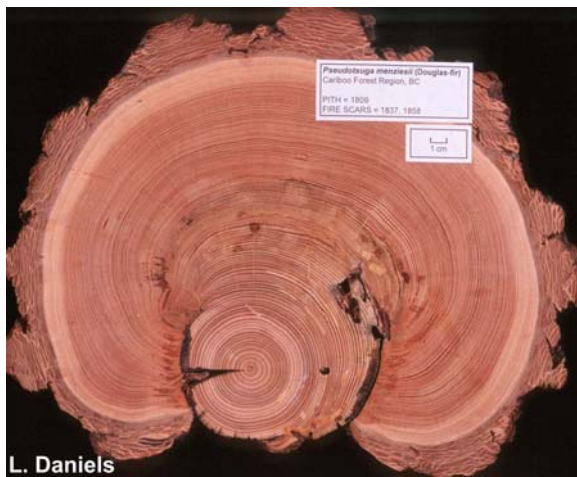# Climate-Fire-Vegetation Interactions in the Cariboo Forests: A Dendrochronological Analysis

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EXECUTIVE SUMMARY

Dendrochronological techniques yield high-quality data for reconstructing historical change in forests and quantifying temporal aspects of disturbance regimes. In this study, we used annual-resolution tree-ring data to investigate:
> (1) the influences of year-to-year climate variation on tree growth and fire occurrence, and
> (2) the impacts of fire on forest structure and dynamics in the Cariboo region of British Columbia.

We developed 14 new ring-width chronologies, six for Douglas-fir and eight for lodgepole pine. The chronologies were used to crossdate age and fire scar samples and to test for climate-tree growth relationships. Chronologies for both species were positively correlated with Williams Lake precipitation, indicating that wet (dry) summers result in wide (narrow) annual rings. The Douglas-fir chronologies were selected for climatic reconstruction since they were longer, exhibited more inter-annual variation, and had a stronger common signal between trees than the lodgepole pine chronologies. The Douglas-fir ring-width chronology from site 6 was combined with a ponderosa pine late-wood chronology from Chasm (provided by E. Watson) in a statistical model that we used to reconstruct precipitation in our study area from c. 1630 to 1995.

Crossdating of 136 samples yielded 280 fire-scar dates ranging from 1575 to 1988. At the plot spatial scale, fire intervals ranged from two to 59 years, with median intervals of 13 to 22 years. Fire intervals doubled when we considered only fires that scarred at least two recorder trees per plot, indicating that severe fires burned less frequently than low-severity fires.

Fire was a primary determinant of stand structure and dynamics in the Douglas-fire – lodgepole pine forests of the Cariboo region. The mixed fire regime includes both low-severity stand-maintaining fires and less frequent stand-replacing fires. Evidence of stand-maintaining fires included uneven age-structures, low density of veteran trees, Douglas-fir with up to eight fire scars, and lodgepole pine with multiple fire scars. Discrete cohorts of trees with fast initial growth rates indicated stand-replacing fires. In eight of the nine study plots, cohorts of trees established following fires that burned in the late 1800s or early 1900s. Post-fire stand development processes such as crown closure, inter-tree competition and self-thinning were evident in the radial growth suppressions and releases of individual trees.

For forests with mixed fire regimes that include stand maintaining and stand-replacing fires, it is difficult to quantify the impacts of fire suppression and to determine whether current stand differ from historic stands. Nevertheless, the current fire-free interval exceeded the median fire return interval at all plots and the maximum interval at all but two plots. Weak correlations suggested that long fire intervals may explain the density of canopy and subcanopy trees observed in some plots, but additional data are needed to draw meaningful conclusions. The radial growth rates of contemporary saplings are much lower that the initial growth rates of subcanopy and canopy trees. Slow sapling growth may be due to competition from overstory trees and low light availability, implying that current stand structures are different from historical conditions.

We used our fire scar records, precipitation reconstruction, and El Niño-Southern Oscillation (ENSO) indices to test for climatic influences on fire occurrence between 1700 and 1970. Links between El Niño-Southern Oscillation, interannual variation in climate, and fire in the Carbioo region were consistent with climate-fire relationships in other dry forests in North and South America. Fire occurrence was related to droughts that last three to five years and correspond with the onset of strong La Niña events. Fires commonly burned in the second year of a drought, following desiccation of fine and coarse fuels. Years of above average precipitation preceded fire years and likely contributed to build up of understory vegetation and fine fuels. Future research will test for climate-driven changes in the fire regime over periods of decades to centuries and attempt to differentiate between the influences of climate and human impacts on the Cariboo fire regime.

The links between climate and fire are regionally important given the current mountain pine beetle outbreak in British Columbia. This research suggests that risk of catastrophic fire in the Cariboo forests will be greatest if a strong La Niña event coincides with peak fuel accumulations resulting from the current outbreak. In 2002, we experienced a moderate El Niño event - La Niña events typically follow El Niños by three to five years.

PART 1: INTRODUCTION

Fire is among the dominant disturbance agents in British Columbia. The fire regime of the dry forests of the Interior Douglas-fir (IDF) zone is classified as Natural Disturbance Type 4 (NDT 4), which is described as frequent stand-maintaining fires (BCMoF 1995). This fire regime is considered to be similar to the fire regimes of forests in other dry climates in North America. Historically, frequent, low-severity fires are believed to have maintained an uneven-aged forest canopy and limited the accumulation of flammable fuels. Stand-initiating fires were less frequent, occurring at intervals of 150 to 250 years. Since European settlement and under the influence of fire suppression, it is hypothesized that the fire regime of interior Douglas-fir forests has been altered and the risk of stand-replacing fire has subsequently increased. This model of fire regime and human impacts on fire is largely based on well-documented changes to dry forests in the southwest of the United States. Veblen (2002) suggests that this fire paradigm has become standard in North America, but notes that it has been uncritically applied to policy and management of many forest types, with negative consequences for ecosystem management based on natural range of variation.

Research by Gray et al. (2002) in the Cariboo region of British Columbia, showed partial support for the frequent stand-maintaining fire paradigm. They concluded that surface fires predominated at low elevations. They inferred that these stands historically were open, park-like forests dominated by uneven-aged Douglas-fir with a grass-dominated understory. At middle and high elevation stands, the fire regime was mixed, including stand-replacing fires and more frequent surface fires. The mixed fire regime would have resulted in a range of forest structures within the landscape, including uneven-aged structurally diverse stands to even-aged post-disturbance stands. With effective fire suppression since 1961, the frequency of fires has decreased. Gray et al. (2002) have suggested that current forests have higher densities of regeneration, smaller diameter overstory trees, increased layers in the canopy, and an accumulation of surface fuels due to infrequent fires. They recommend that strategies be developed to mitigate these changes and reduce fire hazard and risk.

Undoubtedly, increased tree density and fuel accumulation have resulted from reduced surface frequency in some stands. However, an alternative explanation is that some contemporary stand structures arethe result of stand development following severe fires in the latter half of the 19th century (sensu Veblen 2002). The legacy of severe fires that burned a century ago would remain in the landscape today. For example, fire regime research in montane forests of Colorado have shown that infrequent drought years with extreme fire-weather conditions are associated with widespread, stand- replacing fires that have had lasting effects on forest structure at the stand- and landscape-scales (Veblen et al. 2000). Similarly, dendroclimatic analyses suggest that 1869 growing-season was extremely dry in the Cariboo region (Stan et al. 2002) and many trees were scarred by fire in that year (Gray et al. 2002). Widespread fires may also have been relatively severe. Today, it may be difficult to differentiate between structures resulting from post-fire stand development and those resulting from recent fire suppression. This example illustrates the importance of long-term effects of individual years of widespread fire and the need to consider temporal changes in fire frequency and severity when interpreting fire regimes and their impacts on forest landscapes.

In this study, I have applied dendroecological techniques to examine the temporal aspects of the fire regime of the IDFdk3 biogeoclimatic variant. This research achieved four objectives: (1) to quantify climate influences on tree growth, (2) to quantify fire return intervals, (3) to determine the impacts of fire on stand structure and dynamics, and (4) to quantify patterns of climate variation associated with historic fires. Understanding historic fire regimes, the factors that cause variation in the regime, and the effects of fire on forest structure and dynamics will inform timber management, fire risk and hazard assessments, and efforts to restore forests in the Cariboo region.

PART 2: STUDY AREA AND METHODS

A. Study Sites

Research plots were established in nine stands located in the IDFdk3, in the Cariboo region between 150 Mile House and Clinton, British Columbia (**Figure 1**). Elevation ranged from 900 to 1285 m.a.s.l. The stands were located on flat sites, except stands 1 and 2 which had slopes of 37% and 20%, respectively. Stands with the following structural attributes were selected for study:

(1) multiple canopy strata, possibly indicating multiple age cohorts,
(2) evidence of past fires including charcoal in the soil profile, burned snags and
    coarse woody debris, and basal fire scars on canopy dominant trees, and
(3) no evidence of harvesting.

These criteria ensured that the current stand structure reflected the influence of past forest fires (e.g. targeted sampling approach, Baisan and Swetnam 1996) and that recent human influences (e.g., logging) had not obscured past disturbance events.
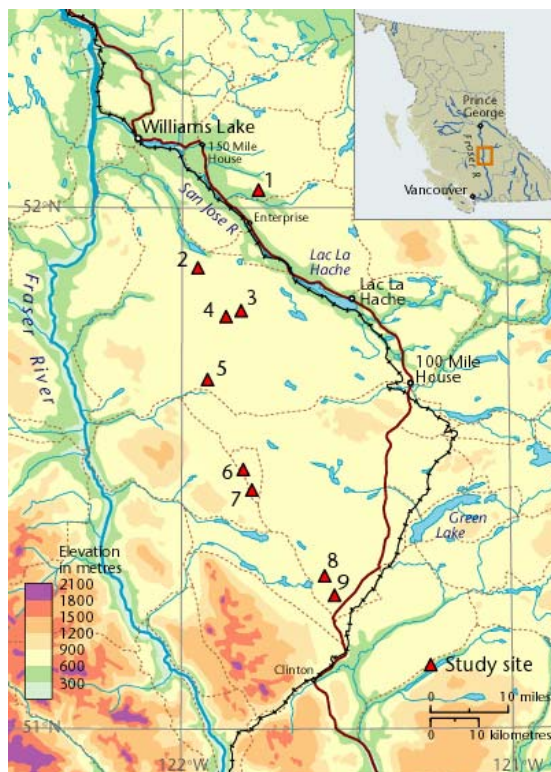

Figure 1. The nine study plots (triangles) are in the Cariboo Region of central British Columbia. Climate data are from Williams Lake.

B. Field Methods
In each stand, I established a 30 m by 30 m plot that was oriented to include trees of all canopy strata and to encompass as many scarred trees as possible. In each plot, the species and diameter at breast height (dbh) of all live and dead standing trees (dbh $\geq$ 5 cm) were recorded. Subcanopy trees included trees with dbh between 5 and 10cm. In plots with few subcanopy trees, all were sampled for age. A subsample was taken in plots with more than 15 subcanopy trees for a given species. The first subcanopy tree to be aged was randomly selected, after which every third tree was systematically sampled by cutting a basal disk from the stem. An increment core was extracted from the base of all canopy trees (dbh $\geq$ 10 cm). When necessary, multiple cores were taken from each tree to include the pith or to be as close to the pith as possible. Coring height was recorded for each tree to facilitate corrections for tree growth to coring height. Partial increment cores were extracted from some decayed trees and cores could not be sampled from highly decayed trees.

Five randomly located 2 x 2 m quadrats were established in each plot. In each quadrat, all seedlings (height $\leq$ 100 cm) and saplings (height > 100 cm and dbh < 5 cm) of each species were tallied. Five saplings of each species, one located in or near each quadrat, were cut at ground level and stem discs were sampled at 10 cm intervals to 70 cm. These "stem analysis" data provided information on tree ages in the understory and were used for age corrections at coring height.

Charred bark and external basal scars on all trees in each plot were recorded. My goal was to sample 10 fire scars in the sample plots or within a 60 m radius (c. 1 ha) of the plot. The number of scarred trees sampled per site ranged from 10 to 25, due to differences in the density of scarred trees among plots. For trees with one scar and dbh <15 cm, increment cores were extracted to date the scars. Cores were taken through the face of the scar, through the living part of the bole, and one or two cores through the scar lobes. For larger trees and trees with multiple scars, cross-sectional discs were cut at height 5 to 160 cm from the ground.

Twenty dominant trees of Douglas-fir and/or lodgepole pine in or near each plot 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 or two increment cores were extracted at breast height from each tree and species and dbh were recorded.

C. Laboratory Methods
In total, 373 increment cores (208 Douglas-fir and 165 lodgepole pine) were sampled for ring-width chronologies; 268 cores from canopy trees and 128 discs from subcanopy trees were sampled for age determination; 195 Douglas-fir discs and 300 lodgepole pine discs have been collected from saplings to determine age and height growth rates; increment cores and cross-sectional disks were taken 136 fire scarred trees. All increment cores were mounted on wooden supports and discs from partially decayed trees were mounted on plywood. Cores and discs were sanded with a belt sander and/or palm sander using successively finer sand paper to 400 grit (Stokes and Smiley 1968).

PART 3. THE DENDROCLIMATIC SIGNAL IN DOUGLAS-FIR AND LODGEPOLE PINE CHRONOLOGIES FROM THE CARIBOO REGION

A: CHRONOLOGY DEVELOPMENT AND EVALUATION

Chronology Development and Characteristics

We have developed 14 new site-specific ring-width chronologies, six for Douglas-fir and eight for lodgepole pine. The increment cores for 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 climatic signal in most tree-ring series is superimposed on a non-climatic, age-related decline in ring width from the pith to the bark of a tree. The computer program ARSTAN (Cook, 1985) was used to correct for this age-related trend 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 raw ring-width series. The series were then divided by the value of the curve and averaged together to produce the mean indexed chronology for each site (Grissino-Mayer et al. 1996). ARSTAN computes the mean chronology using a biweight mean, which discounts the influence of outliers caused by non-synchronous disturbances (Cook, 1985; Cook et al., 1990). The deterministic growth-trend models applied in this study are considered to be conservative (Cook 1985; Meko et al. 1993) in that they permit the retention of as much of the low-frequency (long-term) variance that is resolvable given the length of the individual tree-ring series (Cook et al. 1995).

Table 1 presents summary statistics and characteristics for the six new Douglas-fir and eight lodegepole pine chronologies. The Douglas-fir chronologies range from 300 to 558 years in length (mean length = 426 years). The lodgepole pine chronologies are considerably shorter with a mean length of only 170 years (range 114 to 229 years). The mean segment length, an important determinant of the maximum timescale of climatic information resolvable from a chronology, is over 120 years longer for the Douglas-fir chronologies than the lodgepole pine chronologies.

Mean sensitivity (Fritts, 1976) and standard deviation values provide a measure of the year-to-year variability in the ring-width chronologies (**Table 1**). The average mean sensitivity and standard deviation values for the Douglas-fir chronologies (0.24 and 0.32 respectively) are higher than those for the shorter lodgepole pine chronologies (0.17 and 0.27). First-order autocorrelation coefficients (AC(1)) are higher for the lodgepole pine chronologies than for the Douglas-fir chronologies. The mean sensitivity values are generally lower and the AC(1) coefficients are higher than those for other Douglas-fir chronologies developed for the region (Watson and Luckman 2001a,b) which probably reflects differences in site selection and sampling strategy. For example, our objective was to develop chronologies to test ecological hypotheses; we did not target sites that were most sensitive to climatic stress.

Table 1. Summary characteristics for the Douglas-fir and lodgepole pine chronologies.

Site Name	Species	Latitude	Longitude	Approx. Elev. (m)	No. Cores	No. Trees	start	end	Mean Seg. Length	Mean Sens.	Std. Dev.	AC(1)	mean rmt	mean rwt	mean rbt	# trees EPS 0.85	Year EPS >0.85
FD1	DF	52º01'N	121º45'W	900	42	25	1523	1994	252	0.33	0.35	0.31	0.55	0.79	0.55	5	1720
FD2	DF	51º52'N	121º55'W	1048	25	23	1491	1995	239	0.25	0.33	0.50	0.47	-	0.47	6	1701
FD4	DF	51º48'N	121º51'W	1175	18	18	1695	1994	193	0.25	0.34	0.59	0.49	-	0.49	6	1801
FD5	DF	51º39'N	121º53'W	1129	31	21	1632	1995	233	0.22	0.31	0.60	0.43	0.75	0.42	8	1710
FD6	DF	51º29'N	121º49'W	1285	40	20	1437	1994	326	0.20	0.33	0.71	0.44	0.74	0.43	7	1614
FD9	DF	51º15'N	121º31'W	1138	40	20	1637	1994	228	0.21	0.28	0.55	0.52	0.72	0.51	5	1722
			MEAN	1113	33	21	1569	1994	245	0.24	0.32	0.54	0.48	0.75	0.48	6	
PL2	LP	51º52'N	121º55'W	1048	5	5	1881	1995	100	0.19	0.34	0.77	0.65	-	0.65	3	1889
PL3	LP	51º49'N	121º49'W	1150	16	16	1767	1995	162	0.15	0.24	0.69	0.22	-	0.22	20	NA
PL4	LP	51º48'N	121º51'W	1175	20	20	1818	1995	101	0.17	0.29	0.76	0.23	-	0.23	19	1924
PL5	LP	51º39'N	121º53'W	1129	20	20	1875	1995	96	0.17	0.23	0.53	0.31	-	0.31	12	1898
PL6	LP	51º29'N	121º49'W	1285	16	15	1775	1996	115	0.19	0.34	0.72	0.50	-	0.50	6	1884
PL7	LP	51º27'N	121º47'W	1168	15	15	1783	1995	177	0.14	0.20	0.62	0.26	-	0.26	16	NA
PL8	LP	51º17'N	121º33'W	1150	19	20	1823	1995	127	0.17	0.25	0.60	0.45	-	0.45	7	1858
PL9	LP	51º15'N	121º31'W	1138	27	18	1882	1995	87	0.17	0.25	0.69	0.53	0.62	0.53	5	1892
			MEAN	1155	17	16	1826	1995	121	0.17	0.27	0.67	0.39	0.62	0.39	11	

Notes: Mean Seg. Length is the mean length of each core in the mean chronology. Mean Sens., Std. Dev. And AC(1) are mean sensitivity, standard deviation and first order autocorrelation respectively. Mean rmt, rwt and rbt are mean correlations overall, between ring-width series extracted from the same tree and between cores taken from different trees. The number of trees required to attain an EPS value of 0.85 and the first year this occurs are listed in the last two columns. Mean values for all variables are listed for each species (shaded grey).

Briffa (1995) defines the empirical signal in tree-ring series as the strength of the common signal in the tree-ring chronology. This is related to both signal strength and replication and has been described using a number of statistics (Fritts 1976; Wigley et al., 1984; Briffa and Jones 1990). Mean r_{mt}, r_{bt} and r_{wt} (mean, between, and within-tree correlations, respectively) values for the Douglas-fir and lodgepole pine chronologies are presented in **Table 1**. The mean r_{bt} values serve as a preliminary and conservative estimate (they exclude within-tree correlations) of the common signal in the tree-ring chronologies. Mean r_{bt} values are on average higher for the Douglas-fir chronologies than the lodgepole pine chronologies. The overall mean r_{bt} for the Douglas-fir chronologies (0.48) indicates that, on average, six trees are required to yield an EPS value of 0.85 which has been "tentatively suggested as desirable" for climate reconstruction work (Briffa 1995; Wigley et al. 1984; Briffa and Jones 1990). An average of 11 trees are necessary for the lodgepole pine chronologies to reach the same threshold which is an unfavourable circumstance given that they are less well replicated than the Douglas-fir chronologies.

Overall, the Douglas-fir chronologies are considerably longer, more sensitive and have a stronger common signal than the lodgepole pine chronologies. As such, they may be better for climate reconstruction work.

Evaluating the Common Signal in the Chronologies
A key element in determining the dendroclimatic utility of a set of tree-ring chronologies is the degree to which they exhibit common growth variability. If the chronologies in a network 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. In this study, it is important to differentiate between the two because the sites have a considerable amount of fire disturbance and may not suitable for reconstruction work. In this section we will attempt to demonstrate through comparisons within and between the sites that they have a common signal. Strong relationships with chronologies from more distant sites are an important verification that common variability is not related to local (possibly non-climatic) controls.

Marker Rings
Individual wide or narrow "marker" rings that are temporally synchronous within and between chronologies suggest a common forcing of tree growth. Based on previous work with Douglas-fir in this region (Schulman, 1947; Robertson and Jozsa, 1988; Watson, 2002; Watson and Luckman, 2001a, 2001b, 2002), these common marker rings are most likely related to precipitation and are probably indicative of extreme wet and dry years.

In this study, marker rings are defined as those years when the normalised ring-width value of the residual chronology is more than one standard deviation from the chronology mean. The degree of commonality of these positive and negative marker rings can be assessed through an examination of **Figure 2** which shows the percentage of chronologies available in each year (1600-1994) that display positive or negative marker rings. **Table 2** lists positive and negative marker rings common to ≥ 60% of the total number of chronologies available in each year. Recall that the lodgepole pine chronologies are much shorter than the Douglas-fir chronologies (**Table 1**). As such **Table 2** also gives information for each species and marker rings common to both species (those from the 19th century onwards) are shaded grey. Thirty-five negative and 28 positive marker rings common to ≥ 60% of the chronologies are identified (**Table 2**).
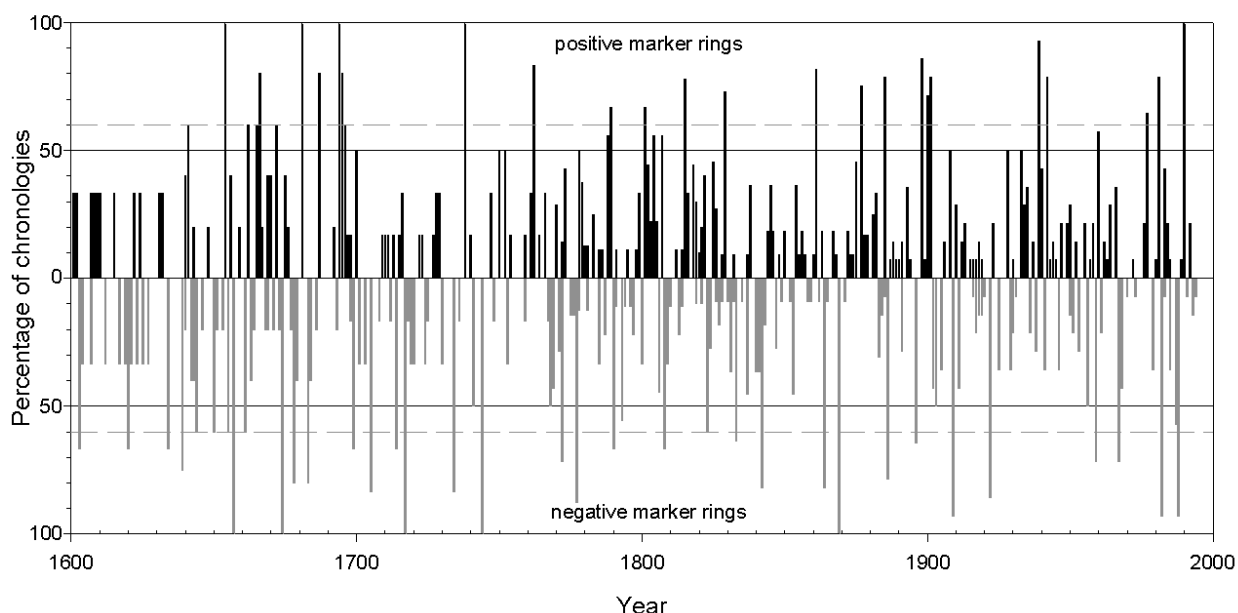
Figure 2. Percentage of the residual chronologies which show a marker ring (Z >1 or <-1) in each year. Years when >60% of chronologies (dashed line) have a marker ring of the same sign are listed in Table 2.

This indicates that the chronologies do have a common presumably climate-related signal. This is reinforced by the fact that many of the most common marker rings correspond with those identified in a larger network of moisture-sensitive chronologies from across the southern Canadian Cordillera (Watson and Luckman, 2001b; see **Table 2**).

Correlations Within Species
Correlations calculated between the Douglas-fir chronologies over their maximum paired interval are shown in **Table 3a**. All correlations between the six Douglas-fir chronologies are statistically significant (p<0.05) and are quite high ranging from 0.47-0.77 (mean = 0.59; n = 15) indicating that there is a fairly strong common signal between the series. On average, the Douglas-fir chronologies from sites 1 and 9 (the most northerly and southerly collected respectively) correlate most weakly with the other Douglas-fir chronologies.

Seventy-five percent of the correlations between all pairings of the eight lodgepole pine chronologies exceed 0.40 (**Table 3b**). The mean correlation between the lodgepole pine chronologies (r = 0.50, n=28) is lower than that between the Douglas-fir chronologies. However, the mean correlations for the two species are not significantly different (p<0.05). The lodgepole pine chronologies from Sites 3 and 4 have the lowest mean correlations with the other lodgepole pine chronologies and the weakest common signal (as measured by rbt; **Table 1**). The only non-significant pairing is between the chronologies from Sites 2 and 4 (Douglas-fir chronologies from these two sites are significantly correlated p<0.05) and is probably related to the chronology from Site 4 (see comment above).

Table 2. The most extreme (a) narrow and (b) wide marker rings identified in the chronologies.

(a)

	Negative	DF_neg	LP_neg	N	n DF	n LP
1657	**100.0**	**100.0**	**-**	**5**	**5**	**0**
1674	100.0	100.0	-	5	5	0
1717	100.0	100.0	-	6	6	0
1744	100.0	100.0	-	6	6	0
1869	**100.0**	**100.0**	**100.0**	**11**	**6**	**5**
1909	92.9	100.0	87.5	14	6	8
1982	92.9	83.3	100.0	14	6	8
1988	**92.9**	**83.3**	**100.0**	**14**	**6**	**8**
1777	87.5	100.0	50.0	8	6	2
1922	85.7	66.7	100.0	14	6	8
1705	83.3	83.3	-	6	6	0
1734	83.3	83.3	-	6	6	0
1842	**81.8**	**83.3**	**80.0**	**11**	**6**	**5**
1864	81.8	100.0	60.0	11	6	5
1678	80.0	80.0	-	5	5	0
1683	80.0	80.0	-	5	5	0
1886	78.6	100.0	62.5	14	6	8
1639	**75.0**	**75.0**	**-**	**4**	**4**	**0**
1772	71.4	83.3	0.0	7	6	1
1959	71.4	100.0	50.0	14	6	8
1967	71.4	66.7	75.0	14	6	8
1603	66.7	66.7	-	3	3	0
1620	66.7	66.7	-	3	3	0
1634	**66.7**	**66.7**	**-**	**3**	**3**	**0**
1699	66.7	66.7	-	6	6	0
1714	66.7	66.7	-	6	6	0
1790	66.7	83.3	33.3	9	6	3
1808	66.7	50.0	100.0	9	6	3
1896	64.3	66.7	62.5	14	6	8
1833	63.6	83.3	40.0	11	6	5
1644	60.0	60.0	-	5	5	0
1650	60.0	60.0	-	5	5	0
1655	60.0	60.0	-	5	5	0
1661	60.0	60.0	-	5	5	0
1823	60.0	50.0	75.0	10	6	4

(b)

	Positive	DF_pos	LP_pos	N	n DF	n LP
1654	100.0	100.0	-	5	5	0
1681	100.0	100.0	-	5	5	0
1694	100.0	100.0	-	5	5	0
1738	100.0	100.0	-	6	6	0
1990	**100.0**	**100.0**	**100.0**	**14**	**6**	**8**
1939	92.9	83.3	100.0	14	6	8
1898	85.7	100.0	75.0	14	6	8
1762	**83.3**	**83.3**	**-**	**6**	**6**	**0**
1861	81.8	83.3	80.0	11	6	5
1666	80.0	80.0	-	5	5	0
1687	80.0	80.0	-	5	5	0
1695	80.0	80.0	-	5	5	0
1885	78.6	66.7	87.5	14	6	8
1901	78.6	100.0	62.5	14	6	8
1942	**78.6**	**66.7**	**87.5**	**14**	**6**	**8**
1981	78.6	50.0	100.0	14	6	8
1815	77.8	83.3	66.7	9	6	3
1877	75.0	83.3	66.7	12	6	6
1829	72.7	83.3	60.0	11	6	5
1900	**71.4**	**50.0**	**87.5**	**14**	**6**	**8**
1789	66.7	66.7	66.7	9	6	3
1801	**66.7**	**66.7**	**66.7**	**9**	**6**	**3**
1977	64.3	83.3	50.0	14	6	8
1641	60.0	60.0	-	5	5	0
1662	60.0	60.0	-	5	5	0
1665	60.0	60.0	-	5	5	0
1672	60.0	60.0	-	5	5	0
1696	60.0	60.0	-	5	5	0

Notes: Ring-width values in the years listed are more than one standard deviation from the mean in ≥ 60% of the total number of chronologies available in each year. The percentage of Douglas-fir (DF_neg/DF_pos) and lodgepole pine (LP_neg/LP_pos) chronologies which exhibit marker rings in these years is also listed. Years common to 60% of chronologies from both species are shaded grey and years that correspond with those identified in Watson and Luckman (2001b) are boldfaced. For each year the total number of chronologies (N) are listed along with the number of Douglas-fir (n DF) and lodgepole pine (n LP) chronologies.

Table 3. Correlation coefficients calculated between the (a) Douglas-fir chronologies (b) lodgepole pine chronologies (c) Douglas-fir and lodgepole pine chronologies and (d) previously developed chronologies from adjacent sites.

(a)	FD1	FD2	FD4	FD5	FD6	FD9
FD1	1	0.43	0.51	0.68	0.47	0.42
FD2	0.43	1	0.60	0.72	0.54	0.62
FD4	0.51	0.60	1	0.70	0.77	0.49
FD5	0.68	0.72	0.70	1	0.73	0.67
FD6	0.47	0.54	0.77	0.73	1	0.55
FD9	0.42	0.62	0.49	0.67	0.55	1
mean	0.50	0.58	0.61	0.70	0.61	0.55

(b)	PL2	PL3	PL4	PL5	PL6	PL7	PL8	PL9
PL2	1	0.34		0.50	0.79	0.55	0.50	0.73
PL3	0.34	1	0.61	0.35	0.45	0.38	0.50	0.40
PL4	0.06	0.61	1	0.44	0.36	0.35	0.45	0.23
PL5	0.50	0.35	0.44	1	0.73	0.54	0.54	0.59
PL6	0.79	0.45	0.36	0.73	1	0.43	0.52	0.83
PL7	0.55	0.38	0.35	0.54	0.43	1	0.50	0.57
PL8	0.50	0.50	0.45	0.54	0.52	0.50	1	0.76
PL9	0.73	0.40	0.23	0.59	0.83	0.57	0.76	1
mean	0.56	0.50	0.49	0.59	0.64	0.54	0.60	0.64

(c)	PL2	PL3	PL4	PL5	PL6	PL7	PL8	PL9	mean
FD1	0.39	0.26	0.40	0.42	0.33	0.37	0.48	0.35	0.38
FD2	0.59	0.42	0.37	0.52	0.53	0.45	0.55	0.59	0.50
FD4	0.36	0.55	0.69	0.50	0.46	0.42	0.56	0.50	0.51
FD5	0.19	0.51	0.64	0.49	0.41	0.45	0.62	0.35	0.46
FD6	0.45	0.40	0.56	0.53	0.55	0.57	0.68	0.58	0.54
FD9	0.26	0.37	0.38	0.35	0.33	0.38	0.65	0.53	0.41
mean	0.37	0.42	0.51	0.47	0.44	0.44	0.59	0.48	

(d)	FD1	FD2	FD4	FD5	FD6	FD9	PL2	PL3	PL4	PL5	PL6	PL7	PL8	PL9
LAC	0.57	0.50	0.54	0.56	0.54	0.46	0.22	0.21	0.43	0.48	0.21	0.25	0.48	0.32
CHADF	0.52	0.55	0.65	0.71	0.66	0.73	0.32	0.42	0.44	0.38	0.42	0.42	0.64	0.46
CHAPP	0.46	0.56	0.55	0.58	0.56	0.59	0.55	0.41	0.27	0.43	0.54	0.45	0.65	0.65
MED	0.55	0.61	0.60	0.67	0.71	0.63	0.21	0.40	0.44	0.36	0.41	0.31	0.52	0.36
DP	0.62	0.47	0.47	0.57	0.49	0.42	0.30	0.30	0.44	0.35	0.30	0.26	0.49	0.29
GR	0.54	0.51	0.58	0.63	0.56	0.45	0.24	0.35	0.48	0.41	0.34	0.30	0.49	0.32
CC	0.43	0.34	0.46	0.51	0.46	0.41		0.27	0.46	0.26	0.24	0.21	0.40	
mean	0.53	0.51	0.55	0.61	0.57	0.53	0.31	0.34	0.42	0.38	0.35	0.31	0.52	0.40

Notes: All correlation coefficients are statistically significant at or beyond the 0.05 level and are calculated over the interval of maximum overlap between each pair. Boxed values in **(c)** are the correlations between co-located Douglas-fir and lodgepole pine chronologies. Boxed values in **(d)** identify the maximum correlation between each of the chronologies developed in this study and chronologies from neighbouring sites (see Watson, 2002; Watson and Luckman, 2001b). LAC = Lac la Hache, CHADF and CHAPP are Douglas-fir and ponderosa pine chronologies from Chasm. MED, DP, GR and CC are Douglas-fir chronologies from Deer Park, Gang Ranch and Churn Creek (Figure 1).

Correlations Between Species
All correlations between the six Douglas-fir and eight lodgepole pine chronologies are statistically significant (p<0.05; **Table 3c**). As was noted for the Douglas-fir chronologies alone, the Douglas-fir chronologies from Sites 1 and 9 have the lowest mean correlation (mean r = 0.38 and 0.41 respectively, n=8) with the lodgepole pine chronologies. These correlations may be attributable to their greater mean distance from the other sites as the Douglas-fir chronologies from Sites 1 and 9 are well-replicated and appear to have a strong common signal (**Table 1**). The lodgepole pine chronology from Site 8 has the highest mean correlation with the six Douglas fir chronologies (r = 0.59) while the chronology from Site 2 has the lowest (r = 0.37). There are five sites for which both

Douglas-fir and lodgepole pine chronologies were developed. Correlations between these co-located chronologies are statistically significant and range from 0.49 to 0.69. This, along with an examination of plots of the co-located chronologies (**Figure 3**), suggests that ring-width variability in the two species is controlled by a common factor (presumably precipitation). Although they are very similar at lower-frequencies, there are short intervals when variability in the co-located chronologies from the two species are of the same direction but different magnitude (**Figure 3**). For example, the period of wider ring-widths in the chronologies from all five sites centred around 1915 is always more pronounced in the Douglas-fir chronologies. These differences may reflect differing sensitivity to growth conditions between the two species or perhaps to species specific disturbances (e.g. insect infestations).

Correlations With Other Chronologies
To further evaluate the regional extent (or representativeness) of the ring-width variability exhibited by the chronologies they were correlated with seven chronologies (six Douglas-fir and one ponderosa pine) from nearby sites (**Table 3d; Figure 1**). These chronologies are part of a larger network of low-elevation, moisture-sensitive chronologies that have been used to develop precipitation reconstructions for sites in B.C. and Alberta (see Watson and Luckman, 2001a, 2001b, 2002 and Watson, 2002). The six Douglas fir chronologies developed in` this study correlate significantly with all seven of the neighbouring chronologies. The highest correlations are generally with the Douglas-fir chronologies from Chasm and Indian Meadows which are located south of the majority of the study sites and east of the Fraser River.

Correlations between the lodgepole pine chronologies and the seven chronologies developed by Watson (2002) are generally weaker which is not surprising as they are developed from a different species. However, maximum correlations for 5 of the 8 lodgepole pine chronologies are with the ponderosa pine chronology from Chasm and range from 0.45-0.65. Again the lodgepole pine chronology from site 4 appears to be different from the others, as it is the only chronology that correlates most highly with a chronology from west of the Fraser River (Gang Ranch, Douglas-fir).

Principal Components Analysis (PCA)
A PCA was conducted over the interval common to the 14 chronologies (1882-1994). Two components accounting for 71% of the variance in the 14 chronologies were retained and subjected to an orthogonal varimax rotation (**Table 4**). The loadings on the two PCs identify two distinct groupings: the Douglas-fir chronologies load on PC1 and the lodgepole pine chronologies load most highly on PC2 (except Sites 3 and 4). These results suggest that the major differences within the chronology dataset are related to species not location within the network. This also suggests that in subsequent analysis of the climate signal in the chronology dataset it may be useful to generate a mean regional series for each species.
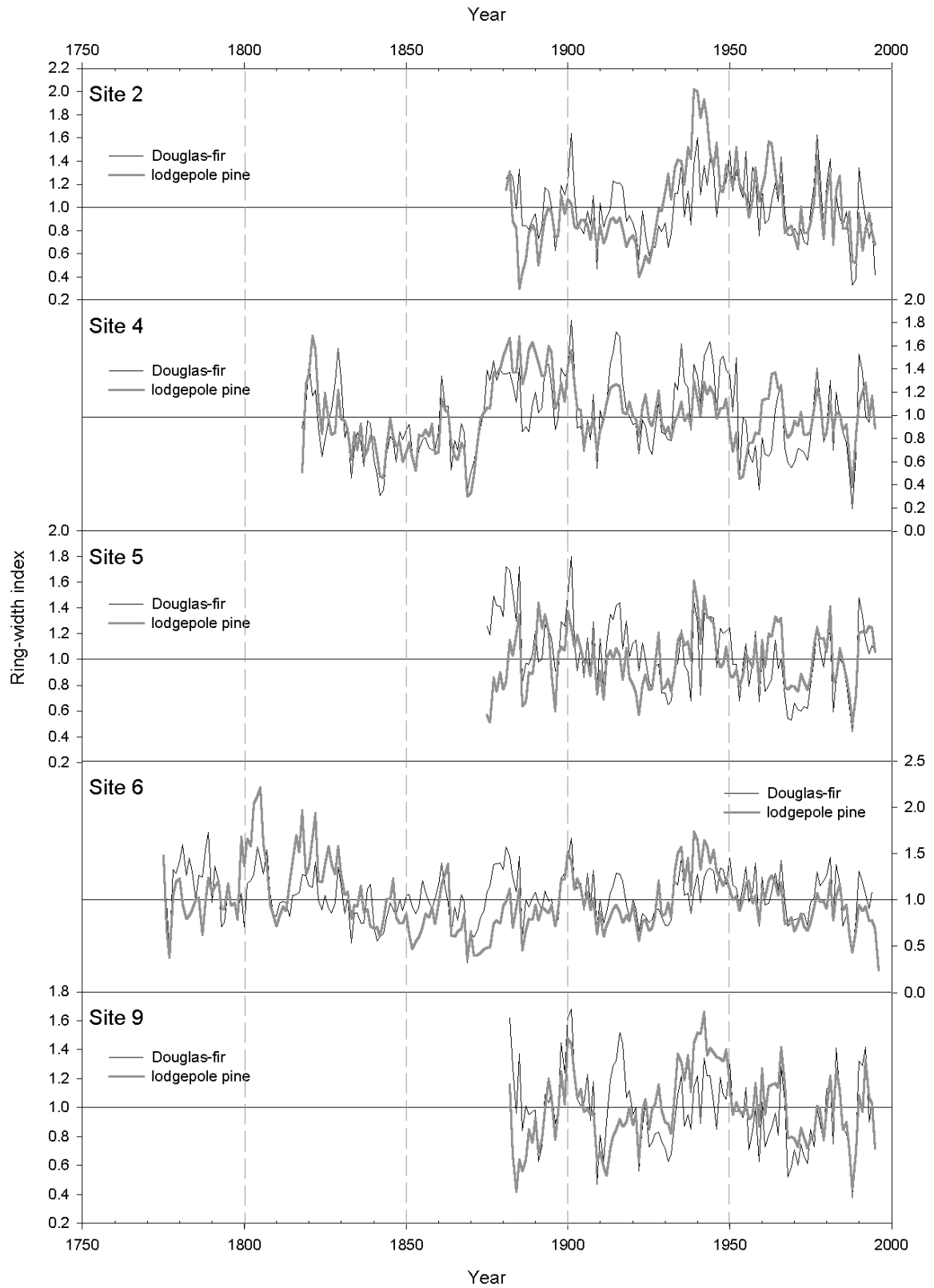
Figure 3. Time series plots of Douglas-fir and lodgepole pine chronologies sampled at the same site.

Table 4. Results of a principal components analysis conducted on the full 14 chronology dataset over their common interval (1882-1994).

Site Name	PC1	PC2
FD1	**0.57**	0.39
FD2	**0.62**	0.60
FD4	**0.83**	0.33
FD5	**0.92**	0.19
FD6	**0.71**	0.54
FD9	**0.81**	0.31
PL2	0.01	**0.91**
PL3	**0.57**	0.31
PL4	**0.79**	-0.02
PL5	0.56	**0.58**
PL6	0.30	**0.89**
PL7	0.45	**0.64**
PL8	0.53	**0.67**
PL9	0.22	**0.86**
Eigenvalue	8.29	1.71
% Total Variance	59.2	12.2

Notes: The retained components were subjected to a varimax rotation. Bold values identify the highest loading for each chronology.

Analysis of Time Series Plots
Douglas-fir chronologies

The standardised Douglas-fir and lodgepole pine chronologies are plotted from north-south by species in **Figure 4**. The lower-frequency variability in the Douglas-fir chronologies, as emphasised by the 25-year splines plotted in **Figure 5**, is quite similar. During the 20th century all six chronologies show a period of wider rings around 1900, narrower rings through the 1920s and 1930s, a period of wide rings centred around 1945 and an interval of narrow rings centred around 1970. The latter period is less pronounced in the chronologies from sites 2 and 6. This pattern is present in both instrumental and reconstructed precipitation records from the region (Watson and Luckman, submitted). Variability in the 19th century is less similar with site 4, and, to a lesser extent, sites 5 and 6, exhibiting a period of reduced growth during the middle of the century. This coincides with an interval of below normal precipitation identified in a number of precipitation reconstructions developed for the region (Watson and Luckman, submitted). Chronologies from the other three sites show generally wider than average annual rings for the same period (**Figure 4**).

Five of the six Douglas-fir chronologies show narrow rings during the 1790s (a commonly reconstructed dry period; see Watson and Luckman, submitted; Case and MacDonald, 1995; Sauchyn and Beaudoin, 1998). The chronologies from Site 2 and 9 have below normal ring-widths for much of the 1700s. All chronologies except Site 1 show narrow rings during the early 1700s (approximately 1700-1725). This interval is particularly pronounced in the chronology from Site 4 but sample depth is low during this interval. Variability over the 17th century is very similar with all series showing below normal growth during the first half of the century and double peaks of wider than average rings during the latter part of the century. The three chronologies that extend into the 16th century show wider than normal rings around 1600, which correspond with an interval of wetter than normal conditions identified in precipitation reconstructions for Williams Lake, Big Creek, Lytton, Banff, Winnipeg and the Rocky Mountain Foothills (Watson and Luckman, submitted, St.George and Nielsen, 2002; Case and MacDonald, 1995).
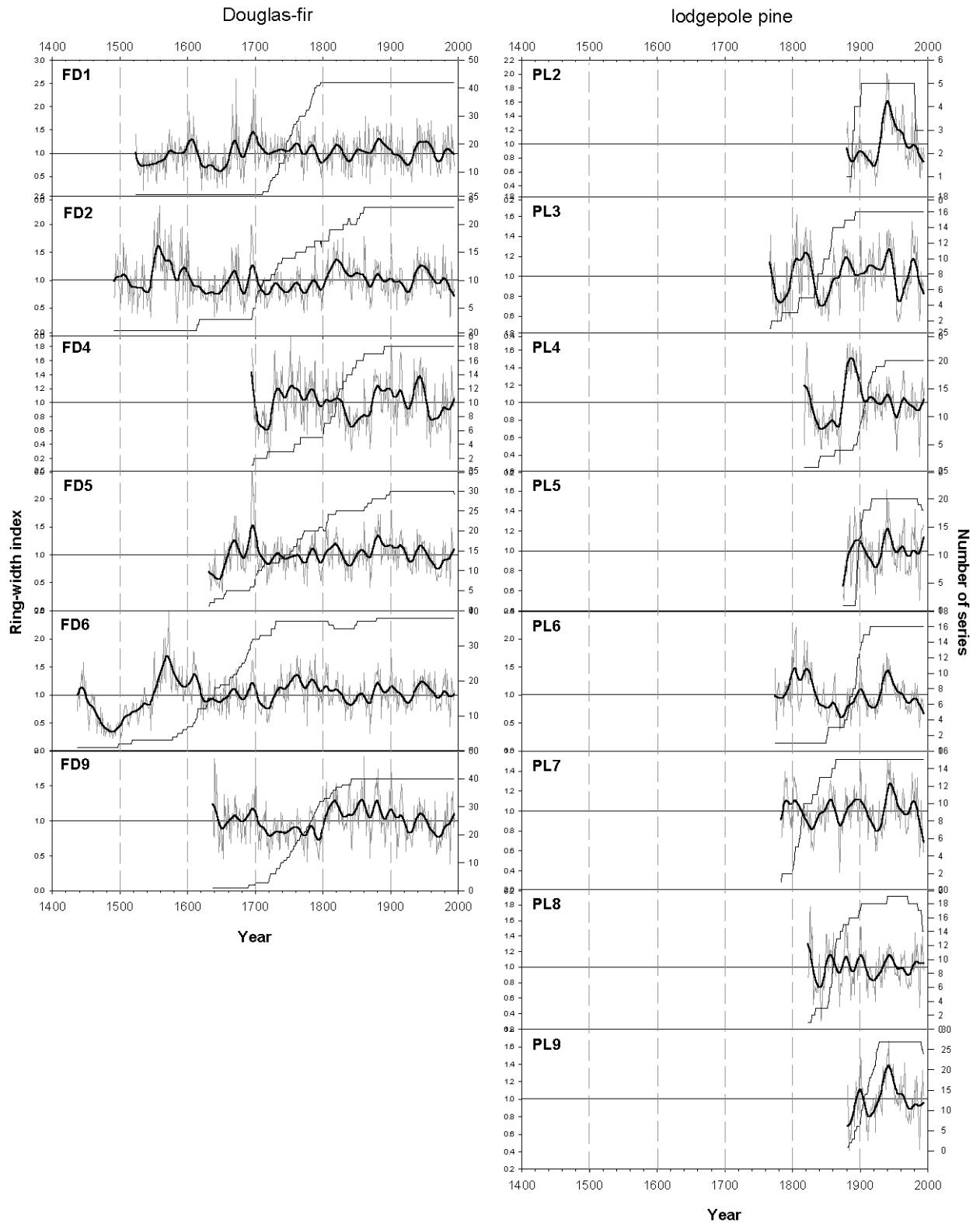
Figure 4. Standardised Douglas-fir and lodgepole pine chronologies developed in this study. The thick line fitted to each series is a cubic smoothing spline with a 50% frequency cutoff of 25 years. Sample depth through time is given for each chronology.
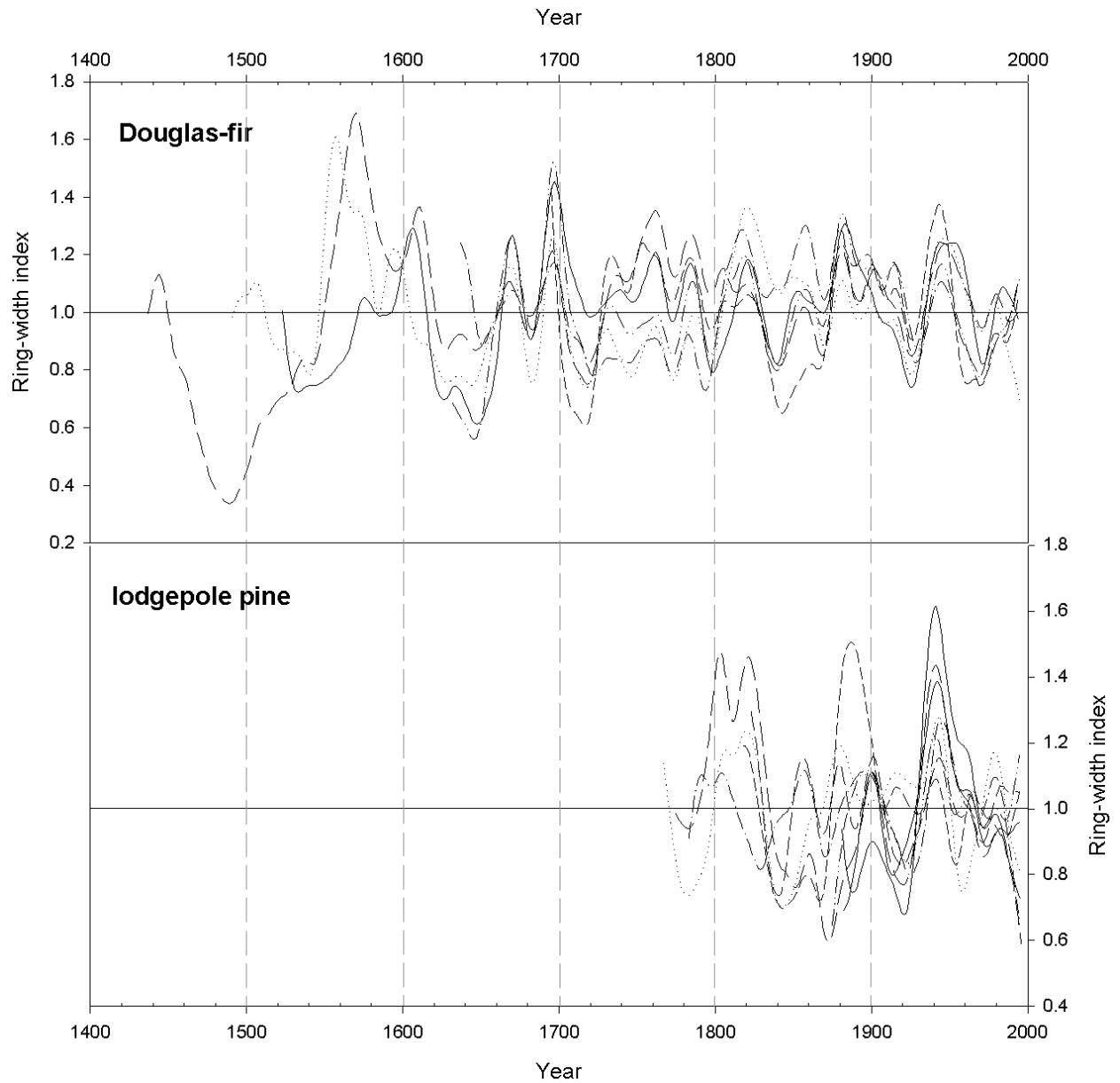
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Figure 5. Overlay plots of the six Douglas-fir and eight lodgepole pine chronologies. Series have been smoothed with a 25-year filter to emphasise lower frequency variability.

Lodgepole pine Chronologies
The lodgepole pine chronologies are considerably shorter than the Douglas-fir chronologies developed in this study but exhibit a similar level of common variability, especially when Sites 3 and 4 are removed (**Figures 4 and 5**). Over the 20th century the lodgepole pine chronologies are quite similar with a pronounced period of wider than average rings centred around 1940 (about 5-10 years earlier than the peak seen in the Douglas-fir chronologies; **Figures 4 and 5**). All series (apart from those from sites 3 and 4) show below normal growth during the 1920s (again slightly earlier than that seen in the Douglas-fir chronologies; **Figure 4**). The chronologies from sites 3 and 4 also show a unique period of narrow rings centred around 1960 which is seen in some of the Douglas-fir chronologies and may explain why they load more highly on PC1 (the Douglas-fir component; **Table 3**). The five most southerly lodgepole pine chronologies exhibit a period of enhanced growth around 1900. A similar peak occurs about 10 years earlier in the chronology from Site 4 (**Figure 4**). As seen in several of the Douglas-fir chronologies, the majority of the lodgepole pine chronologies show narrow rings during the period ~1840-1880. Ring-widths are above average at most sites from 1800 to about 1830 which contrasts a shorter interval of narrow rings in the Douglas-fir chronologies centred near 1800.

B. PRECIPITATION RECONSTRUCTION
Chronology-Climate Correlations
To investigate the strength and nature of the climate signal in the chronologies from the two species, simple product-moment correlation coefficients were calculated between the chronologies from both species and precipitation, PDSI and temperature records from proximal meteorological stations. The best relationships occurred with the precipitation record from Williams Lake (**Figure 1**). Correlations between the chronologies and monthly and seasonal precipitation at Williams Lake are presented in **Figure 6**.

All six Douglas-fir chronologies exhibit statistically significant ($p<0.05$) positive correlations with precipitation from the previous August (r=0.36-0.50). The two most southerly Douglas-fir chronologies (FD6 and FD9) are also significantly correlated with prior July precipitation and FD1 is significantly correlated with prior June precipitation. There are only four statistically significant correlations with precipitation in the current year (Figure 6). These positive correlations occur between the Douglas-fir chronologies from sites 1, 2, 5 and 6 and current June precipitation and are not as strong as those with prior summer precipitation. When the monthly precipitation records are summed over various intervals of the growing season (MJJ, JJ and JJA) the correlations are improved but again the highest correlations are with previous summer conditions. Maximum correlation coefficients for four of the six chronologies occur with pJJA precipitation (r = 0.34-0.58, n=6). This type of lagged relationship with precipitation was also noted for Douglas-fir and ponderosa pine chronologies in the southern Canadian Cordillera by Watson and Luckman (2002).

The lodgepole pine chronologies show a similar pattern of correlations with Williams Lake precipitation to those seen with the Douglas-fir chronologies. Two of the eight lodgepole pine chronologies are positively correlated ($p<0.05$) with prior July precipitation and six with prior August precipitation (r = 0.36-0.46). Apart from Site 9, the significant correlations with prior summer are higher for the co-located Douglas-fir chronologies (**Figure 6**). Only the lodgepole pine chronology from Site 5 is significantly correlated with current June precipitation. The only other significant correlations with
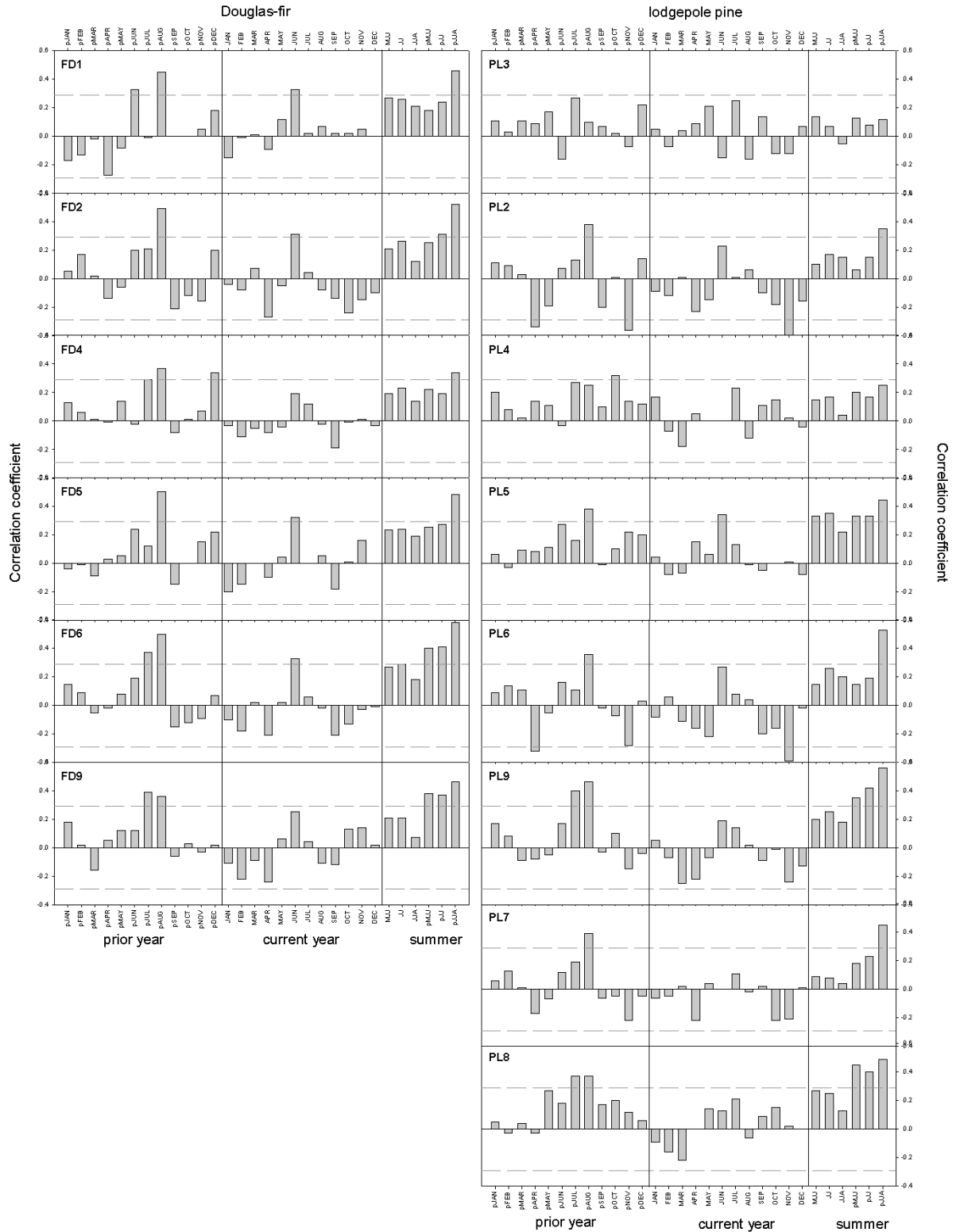
Figure 6. Correlation coefficients between the chronologies and monthly and seasonal groupings of the Williams Lake precipitation record. The dashed line denotes statistical significance (p<0.05, n=47).

current year precipitation are negative with November at Sites 2 and 6. All sites except 3 and 4, which have been previously identified as unusual, correlate highly with prior July-August precipitation.

Overall the positive correlations with Williams Lake precipitation indicate that wet (dry) summers result in wide (narrow) annual growth rings and are consistent with many previous studies using conifers from arid sites (e.g., Fritts, 1976; Watson and Luckman, 2001a) and reflect the relationship between precipitation and soil moisture levels. It should be noted however that the lodgepole pine chronologies are considerably younger than the Douglas-fir chronologies (**Table 1**) so it is possible that some of the differences in the correlations between the two species are related to tree-age.

Precipitation Reconstruction

Based on the results of the correlation analyses discussed in the previous section, stepwise multiple linear regression analysis was used to develop a model that can be used to hindcast June-August (JJA) precipitation at Williams Lake. The correlation analyses also indicate that annual ring-width variability is related to monthly precipitation totals split over two summers. To model this complex relationship, the Douglas-fir chronologies in years t and t+1 were included as potential predictors in the model. The lodgepole pine chronologies were not considered because of their restricted length. The latewood chronologies from Chasm PP and DF, Lac La Hache, Deer Park, Indian Meadows, Churn Creek and Gang Ranch were also included because they have a strong relationship with current summer precipitation and should therefore provide ring-width information for the current summer in the model.

Two chronologies enter the regression model: the Douglas-fir chronology from Site 6 lagged forward one year (FD6 t+1) and the latewood ponderosa pine chronology from Chasm (CHAPP t). The calibration and verification statistics for the model are provided in Table 5. The multiple R value for the full model is 0.66 and the model explains about 40 percent of the variance in the instrumental record (based on adjusted R^2). The regression equation is given below:

JJA precipitation (mm) = -43.755+115.783(FD6 t+1)+102.658(CHAPP t)

The calibration model was verified against independent data generated using a standard split-period approach and the "leave-out-one method" (Gordon, 1982). In the standard approach, the model is calibrated on the first half of the precipitation record and verified against the second half of the record and then the periods are reversed allowing an assessment of the temporal stability of the modeled relationship. Using the leave-out-one method, a single year is removed from the analysis and a regression model is generated and used to estimate the excluded year. This process is repeated for each year until a set of estimates is generated for the entire period of the instrumental record. The verification tests were repeated using first-differenced data to evaluate the performance of the models at high-frequencies. The reconstruction passes all of the verification tests except the sign-test in the first differenced verification but this is not considered to be a major problem (**Table 5**).

Table 5. Calibration and verification statistics for the Williams Lake June-August precipitation reconstruction.

	CALIBRATION					VERIFICATION								
						standard reconstructions					first differenced data			
Model	Years	SE^1	R	R^2_{adj}	D-W d^2	Period	r	RE^3	CE^4	Sign Test	r	RE	CE	Sign Test
WILLIAMS LAKE (1633-1996)														
Early	1948-1970	43.75	0.73	0.48	2.55	1971-1993	0.59*	0.56	0.51	17/6*	0.62*	0.46	0.23	18/5*
Late	1971-1993	64.81	0.60	0.35	1.78	1948-1970	0.73*	0.39	0.34	19/4*	0.47*	0.23	0.20	12/10 ns
Full	1948-1993	57.35	0.66	0.40	2.02	1948-1993	0.60*	0.38	NA	37/9*	0.46*	0.23	NA	29/16*

[1] is the standard error of the precipitation estimate in mm. Doubling this value yields approximate 95% confidence intervals.
[2] These non-significant Durbin-Watson D values indicate that the residuals from the regression models do not exhibit statistically significant (p<0.05) first order autocorrelation. Significance testing of the D-W d value for negative autocorrelation in the residuals from the early model was inconclusive.
[3] Reduction of Error (RE) statistic
[4] Coefficient of Efficiency (CE) statistic. Positive values of both RE and CE indicate that there is some skill in the reconstruction and that it provides better precipitation estimates than if one simply used the mean of the calibration (RE) or verification (CE) period (see Cook *et al*., 1994; Fritts, 1976, 1991; Fritts *et al*. 1990).

Instrumental and reconstructed JJA precipitation are plotted over the calibration period in **Figure 7** and the full reconstruction is plotted in **Figure 8**. Below normal precipitation is reconstructed for the beginning of the record (~1630-1660); the first three decades of the 18th century; for three shorter intervals centred around 1840, 1870 and 1890; during the 1920s-30s and for the last quarter of the 20th century. The most severe and prolonged dry interval reconstructed is the one identified in the early part of the 18th century followed by the well-documented drought in the early part of the 20th century. To evaluate and further verify the patterns seen in this reconstruction, it is compared with three annual (pJuly-June) precipitation reconstruction developed for nearby sites (Figure 9; Watson and Luckman, submitted). As one would anticipate, the JJA Williams Lake reconstruction compares well with the pJuly-June Williams Lake precipitation reconstruction (r = 0.38, n=361). Correlations between the Williams Lake JJA reconstruction and the Big Creek and Lytton annual reconstructions are 0.45 and 0.24 (p<0.05, n=361) respectively. The most notable differences between the two Williams Lake reconstructions are seen in the intervals ca. 1900-1915 (JJA wet, pJJ dry); 1790-1810 when the pJJ reconstruction shows a much more pronounced and prolonged dry interval; the early part of the 18th century when the JJA shows much drier conditions; and around 1660-1670 (JJA wetter than pJJ). The intensity of the dry interval seen in the Williams Lake JJA reconstructions in the early 18th century is more similar to that reconstructed for Lytton. Overall, the major dry periods in the Williams Lake JJA reconstruction correspond well with those identified in reconstructions from across a much larger region (see caption **Figure 9**).
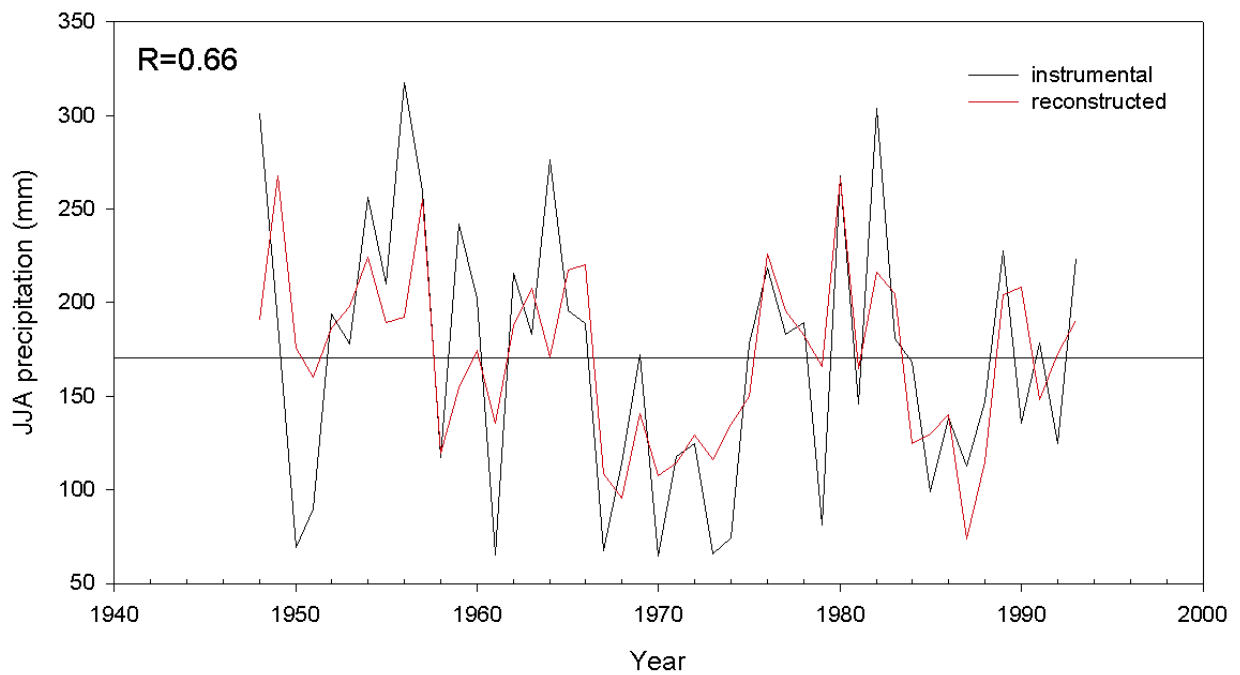
Figure 7. Actual June-August (JJA) precipitation at Williams Lake and reconstructed JJA precipitation over the calibration interval. The horizontal line is the mean of the instrumental record. The Multiple R value for the full calibration model is given in the upper left hand corner of the figure.
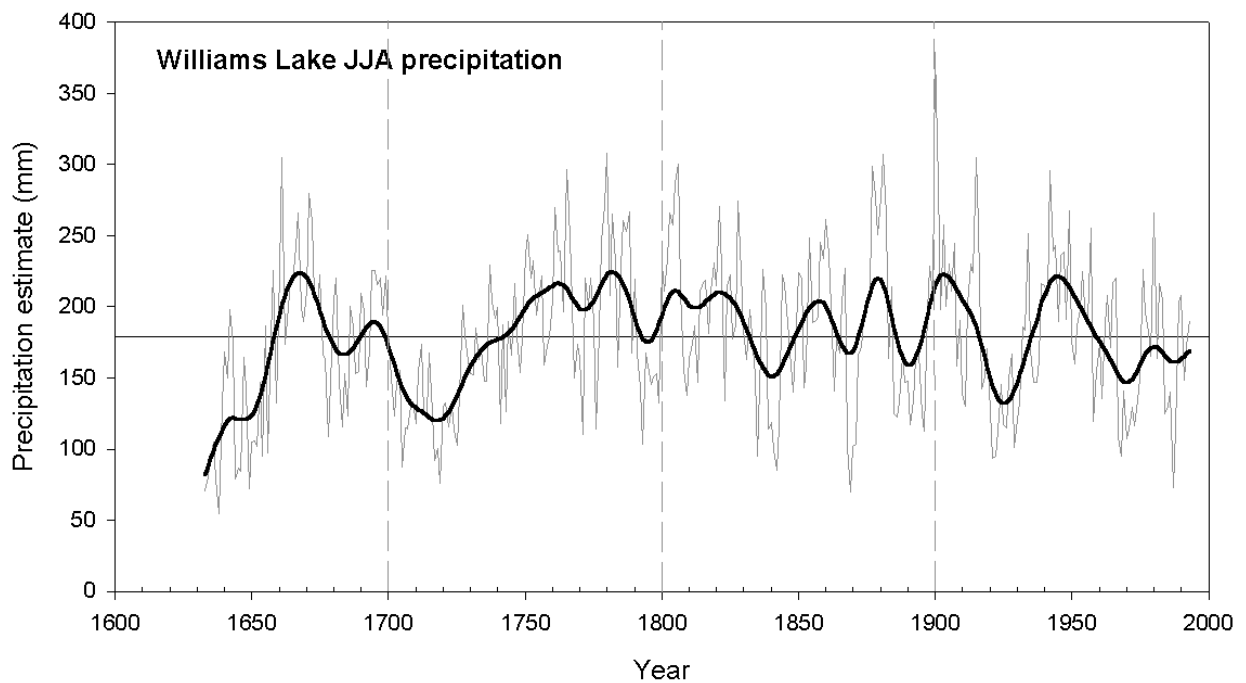

Figure 8. Reconstructed June-August precipitation for Williams Lake. The thick line fitted to the series is a 25 year smoothing spline.
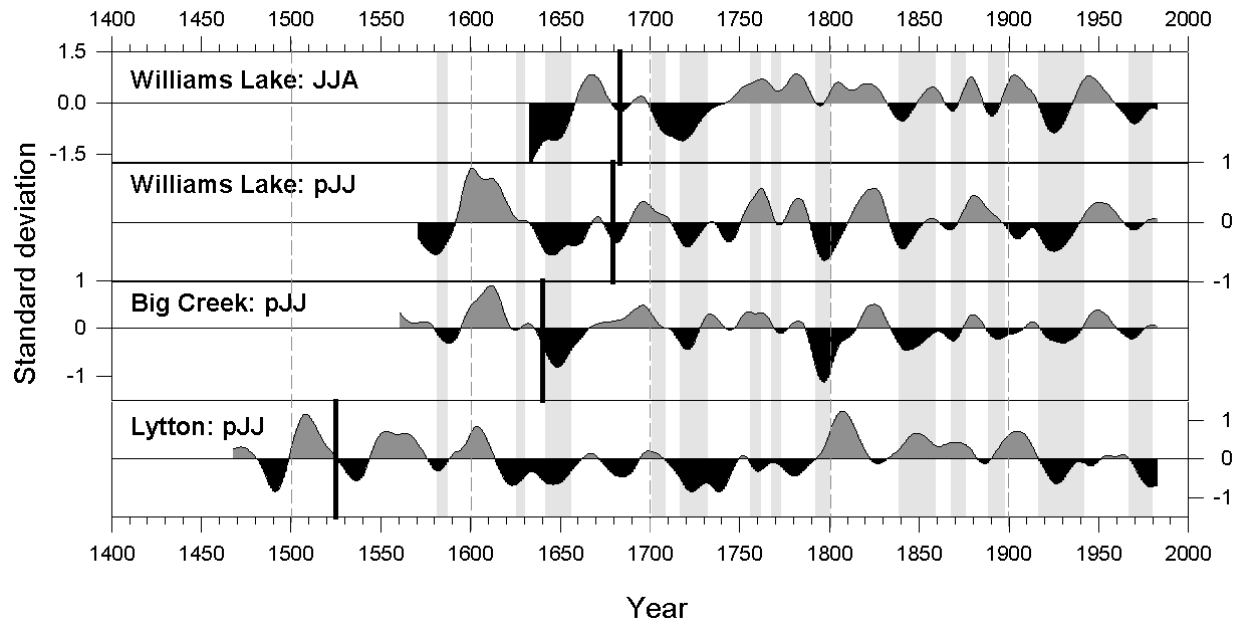
Figure 9. A comparison of the JJA Williams Lake precipitation reconstruction with selected annual (pJuly-June) precipitation reconstructions from the region (source: Watson and Luckman, submitted). All series have been converted to z-scores over their full length and smoothed with a 25 year filter. The thick vertical line in each plot indicates the first year for which the subsample signal strength (SSS; Wigley *et al*., 1984; Briffa and Jones, 1990) in the shortest chronology used as a predictor in each reconstruction exceeds 0.85. The vertical shading highlights intervals of spatially extensive dry conditions in the southern Canadian Cordillera identified by Watson and Luckman (submitted).

PART 4: FIRE IMPACTS ON STAND STRUCTURE AND DYNAMICS

A. DETERMINING YEARS OF FIRE OCCURENCE

Fire Scars

I sampled 136 scarred trees, including 119 samples from live trees, 17 from snags or coarse woody debris, 71 from Douglas-fir and 65 from lodgepole pine. Fire scars were differentiated from scars caused by mountain pine beetle or other disturbance agents using three criteria (McBride 1983, Dietrich and Swetnam 1984): (a) Scar morphology. 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 (**Figure 10**). (b) Fungal stains in the wood. The wood samples were examined to determine if they were stained by fungi. Red stain indicates fire, whereas blue stain indicates disturbance by mountain pine beetle. In this study I report only scar dates caused by fire; however some trees had been killed by mountain pine beetle as indicated by the blue stain in the wood closest to the bark. (c) Comparison of scar dates. I compared the scar dates among trees at the same site. Scars caused by a single fire have a common calendar year. Scars cause by disturbance agents other than fire (e.g., mountain pine beetle or wind throw) do not necessarily occur in the same year. For the third criterion to be effective, scars must be precisely dated at an annual resolution.

Figure 10. Examples of trees Douglas-fir (left) and lodgepole pine (right) trees sampled for fire scars. Morphological features of a fire scar include: triangular shape, low scars at the base of trees, multiple scar lobes, and charcoal may be present. The wood surrounding a fire scar is often stained red due to fungi that colonize the wood after fire. Wood that is stained blue indicates disturbance by mountain pine beetle rather than fire.

Fire Dates

Scars on cores and cross-sectional disks from live trees were visually crossdated by matching the negative marker rings from the site- and species-specific master chronologies (Yamaguchi 1991). Crossdating backwards from 1995, the outermost ring beneath the bark, determined the date of each scar. For fire scars from dead trees and/or trees for which visual crossdating was uncertain, I measured the ring-width series and used the program COFECHA to statistically crossdate the series. The ring-width series from scarred trees were compared with the site- and species-specific master ring-width series (Daniels et al. in prep.) by correlating 50-year segments overlapped by 25 years. I included only the fire scars that were dated to an annual resolution for subsequent analyses. I was unable to verify the accuracy of the fire scar dates for samples from plot 1; therefore, the fire dates for plot 1 were used to interpret fire influences on stand structure, but they were not included in the climate-fire analyses.

Seasonality of Fire Scars

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. The majority of scars were dormant-season scars, meaning the scar tip was along the boundary between two annual rings. Assigning a single year to dormant-season scars 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. I used the following criteria to determine whether dormant-season scars resulted from spring or fall burns:

    (a) I 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 I reported all dormant-season scars to be consistent with that observation.
    (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 (Veblen et al. 2000, Lertzman 2002).

Fire Record

The 136 fire scar samples yielded 280 fire dates (**Figure 11**). Most samples included one fire scar; the largest Douglas-fir samples included up to 8 scars per tree. The oldest scars were from fires in 1575 and the early 1600s, recorded by Douglas-firs in plots 6, 5 and 2. The frequency of scars per year was greatest between 1830 and 1940. Due to mortality and decay of trees, evidence of the oldest fires is lost through time (Swetnam et al. 1999, Veblen 2002). In this study, the number of fire scars and number of recorder trees declined prior to the 1830s. Few fires have burned and scarred trees since the 1940s, corresponding with cessation of burning by First Nations, changes in land use with increase grazing and industrial forestry, and effective fire suppression in the Cariboo region (Gray et al. 2002). The number of samples peaked in the 1950s (**Figure 11**) and declined since then as mountain pine beetle has caused tree mortality in several plots.

The years 1869 and 1919 stand out as major fire years when the number of scars, percent of recorder trees scarred, and number of plots that burned are considered simultaneously (**Figure 11**). In 1869, 31 trees or 39% of recorder trees were scarred and seven of the eight plots burned. In 1919, 25 trees or 24% of recorder trees were scarred, with evidence of fire in half of the plots. Fires in 1797 caused only 6 fire scars that were
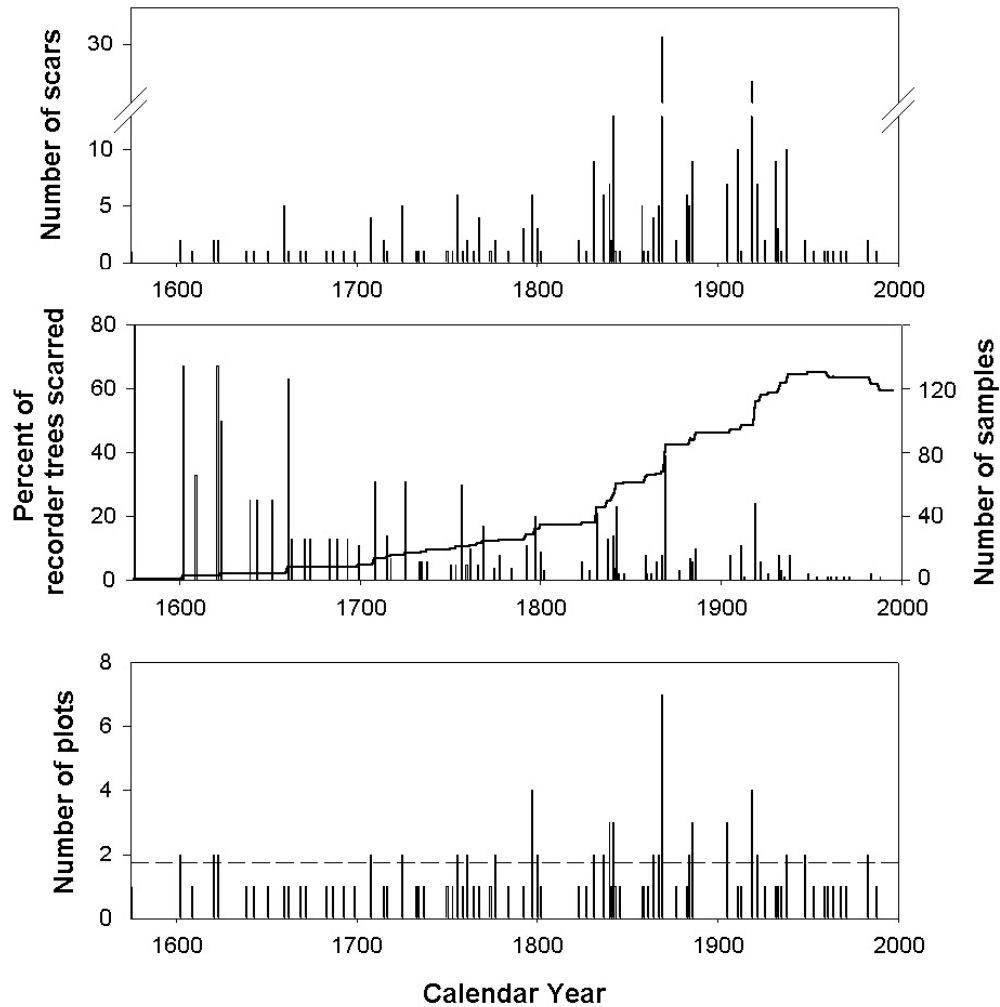
Figure 11. Fire scar dates 1600 and 1995 for all study plots (n = 280). The number of scars per year increases after c. 1850 (top), partly due to increased sample size (middle). Conversely, the percent of recorder trees scarred per year decreases as sample size increases (middle). In the bottom figure, the dashed line (bottom) separates local fires that scarred trees in only one plot from major fire years in which ≥ 2 plots burned in the study area during the same year.

sampled, however half of the plots and 20% of the recorder trees burned in that year. Conversely, eleven trees were scarred in 1911, all of which were in plot 9. The 1911 fire was significant locally, but there is no evidence that burning was wide spread. The latter two examples illustrate the need to consider multiple aspects of the fire scar record when assessing the relative impacts of fire at the stand and landscape spatial scales.

B. FIRE INTERVAL ANALYSIS
Fire Return Intervals
The return interval is an important temporal attribute that describes a disturbance regime. In this study, I have used fire scar dates to quantify the intervals between fires. Individual trees measure the interval or number of years between fires a specific point (point interval). Once scarred, trees are more likely to be scarred during subsequent fires due to the loss of bark and exposure of the cambium. Thus, trees are considered "recorder" trees only after they have been scarred by fire (Romme 1980). Fire scar data from many trees in a plot or group of plots within a designated study area are combined to calculate the composite fire interval, the number of years between consecutive fires burning the same area (Dietrich 1980). In this study, fire scars were collected from 0.09 ha study plots and the c. 1ha area surrounding the plot. I have assumed that each fire scar recorded in the plot represents a fire that burned the entire 1 ha study plot.

I developed composite fire intervals for plots 2 to 9 and for the study area (eight plots combined) using the computer program FHX2 (Grissino-Mayer 2001; **Figure 12**). For individual plots, fire intervals were analysed using all fire scars and a subset of the data that included fire years in which two or more recorder trees were scarred. The latter dataset is more conservative as it ensured that all scars included in the analyses were caused by fire. For the analyses of scar data from all plots combined, I analysed fire years in which two or more recorder trees were scarred in each plot <u>and</u> at least two plots recorded fire scars. When computing fire intervals, I included only scar-to-scar dates and excluded the interval between stand initiation and the first fire scar and the interval between the last fire scar to the present.
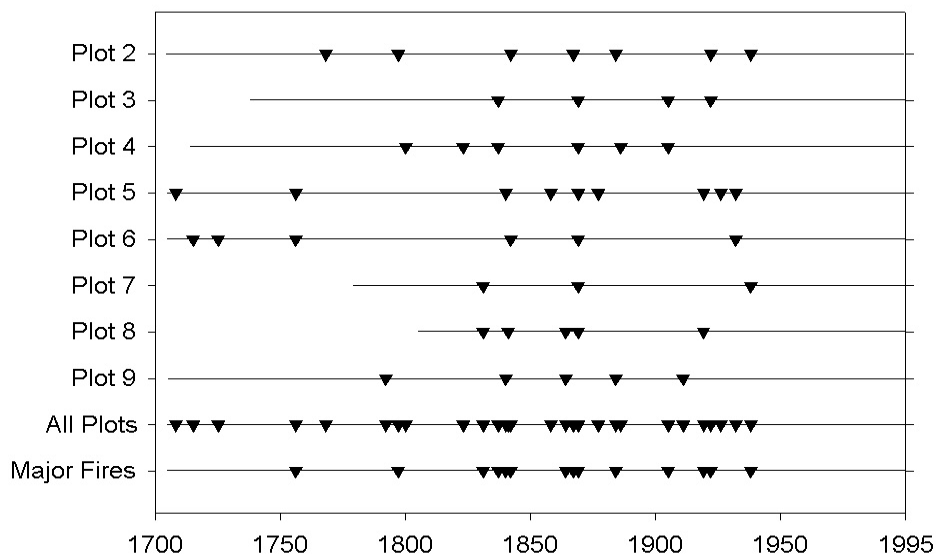
Figure 12. Fire occurrence from 1700 to 1995 at plots 2 to 9. Triangles mark the year of fires that scarred ≥2 recorder trees in each plot. Combined, there were 27 fire years (all plots); 14 of which were major fires that scarred trees at ≥2 plots.

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Mean fire interval (MFI) and the Weibull median probability interval (WMPI) were calculated from fire interval distributions (**Table 6**). MFI is average number of years between consecutive fires in the composite fire chronology (Dietrich 1980, Romme 1980). MFI assumes the interval data are normally distributed, whereas most fire interval data are positively skewed (Baker 1992) and better described by a Weibull distribution. WMPI is a measure of central tendancy 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.

Fire Intervals in the Cariboo
The longest periods of analysis were 538, 505 and 412 years for plots 6, 2 and 5, respectively, and included 47 or 48 scar dates per plot (**Table 6**). The shortest analysis period was 196 years for plot 8. Fire intervals are similar among the study plots, except plot 7. Analysis of all fire scars showed that two to 59 years separated successive fires in each plot; WMPI ranged from 13 to 22 years. At plot 7, there were only three intervals that averaged 36 years between fires. Fire intervals approximately doubled when only fires that scarred a minimum of two trees per plot were considered (**Table 6**). Fires that scar multiple trees in a plot may be more severe than fires recorded by only one tree. In general, fire frequency decreases as severity increases and the intervals between successive major fires are relatively long. Conversely, severe fires may follow long fire-free intervals. In all eight study plots, the number of years since the last fire (and major fire) exceeded WMPI. However, only in plots 2, 7, and 8 did the number of years since last fire scar exceeded the maximum interval between successive fire scars (**Table 6**). For major fires, time since last fire exceeded the maximum interval between major fires in all plots, except plots 5 and 6. In conclusion, the current fire intervals commonly exceed the natural range of variation for the study stands, indicating a change to the historic fire regime.

Table 6. Composite fire intervals for plots 2 to 9. The period of analysis and numbers of samples and trees vary among plots depending on stand age and fire history. Weibull mean fire interval (WMP) was calculated using the entire fire record for each plot. The range indicates the minimum and maximum numbers of years between successive scars in the plot. Fire interval statistics were calculated using all fire scar years and years in which at least two trees were scarred.

Plot	Period analysed	No. of trees	No. of scars	All fire scars			> 2 trees scarred			Years since fire[2]
				N[1]	WMPI (yrs)	Range (yrs)	N[1]	WMPI (yrs)	Range (yrs)	
2	1491 – 1948	19	48	22	14.7	2 - 36	6	28.2	16 - 45	48 (58)
3	1733 – 1983	12	25	13	14.7	2 - 40	3	28.8	17 - 36	13 (74)
4	1709 – 1961	14	26	10	13.2	2 - 40	5	21.0	14 - 32	35 (91)
5	1584 – 1983	25	48	22	15.7	5 - 43	8	21.3	7 - 84	13 (63)
6	1458 – 1988	14	47	19	17.1	2 - 58	6	41.9	10 - 86	8 (64)
7	1775 – 1938	10	16	3	35.7	19 - 50	2	NA	38 - 69	58 (127)
8	1800 – 1919	18	27	5	16.1	5 - 35	4	17.9	5 - 50	77 (77)
9	1690 – 1971	18	31	12	19.1	3 - 55	4	29.5	19 - 48	25 (85)

[1]N is the number of fire intervals identified for the period of analysis.
[2] Years since the last fire scar was calculated for 1995, when trees were sampled. It is followed by time since the last major fire, the last year in which at least two trees recorded a scar.

Fire Intervals and Spatial Scale
Fire intervals calculated from fire scar data will vary depending on the size of the study area. Thus, the spatial scale (e.g., plot versus landscape) corresponding with the interval values must be clearly indicated. For example, at the plot spatial scale, WMPI calculated from all fire scars were c. 15 to 20 years (n=3 to 22 intervals per plot, **Table 6**). When the data from individual plots were combined into a landscape dataset and analysed using the same statistics, WMPI was only 4.6 years (n=74 intervals). This landscape median fire interval indicates that fire burned once every 4 to 5 years *somewhere* in the study area; however, neither individual plots or the entire study area burned that frequently.

C. FIRE IMPACTS ON THE CARIBOO FOREST

Composition and Size Structure
Species composition of stands was variable. Plot 1 was comprised of Douglas-fir; plots 3, 7, and 8 were lodgepole pine dominated stands with few Douglas-fir dispersed in the surrounding forest; and, plots 2, 4, 5, and 9 included both Douglas-fir and lodgepole pine in all canopy strata. Hybrid spruce was present in the understory and/or subcanopy of plots 2 and 3.

The density of understory, subcanopy and canopy trees was calculated for each species (**Table 7**). Canopy tree density ranged from 22 to 64 per 0.09 ha plot (240 to 710 per ha) and subcanopy trees were 18 to 54 per plot (200 to 600 per ha). In plots 1,3 and 4, canopy density (60 to 64 trees) was about twice that of subcanopy trees (33 to 35 trees). A plot 7, the subcanopy (54 trees) was denser than the canopy (38 trees), while the subcanopy and canopy densities were similar in plots 2, 5,6, 8 and 9.

The largest Douglas-fir tree measured 78.9 cm in diameter at breast height; the largest lodgepole pine was 50.6 cm (**Table 7**). Tree diameters were grouped into 5 cm size classes from 5 to 80 cm (**Figure 13**). The 5 cm class width served two purposes: (1) it differentiated the subcanopy trees (5-10 cm) from the canopy trees (>10 cm) and (2) it resulted in 15 classes making the size and age distributions for the stands directly comparable. In all plots, the diameter distributions conformed to the reverse-J or negative exponential distribution. The number of trees was greatest in the subcanopy size class and generally decreased as size increased. Discrete groups of trees that may represent a cohort of similar-aged individuals could not be identified from the diameter distributions (**Figure 13**).

To determine if fire suppression has had an impact on forest structure, I calculated correlations between stand density (canopy trees, subcanopy trees, understory Douglas-fir and lodgepole pine) and the number of years since last (major) fire. These tests indicated that forest density may be increasing in absence of fire, but the correlations were not statistically significant and sample size (n=9) was too low to draw meaningful conclusions. Preliminary results showed that the density of canopy and subcanopy trees were positively correlated with the number of years since the last fire (r=0.24, p=0.53 and r=0.32, p=0.40, respectively), with stronger correlations with time since the last major fire (n=9, r=0.42, p=0.26 and r=0.59, p=0.10, respectively). The density of understory Douglas-fir was negatively correlated with time since fire (r = -0.38, p = 0.31 for major fires). Additional data are needed to test the impacts of fire suppression on stand structure.

Table 7. Tree population structure for Plots 1 to 9. Understory trees (dbh<5cm) were sampled in five randomly located 4m² quadrats; the mean (standard deviation) indicates the number of individuals per 0.09 ha plot. All subcanopy (dbh 5-10 cm) and canopy trees (dbh > 10cm) in 0.09 ha plots were measured. Summaries of diameter at breast height (DBH) are for subcanopy and canopy trees combined.

Plot	Species	Understory			Subcanopy trees			Canopy trees			DBH (cm)		
		Density mean (sd)	Age range (years)	Pith date (calendar years)	Live	Snags	Aged	Live	Snags	Aged	Min.	Max.	Mean (sd)
1	D-fir	180 (402)	89-111	1885-1907	33	0	14	60	0	54	5	50	16 (12)
2	D-fir	1125 (1019)	36-61	1935-60	36	0	15	32	0	27	5	73	20 (20)
2	L. pine	45 (101)		1957-60	0	0	–	3	0	1	14	25	18 (6)
3	D-fir	–	–	–	0	0	–	3	0	3	12	14	13 (1)
3	L. pine	405 (433)	36-39	1932-57	31	2	10	59	1	40	5	43	18 (10)
3	Spruce	–	–	–	3	0	3	0	0	–	7	8	7 (0.5)
4	D-fir	1530 (1664)	50-72	1924-46	28	1	11	57	3	27	5	77	20 (17)
4	L. pine	–	38-66	1930-58	6	0	4	6	0	2	5	24	12 (6)
4	Spruce	–	–	–	1	0	1	1	0	1	5	22	14 (12)
5	D-fir	1923 (2060)	57-77	1919-39	15	0	8	14	0	11	5	72	20 (19)
5	L. pine	135 (401)	35-77	1919-61	12	3	12	20	1	18	5	27	13 (6)
6	D-fir	225 (318)	69-82	1914-27	6	0	6	11	0	8	5	78	39 (29)
6	L. pine	135 (201)	36-60	1936-60	12	0	12	11	1	8	5	32	13 (8)
7	L. pine	765 (922)		1906-43	54	0	15	38	1	23	5	32	14 (10)
8	L. pine	1710 (936)		1943-56	24	3	9	36	0	27	5	51	15 (10)
9	D-fir	1440 (1481)	52-65	1931-44	20	0	8	7	0	4	5	79	19 (25)
9	L. pine	–	21-55	1941-75	13	2	6	17	3	13	6	38	13 (7)
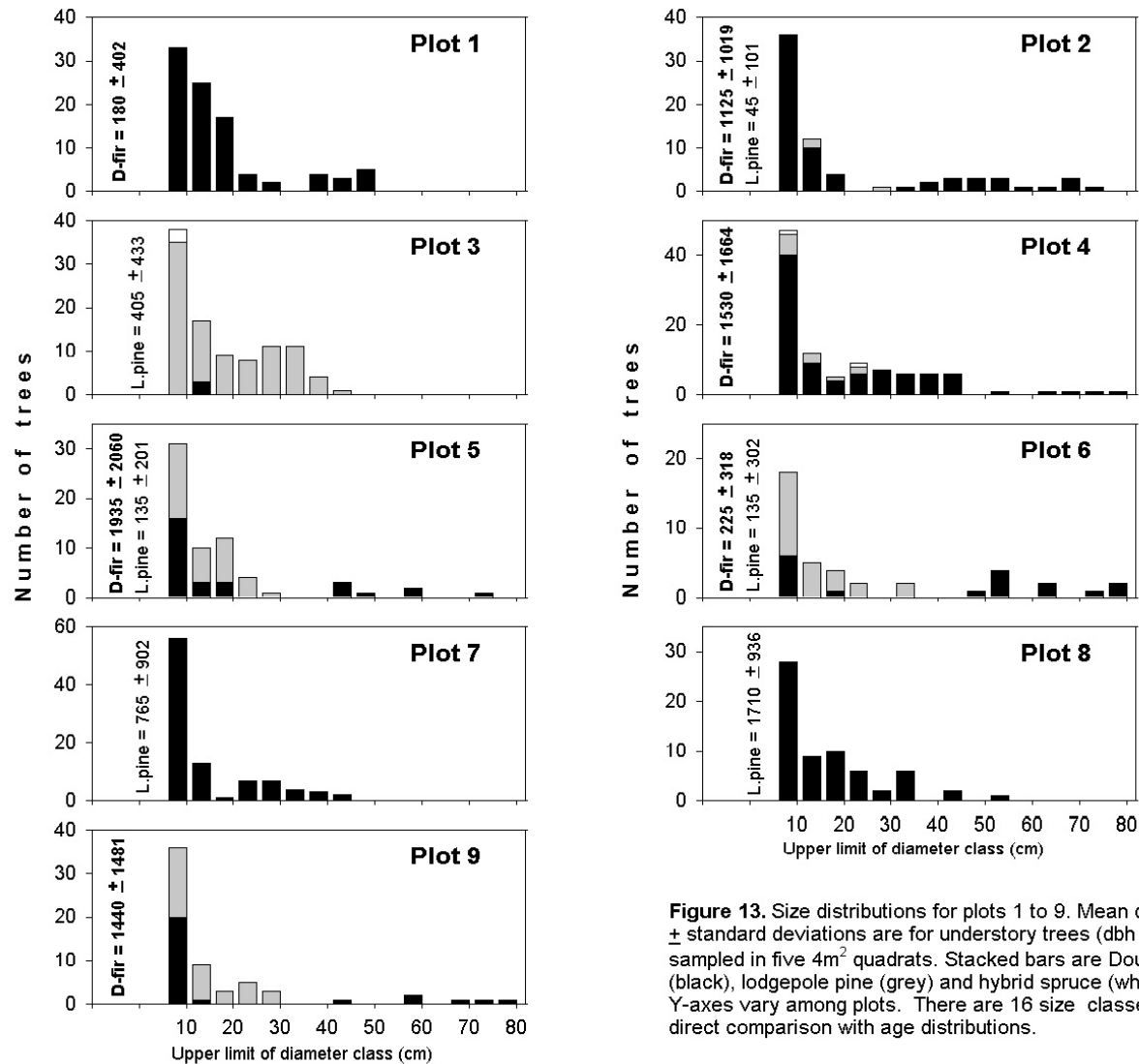
Figure 13. Size distributions for plots 1 to 9. Mean density ± standard deviations are for understory trees (dbh <5cm) sampled in five 4m^2 quadrats. Stacked bars are Douglas-fir (black), lodgepole pine (grey) and hybrid spruce (white). Y-axes vary among plots. There are 16 size classes for direct comparison with age distributions.

D. FIRE INFLUENCES ON AGE STRUCTURE AND TREE GROWTH

Determining Tree Age – A Three-Step Process

Tree ages and static age structures are used to study tree population dynamics and to estimate the date of past disturbances and anthropogenic impacts on forests (Lorimer, 1985; Veblen, 1992). High quality age data from individual trees and from populations are critical for quantifying temporal aspects of change in forests. For example, my research objective is to relate tree regeneration patterns to year-to-year climatic fluctuations and discrete disturbances such as fire. To achieve this objective, tree ages must be determined with high level of accuracy. Data on tree ages are derived from increment core samples or stem cross-sections extracted from trees. However, there are limitations to the accuracy of age data derived from both types of samples. Several strategies have been developed to address three primary sources of error and to increase accuracy of age estimates (Norton and Ogden, 1990; Wong & Lertzman, 2001), including the following:

> (1) Tree rings are visually and/or statistically crossdated to identify false and missing rings and to ensure that the accurate calendar year is assigned to each tree ring (Fritts, 1976; Holmes, 1986; Yamaguchi, 1991).
> (2) Because of asymmetrical growth, heartwood decay, and large size of some stems, increment cores may not intercept the pith (tree centre) of the radius sampled. For cross-sections with heartwood decay, the pith may not be present. Thus, the number of rings to the pith that are missing must be estimated using graphical or geometric methods (Norton, Palmer & Ogden, 1987; Duncan, 1989; Stephenson & Demetry, 1995; Villalba & Veblen, 1997a, 1997b).
> (3) Increment cores and cross-sections are difficult to extract at the root-shoot interface of the stem tissue. Typically, samples are extracted from the stem as close to the ground as possible, and a correction factor for the number of years for the tree to grow to sampling height is added to the number of rings to determine age. Corrections may be estimated from cores sampled at ground level and at a standard sampling height for a subset of trees (Henry & Swan, 1974; Wong & Lertzman, 2001) or from seedling and sapling height-growth rates (Romme & Knight, 1981; Veblen et al., 1991; Daniels et al. 1995; Villalba & Veblen, 1997a, 1997b; Mast, Veblen & Linhart, 1998; Wong & Lertzman, 2001).

In this study, I determined tree ages using a three-step process. First, all increment cores and disks were visually crossdated to ensure that their ring-width patterns matched the narrow marker rings in the species- and site-specific master ring-width chronologies (Daniels et al. 2003). This step determined the calendar year of the pith or inner-most ring for cores that did not intercept the pith (Fritts 1976, Yamaguchi 1991). Second, I estimated the number of rings missing for cores that did not include the pith by measuring the geometric dimensions of the rings closest to the pith to calculate the number of missing rings (Duncan 1989).

In the third step, I estimated the number of years for each sampled tree to grow to sampling height, the height from which the increment core was extracted (Villalba and Veblen 1997, Wong and Lertzman 2001). The rings on discs from seedlings and saplings were counted to estimate total age and age at heights 10 to 70 cm above the ground (**Figure 14**). Linear regressions of age-on-height for each species were used to calculate estimate the number of years for trees to grow to sample height. This
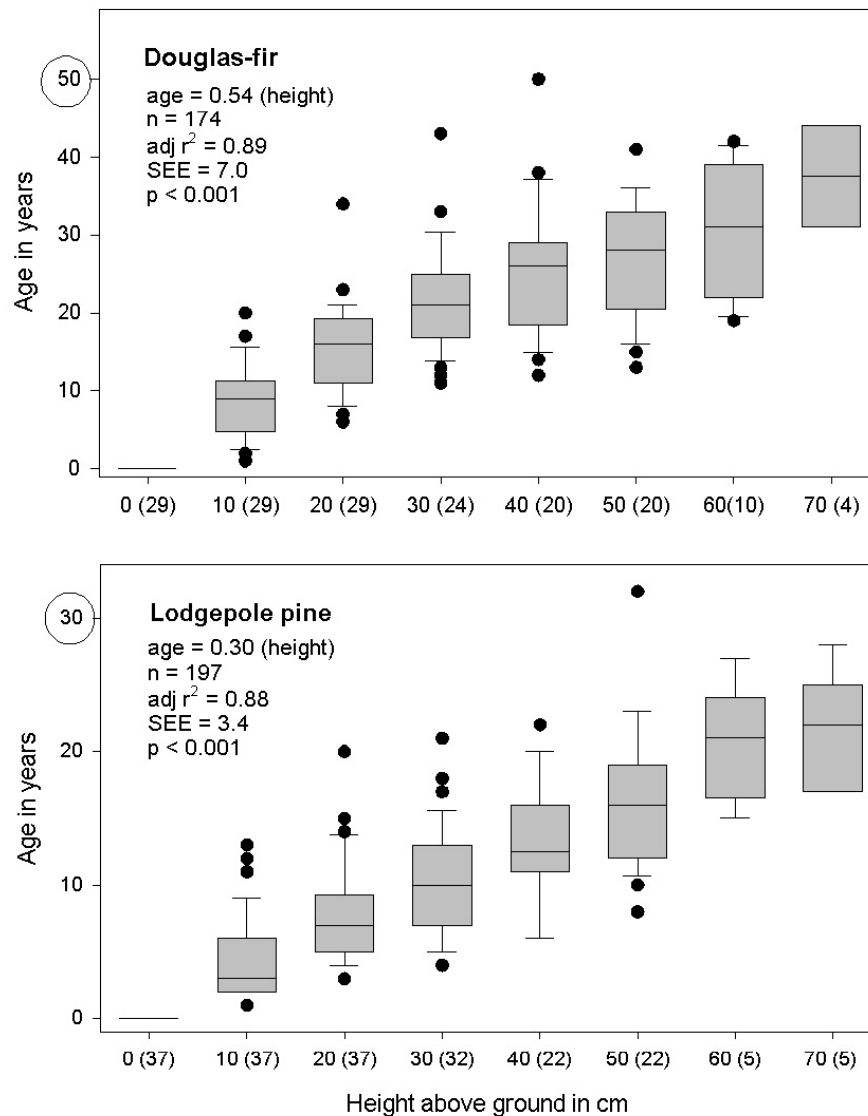
Figure 14. Species-specirfic age corrections for sample height. Seedling age distributions include ages determined at ground level and 10 to 70 cm above the ground. Median age is represented by the horizontal line in each box; the box represents the 25th to 75th percentiles; bars represent the 10th and 90th percentiles. Sample sizes are in parentheses along the x-axis. Note, y-axis differ between plots.

regression approach assumes that contemporary seedlings and saplings are growing at rates similar to the initial growth rates of the sampled trees, which proved to be untrue. I tested this assumption by comparing the width of rings closest to the pith between the understory and trees. Trees were categorized as slow growing if the rings closest to the pith were narrower than the average ring-width over the lifespan of the tree; fast-growing trees had wide rings closest to the pith. Ring-widths (growth rates) of seedlings were less than the ring-widths of slow- and fast-growing trees (**Figure 15**), providing over-
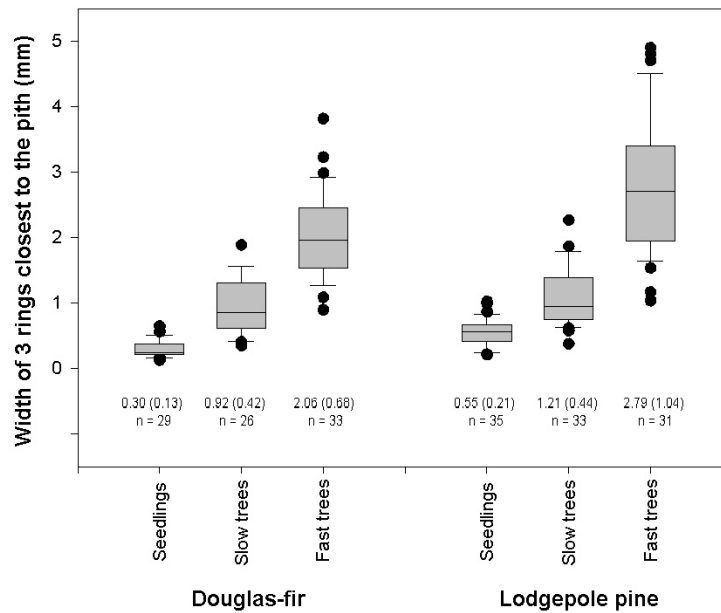
Figure 15. Comparison of initial growth rates of contemporary understory trees (seedlings) with canopy trees with narrow rings near the pith (slow) and wide rings (fast). Median age is represented by the horizontal line in each box; the box represent the 25th and 75th percentiles, bars reperesent the 10th and 90th percentiles. Means (standard deviations) and sample size are along the x-axis. I used these data to determine weighting factors to correct tree growth rates to sample height.

estimates of the years to sample height for trees. Thus, the ratio of the tree-to-seedling growth rates was used to adjust the regression outcomes and more accurately estimate the number of years for the tree to grow to sample height. The species- and growth-specific correction equations were:

Douglas-fir, slow initial growth: age correction (years) = 0.54 (height in cm) / (0.92/0.30)

Douglas-fir, fast initial growth: age correction (years) = 0.54 (height in cm) / (2.06/0.30)

Lodgepole pine, slow initial growth: age correction (years) = 0.30 (height in cm) / (1.12 /0.55)

Lodgepole pine, fast initial growth: age correction (years) = 0.54 (height in cm) / (2.79/0.55)

The age assigned to each tree was calculated as follows:

age = (1995 – pith year + 1) + (correction for rings to pith) + (correction for sample height)

For cross-sections and cores that intercepted the pith, the correction for rings to pith was zero. The correction for sample height was applied to disks and cores and generally was lower for disks since they were cut as close to ground level as possible.

Assessing Quality of Age Data
Combined, the age corrections for missed piths and sample height ranged from zero to 65 years (**Figure 16**). I tested the quality of the age data for biases related to species, canopy class and presence/absence of the pith. Kruskal-Wallis one-way analysis of variance on ranks and pairwise multiple comparisons using Dunn's method (Jandel 1992) differentiated to groups of trees according to age corrections (H = 320, d.f. = 7, p < 0.001). In group 1, age corrections were 0 to 2 years for subcanopy trees (Douglas-fir and lodgepole pine) and lodgepole pine canopy trees that included the pith. Sampling error was low since cross-sections were cut from the base of subcanopy trees close to the ground and many canopy lodgepole pine had fast initial growth rates. Group 2 included trees that were sampled with increment cores that missed the pith and canopy Douglas-fir trees for which cores intercepted the pith. The greatest corrections were for large canopy trees that missed the pith. Within this group, the age correction was not significantly correlated with tree age (r = 0.09, n = 206, p < 0.20), therefore no bias is introduced to the data by eliminating 18 age estimates with corrections that exceeded 20 years. Since 75-100% of the age corrections were less than 20 yearsfor all categories of trees (**Figure 16**), I selected a class width of 20 years to represent the age structure of the nine study plots.
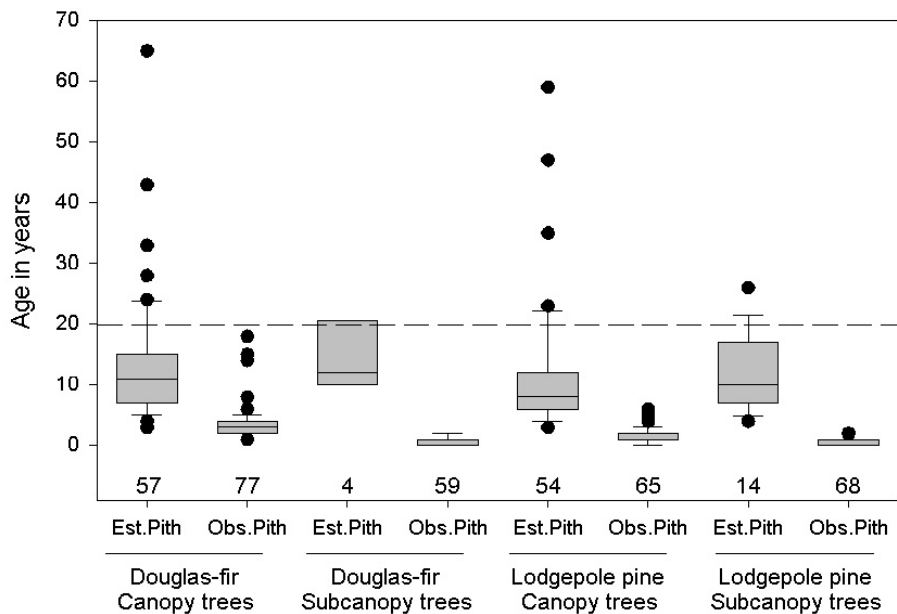
Figure 16. Age corrections for sample height and missed piths. Trees are categorized by type of sample (pith estimated or observed), species and canopy position. Median age is respresented by the horizontal line in each box; the box represents the 25th and 75th percentiles; bars represent the 10th and 90th percentiles. The majority of age corrections were <20 years (dashed line); ages with corrections >20 years were eliminated from subsequent analyses. Sample sizes are along the x-axis.

Age Structures

The oldest Douglas-fir and lodgepole pine trees were 444 (pith=1552) and 229 (pith=1767) years respectively. On average, 45% of subcanopy trees and 75% of canopy trees were aged per site. The youngest trees in the plots were 36 to 70 years and established between 1926 and 1960. Seedling and sapling ages were not included, thus the age distributions were arbitrarily truncated because I aged only trees with diameters >5 cm at breast height.

The age structures of the sampled trees (**Figure 17**) showed three general patterns. In all plots, the modal age class was less than 120 years. Plots 1, 3 and 7 included trees with a broad range of ages, with several trees per class in many age classes greater than 120 years. Plots 2 ,5, 6, 8, and 9 had distinct cohorts <120 years, plus old Douglas-fir and lodgepole pine veterans. In plots 2, 5, and 6, the oldest trees were greater than 320 years, however they did not form a distinct cohort. Rather, no more than two trees were in the same age class at any given site. The age structure of plot 4 was bimodal. A cohort of canopy-dominant Douglas-fir established between 1766 and 1806 and a second cohort established 61 to 100 years ago.
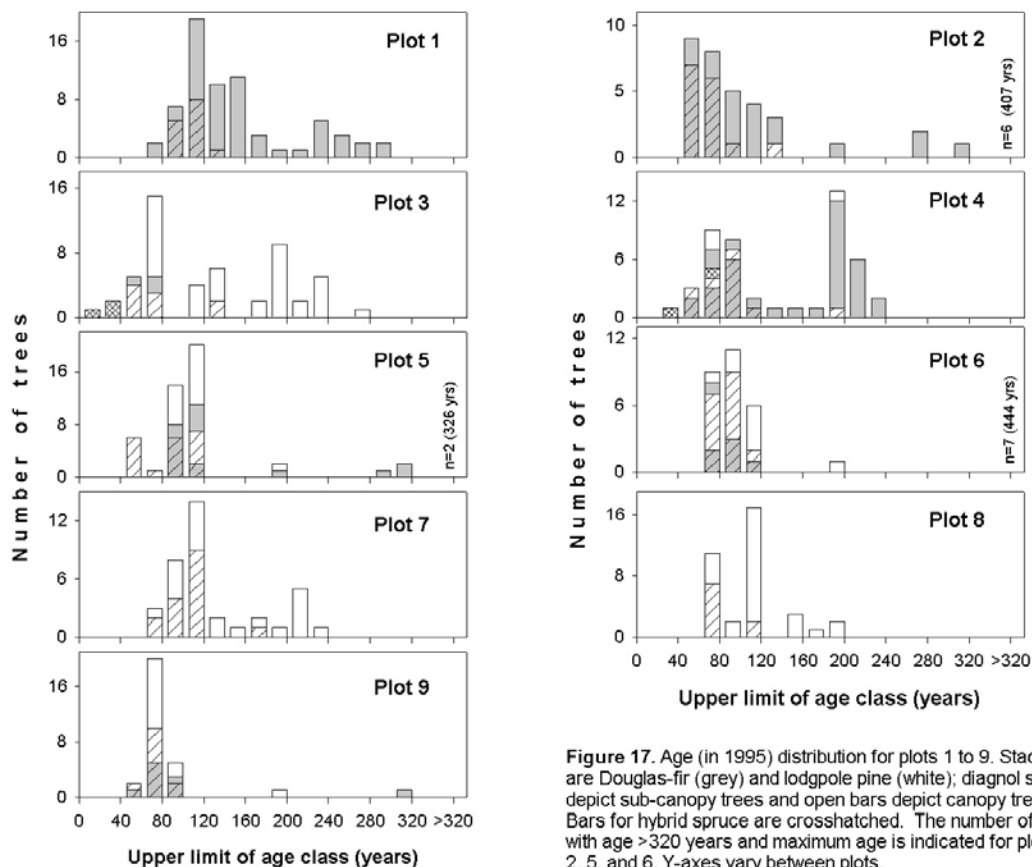
Figure 17. Age (in 1995) distribution for plots 1 to 9. Stacked bars are Douglas-fir (grey) and lodgepole pine (white); diagnol strips depict sub-canopy trees and open bars depict canopy trees. Bars for hybrid spruce are crosshatched. The number of trees with age >320 years and maximum age is indicated for plots 2, 5, and 6. Y-axes vary between plots.

Tree Radial-Growth Histories

Increment cores and disks from all subcanopy and canopy trees were assessed to document changes in radial growth through time. Initial growth was described as "fast" or "slow". Trees were categorized as fast-growing if the rings closest to the pith were wide relative to the average ring-width over the lifespan of the tree. Fast-growing trees commonly establish following major stand-level disturbances that create open growing space with little competition from existing overstory trees. Narrow rings closest to the pith suggest slow growth. Slow-growing trees likely established beneath an existing canopy layer and were suppressed.

Periods of suppression and release were identified for all subcanopy and canopy trees. All increment cores and disks were visually assessed starting from the pith toward the bark to identify abrupt changes in growth that were sustained at least 10 years. For all abrupt decreases in growth, I measured the width of first ten narrow rings and the width of the ten rings that preceded the onset of suppression (control rings). The ratio of narrow-to-control rings indicated the magnitude of suppression; only suppression of at least a 1.5-fold decrease in ring width were used in subsequent analyses. The calendar year of the first narrow ring indicated the timing of the suppression. Of 238 suppressions in 401 trees, the median magnitude of suppression was 2.24-fold (**Figure 18**). I ranked the magnitude of suppression as follows:

Minor suppression:	< 25th percentile, magnitude of 1.5 to 1.88
Moderate suppression:	26th to 75th percentiles, magnitude 1.89 to 2.80
Major suppression:	>76th percentile, magnitude $\leq$ 2.81

For all increases in growth, I measured the width of the first ten wide rings and the width of the ten rings that preceded the onset of the release (control rings). The ratio of wide-to-control rings indicated the magnitude of release; only releases of at least 1.5-fold increase in ring width were used in subsequent analyses. The median magnitude of 214 releases was 2.34 (**Figure 18**). I ranked the magnitude of release as follows:

Minor release:	< 25th percentile, magnitude of 1.5 to 1.95
Moderate release:	26th to 75th percentiles, magnitude 1.96 to 2.98
Major release:	>76th percentile, magnitude $\geq$ 2.99

The frequency of suppressions and releases per 20-year age class were calculated and compared with other age data for each plot (**Figures 19 to 27**).

E. FIRE INFLUENCES ON STAND DYNAMICS

Fire disturbances clearly influence the age structure and dynamics of the forests in the Cariboo study area. Processes related to stand initiation, tree establishment in relation to fire, and stand development are evident in the fire history and stand dynamics diagrams (**Figures 19 to 27**). In general, fires were low-severity, stand-maintaining fires rather than high severity stand-initiating disturbances. As a result, the oldest trees in each plot were uneven-aged veterans. Only one distinct cohort of trees had established prior to 1800 (plot 4, **Figure 22**); however, these Douglas-fir trees were grew slowly at first. Slow initial growth suggests that the trees established beneath an existing canopy rather than forming a post-fire, stand-initiating cohort. In contrast, the oldest trees in plot 7 were a
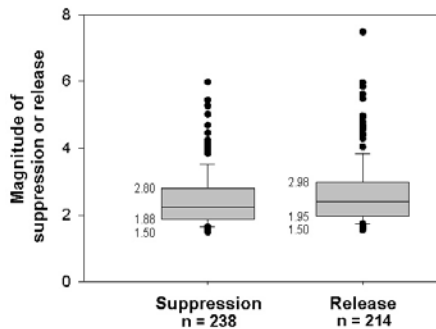
cohort of fast-growing lodgepole pine established in the late 1700s, possibly following a stand-replacing fire (**Figure 25**). Plot 9 best represents a stand that primarily initiated after fire. With the exception of two veterans, trees in plot 9 established after consecutive, major fires in 1883 and 1911. The 1883 fire caused moderate and major suppression of the veteran trees. The 1911 fire was locally severe, scarring 10 of 17 (59%) recorder trees sampled from the forest surrounding the plot. All canopy and subcanopy trees (except the veteran trees) established within 15 years of the 1911 fire.

Figure 18. Magnitude of suppression and release for trees showing at least a 1.5-fold change (decrease or increase, respectively) in ring width. Median magnitude change is represented by the horizontal line in each box. The box, bound the 25th and 75th percentiles, represent moderate changes. Observations below the 25th percentile represent minor changes. Observations above the 75th percentile represent major changes.

Stand-maintaining fires commonly burned during the 19th century and the early part of the 20th century with direct affects on the age structure and tree growth in most plots. During periods of relatively frequent, major fires (e.g. 1769-1858 in plot 1, **Figure 19**; 1733-1938 in plot 2, **Figure 20**; 1837-1922 in plot 3, **Figure 21**; 1837-1905 in plot 4, **Figure 22**;1840-1869in plot 5, **Figure 23**; 1832-1869 in plot 8, **Figure 26**; and 1864-1911 in plot 9, **Figure 27**), tree establishment and survival were limited. In some cases no trees established and survived over periods of 30 to 90 years when multiple fires burned. During these periods, young trees would be particularly susceptible to fire until they had grown thick, fire-resistant bark. Established trees that survived the fires exhibited both suppressions and releases following distubance. Damaged trees may undergo suppression after fire. Other trees may release, benefiting from increased above- and below-ground resource availability and decreased competition following fires that cause some tree mortality.

Five of the nine plots (plots 1 to 4, and 7; **Figures 19-22 and 25**) included trees with a range of ages and a cohort that established during the 20th century. The subcanopy and, in some cases, much of the canopy of these plots developed since the last major fire. All five plots have burned since the last major fire; the recent fires facilitated establishment of some fast-growing trees during the 1900s. The high frequency of suppression and release since c. 1900 is likely caused by recent fires, combined with stand development processes. With high tree density, the canopy closes and competition between trees increases, causing radial growth rates to be suppressed. Concurrently, within-stand disturbances such as windthrow or mountain pine beetle cause mortality of some trees but increase resources to other trees, explaining many recent releases.

At plots 5, 6 and 8, cohorts of 15 to 30 trees established following fires in the late 1800s. Those trees survived fires during the 20th century, including three major fires between 1919 and 1933 in plot 5, and now dominate the plot canopies. Trees that have established since 1900 generally occupy the subcanopy. Crown closure and competition explain growth suppressions during the mid to late-20th century at these three plots.
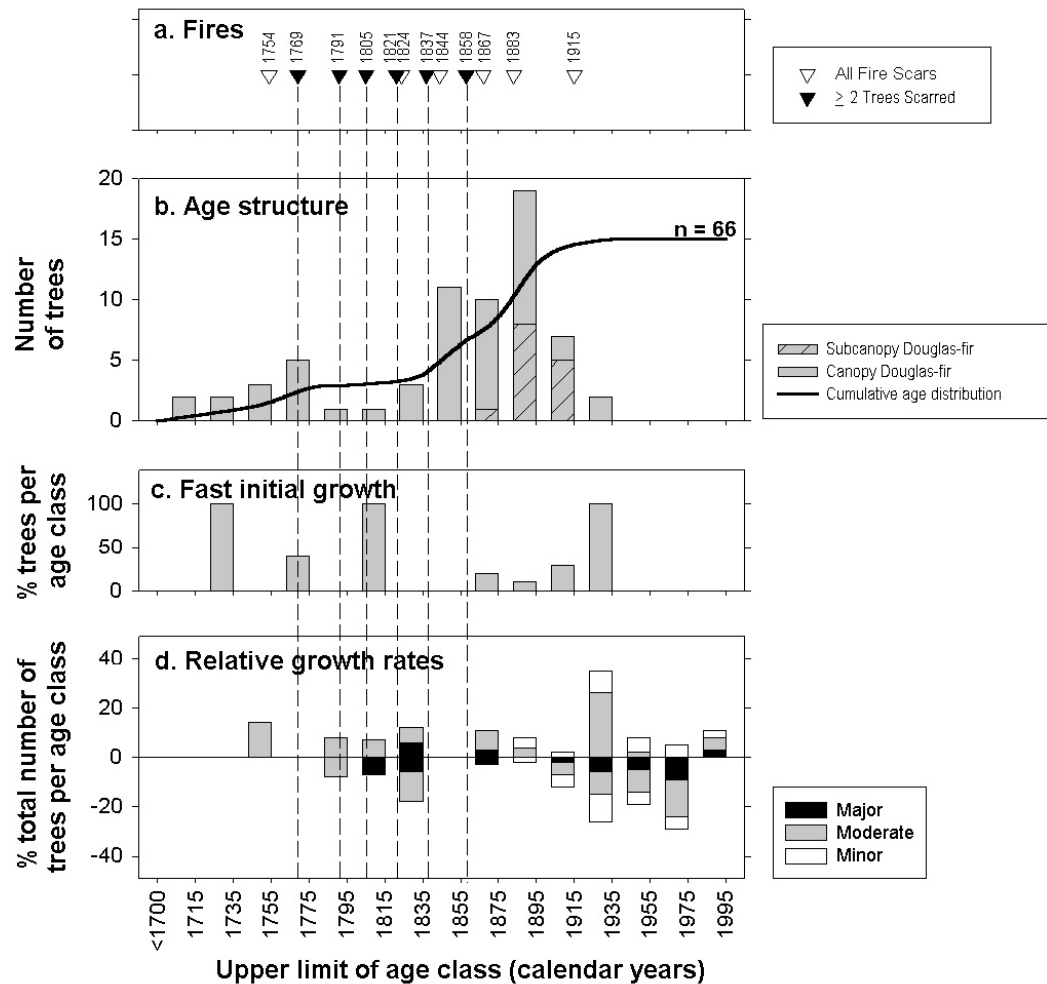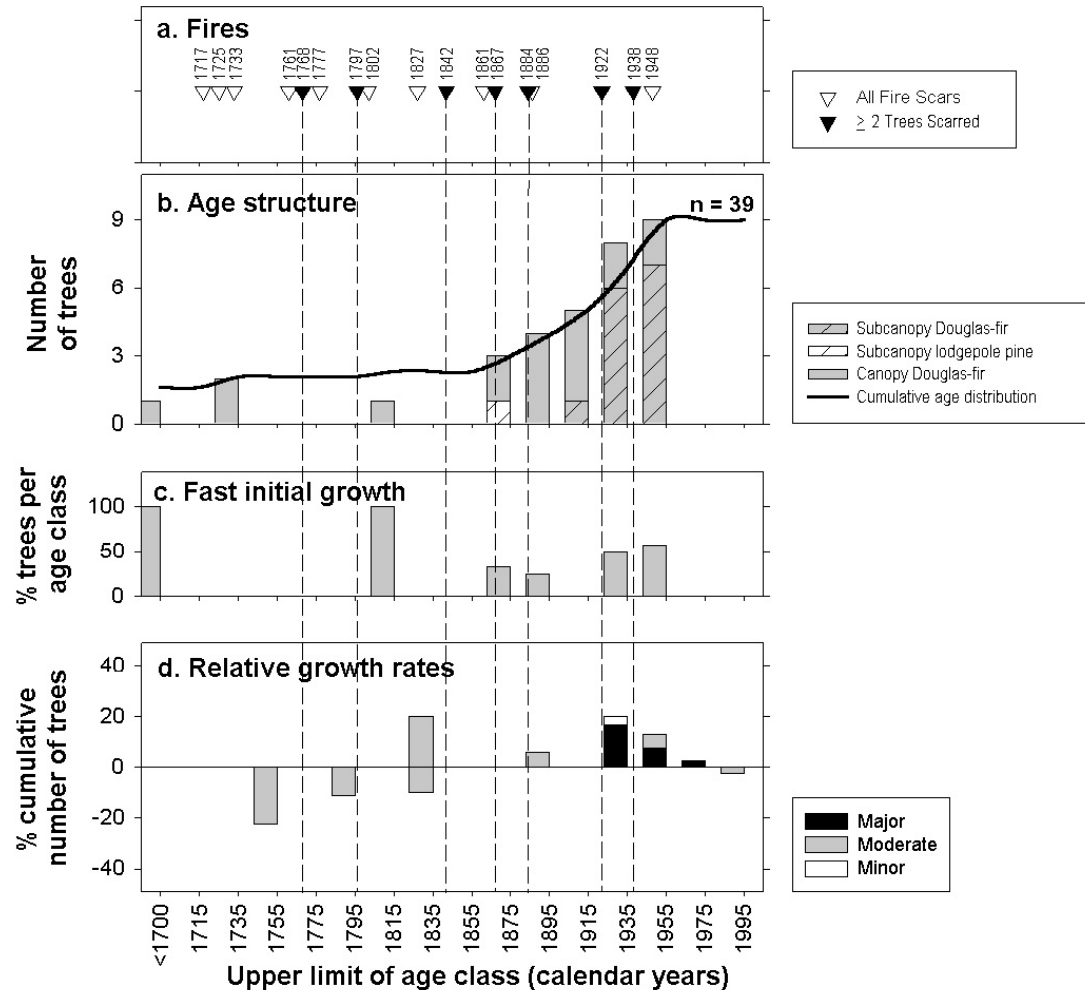
Figure 19. Fire history (a) and stand dynamics (b to d) of Plot 1. (a) Triangles indicate fire scars and major fires (black) that scarred at least 2 trees. Vertical lines mark major fire years. (b) Bars represent the frequency of trees in 20-year age classes for subcanopy (hatched) and canopy (no pattern) trees of Douglas-fir (grey). There were no lodgepole pine. The superimposed line shows the cumulative age distribution for 66 live trees. (c) Bars depict the percentage of trees in each age class with wide rings close to the pith indicating fast initial growth. The cumulative age distribution (b) was used to calculate the percentage of trees that released or became suppressed during each 20-year period (d). Positive departures show the percentage of live trees that released; negative departures indicate suppressions. See text for criteria differentiating major (black), moderate (grey) and minor (white) growth releases and suppressions.
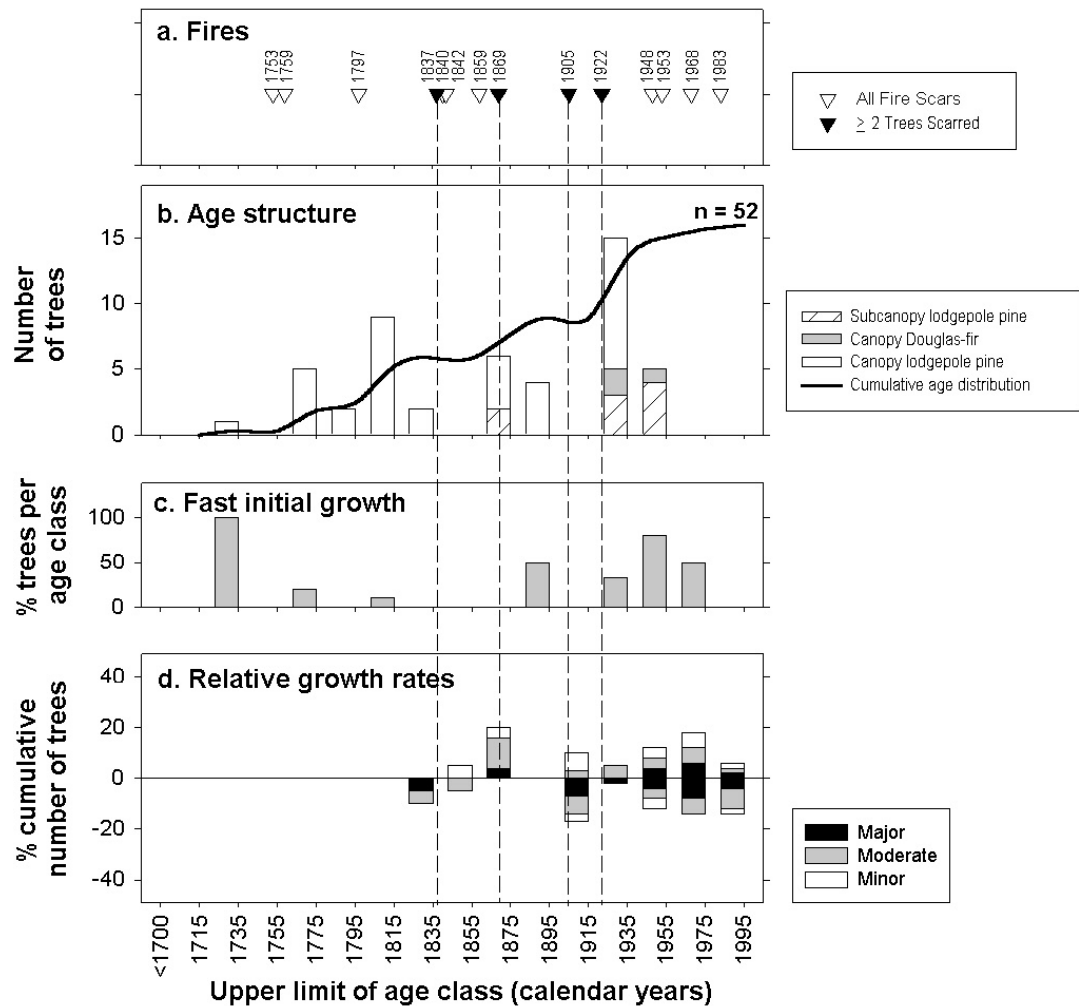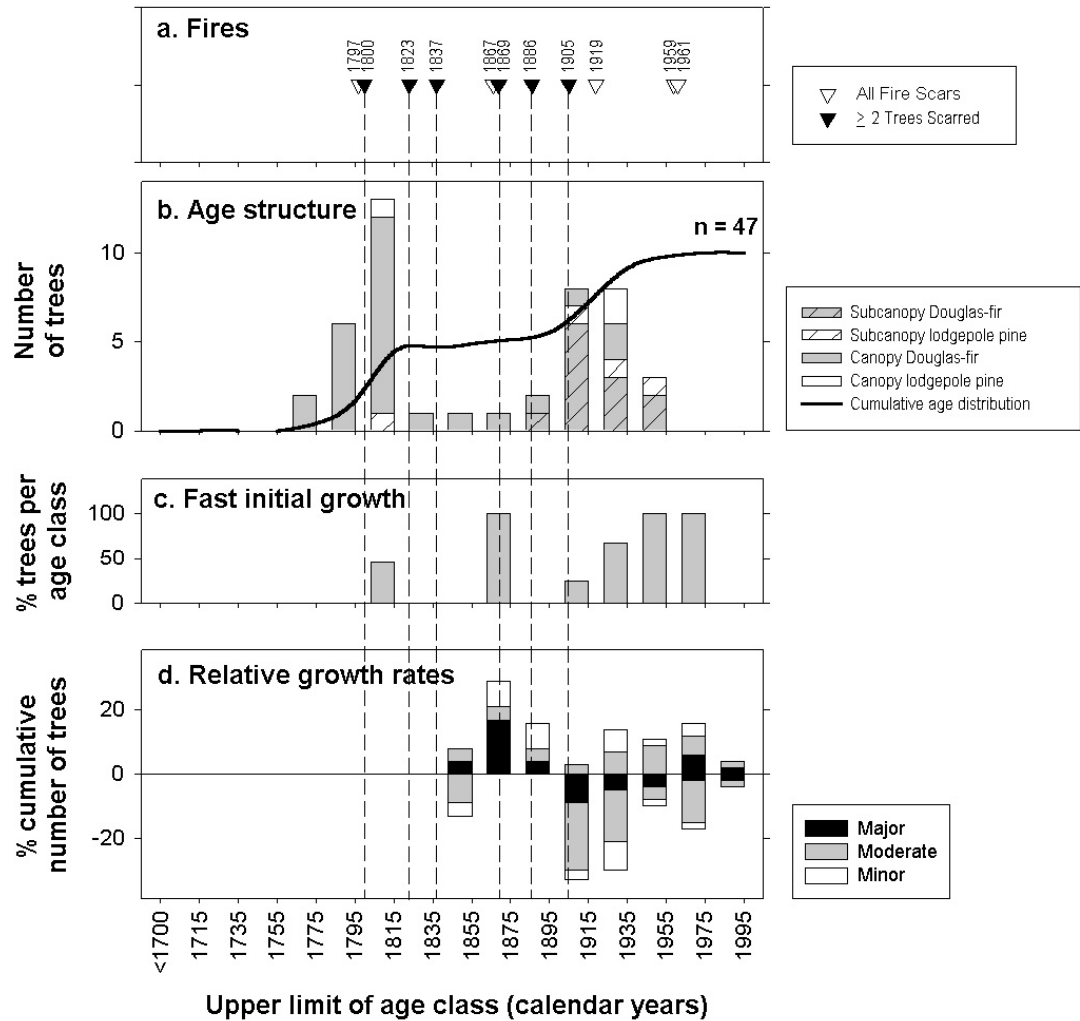
Figure 20. Fire history (a) and stand dynamics (b to d) of Plot 2. (a) Triangles indicate fire scars and major fires (black) that scarred at least 2 trees. Vertical lines mark major fire years. (b) Bars represent the frequency of trees in 20-year age classes for subcanopy (hatched) and canopy (no pattern) trees of Douglas-fir (grey) and lodgepole pine (white). The superimposed line shows the cumulative age distribution for 39 live trees.

(c) Bars depict the percentage of trees in each age class with wide rings close to the pith indicating fast initial growth. The cumulative age distribution (b) was used to calculate the percentage of trees that released or became suppressed during each 20-year period (d). Positive departures show the percentage of live trees that released; negative departures indicate suppressions. See text for criteria differentiating major (black), moderate (grey) and minor (white) growth releases and suppressions.

Figure 21. Fire history (a) and stand dynamics (b to d) of Plot 3. (a)Triangles indicate fire scars and major fires (black) that scarred at least 2 trees. Vertical lines mark major fire years. (b) Bars represent the frequency of trees in 20-year age classes for subcanopy (hatched) and canopy (no pattern) trees of Douglas-fir (grey) and lodgepole pine (white). The superimposed line shows the cumulative age distribution for 52 live trees.

(c) Bars depict the percentage of trees in each age class with wide rings close to the pith indicating fast initial growth. The cumulative age distribution (b) was used to calculate the percentage of trees that released or became suppressed during each 20-year period (d). Positive departures show the percentage of live trees that released; negative departures indicate suppressions. See text for criteria differentiating major (black), moderate (grey) and minor (white) growth releases and suppressions.
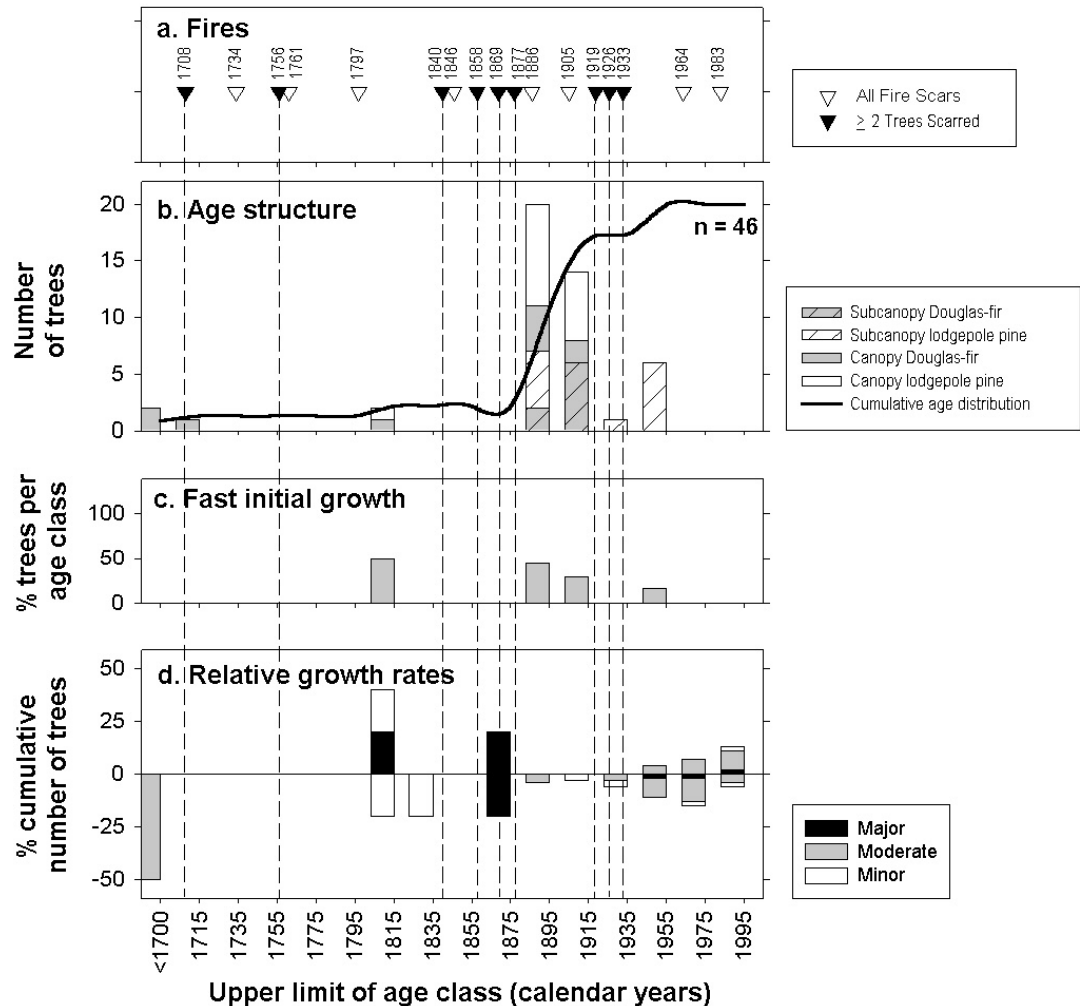
Figure 22. Fire history (a) and stand dynamics (b to d) of Plot 4. (a) Triangles indicate fire scars and major fires (black) that scarred at least 2 trees. Vertical lines mark major fire years. (b) Bars represent the frequency of trees in 20-year age classes for subcanopy (hatched) and canopy (no pattern) trees of Douglas-fir (grey) and lodgepole pine (white). The superimposed line shows the cumulative age distribution for 47 live trees.

(c) Bars depict the percentage of trees in each age class with wide rings close to the pith indicating fast initial growth. The cumulative age distribution (b) was used to calculate the percentage of trees that released or became suppressed during each 20-year period (d). Positive departures show the percentage of live trees that released; negative departures indicate suppressions. See text for criteria differentiating major (black), moderate (grey) and minor (white) growth releases and suppressions.
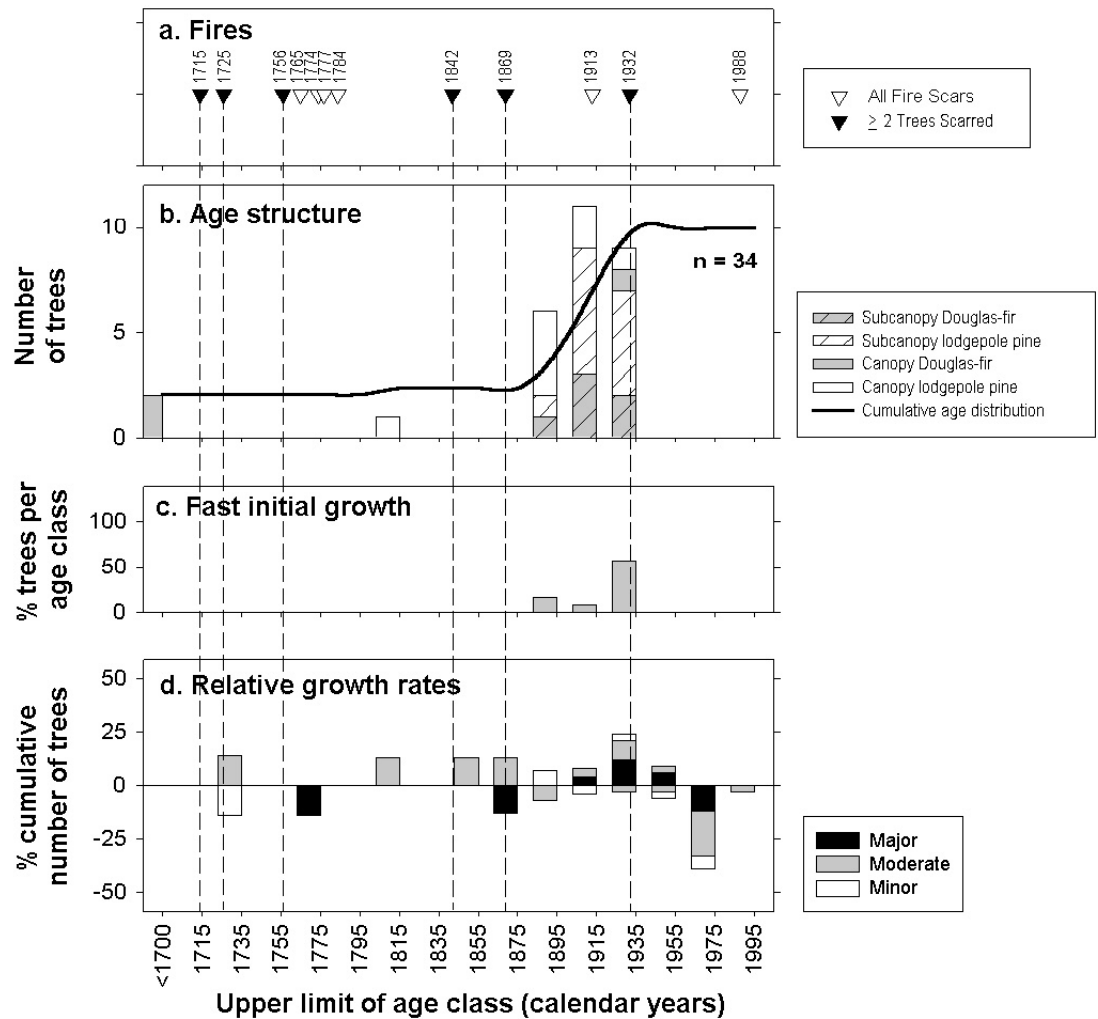
Figure 23. Fire history (a) and stand dynamics (b to d) of Plot 5. (a)Triangles indicate fire scars and major fires (black) that scarred at least 2 trees. Vertical lines mark major fire years. (b) Bars represent the frequency of trees in 20-year age classes for subcanopy (hatched) and canopy (no pattern) trees of Douglas-fir (grey) and lodgepole pine (white). The superimposed line shows the cumulative age distribution for 46 live trees.

(c) Bars depict the percentage of trees in each age class with wide rings close to the pith indicating fast initial growth. The cumulative age distribution (b) was used to calculate the percentage of trees that released or became suppressed during each 20-year period (d). Positive departures show the percentage of live trees that released; negative departures indicate suppressions. See text for criteria differentiating major (black), moderate (grey) and minor (white) growth releases and suppressions.
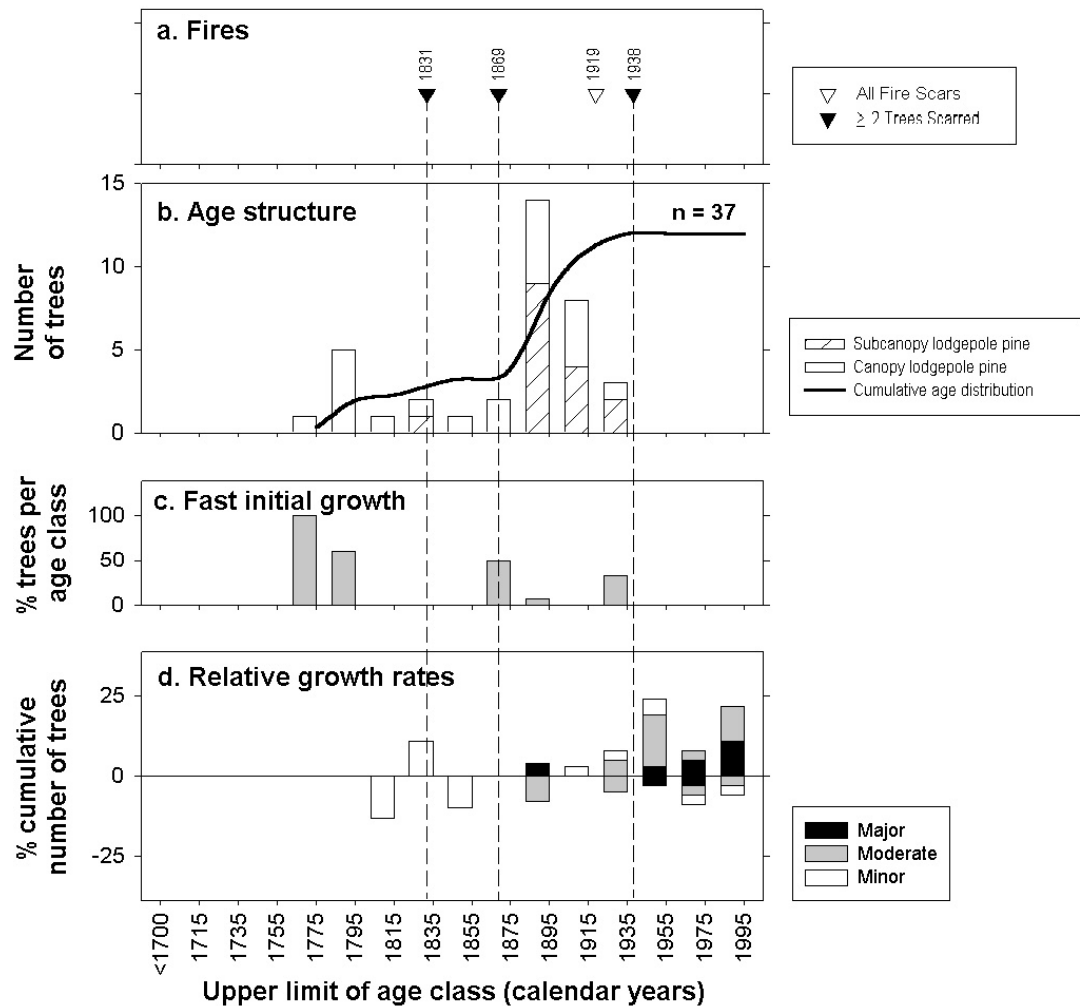
Figure 24. Fire history (a) and stand dynamics (b to d) of Plot 6. (a) Triangles indicate fire scars and major fires (black) that scarred at least 2 trees. Vertical lines mark major fire years. (b) Bars represent the frequency of trees in 20-year age classes for subcanopy (hatched) and canopy (no pattern) trees of Douglas-fir (grey) and lodgepole pine (white). The superimposed line shows the cumulative age distribution for 34 live trees.

(c) Bars depict the percentage of trees in each age class with wide rings close to the pith indicating fast initial growth. The cumulative age distribution (b) was used to calculate the percentage of trees that released or became suppressed during each 20-year period (d). Positive departures show the percentage of live trees that released; negative departures indicate suppressions. See text for criteria differentiating major (black), moderate (grey) and minor (white) growth releases and suppressions.
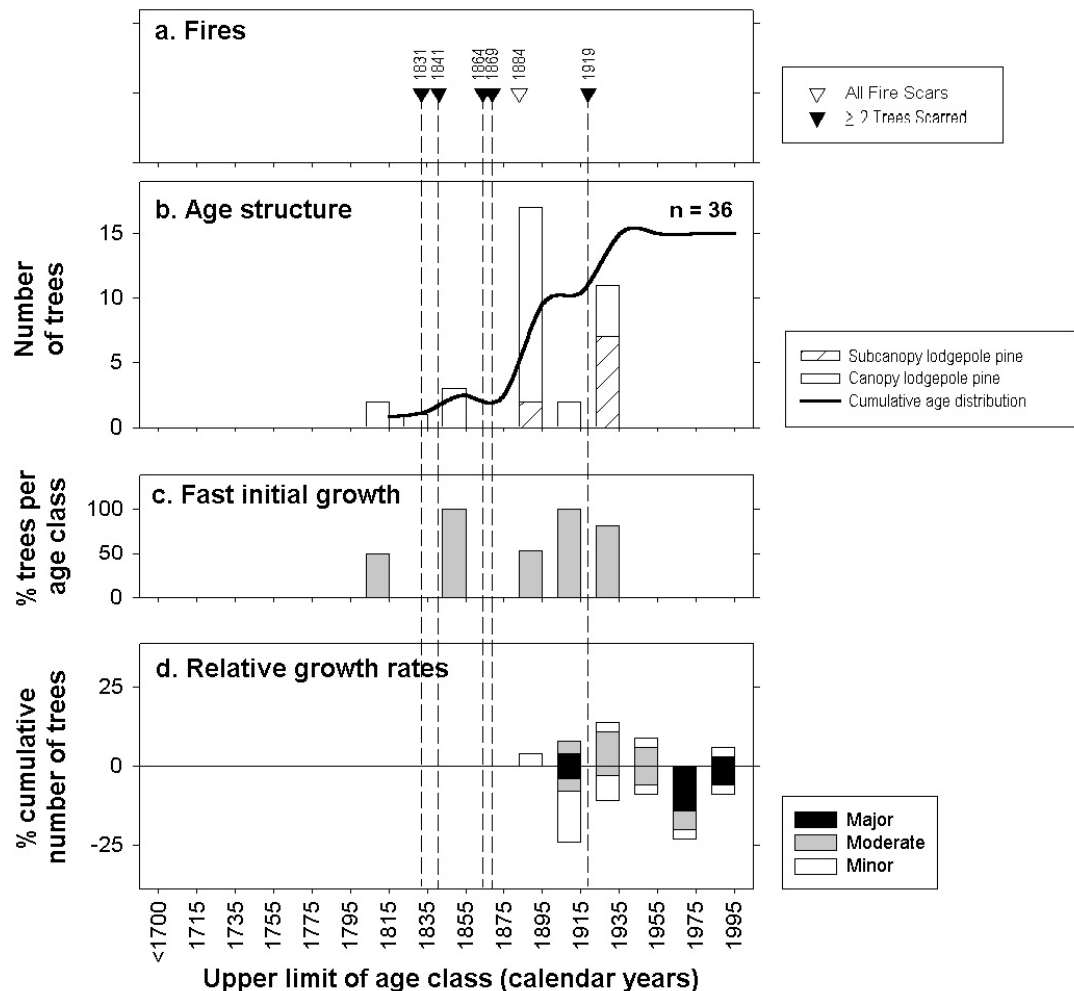
Figure 25. Fire history (a) and stand dynamics (b to d) of Plot 7. (a) Triangles indicate fire scars and major fires (black) that scarred at least 2 trees. Vertical lines mark major fire years. (b) Bars represent the frequency of trees in 20-year age classes for subcanopy (hatched) and canopy (no pattern) trees of Douglas-fir (grey) and lodgepole pine (white). The superimposed line shows the cumulative age distribution for 37 live trees.

(c) Bars depict the percentage of trees in each age class with wide rings close to the pith indicating fast initial growth. The cumulative age distribution (b) was used to calculate the percentage of trees that released or became suppressed during each 20-year period (d). Positive departures show the percentage of live trees that released; negative departures indicate suppressions. See text for criteria differentiating major (black), moderate (grey) and minor (white) growth releases and suppressions.
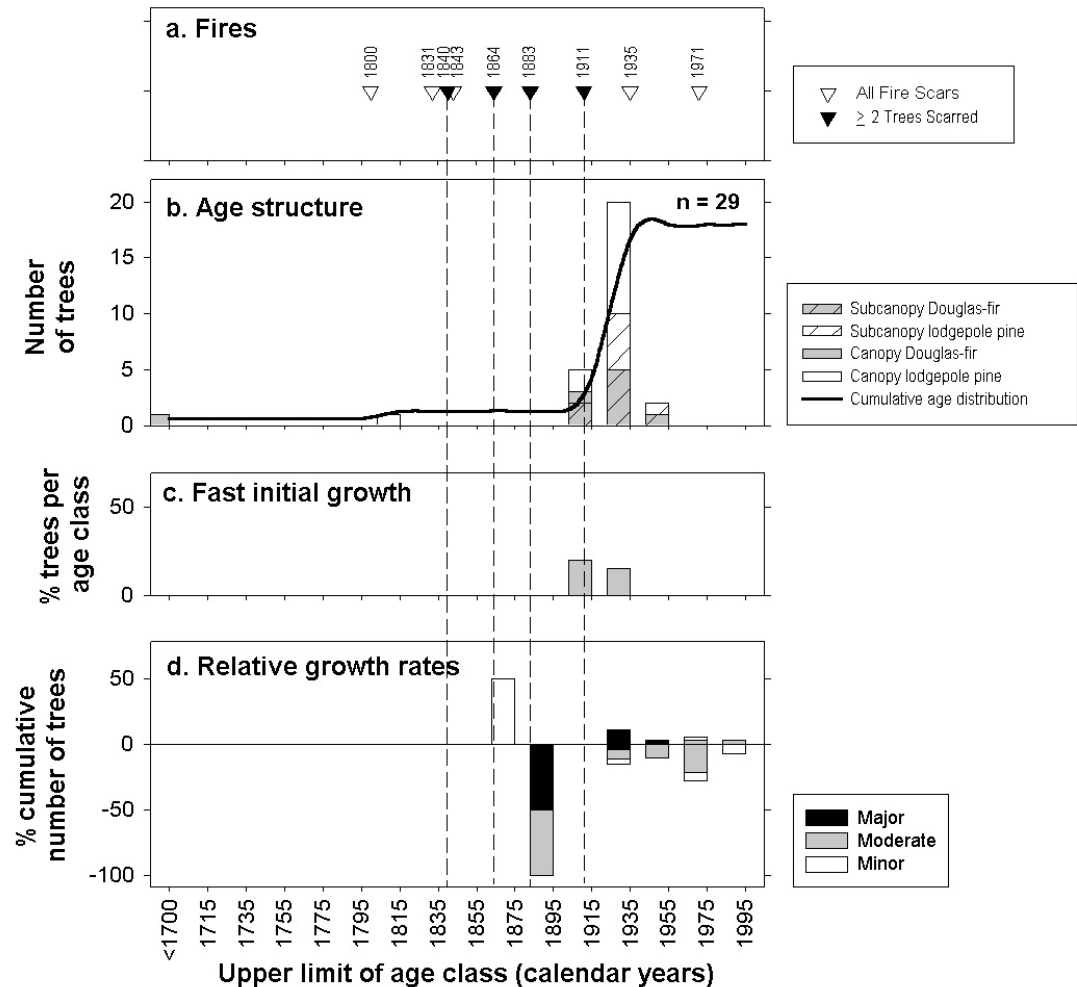
Figure 26. Fire history (a) and stand dynamics (b to d) of Plot 8. (a)Triangles indicate fire scars and major fires (black) that scarred at least 2 trees. Vertical lines mark major fire years. (b) Bars represent the frequency of trees in 20-year age classes for subcanopy (hatched) and canopy (no pattern) trees of Douglas-fir (grey) and lodgepole pine (white). The superimposed line shows the cumulative age distribution for 36 live trees.

(c) Bars depict the percentage of trees in each age class with wide rings close to the pith indicating fast initial growth. The cumulative age distribution (b) was used to calculate the percentage of trees that released or became suppressed during each 20-year period (d). Positive departures show the percentage of live trees that released; negative departures indicate suppressions. See text for criteria differentiating major (black), moderate (grey) and minor (white) growth releases and suppressions.

Figure 27. Fire history (a) and stand dynamics (b to d) of Plot 9. (a) Triangles indicate fire scars and major fires (black) that scarred at least 2 trees. Vertical lines mark major fire years. (b) Bars represent the frequency of trees in 20-year age classes for subcanopy (hatched) and canopy (no pattern) trees of Douglas-fir (grey) and lodgepole pine (white). The superimposed line shows the cumulative age distribution for 29 live trees.

(c) Bars depict the percentage of trees in each age class with wide rings close to the pith indicating fast initial growth. The cumulative age distribution (b) was used to calculate the percentage of trees that released or became suppressed during each 20-year period (d). Positive departures show the percentage of live trees that released; negative departures indicate suppressions. See text for criteria differentiating major (black), moderate (grey) and minor (white) growth releases and suppressions.

PART 5: CLIMATE-FIRE INTERACTIONS

Climate Records

Climate-fire analyses investigated relationships among regional climate, tree growth, and fire occurrence for 1700 to 1970. Instrumental climate records for the Cariboo region are generally short and correspond with the period of indirect and direct fire suppression during the 20th century. To allow analysis of climate-fire relationships over three centuries, I used tree-ring proxy climate records. For precipitation, I used the growing season (June-July-August) record reconstructed from tree-rings developed in the study area (Daniels et al, in prep.).

In many dry forests types in North and South America, El Niño Southern Oscillation (ENSO) has a significant influence on precipitation and fire regimes (Simard et al. 1985, Swetnam and Betancourt 1990, 1998, Veblen et al. 2000). To test the influence of ENSO in the Cariboo region, I used two ENSO records: (1) winter Southern Oscillation Index (SOI) for 1699 to 1970, reconstructed from tree-rings (Stahle and Cleaveland 1993, Stahle et al. 1998). This reconstruction was base on tree-ring data from the southern United States. It explains 41% of the variance in winter SOI from 1900 to 1971. Positive values of SOI correspond with La Niña events and negative values correspond with El Niño events. (2) Documentary records of El Niño events include 65 strong El Niño events between 1700 and 1970 (Quinn 1992).

ENSO Influences on Precipitation in the Cariboo Region

I used superposed epoch analysis (SEA) to test the null hypothesis that there is no relationship between ENSO and precipitation in the years preceding and during El Niño events. SEA tests for differences in climate (precipitation) during event (EL Niño) versus non-event (non-El Niño) years. Mean growing season precipitation was calculated for eleven-year windows that included each El Niño event and the five years preceding and following each event. To allow comparison to non-El Niño years, variation in the precipitation record was quantified using Monte Carlo simulations that randomly selected years and calculated means and 95% bootstrap confidence intervals (Mooney and Duval 1993, Grissino-Mayer 2001). The number of randomly selected years equalled the actual number of El Niño events in the analysis. The results (**Figure 28**) depict climate during El Niño events and are presented as departures (in standard deviations) from the mean climate values for the randomly selected non-El Niño years.
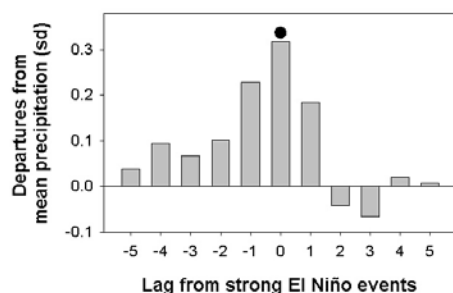

Figure 28. Growing season precipitation corresponding to 65 strong El Niño events between 1700 and 1970 in the Quinn (1992) documentary record. Departures are measured in standard deviations from mean precipitation, comparing El Niño and non-El Niño years. The dot indicates statistical significance determined from bootstrap 95% confidence intervals based on Monte Carlo simulations.

During strong El Niño events growing season precipitation is above average (**Figure 28**). Increased precipitation is likely related to convective rain during summer thunderstorms since El Niño events are associated with blocking high-pressure cells centred over British Columbia (I. McKendry, pers. comm.). Since El Niño and La Niña events generally have opposite impacts on climate, La Niña events likely correspond with relatively dry summers in the Cariboo region.

Climate Influences on Fire

I used superposed epoch analysis (SEA) to test the null hypothesis that there is no relationship between fire occurrence and climate in the years preceding and during the fire year. In these tests, events were fire years and the climate data were precipitation and winter SOI. Fire was significantly correlated with growing season droughts that started the year before fires burned and lasted up to four or five years (**Figure 29**). Fire years were preceded by one very dry year, during which fine and course fuels desiccate increasing the chance of fire ignition and spread. Severe drought, indicated by statistically significant negative precipitation departures, was associated with major fire years. During extremely dry years, fire is more likely to burn at multiple points in the landscape. Both local and major fires were preceded by above average precipitation during the three to five years prior to fire occurrence. This positive relationship was statistically significant four years prior to local fires (**Figure 29**). Increased plant productivity in the herb layer during wet summers increases fine fuels and the risk of fire during subsequent droughts (Swetnam et al. 1999, Veblen et al. 2000)

The pattern of above average precipitation followed by fire years associated with drought have been linked to ENSO activity and sequential El Niño-La Niña events in many dry forests in North and South America (Veblen et al. 2000, Veblen and Kitzberger 2002, Kitzberger et al. 2001). Given the strong precipitation patterns associated with fire (**Figure 29**) and the link between strong El Niño events and precipitation (**Figure 28**), I anticipated that SOI would be negative three to five years prior to fire years and positive in the years immediately preceding and following fire. In fact, the SOI departure is significantly positive in the year preceding major fires, indicating that strong La Niña events are linked to drought and high fire risk in the Cariboo Region (**Figure 29**). However, the SOI departures did not support the interpretation that above average precipitation prior to fire years is consistently caused by El Niño events.
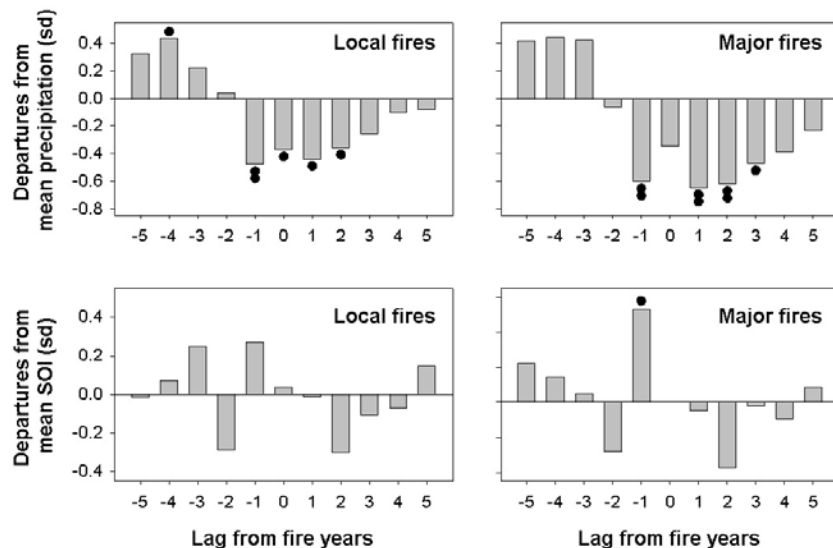

Figure 29. Growing season climate corresponding to local and major fires. Local fires scarred ≥ 2 trees in a plot (n=27); major fires scarred ≥ 2 trees in ≥ 2 plots (n=14). Departures are measured in standard deviation from mean growing season precipitation (top) and winter SOI (bottom) for 1700 to 1970 and compare climate conditions during fire years and non-fire years. Dots indicate statistical significance determined from bootstrap 95% and 99% confidence intervals based on Monte Carlo simulations.

PART 6: DISCUSSION AND MANAGEMENT IMPLICATIONS

Dendrochronology and Fire History Research
Accurate tree-ring data are critical for reconstructing historical change in forests and quantifying temporal aspects of disturbance regimes. When properly applied, dendrochronological (tree-ring) techniques yield high quality data on tree age, growth rates and disturbance events. In this study, I have applied several tree-ring methods to investigate the influences of year-to-year climate variation on tree growth and fire occurrence and the impacts of fire on forest structure and dynamics. Specifically, crossdated ring-width series were combined in replicated, multi-century chronologies that were successfully correlated with climate records and used to reconstruct precipitation over 325 years (**Table 1, Figure 8**). Visual and statistical crossdating resulted in 280 fire scar dates, accurate at an annual resolution (**Figure 11**). In many cases, the season of the fire could be discerned. High quality age data are essential to understand the links between climate, fire and forest dynamics. Ages derived from increment cores were crossdated to avoid counting errors due to false and missing rings and corrected for errors due to missed piths and sample height (**Figure 16**). The resulting age structures clearly showed the influence of disturbance on forest structure and dynamics (**Figures 17, 19 to 27**).

Fire Intervals and Timing
Fire intervals calculated for the eight plots are consistent with a regional analysis of fire in the IDFdk3 forests of the Cariboo (Gray et al. 2002). Based on my analysis of all fire scars per plot, two to 59 years separated successive fires and the Weibull median probability interval (WMPI) was 13 to 22 years. Fire intervals doubled when I considered only fires that scarred at least two recorder trees per plot. This more conservative data set likely represented more severe fires that burned less frequently.

Links among El Niño-Southern Oscillation, interannual variation in climate, and fire in the Carbioo region are consistent with climate-fire relationships in other dry forests in North and South America (Swetnam et al. 1999, Veblen et al. 2000, Veblen and Kitzberger 2002, Kitzberger et al. 2001). At the landscape scale, I combined data from the eight study plots to create a conservative dataset that included years in which at least two recorded trees were scarred per plot (n = 27) and at least two plots recorded fire (n=14; **Figure 12**). These data represented more severe fires within plots and regionally significant fire years, respectively. Fire occurrence is related to droughts that last three to five years and correspond with the onset of strong La Niña events (**Figure 29**). Fires commonly burned in the second year of a drought, perhaps following desiccation of fine and coarse fuels. Years of above average precipitation preceded fire years and likely contributed to build up of understory grasses, the dominant fuel for stand-maintaining fires. Although above average precipitation is associated with El Niño events in the Cariboo region, a direct link between ENSO and the wet conditions preceding fires was not established.

The links between climate and fire at the inter-annual scale raise interesting questions about climate-driven changes in the fire regime over periods of decades to centuries. Research in the United States and Patagonia have shown fire frequency during the 18th ad 19th centuries varied with ENSO activity, independently of human influences on the fire regime (Baisan and Swetnam 1990, Swetnam and Baisan 1996, Kitzberger et al. 2001, Veblen et al. 2000, Veblen and Kitzberger 2002). To test for similar variation in fire frequency over time in the Cariboo region will require temporal analysis of fire dates that

represent the regional spatial scale. In 2003-4 I will collaborate with Gray et al. (2002) and use our combined datasets from the Cariboo region to identify years of widespread fire, when multiple sites burned in a single year. We will quantify the climate conditions under which regionally widespread fires burned. Secondly, our combined data includes >700 fire scars and increases the number of observations prior to the 1830s. Increased sample sizes will allow temporal comparisons of fire return intervals through time. Specifically we will compare fire intervals during 1781 to 1830, a 50-year period of low ENSO activity (Veblen et al. 2000), with fire intervals during 1731 to 1780 and 1831 to 1880 (the 50-year periods immediately preceding and following 1781 to 1830) to test for long-term influences of climate on the Cariboo fire regime. Similarly, comparison with 50-year periods starting in 1881 will test for human influences on the fire regime during the 20th century. Understanding the conditions under which widespread fires burn and their impacts on forest composition and structure will provide information that is critically needed to assess the susceptibility of the current forest to fire, insects and disease.

Fire Impacts on Forest Structure and Dynamics
Fire is a primary determinant of stand structure and dynamics in the Douglas-fire – lodgepole pine forests of the Cariboo region. The mixed fire regime includes both low-severity stand-maintaining fires and less frequent stand-replacing fires. Evidence of stand-maintaining fires included uneven age-structures, low density of veteran trees, Douglas-fir with up to eight fire scars, and lodgepole pine with multiple fire scars although this species is intolerant of moderate to high severity fires. Discrete cohorts of trees with fast initial growth rates indicated stand-replacing fires.

In eight of the nine study plots, cohorts of trees established following fires that burned late in the 1800s or early in the 1900s (**Figures 19 to 27**). These age cohorts currently dominate each stand, although fire scars indicate that the plots burned since the trees established. Post-fire stand development processes such as crown closure, inter-tree competition and self-thinning are evident in the suppression and release patterns exhibited in the radial growth of individual trees. Growth suppression results from competition between trees, where as releases occur following within stand disturbances and mortality of individual trees that increase resource availability to surviving trees.

There is evidence from dry forests throughout North America that severe fires may burn following long fire-free intervals. This is a concern for the Cariboo forests as fire return intervals are exceeding the natural range of variation in the historical record. For example, the current fire-free interval exceeded the median fire return interval (WMPI) at all plots and it exceeded the maximum interval between major fires at all but two plots (**Table 6**). Decreased fire frequency may significantly alter forest composition and structure, resulting in higher densities of regeneration and subcanopy trees, increased layers in the canopy, and fuel accumulations in the Cariboo forest (Gray et al. 2002).

For forests in which stand maintaining fires dominate and stand-replacing fires are rare, the negative impacts of fire suppression on forest structure and fire regimes are well documented and unequivocal (Swetnam et al. 1999). For forest with mixed regimes that include stand-maintaining and stand-replacing fires, it is more difficult to determine whether the size and age structure of the current stands differ from historic stands (Veblen et al. 2000, Veblen 2002). My correlation analyses suggested that increased fire intervals may explain the high density of canopy and subcanopy trees observed in the plots, but data from additional plots are needed to draw meaningful conclusions. The initial growth rates of trees of different ages provide a second line of evidence that

supports the hypothesis that fire suppression has altered forest dynamics (**Figure 15**). The radial growth rates of contemporary saplings are much lower that the initial growth rates of trees that now occupy the subcanopy and canopy. Slow growth suggests that the saplings are suppressed due to competition from overstory trees and low light availability in the understory. The low growth rates imply that the current stand structures are unprecedented.

Management Implications
Understanding spatial and temporal aspects of disturbance regimes provides the scientific basis for ecosystem management (Christensen et al. 1996, Landres et al. 1999). For example, in boreal forests where stand-replacing fires are common, results from fire regime research have been incorporated into harvesting schedules and cut block design (Andison and Marshall 1998). In contrast, the historic fire regime of the ponderosa pine forests of the southwestern United States was almost exclusively frequent, low-severity, stand-maintaining fires (Swetnam et al. 1999). Research has shown that these forests have been significantly altered by fire suppression, increasing the occurrence of large, intense wildfires (Moore et al. 1999). Thinning and prescribed fire have been incorporated into adaptive management programs that aim to restore forest structure and dynamic processes of these ponderosa pine forests (Covington et al. 1997, Moore et al. 1999, Swetnam et al. 1999).

Ecological restoration using prescribed burns and fuels reduction by thinning have been advocated for many dry forests in North America, including British Columbia. However, Veblen (2002) cautions that assessing the impacts of fire suppression on forests with a mixed fire regime is more complex than for forests affected primarily by one fire regime (e.g., stand-replacing fires or stand-maintaining fires). For example, where stand-replacing disturbances burned relatively recently, tree density and fuels may be relatively high in post-fire stands because of stand development processes rather than fire exclusion effects. In these stands, ecological restoration may not be warranted; however, fuels reduction to reduce fire hazard may be justified if the stands are managed for timber. In the Cariboo forests, the current fire free interval generally exceeds the historic maximum intervals (**Table 6**, Gray et al. 2002). Gray et al. (2002) identified several general trends associated with reduced fire frequency during the 20th century that can guide management practices; however, effective mitigation and restoration will need to be site specific, as a single prescription for forests with mixed fire regimes is not possible (Veblen 2002).

Understanding climate-fire relationships may contribute to models that forecast fire (Swetnam et al. 1999). In this study, I have demonstrated links between El Niño-Southern Oscillation, precipitation, and fire in the Cariboo region (**Figure 29**). These results are particularly important given the current mountain pine beetle outbreak in British Columbia. By the end of 2002, 355,000 km^2 of forests and *c.*108 million m^3 of timber were affected by mountain pine beetle. Tree mortality in the Cariboo region has been significant, altering forest composition and structure and increasing fuel availability at stand and landscape scales. My research suggests that risk of catastrophic fire in the Cariboo forests will be greatest if a strong La Niña event coincides with peak fuel accumulations due to the beetle epidemic. In 2002, we experienced a moderate El Niño event - La Niñas typically follow El Niños by three to five years.

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