The Interaction of Changing Patterns of Land Use, Sub-Alpine Forest Composition and Fire Regime at Buck Lake, Mount Rainier National Park, USA.

by

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Introduction

Recent studies in both archaeology and ecology emphasize the necessity of understanding long-term landscape change as the outcome of both natural and social processes (Kirch 2005, Briggs et al 2006). Recognizing both facets of environmental change is particularly important in the sub-alpine parklands and forests of Mount Rainier National Park. The park was created to protect Mount Rainier's scenic beauty and its biological and geological features. However, research in recent decades has also uncovered an archaeological record of extensive human occupation over at least the last 3500 years (Burtchard 1998). Understanding the history of human interaction with the physical and biological landscape is essential to both explaining how the current landscape developed its distinctive features and how continued human interaction will transform the ecosystems of Mount Rainier in the future (Cronon 2000).

Buck Lake, located on the northeastern flank of the mountain, is an ideal site to explore the history of human land use and environmental change in Mount Rainier National Park. Buck Lake is a small, shallow ombrotrophic lake situated just below forest line at approximately 1700 meters elevation. The forest surrounding the lake is dominated by sub-alpine fir (*Abies lasiocarpa*) with open meadow vegetation developing on the steep slopes south of the lake. Preliminary archaeological investigations on the table landform adjacent to the lake provide evidence for human occupation of the site in the distant past. Soil pit excavations indicate a remarkably high density of cultural materials in sediments directly atop, and dug into, Mount St. Helen's Yn tephra (MSH-Y, 3400 ^{14}C years BP). The increase in cultural materials just after the MSH-Y eruption contrasts sharply with a moderate to low lithic density in the paleosol immediately below the tephra layer (G. Burtchard, personal communication). The abundance, type and spatial distribution of the cultural materials at the Buck Lake site (FS 71-01) are interpreted as indicating the presence of a multi-task, mixed group residential base camp (Burtchard 1998).

A sediment core was extracted from Buck Lake to provide a record of environmental change to assist in the interpretation of the Buck Lake FS 71-01 archaeological site. Pollen analysis was used to reconstruct past forest composition and possible climatic fluctuations. Charcoal analysis was used to reconstruct changing fire regimes. The analysis sought to provide a general picture of how the vegetation and fire regime at Buck Lake changed through the Holocene. Given the site's location just below the modern forest line the analysis especially focused on reconstructing July temperature and January precipitation which are the particular climatic factors most likely to have an impact on the location of the forest line in the past (Rochefort et al 1994). Additionally the analysis sought to determine whether the vegetation at Buck Lake after the MSH-Y eruption was more amenable to human occupation than at previous times and whether site occupation or subsequent visitation altered the forest composition or fire regime at Buck Lake over longer time periods. Addressing these questions will provide important environmental context for the interpretation of the archaeological record and also provide insight into how specific human land use decisions interacted with environmental change to shape the current sub-alpine landscape of Mount Rainier.

Methods

Core Extraction and Chronology

A 4.72 meter long, 3 cm diameter sediment core was extracted from Buck Lake in September, 2004 by Steven Athens of IARII. The core had substantial tephra deposits which were sent to Nick Foit at Washington State University for microprobe identification. The core drive penetrated the thick Mazama-O tephra deposit and continued to bedrock. The age chronology of the core was constructed mainly from the tephra deposits but the Mazama tephra was bracketed by an organic bulk sediment AMS radiocarbon date from the base of the core and an AMS radiocarbon date of wood on top of the tephra layer. Linear interpolation between tephra layers and AMS dates was used to construct an age-depth model for the core. The core was cut into 1 or 2 cm thick sampling intervals and sent to Michael Tweiten at the University of Wisconsin-Madison for pollen and charcoal analysis.

Pollen Analysis

Twenty-eight pollen samples were extracted and processed using standard methods including hot 10% HCl and 10% KOH treatments, sieving with 500 micron mesh test sieves and, for ten samples, treatment with hot HF (Faegri and Iversen 1989). Samples were chosen to document the beginning and ending of sediment cores, to bracket the four tephra deposits, and to provide a stratified set of samples across the entire core. Sampling intensity was increased both above and below the MSH-Y tephra to provide a better description of potential vegetation changes before and during intensified human occupation of the site.

The slides were counted in a randomly selected order to avoid biasing the temporal sequences. The first three slides were counted in 50 grain increments to determine the total pollen sum at which pollen-type percentages stabilized. A total grain count of 300 captures the distribution of the dominant pollen-types and was used for every slide. In summary diagrams deciduous tree species excluding *Alnus sinuata* and *Alnus rubra* were lumped into a single “Deciduous” category. Likewise, non-arboreal pollen types were lumped into a “Non-arboreal pollen” category except for the Artemisia, Asteraceae sub-familiy Asteroidea, Poaceae and Cyperaceae pollen types which were analyzed individually.

Changes in pollen assemblages through time were analyzed with non-metric multidimensional scaling (NMS) using the *MASS* and *vegan* packages in the R statistical environment (R Core Development Team 2005, Venables and Ripley 2002, Oksanen, Kindt, and O'Hara 2005). NMS is a data visualization technique that attempts to portray the relationships between samples with many variables in a more easily comprehended diagram. The technique assigns samples a set of coordinates in a reduced geometric space (in this analysis two dimensions were chosen), then iteratively rearranges the coordinates until it finds the set of coordinates that best preserves the rank order of multi-variate distances calculated for the original data. Un-transformed Euclidean distances were chosen to construct the multi-variate distance matrix. The *metaMDS* program in the *vegan* package re-calculates the iterative solution from multiple random starts to insure the optimal solution is reached. The program rotates the solution so the greatest variation is on the first axis and scales sample and species scores so they have the same variance and can be reported on the same diagram. R-squared values of the Spearman rank order correlation between distances in the ordination diagram and distances in the multi-variate distance matrix were calculated for each axis to provide a gauge as to how well the diagram can be interpreted as a simple two-dimensional space. Pollen types are plotted on the ordination diagram in locations reflecting their greatest abundance but the only types with Spearman's R-squared values with the ordination axes close to or greater than 0.4 are discussed in the text.

Modern Analog Reconstruction

The "method of modern analogs" (Hutson 1980, Overpeck, Webb and Prentice 1985, Whitmore et al 2005) is a well established method for estimating climate conditions of the past. It is based on the assumption that multi-variate floral assemblages with similar climatic regimes should foster similar pollen assemblages. The Buck Lake pollen record was compressed into estimates of January precipitation and July temperature by taking the "squared chord distance" (Overpeck, Webb and Prentice 1985, Prentice 1980) between each sample and surface sample pollen data from the North American Surface Sample database (Whitmore et al 2005). Entries in the surface sample database were screened on methodological grounds to include only 1) lakes and mires, and 2) samples with grain counts of greater than 200 pollen grains. To eliminate representation of physiologically different species with similar pollen-types (e.g. Eastern Hemlock, Balsam Fir) the database was further pruned to only include sites west of 111°W longitude between of 42°N and 46°N latitude, west of 112°W longitude between of 46°N and 49°N latitude and, west of 112°W longitude between of 49°N and 52°N latitude. This limits the surface sample dataset to 142 reference sites. Reconstructed January precipitation and July temperature for each fossil pollen sample were calculated as a weighted mean of the measured climatic parameters from all modern sites with a square chord distance less than 0.25 (see Lytle and Wahl 2005). Surface sample values were weighted as the inverse of the square chord distance (Bartlein and Whitlock 1993).

Charcoal

Fluctuations in the amount of macroscopic charcoal in sediments provide a basis for comparing fire regimes over centuries and millennia. Empirical and theoretical studies (reviewed in Whitlock and Larsen, 2001) demonstrate that macroscopic charcoal (>125 µm) is deposited close to the source fire, thus supporting the use of sedimentary charcoal peaks to identify fires burning within the watersheds of small lakes. Macroscopic charcoal was identified and counted in contiguous 1 to 2-cm thick, 1 cm^3, samples producing a charcoal record with a resolution of 75 to 80 yrs through most of the core. The samples were counted in a randomly selected order to avoid biasing the temporal sequences. Charcoal records consist of a charcoal peak component indicating local fire events as well as a background component of charcoal derived from long distance transport, charcoal from the soil and standing dead wood and re-deposited charcoal from the lake sediments. The background component was determined by LOWESS smoothing the record with a 1000 year wide sampling window (Long et al 1998). A plot of the charcoal residuals relative to the LOWESS background curve was used to more objectively determine what level of charcoal concentration indicated a local fire (Gavin et al 2006). Residual plots of charcoal data consist of a Gaussian distribution of additional noise above and below the moving average curve and a long positive tail component defining peaks in the record which indicate local fire events.

Results

Core Chronology

Tephra events were identified as the Mazama-O at 6800 ^{14}C years BP, Mount Saint Helens Y (MSH-Y) at 3400 ^{14}C years BP, Mount Rainier C (MR-C) at 2300 ^{14}C years BP and the Mount Saint Helens W (MSH-W) at 470 ^{14}C years BP. Additionally AMS dating of organic sediment from the base of the core returned a date of 7143 ± 49 ^{14}C years BP and a wood sample from above the Mazama-O layer yielded a date of 6732 ± 46^{14}C years BP. The age depth model calculated for Buck Lake is depicted in Figure 1 and the calculated ages for each sampling interval are given in Table 1. The slope of the lines between tephra layers does not vary much indicating a fairly constant sedimentation rate over the length of the record (Figure 1).

Vegetation Change

The fifteen pollen types analyzed were found throughout the entire record indicating that the plant community surrounding the site had developed a similar-to-modern species complement before the formation of the lake (Figure 2). The raw count data for all 39 identified pollen types is presented in Table 2. Abies, Pinus, *Tsuga heterophylla* and *Alnus sinuata* were the most abundant pollen types and also seemed to have the most variability through time. Pollen of *Tsuga mertensiana* was always present, but unlike pollen records from moister locations on Mount Rainier (Paradise River watershed, Dunwiddie 1986), *T. mertensiana* never became a major component of the pollen record at Buck Lake. The major pollen types appear to co-vary in a dynamic pattern through time but there are no visually recognizable pollen zones indicating major shifts in forest type.

The NMS analysis of the pollen samples reveals that four of the pollen types show consistent patterns of co-variance and define two temporal phases to the Buck Lake record (Figure 3, coordinates of each sample are presented in Table 3). A two-dimensional representation of the original fifteen dimensional pollen-type similarity matrix explains 99.3% of the variation in the original distance matrix. Thus, in the NMS ordination diagram (Figure 3) the samples with most similar pollen data are closest together. The first axis of the ordination explains 70.1% of the variation in the similarity matrix and describes changes from high values of Pinus and Asteraceae pollen on the positive end to high values of *Tsuga heterophylla* and Abies on the negative end (see Table 4 for Spearman rank-order correlation values of all types). The first axis is likely a compositional gradient from forests with an increased presence of pine and a more open or patchy understory to a more closed forest with increased abundance of Abies. The second axis explains 15.1% of the variation in the similarity matrix with higher values of Abies at the positive end and higher values of *Tsuga heterophylla* at the negative end. However, no taxa has high rank order correlations with the second axis and variation on the second axis most likely reflects random noise and extra-local pollen.

Two temporal phases are apparent from the NMS ordination with two notable exceptions. The oldest eight samples, dating from 7173 to 4966 ^{14}C years BP, occur on the right side of the diagram showing a distinctive phase of more open forests with increased abundance of pine co-incident with the Hypsithermal climatic optima observed by other researchers from 7800 to 4500 ^{14}C years BP (Heusser 1977, Thompson et al 1993). The exception is the sample taken at approximately 5317 ^{14}C years BP showing increased Abies and decreased Pinus and Asteraceae pollen manifested as a decreased NMS axis 1 score (Figure 3 and Figure 5). The shift to lower axis 1 scores reflects a several centuries long shift to more closed forest with a higher Abies component that eventually reverts to a more open forest type (indicated with green arrows in Figure 3). By 4100 ^{14}C years BP the samples are uniformly in the more closed, Abies dominated end of the spectrum (left of dashed line in Figure 3) consistent with the onset of generally moister conditions in the late Holocene (Thompson et al 1993). The sole exception is the sample immediately following the deposition of the Mount Saint Helens Y tephra dating from 3350 to 3400 ^{14}C years BP. The sample shows a marked increase in Pinus and Asteraceae pollen and a decrease in Abies pollen indicating a return to a more open forest type (indicated with blue arrows in Figure 3). The more open conditions are short-lived and by the next sample, dating from 3309 to 3355 ^{14}C years BP, Pinus and Asteraceae percentages have declined and Abies has recovered.

Climate Change

The modern analog reconstructions from Buck Lake were put into an interpretive context by comparing the reconstructed climate parameters to the climatic constraints to forest line found on modern landscapes (Rochefort et al 1994). The recorded values for January precipitation (PJAN) and July temperature (TJUL) are plotted against each other for all 142 reference sites (Figure 4). Sites with forest cover less than 25% as determined by Landsat imagery (Williams 2002) are marked with medium-sized enlarged circles and indicate four areas of climatic constraint on forest line in the Pacific Northwest. Snow pack is limiting at high PJAN and low TJUL as evident from reference samples from Mt. Rainier itself (noted on the diagram). At low levels of PJAN forest line is limited by winter exposure at low TJUL (Canadian Rockies), topographic constraints at moderate TJUL (Washington and Idaho interior ranges), and summer drought at high TJUL (rainshadow of the American Rockies and Great Basin Ranges). The picture is entirely consistent with what we know of the ecological constraints on tree establishment in different climatic contexts in western North America (Rochefort et al 1994).

The reconstructed combinations of PJAN and TJUL from the fossil record at Buck Lake are shown as the large circles in Figure 4 and, all together, delineate the climatic envelope experienced by the site through the Holocene. At no point do the reconstructed values push into the zones of climatic constraint on forest line but remain within the climatic boundaries for forest cover. The result is also borne out by looking at the particular reference sites with the most similar pollen signatures to the fossil samples (the four most similar reference sites to samples from the fossil record are indicated in red in Figure 4). Early in the record the pollen from Buck Lake has square chord distance values most similar to reference sites in the Klamath Mountains of southwest Oregon, which are dry but forested. For most of the fossil record the best analogs are at sites on the east side of Mount Hood, Oregon or in the Southern Cascades of Washington State. It is possible that the forest limit manifested near Buck Lake at the present time is a result of local edaphic constraints and long recovery times following large fires.

Standardized curves of the reconstructed July temperatures and January precipitation begin in the Hypsithermal period both relatively warm and with lower snow pack (Figure 5). Winter precipitation remains low but summer temperatures become cooler from 6500 to 5300 ^{14}C years BP when increases in Abies and a large severe fire accompany increasing winter precipitation. Abies declines as summer temperatures become warm and winter precipitation remains low until the transition to a late Holocene forest type, with less Pinus and more Abies, around 4000 ^{14}C years. These more subtle climatic fluctuations, especially the changes around 5300 ^{14}C years BP, show that the Hypsithermal was not monolithically dry and warm at this site but instead persistently supported more stress tolerant vegetation for a variety of reasons until the climate generally ameliorated around 4000 ^{14}C years BP.

The 600 years prior to the MSH-Y tephra show the coolest summer temperatures in the entire record but with near modern winter precipitation. After the deposition of the MSH-Y tephra, cooler temperatures persist until about 2800 ^{14}C years BP when there is a shift to warmer summer temperatures which peaks just prior to the MR-C tephra at 2400 ^{14}C years BP. From 2300 ^{14}C years BP until the present reconstructed temperatures fluctuate within half a standard deviation of the mean for the record (14.6 C). From 4000 ^{14}C years BP to the present winter precipitation is high except for excursions around 789, 2347 and 3400 ^{14}C years BP. The reconstructed climate fluctuations after 4000 ^{14}C years BP are driven primarily by changes in *Tsuga heterophylla* pollen abundance and are extra-local in origin.

Fire

Fires, as defined by count values greater than 60 above the LOWESS smoothed background charcoal component (Figure 6), were rare throughout the Holocene (Figure 7). There are long periods of time in which all the charcoal collected in the lake is most likely deposited from the soil, the lake basin or from distant fires. There were three fires in the last millennium giving an average fire return interval of 430 years, consistent with estimates derived for sub-alpine and montane forests in twentieth century stand age studies (Agee 1993, Hemstrom and Franklin 1982). If the cumulative number of fires over time is plotted (Hu et al, in press) two periods of time suggests changes in fire frequency (Figure 8). The first is a large peak occurring from 5700 to 5500 ^{14}C years BP which precedes a peak in Abies pollen and corresponds to an increase in reconstructed January precipitation. Increased winter moisture may have provided additional plant biomass in the following summer to allow more severe burns and greater charcoal production. The second is a general increase in the frequency of fire events in the late Holocene starting with the larger peak at 2691 ^{14}C years BP suggesting more regular fire events since 2700 ^{14}C years BP.

Discussion

Interaction of human occupation and vegetation

Through the Holocene human utilization of the Mount Rainier landscape was concentrated primarily in open sub-alpine parkland and alpine settings (Burtchard 1998). Buck Lake may have provided better resource availability in the early Holocene before 4000 ^{14}C years BP when the forest had a greater presence of pines and perhaps a more open structure. After 4000 ^{14}C years BP the forest became dominated by Abies and perhaps developed greater tree cover. The micro-climate at Buck Lake on the drier northeastern flank of the mountain did not produce pollen assemblages in the late-Holocene consistent with either drought or snow pack constrained forest limits. The meadows presently to the south of lake occur on steep, well drained slopes that may inhibit colonization by trees; an edaphic constraint that also existed in the past. Currently forest cover is thick on the more level bench on the north and east sides of the lake (personal observation).

The density of cultural materials and features in soil pits excavated at the Buck Lake site increased substantially immediately following the deposition of the Mount Saints Helens Y tephra (G. Burtchard, personal communication). The pollen record shows a shift from denser Abies dominated forests to more open forests with increased abundance of Pinus pollen (Figure 3, 5) immediately after the MSH-Y tephra. In soil pits the MSH-Y tephra is quite thick, measuring 20 to 35 cm in depth even after subsequent compaction and soil development. The deposition of the tephra itself seems to have caused substantial tree mortality (Dunwiddie 1986, Seymour et al 1983) and opened up the forest. Reduction in forest cover may have made the site more favorable for use as a residential site or perhaps increased the local abundance of resources.

Occupation of the site following the MSH-Y tephra did not have lasting, major impacts on the plant community. Succession from a more spacious forest with increased pine pollen abundance to a denser, fir dominated forest took 150 years, a rapid recovery at this elevation. Human occupation also did not appreciably alter the trajectory of increasing Abies and decreasing Pinus pollen from 4000 to 2000 ^{14}C years BP indicated by progressively decreasing axis 1 scores on the NMS ordination (Figure 5). However, human utilization more than likely impacted the demographics, gene frequencies and inter-specific interactions of plant and animal populations being exploited in ways that cannot be registered in a pollen record.

Interaction of human occupation and fire regime

Fire regime was also unaffected by increased utilization of the Buck Lake site following the MSH-Y eruption. There is no difference in fire frequency between the 500 years before or after the MSH-Y eruption (Figure 7 and Figure 8). The lack of a fire regime shift is surprising since the close proximity of a human settlement or semi-permanent encampment is often considered to be a source of accidental or intentional ignition of fire (Clark and Royall 1995). The Buck Lake charcoal record is coarse grained due to slow sediment accumulation rates and a coarse sampling regimen. It is possible that increased human occupation of the site may have increased the frequency of low severity ground fires that do not register well in sediment records (Higuera, Sprugel and

Brubaker 2005) and were either missed or indistinguishable from the background charcoal component in the Buck Lake record.

The Buck Lake charcoal record shows a marked increase in the frequency of fires beginning around 2700 ^{14}C years BP (Figure 7 and Figure 8). The shift in fire regime is contemporaneous with the beginning of the regional intensification of subsistence strategies from 3000 to 2000 years ago brought about by growing human populations (Mierendorf 1986, Schalk 1988, Burtchard 1991, Schalk and Atwood 1994, Burtchard 1998). In general, change in proxy data in terrestrial paleo-ecological records can be attributed to some combination of 1) the changing influence of sedimentary processes affecting the fidelity of the record, 2) changes in community composition due to autogenic, successional processes 3) changes in the physical environment due to climate change and, 4) changes brought on by altered human presence or utilization of the landscape (Grimm 1983). Examination of each potential source of variation in the charcoal record shows that changing human resource use is the most likely explanation for the shift in fire regime observed in the Buck Lake charcoal record.

A detailed study of the sedimentary history of Buck Lake was not conducted but, the sediment used in the analysis was fairly homogeneous consisting of organic gytta and re-worked tephra. There did not appear to be major changes in sediment accumulation rates after the Mazama tephra as indicated by the consistent slopes of the age-depth line between each subsequent tephra event (Figure 1). Likewise, charcoal is present throughout the record and a major fire event was recorded in the early section of the record. Thus, there is no evidence of any major sedimentological changes that would impact the charcoal record.

The shift in fire regime at Buck Lake beginning at 2700 ^{14}C years BP does not correspond to a major shift in vegetation as shown in the pollen record. The general decrease in Pinus pollen and increase in Abies pollen, as shown by a shift to negative NMS axis 1 scores, occurred around 4000 ^{14}C years BP well before the shift in fire regime. Changes in fuel load, standing biomass or forest structure may have contributed to greater fire danger but there is no evidence for substantial shifts in forest composition from the pollen record. Most of the variability in the pollen record since 4000 ^{14}C years BP is due to changes in the abundance of *Tsuga heterophylla* pollen coming from lower elevations.

Review of other fire histories from sub-alpine forests in the Pacific Northwest show no general increase in charcoal production in last 3000 years ruling out a regional climatic explanation for the shift in fire regime. While it is somewhat difficult to compare charcoal records from macrofossil analysis with charcoal from lake sediments, sub-alpine macrofossil charcoal records from the Olympic Mountains (Gavin et al 2001) and the south side of Mount Rainier (Dunwiddie 1986) show no notable increases in charcoal production over the last 3000 years. Lake studies from the North Cascades (Spooner and Brubaker 2005) and southeastern British Columbia (Gavin et al 2006) also do not show overall increases in fire frequency over the last 3000 years. A low land study from the Coast Mountains in Oregon (Long et al 1998) reports a decline in the number of fires per millennia over the last 2800 years. There does not seem to be a regional shift to more frequent fires solely due to changing precipitation patterns or summer temperatures.

The steep slopes to south of Buck Lake support a population of bear grass (*Xerophyllum tenax*) which was sought out for basketry by indigenous groups using the

Mount Rainier landscape in historical times (Smith 2006). Fire is used to promote bear grass for basketry; collectors will typically ignite low intensity ground fires to stimulate shoot growth after basket material is collected at a site (Martinez 2004). Low intensity fires would be lit annually or every few years and may not register in the Buck lake charcoal record as discussed previously. However when severe fire weather conditions did occur this practice could serve as an ignition source and insure that a severe fire would occur every few hundred years. The fire regime at Buck Lake was ignition limited prior to 2700 ^{14}C years BP, despite occupation by seasonal hunting and collecting groups, and this limitation was overcome by the development of a system of persistent fire introduction that only rarely ignited more severe fires when weather conditions permitted it.

The change in fire regime at Buck Lake suggests a testable hypothesis. Charcoal records from sub-alpine forest sites on Mount Rainier with bear grass populations should show a shift in fire regime around 2300 to 2700 ^{14}C years BP to more frequent fire due to intensification of human fire management; similar sites without bear grass populations should not. If the hypothesis is true further research into the impact intensive fire management had on the diversity of sub-alpine plant and animal communities on Mount Rainier is of the greatest interest for the future management of the mountain’s biological and cultural resources.

Conclusions

Forest composition near Buck Lake before 4000 ^{14}C years BP had a greater presence of pines and perhaps a more open structure. After 4000 ^{14}C years BP the forest became dominated by Abies and developed greater tree cover. The sole exception, after 4000 ^{14}C years BP, is a short lived return to a more open forest type immediately following the deposition of the Mount Saint Helens Y tephra dating from 3350 to 3400 ^{14}C years BP. The temporary reduction in forest cover is co-incident with increased abundance of cultural materials in the archaeologiocal record. Occupation of the site following the MSH-Y tephra did not have lasting impacts on the plant community or alter the fire regime at the time. However, the Buck Lake charcoal record shows a marked increase in the frequency of fires beginning around 2700 ^{14}C years BP. The shift in fire regime does not correspond to changes in sedimentology, the pollen record or regional climate. Altered patterns of human resource use and fire management are the most likely explanation for the observed shift in fire regime.

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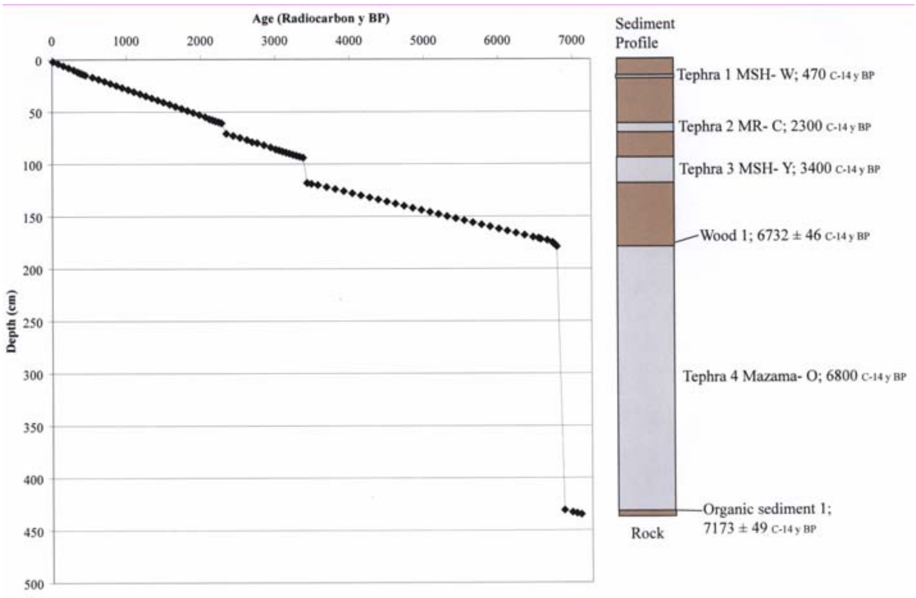

Figure 1: Sediment profile and age-depth model. The Mazama-O tephra is exceptionally deep but well constrained by AMS radiocarbon dates. Age-depth slopes between tephra layers are consistent suggesting no major shifts in sediment accumulation rates.

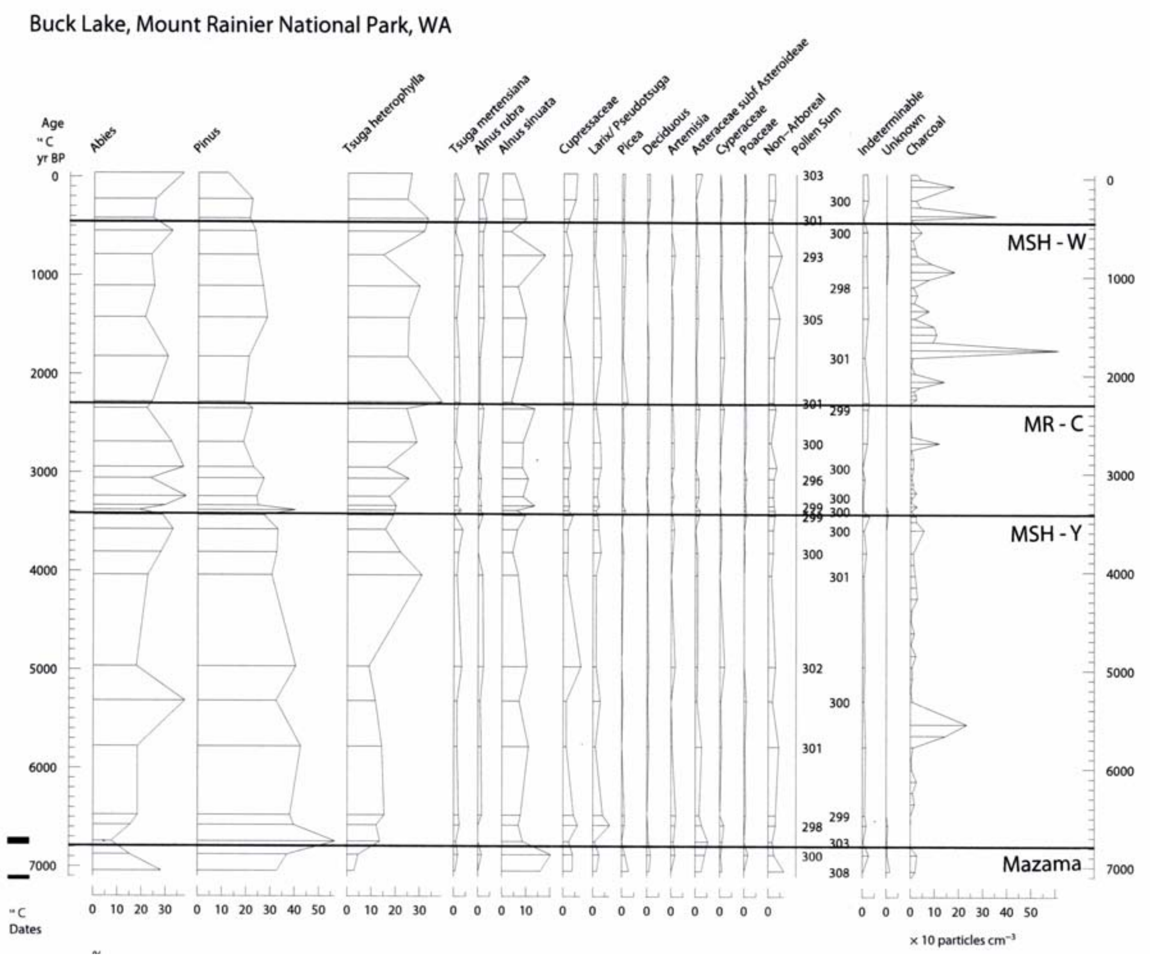

Figure 2: The Buck Lake Pollen Diagram. Tephra layers are noted as thick horizontal lines and the location of radiocarbon dates are presented on the left. Dates are given in radiocarbon years.

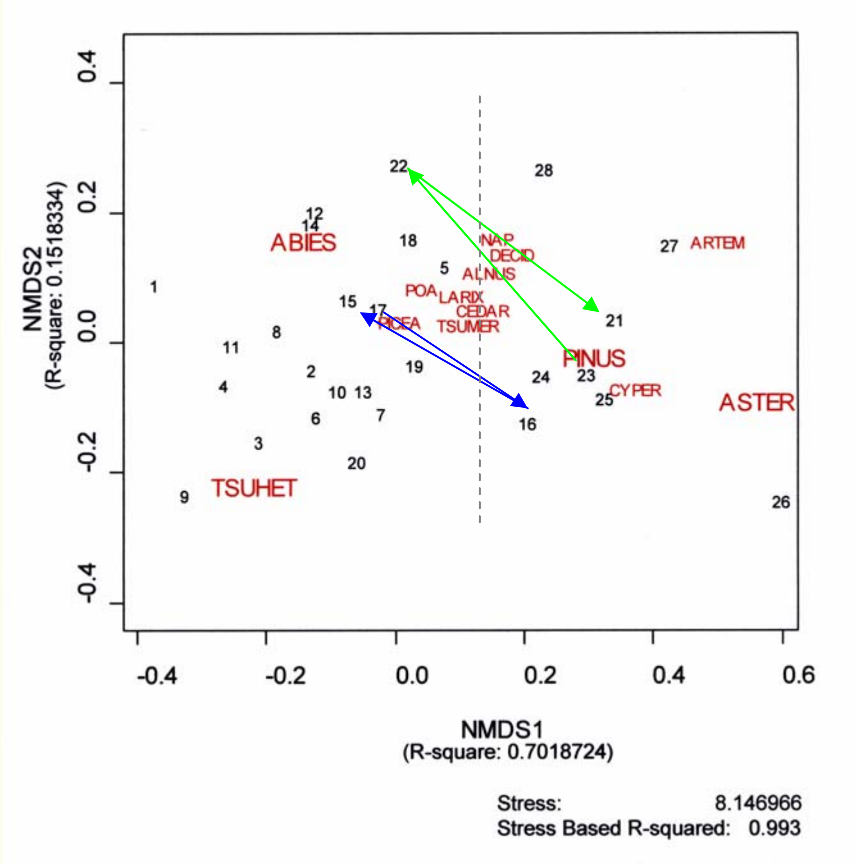

Figure 3: Non-metric Multidimensional Scaling of the Buck Lake pollen data. Samples are numbered sequentially from the surface (1) to the oldest sample (28). Pollen-type names appear near the samples where they achieve maximum abundance. Enlarged lettering marks types with significant rank order correlations with the NMDS axis 1. The ordination is generally divided in two temporal zones marked by a dashed line that divides samples before and after 4000 ^{14}C years BP. The exceptions are sample 22 (5317 ^{14}C years BP) marked with green arrows and sample 16 (3375 ^{14}C years BP) marked with blue arrows.

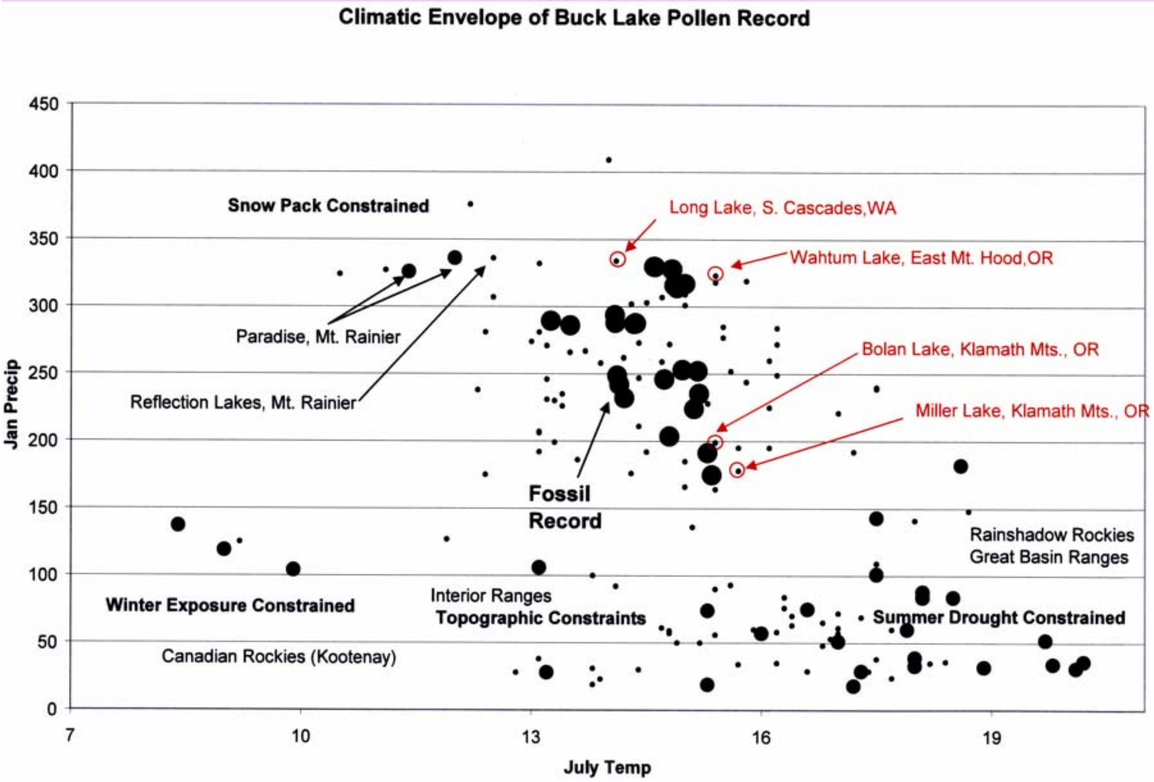

Figure 4: Climate envelope of the buck lake pollen record. July temperature and January precipitation are plotted from all of the142 selected reference samples from the North American Surface Sample dataset. Samples with Landsat derived tree cover less than 25% are indicated with medium enlarged circles. The modern analog reconstructed values of the Buck Lake record are indicated with the largest enlarged circles, delineating the climate space traversed by the fossil record. The best analogs for various stages of the record are indicated with red circles.

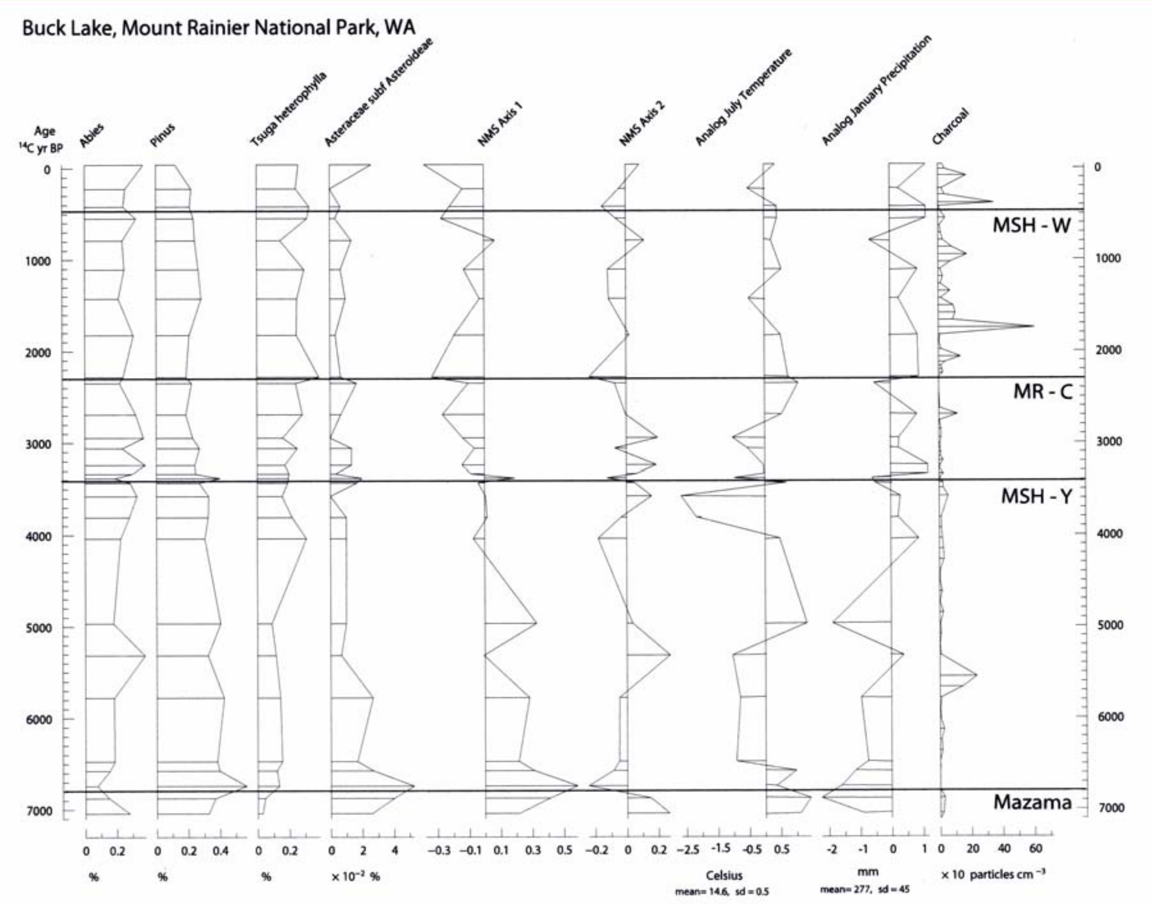

Figure 5: Compiled pollen and climate reconstruction diagram. Pollen types with significant correlations to the first NMS axis are in the first four columns. NMS axis scores and the reconstructed July temperature and January precipitation are plotted through time in columns 5 thru 8. The last column is the charcoal concentration record.

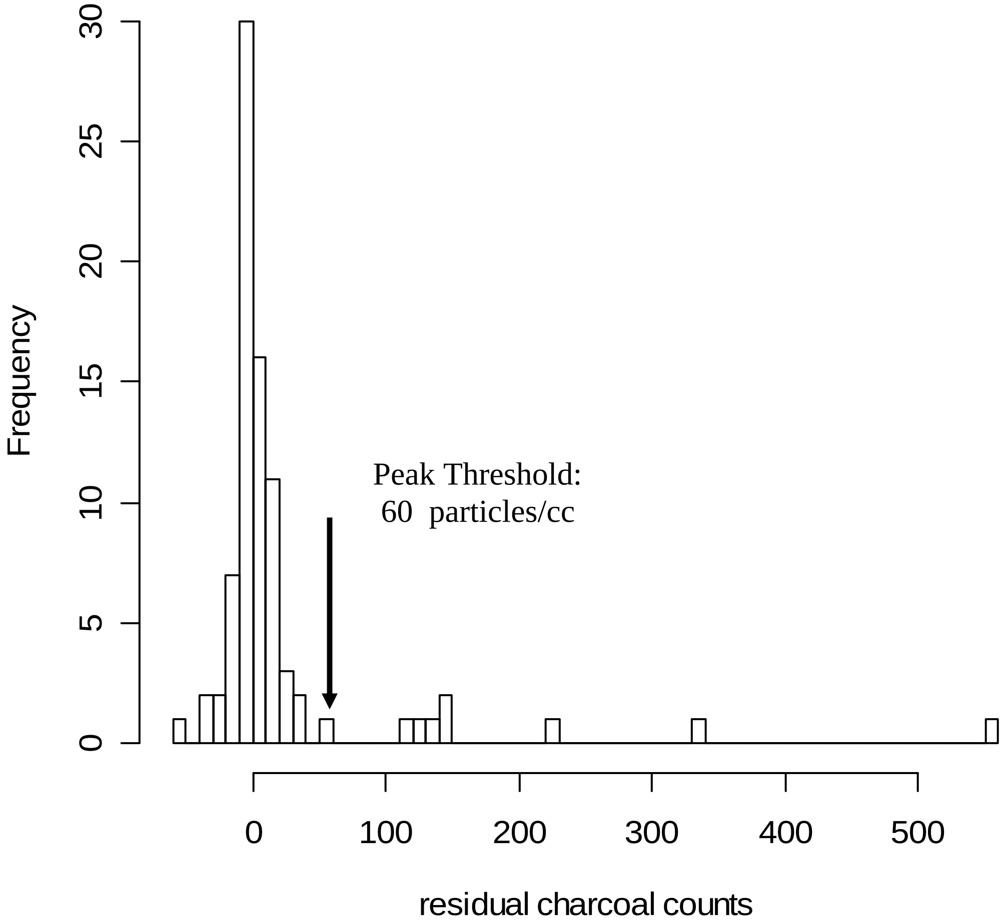

Figure 6: Residual plot of the charcoal record derived from subtracting observed values from the LOWESS smoothed 1000-year window moving average back ground charcoal component. Residual plots of charcoal data consist of a Gaussian distribution of additional noise above and below the moving average curve and a long positive tail component defining peaks in the record which indicate local fire events.

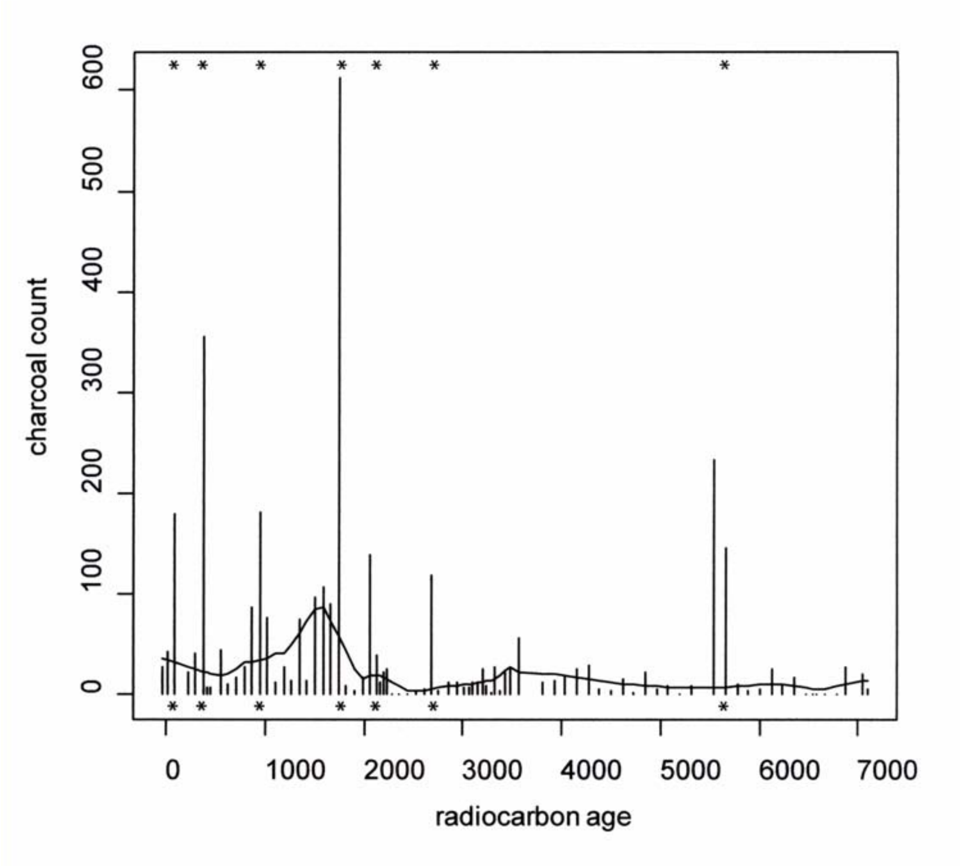

Figure 7: The Buck Lake charcoal record. The line is the 1000 year window LOWESS smoothed background curve. Charcoal concentrations exceeding the peak threshold defined from the residuals plot are marked with stars. There is a notable increase in the number of fire events in the last 2700 ^{14}C years BP.

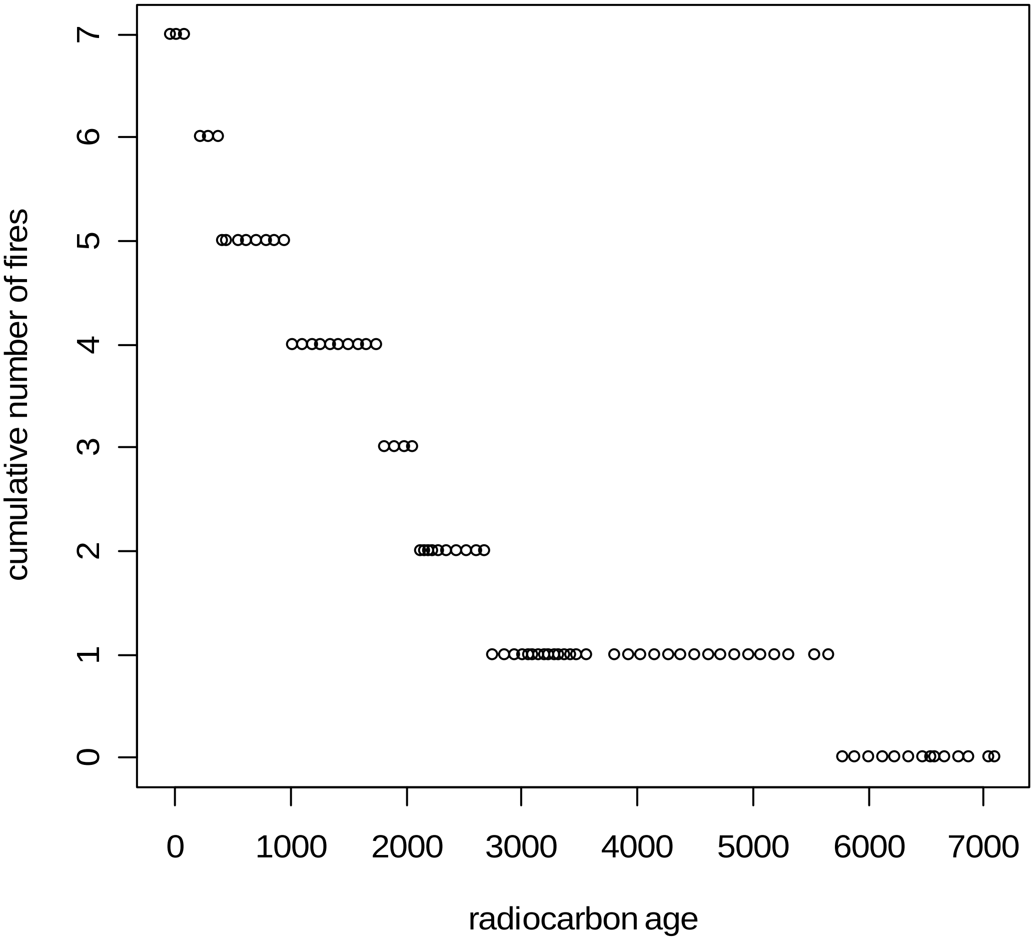

Figure 8: Cumulative number of fire events across the entire Buck Lake charcoal record. Changes in the slope of the cumulative number of events curve demonstrate changes to the fire regime providing another way of visualizing the shift in fire regime at 2700 ^{14}C years BP.

Table 1: Buck Lake, Mt. Rainier, WA Pollen sampling intervals and calculated radiocarbon ages.

Sample	*Interval*	*Age-Top*	*Age-Bottom*	*Age-Mid point*
1	0-1	-55	-20	-38
2	7-9	190	260	225
3	13-14	400	435	418
4	16-18	511	590	550
5	22-24	749	829	789
6	30-32	1068	1147	1107
7	38-40	1386	1465	1426
8	48-50	1784	1863	1823
9	60-61	2261	2301	2281
10	70-72	2301	2393	2347
11	78-79	2668	2714	2691
12	106-108	2897	2989	2943
13	109-110	3034	3080	3057
14	113-114	3218	3264	3241
15	115-116	3309	3355	3332
16	116-117	3355	3401	3378
17	140-141	3401	3459	3430
18	142-144	3517	3633	3575
19	146-148	3749	3865	3807
20	150-152	3980	4096	4038
21	166-168	4908	5024	4966
22	172-174	5255	5371	5313
23	180-182	5719	5835	5777
24	192-194	6414	6530	6472
25	202-202.5	6559	6588	6574
26	206-207	6733	6750	6741
27	460.5-463	6801	6952	6876
28	464-465	7012	7073	7042

Table 3: Non-metric Multidimensional Scaling Coordinates of the Buck Lake Pollen Record.

C-14 y BP	Axis 1	Axis 2
-38	-0.38138	0.089323
225	-0.13755	-0.04126
418	-0.21819	-0.15112
550	-0.27375	-0.06363
789	0.069624	0.117318
1107	-0.1307	-0.11471
1426	-0.03037	-0.10953
1823	-0.19192	0.020431
2281	-0.33433	-0.2338
2347	-0.10371	-0.07335
2691	-0.26738	-0.00346
2943	-0.13925	0.19969
3057	-0.064	-0.07336
3241	-0.14378	0.191401
3332	-0.08696	0.065819
3378	0.191419	-0.12303
3430	-0.04116	0.051929
3575	0.005606	0.160576
3807	0.016092	-0.03389
4038	-0.07425	-0.18085
4966	0.326496	0.037278
5313	-0.00767	0.275837
5777	0.281767	-0.04792
6472	0.212855	-0.04999
6574	0.311196	-0.08671
6741	0.584693	-0.24335
6876	0.409826	0.151363
7042	0.21678	0.269007

Table 4: Rank order correlation of pollen types to Buck Lake pollen record NMS ordination axes. The bold font statistics are featured in the ordination diagram.

	Spearman's r correlation		*Spearman's r-squared*	
Pollen Type	Axis 1	Axis 2	Axis 1	Axis 2
Abies	**-0.6683**	0.5801	**0.4466**	0.3366
Pinus	**0.9293**	-0.0689	**0.8637**	0.0047
Tsuga heterophylla	**-0.8182**	-0.5314	**0.6695**	0.2824
Tsuga mertensiana	0.1629	0.0673	0.0265	0.0045
Alnus	0.2140	0.2714	0.0458	0.0737
Cupressaceae	0.1141	0.1427	0.0130	0.0203
Pseudotsuga- Larix	0.0449	0.2815	0.0020	0.00792
Picea	-0.0458	-0.0928	0.0021	0.0086
Deciduous	0.0286	0.2254	0.0008	0.0508
Artemisia	0.4493	0.2628	0.2018	0.0690
Asteraceae	**0.6034**	-0.1183	**0.3641**	0.0140
Cyperaceae	0.4781	-0.0774	0.2286	0.0060
Poaceae	-0.0113	0.0202	0.0001	0.0004
Non- Arboreal	0.4117	0.2906	0.1695	0.0844

Table 2: Pollen count data from Buck Lake, Mount Rainier National Park, WA

Radiocarbon Age	*Abies*	*Pinus*	*Tsuga heterophylla*	*Tsuga mertensiana*	*Alnus rubra*	*Alnus sinuata*	*Cupressaceae*	*Larix/ Pseudotsuga*	*Picea*	*Acer*	*Betula*	*Corylus*	*Populus*	*Quercus*	*Salix*	*Ambrosia*	*Apiaceae*	*Artemisia*	*Asteraceae - Lactuceae*	*Asteraceae - Asteroideae*	*Berberidaceae*	*Brassicaceae*	*Caryophyllaceae*	*Chenopodiaceae*	*Cyperaceae*	*Dodacatheon*	*Ericaceae*	*Isoëtes*	*Liliaceae*	*Linaceae*	*Poaceae*	*Polypodiaceae*	*Pteridium*	*Ranunculaceae*	*Rhamnaceae*	*Sphagnum*	*Trilete Spores*	*Typha*	*Urticaceae*	Indeterminable	Unknown	Marker	SUM
-38	113	37	80	2	12	15	17	4	3	0	0	0	1	0	2	0	0	0	0	8	0	0	0	1	0	0	0	3	2	0	1	0	0	2	0	0	0	0	0	6	0	20	303
225	77	67	74	12	5	26	15	5	2	0	0	0	2	0	1	0	0	2	0	0	0	0	0	0	2	0	0	0	0	2	2	5	1	0	0	0	0	0	0	7	0	20	300
418	74	64	100	4	10	30	7	4	2	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	1	0	10	301
550	98	71	95	1	6	10	3	3	2	0	0	0	0	0	2	0	1	0	0	1	0	0	0	0	1	0	0	0	1	0	2	3	0	0	0	0	0	0	0	6	1	10	300
789	70	72	43	10	5	52	10	2	4	0	0	0	1	0	1	0	1	4	0	4	4	2	0	0	2	0	0	0	1	1	0	3	1	3	0	0	0	0	0	5	2	15	296
1107	75	80	89	6	6	19	6	6	3	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	1	0	0	1	2	0	1	0	0	1	0	0	0	0	0	6	0	10	298
1426	65	87	77	3	7	30	1	9	2	0	0	0	0	0	0	0	1	2	1	3	0	0	0	0	3	0	0	0	1	1	2	3	3	4	0	0	0	0	0	7	0	18	305
1823	93	63	75	6	2	25	9	10	1	0	1	0	0	0	1	0	0	1	0	1	0	0	0	0	5	0	0	0	0	0	1	3	1	2	1	0	0	0	0	3	0	12	301
2281	73	57	118	7	2	11	12	3	7	0	0	0	0	0	1	0	0	0	0	2	0	0	1	0	1	0	0	0	3	0	1	1	1	0	0	0	0	0	0	8	0	14	301
2347	66	67	73	4	7	40	11	4	1	0	0	0	2	1	0	1	0	2	0	5	0	0	1	0	5	0	0	0	1	1	2	2	0	3	0	0	0	0	0	7	1	17	299
2691	97	56	86	0	3	26	6	9	2	0	0	0	0	0	2	0	1	3	0	2	0	0	0	2	1	0	0	0	0	0	2	0	0	0	0	0	0	0	0	6	0	11	298
2943	112	69	48	10	1	25	9	10	1	0	0	0	1	0	1	0	1	3	0	0	0	0	0	1	0	0	0	1	0	0	0	2	1	3	1	0	0	0	0	0	0	23	300
3057	70	81	75	5	4	32	6	7	2	0	0	0	1	0	1	0	2	0	0	4	0	0	0	0	1	0	0	1	2	0	3	1	0	1	0	0	0	0	0	3	0	4	299
3241	115	73	52	6	2	26	6	5	1	0	0	0	0	0	0	0	2	3	0	4	0	0	1	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	1	0	15	300
3332	89	74	60	4	4	40	8	8	1	1	0	0	0	0	0	0	2	0	1	1	0	1	0	0	0	0	0	0	0	1	2	0	1	1	0	0	0	0	0	1	0	18	299
3378	57	121	59	9	3	18	6	4	4	0	0	0	1	0	1	2	0	0	0	6	0	0	0	0	1	0	0	1	2	0	2	1	0	2	0	0	0	0	0	1	2	5	300
3430	86	81	57	1	6	29	12	6	1	0	0	1	0	0	0	0	0	2	0	5	0	0	0	0	1	1	0	0	1	3	3	2	1	0	0	0	0	0	0	9	2	8	299
3575	99	99	47	11	0	19	6	7	0	0	0	0	0	0	0	0	0	4	0	0	0	1	0	1	2	0	0	0	1	0	0	2	0	1	0	0	0	0	0	2	0	17	300
3807	84	98	66	6	0	13	6	10	2	0	0	1	0	0	0	0	1	2	0	3	0	0	0	0	2	0	0	0	1	0	1	0	0	3	0	0	0	0	1	5	0	12	300
4038	68	92	93	4	6	20	5	4	1	0	0	1	0	0	0	0	1	0	0	3	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	2	0	12	301
4966	54	122	27	10	7	31	22	4	0	0	0	2	0	0	0	0	2	5	0	3	0	0	0	0	6	0	1	0	0	1	0	4	1	0	0	0	0	0	0	3	0	30	302
5313	114	97	35	4	3	21	4	9	1	0	0	1	0	0	0	0	0	0	0	2	0	0	0	0	1	0	0	0	0	0	3	2	1	2	0	0	0	0	0	2	0	17	300
5777	55	128	43	4	4	33	4	3	0	0	0	0	0	0	2	2	0	1	0	8	0	0	0	1	2	0	0	1	4	0	1	2	0	3	0	0	0	0	0	4	0	11	301
6472	55	114	46	6	5	23	13	12	3	0	0	0	0	0	0	0	0	6	2	5	0	0	0	0	0	0	2	0	1	0	2	3	1	0	0	0	0	0	0	3	0	45	299
6574	46	118	36	7	0	20	18	21	3	0	0	0	0	0	1	0	2	5	1	8	0	0	0	0	5	0	0	0	0	0	1	2	0	0	1	0	1	2	0	5	2	35	298
6741	23	172	41	3	0	26	7	2	0	0	0	1	0	0	1	0	0	3	0	16	0	0	0	0	3	0	0	0	4	0	0	1	0	0	0	0	0	0	0	1	1	106	303
6876	45	111	14	5	5	61	12	8	4	1	0	4	0	0	0	0	0	5	1	12	0	1	0	0	1	0	0	0	1	0	5	1	1	2	0	0	0	0	0	8	1	46	300
7042	87	101	9	2	0	49	12	5	9	0	0	2	1	0	0	0	1	0	0	8	0	0	4	3	3	0	1	0	4	0	0	0	5	1	0	1	0	0	0	1	5	10	308

Table 5: Buck Lake, Mt. Rainier, WA sieved charcoal count data. Counts are of individual charcoal pieces greater than 125 microns in the longest axis.

Interval	C-14 Age	Charcoal count	Interval	C-14 Age	Charcoal count	Interval	C-14 Age	Charcoal count	Interval	C-14 Age	Charcoal count
0-1	-38	27	52-54	1983	17	144-146	3691	NA	206-207	6741	NA
1-3	15	43	54-56	2062	139	146-148	3807	12	207-208.5	6763	NA
3-5	85	180	56-57	2122	40	148-150	3923	14	208.5-210	6788	0
5-7	155	NA	57-58	2162	13	150-152	4038	19	210-460.5	6801	NA
7-9	225	22	58-59	2201	23	152-154	4154	25	460.5-463	6876	28
9-11	295	41	59-60	2241	25	154-156	4270	29	463-464	6982	NA
11-12	348	NA	60-61	2281	1	156-158	4386	6	464-465	7042	20
12-13	383	355	61-70	2301	NA	158-160	4502	3	465-466	7102	5
13-14	418	7	70-72	2347	0	160-162	4618	16			
14-15	453	7	72-74	2439	0	162-164	4734	2			
15-16	470	NA	74-76	2530	3	164-166	4850	23			
16-18	550	45	76-78	2622	6	166-168	4966	6			
18-20	630	10	78-79	2691	119	168-170	5081	8			
20-22	710	17	102-104	2759	3	170-172	5197	1			
22-24	789	28	104-106	2851	13	172-174	5313	8			
24-26	869	86	106-108	2943	13	174-176	5429	NA			
26-28	948	182	108-109	3011	7	176-178	5545	233			
28-30	1028	76	109-110	3057	7	178-180	5661	145			
30-32	1107	12	110-111	3103	12	180-182	5777	11			
32-34	1187	28	111-112	3149	10	182-184	5893	3			
34-36	1267	14	112-113	3195	25	184-186	6009	6			
36-38	1346	75	113-114	3241	9	186-188	6125	25			
38-40	1426	14	114-115	3286	2	188-190	6240	10			
40-42	1505	96	115-116	3332	27	190-192	6356	17			
42-44	1585	107	116-117	3378	3	192-194	6472	0			
44-46	1664	90	117-140	3401	NA	201.5-202	6545	1			
46-48	1744	613	140-141	3430	23	202-202.5	6574	0			
48-50	1823	9	141-142	3488	25	202.5-205	6661	0			