<0.001)	0.45 (<0.001)		0.51 (<0.001)	0.20 (0.001)	0.51 (<0.001)	0.64 (<0.001)
Bootleg Creek	0.48 (<0.001)	0.51 (<0.001)	0.54 (<0.001)		0.22 (<0.001)	0.63 (<0.001)	0.88 (<0.001)
Palmer Bar	0.35 (<0.001)	0.41 (<0.001)	0.37 (<0.001)	0.58 (<0.001)		0.30 (<0.001)	0.35 (<0.001)
Etna Creek	0.41 (<0.001)	0.48 (<0.001)	0.49 (<0.001)	0.70 (<0.001)	0.58 (<0.001)		0.82 (<0.001)
Regional Chronology	0.60 (<0.001)	0.72 (<0.001)	0.64 (<0.001)	0.91 (<0.001)	0.67 (<0.001)	0.84 (<0.001)	

(b) Western larch	**Bootleg Creek**	**Perry Creek**	**Dublin Creek**	**Lumber-ton**	**Etna Creek**	**Regional Chronology**
Bootleg Creek		0.65 (<0.001)	0.56 (<0.001)	0.37 (<0.001)	0.56 (<0.001)	0.88 (<0.001)
Perry Creek	0.64 (<0.001)		0.74 (<0.001)	0.57 (<0.001)	0.66 (<0.001)	0.87 (<0.001)
Dublin Creek	0.55 (<0.001)	0.80 (<0.001)		0.58 (<0.001)	0.66 (<0.001)	0.82 (<0.001)
Lumber-ton	0.39 (<0.001)	0.56 (<0.001)	0.58 (<0.001)		0.36 (<0.001)	0.61 (<0.001)
Etna Creek	0.62 (<0.001)	0.55 (<0.001)	0.60 (<0.001)	0.44 (<0.001)		0.71 (<0.001)
Regional Chronology	0.88 (<0.001)	0.88 (<0.001)	0.82 (<0.001)	0.64 (<0.001)	0.74 (<0.001)	

(c) Ponderosa pine	**Bootleg Creek**	**Etna Creek**	**Regional Chronology**
Bootleg Creek		0.41 (<0.001)	0.74 (<0.001)
Etna Creek	0.61 (<0.001)		0.89 (<0.001)
Regional Chronology	0.86 (<0.001)	0.91 (<0.001)	

Fire History

Fire Record

The 77 fire scar samples from nine of the 10 study sites yielded 204 fire scars and 70 unique fire dates from 1567 to 1944 (**Figures 3 and 4**, **Table 5**). The fire scar disks from Semlin Creek had an unusually high incidence of missing rings, which prevented us from determining fire dates at an annual resolution. Therefore, the data from Semlin Creek were excluded from further analyses. Fire occurrence, indicated by the number of fire scars per year, has varied at decadal to century time scales (**Figure 3a**). At the landscape scale, the frequency of fires scars was greatest between 1850 and 1940, roughly corresponding to settlement by Europeans. Few fires have burned and scarred trees since 1944, corresponding with cessation of burning by First Nations, changes in land use with increased grazing and industrial forestry, and effective fire suppression. Prior to 1719, our dataset included fewer than 20 recorder trees (**Figure 3b**). Evidence of the oldest fires is lost through time as trees die and decay, which partly accounts for the decreased number of fire scars through time (Swetnam et al. 1999, Veblen 2003).

Scars were recorded at only one site for the majority of fire years (59 of 70, **Figure 3c**). Notable years in the fire record occurred in years when a large number of trees and/or a large percent of recorder trees were scarred and fires scarred trees at more than one site (**Figure 3**). The highest scar frequencies were in 1720 and 1889, when 60% and 28% of recorder trees were scarred and fires burned at three different sites. Similarly, fires burned at two sites in 1890, scarring nine trees (23% of recorder trees), and in 1869, scarring seven trees (20% of recorder trees). Fires in 1751 at Etna Creek and 1853 at Palmer Bar scarred eight trees or 42% and 24% of recorder trees, respectively, but there were no evidence that burning was wide spread in these years.

The majority of fires scarred only one tree within a site (48 of 85, **Table 5**). Fires in 1652 at Palmer Bar and Jack Creek were the first fires to scar trees at two or more sites in a single year. Regional fires, fires that formed scars at two or more sites indicating synchronous fires in the landscape, burned in 12 years from 1652 to 1922(**Figure 3c**).

Fire Intervals

The period of analysis and number of scars varied among individual sites (**Figure 4**, **Table 5**). Fire scar records were shortest for the three northern sites, Spring Creek, Bittern Lake and Jubilee Mountain. They ranged from 177 to 279 years and included 13 to 23 fire scars, which represented four to six fire intervals at each site. At the other six sites, the fire records ranged from 371 to 470 years and included 14 to 37 fire scars and six to 14 fire intervals (**Table 5**).

Fire intervals were calculated for both the full fire record for each site and the period from 1828 to 2004, which was common to all sites (**Table 5**). The full fire records provide a long-term perspective on fire history in the study area. For the full records, the median interval (WMPI) between fires ranged from 13.8 to 32.4 years. Two to 102 years separated successive fires at each site. With the exception of the 20th century fire-free period, the longest intervals between fires occurred early in each record. When considering only major fires that scarred at least two trees at each site, the number of fires decreased while the minimum, median and maximum intervals between fires increased. At three sites, only two or three major fires were evident in the fire scar record. Therefore, there was insufficient information to calculate the Weibull median probability interval for those sites (**Table 5**).

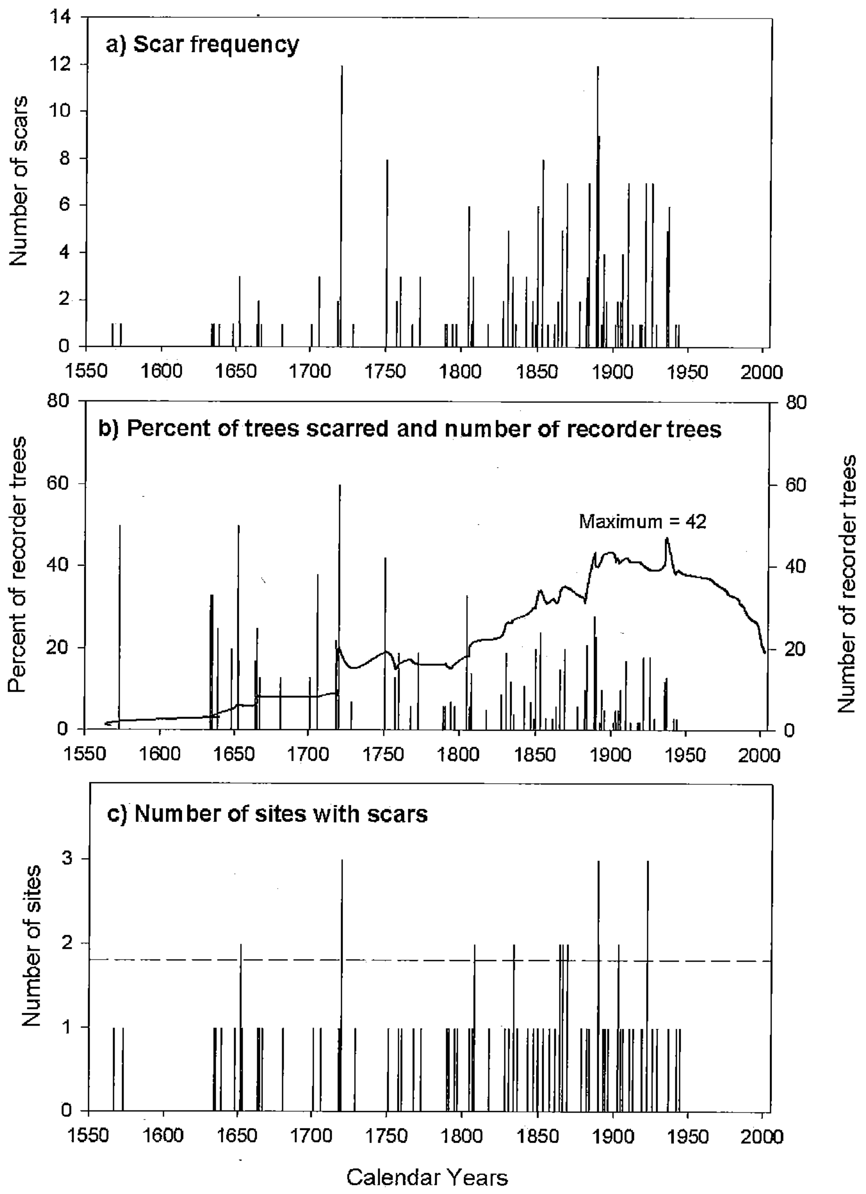

Figure 3. Fire scar record from 1550 to 2005 for nine study sites in the Rocky Mountain Trench. (a) The number of fire scars per year increases after c. 1800, partly due to increased sample depth (b). (b) Conversely, the percentage of recorder trees scarred per year decreases as the sample depth increases. (c) In the bottom graph, the dashed line separates local fires that scarred trees in only one site from major fire years in which two or three sites burned in the same year.