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Regional and local controls on postglacial vegetation and fire in the Siskiyou Mountains, northern California, USA

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ABSTRACT

The Siskiyou Mountains of northwestern California and southwestern Oregon are a floristic hotspot, and the high diversity of conifers there likely results from a combination of geological, ecological, climatological and historical factors. To evaluate how past climate variability has influenced the composition, structure and fire regime of the Siskiyou forests, pollen, charcoal, and lithological evidence was examined from two lakes along a moisture gradient to reconstruct the vegetation, fire and climate history. The late-glacial period was characterized by subalpine parkland and infrequent fire at both sites. During the late-glacial/Early Holocene transition period, subalpine parkland was replaced by a closed forest of *Pinus*, Cupressaceae, *Abies* and *Pseudotsuga* and more frequent fires a 1000 years earlier at the wetter site, and it is likely that reduced Pacific Ocean upwelling created warmer drier conditions at the coast. In the Early Holocene, *Pinus*, Cupressaceae were less abundant and fire less frequent at the coastal site during a period of increased coastal upwelling and fog production. In the Late Holocene, *Abies*, *Pseudotsuga*, *Pinus*, and *Quercus vaccinifolia* increased in the forest at both sites suggesting a widespread response to cooling. Fewer fires at the wetter site may account for the abundance of *Picea breweriana* within the last 1000 years. The comparison of the two records implies that large-scale controls in climate during the last 14,000 cal yr BP have resulted in major changes in vegetation and fire regime. Asynchrony in the ecosystem response of wetter and drier sites arises from small-scale spatial variations in effective moisture and temperature resulting from topographically-influenced microclimates and coastal-to-inland climate gradients.

1. Introduction

The environmental response to climate change in mountainous regions is complex and not well-understood (Shafer et al., 2005). Steep elevational gradients created by mountains transform large-regional scale climate patterns into site-specific microclimates in which different aspects and elevations strongly influence vegetation and fire across the landscape. The Siskiyou Mountains of northwestern California and southwestern Oregon, a subrange of the Klamath Mountains, are known for their heterogeneous landscape and extraordinary gamma diversity (i.e., total number of species across the region). This diversity is attributed to spatial variability in soil, climate, and disturbance regime (DellaSala et al., 1999); however, the role of long-term climate change or stability in shaping vegetation and fire across this complex landscape has only begun to be addressed (West, 1989; Mohr et al., 2000; Briles et al., 2005; Daniels et al., 2005).

The Siskiyou Mountains have traditionally been considered a region where the climate has remained stable during the Cenozoic Era, thereby providing a refuge for temperate forest taxa as conditions became cooler and drier elsewhere in the Pacific Northwest (Whittaker, 1960). This notion of stability is contradicted by evidence from the Quaternary which suggests that the region experienced significant climate fluctuations on millennial and shorter time scales (Kaufman et al., 2004; Vacco et al., 2005). Here we compare the postglacial vegetation and fire history in the northern Siskiyou Mountains from two sites located along a moisture gradient to further describe the nature of environmental change over the last 14,000 years following deglaciation of the region. The two sites are within 20 km of each other on similar substrates, but the site closest to the coast, Sanger Lake, is slightly wetter than the more inland site, Bolan Lake, and has a well established population of endemic conifers including *Picea breweriana* (Brewer's spruce) and *Chamaecyparis lawsoniana* (Port-Orford cedar) unlike the more inland site (see site descriptions below). One objective of this study was to determine whether the present vegetation differences arise from distinct vegetation, fire and climate histories or merely reflect local site differences. Another objective was to determine the geographic extent of early-Holocene trade-offs between haploxylon *Pinus* (likely *Pinus monticola* and Cupressaceae (likely *Calocedrus decurrens*)), that were associated with changes in fire frequency recorded at Bolan Lake (Briles et al., 2005).

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2. Study area

2.1. Study sites

Sanger Lake (Lat. 41°54′06″N, Long. 123°38′49″ W, 1550 m elevation, 4 ha) is located in a late-Pleistocene cirque (Fig. 1). The bedrock around the lake is diorite, and upslope and downslope of Sanger Lake are serpentine deposits. The lake has no permanent inflowing streams and is mainly fed by groundwater. Sanger Lake lies in the *Abies concolor* (white fir) Vegetation Zone (1300–1900 m elevation) (Franklin and Dryness, 1988) (all botanical nomenclature is based on Hickman, 1993). The dominant conifers around the lake include *A. concolor*, *Picea breweriana*, *Chamaecyparis lawsoniana*, *Pinus monticola* (western white pine), and *Pseudotsuga menziesii*. *C. lawsoniana* is restricted to and dominates mesic serpentine slopes within the basin. The dominant shrubs around the lake include *Quercus vaccinifolia* (huckleberry oak), *Chrysolepis chrysophylla* (golden chinquapin), *Lithocarpus densiflora* (tanoak), and *Ceanothus velutinus* (snowbrush).

The modern climate (based on elevation adjusted interpolated station data; Bartlein and Shafer, unpublished data, 2007) at Sanger Lake is characterized by cool winters (1 °C mean temperature) and mild summers (12.7 °C mean temperature). The annual precipitation is about 1300 mm with 48% received in the winter and 15% in summer. Sanger Lake is slightly more humid in the summer, with lower absolute maximum temperatures, and slightly warmer wetter winters than at Bolan Lake.

Young *Pseudotsuga* (<20 years old) on the south side of the lake have charred bark and *Chamaecyparis lawsoniana* on the southeast slope of the lake have fire scars, both attesting to recent fire in the watershed. The north slope of the lake supports a young cohort of trees <100 year old, whereas the east and south slopes have trees >300 years old. Fire return intervals (FRI) for *Abies concolor* forests in the region range between 25 and 64 years (Agee, 1993; Skinner et al., 2006), but the Sanger Lake forests likely have a longer FRI as a result of wetter cooler conditions.

Bolan Lake (Lat. 42.023, Long. 123.458, 1638 m elevation, 5 ha) is located in southwestern Oregon on the California/Oregon border about 20 km northeast of Sanger Lake (Fig. 1). Like Bolan Lake, it also occupies a late-Pleistocene cirque basin underlain by diorite and serpentine and has no inflowing streams. The forest at Bolan Lake is more open than at Sanger Lake and is dominated by *Abies concolor*, *Pinus monticola* and *Pseudotsuga menziesii*. *Picea breweriana* and *Chamaecyparis lawsoniana* do not grow at the site today. The warmer, drier setting, with 190 mm less annual precipitation (mostly in winter as snow), cooler winters (−0.5 °C mean temperature), more snow, and warmer summers (13 °C mean temperature) at Bolan Lake than at Sanger Lake (Bartlein and Shafer, unpublished data), is likely due to its more inland location.

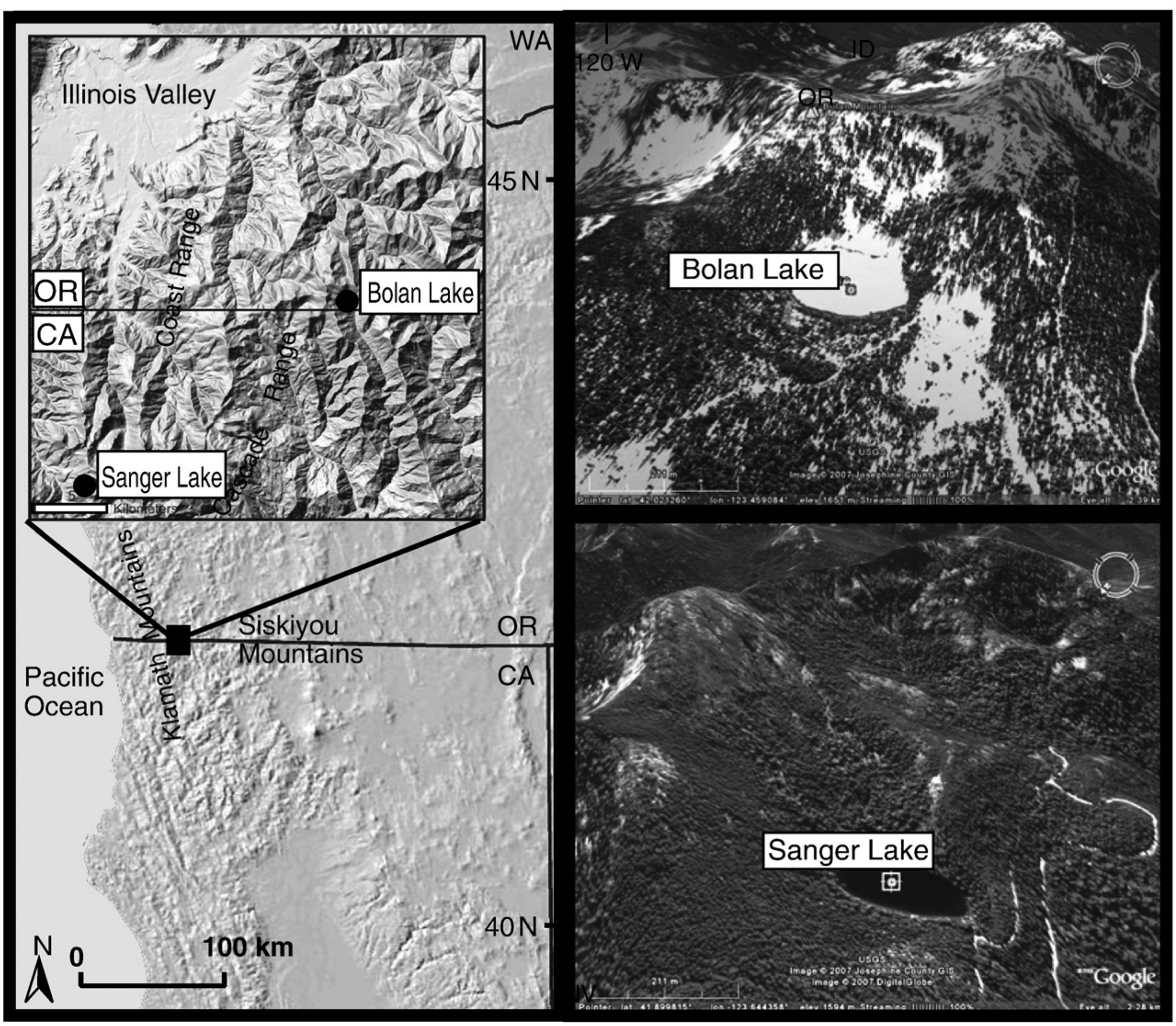

Fig. 1. Map showing location of Sanger and Bolan lakes. Aerial perspective is from late winter for Bolan Lake and summer for Sanger Lake (from Google Earth).

2.2. Regional vegetation and fire patterns

In addition to the *Abies concolor* Zone, five other vegetation zones occur in the Siskiyou region (Franklin and Dyrness, 1988). The Oak Woodland Zone (*Quercus garryana* and *Quercus kelloggii*) occurs up to 800 m elevation and is warmer and drier than other zones. In the Mixed-Evergreen Zone from 800 to 1100 m elevation, *Pseudotsuga*, *Pinus ponderosa* (ponderosa pine), *P. jeffreyi* (Jeffrey pine), *Calocedrus decurrens* and *Lithocarpus densiflora* are common. As conditions become cooler and wetter, *A. concolor* and *Pseudotsuga* become dominant in the Mixed-Conifer Zone, from 1100 to 1300 m elevation. In both the Mixed-Evergreen and Mixed-Conifer zones, mixed-severity fires occur on average every 6–22 years (Taylor and Skinner, 1998). Above the *Abies concolor* Zone, *Abies magnifica* (red fir) and *Tsuga mertensiana* (mountain hemlock) grow from 1900 to 2300 m elevation as conditions become progressively cooler and wetter in the *Tsuga mertensiana* Zone. Fires are generally less frequent and of higher severity in progressively higher zones, with a FRI of >100 yr in the *Tsuga*-dominated forests (Skinner et al., 2006).

Fires in the Siskiyou Mountains usually occur with strong winds and low humidity in summer. Critical fire weather includes a persistent upper-level ridge, strong subsidence that suppresses precipitation, and low relative humidity that dries fuels, followed by a weak upper-level trough that causes atmospheric instability, strong winds, and dry thunderstorms with lightning (Agee, 1993). Topographic features determine areas of similar fire occurrence and size (Taylor and Skinner, 2003). Fires have consumed large areas of the Klamath Mountains in recent decades, including the Uncle, Orleans, and Bar fire complexes of 2006 (60,000 ha), the Biscuit Fire of 2002 (202,000 ha), and the Silver Creek Fire of 1987 (74,000 ha). The Biscuit Fire, currently Oregon's largest recorded fire on record and the 7th largest for the U.S, has spurred federal management decisions (e.g. Health Forest Initiative of 2003; USDA Forest Service, 2004) and scientific debates (Donato et al., 2005).

3. Methods

Methods for the analysis of Sanger Lake record are described below. The Sanger and Bolan lake records were obtained with similar methods as described by Briles et al. (2005). However, to standardize the treatment of each record, the chronology and charcoal analytical methods used for Bolan Lake were modified from the original publication.

3.1. Field and lithological

A 6.66-m-long sediment core and a 60-cm-short core were recovered from Sanger Lake with a floating platform and a 5-cm-diameter modified Livingstone square-rod piston sampler (Wright et al., 1983). Cores were extruded in the field, wrapped in cellophane and aluminum foil and transported to the laboratory where they were refrigerated. In addition, a 7.5-cm-diameter Klein piston corer was used to capture the mud-water interface and the upper sediments. This core was extruded at 1-cm intervals into plastic bags and lithology was noted in the field. In the laboratory, long cores were split longitudinally and changes in lithology and color were noted.

Magnetic susceptibility was measured at 1-cm intervals to assess changes in inorganic allochthonous sediment (Gedye et al., 2000). Measurements were made on 10 cm^3 subsamples using a Bartington magnetic susceptibility meter unit and results were reported as cgs. Organic content of the lake sediments was measured as weight-loss after ignition at 550 °C in 1 cm^3 samples taken at 2 to 5 cm intervals to evaluate changes in lake productivity through time (Dean, 1974).

3.2. Chronology

Radiocarbon dates were obtained on plant macrofossils (seed, twigs, leaves, etc.) and gyttja for Sanger Lake. Dried sediment from the upper 10 cm of the core was ^{210}Pb dated at the USGS-Denver. Age-depth models were constructed based on radiocarbon and ^{210}Pb dating and tephrochronology from both long and short cores. Radiocarbon ages were calibrated using Calib 5.0.2 (Stuiver et al., 2005) for both Bolan and Sanger lakes and age-depth models were constructed using a cubic smoothing spline and a bootstrap approach that allowed each date to influence the age model through the probability density function of the calibrated ages (Higuera et al., 2008). The smoothing parameter for each spline was selected based on the assumption that the predicted ages of each sample fell within the confidence intervals of the calibrated ^{14}C dates. The overall uncertainty of each age estimate (i.e., two standard deviations) was used to weight the influence of each calibrated age in the age-depth model (e.g., Telford et al., 2004), and confidence intervals, reflecting the combined uncertainty of all age estimates in the model, were derived from 10,000 bootstrap-estimated chronologies. For each bootstrap chronology, the specific ages used to develop the chronology were selected randomly based on the probability distribution of the ^{210}Pb or calibrated ^{14}C date. The final chronology represents the median age of each depth from the 10,000 bootstrap-estimated chronologies.

3.3. Charcoal

Macroscopic charcoal samples were prepared following methods described by Whitlock and Larsen (2001) and the data was used to reconstruct past fire activity. Sediment samples of 2 cm^3 were taken at contiguous 1-cm intervals and soaked in 5% sodium metaphosphate and bleach for 24 h. They were washed through 250- and 125-micron-mesh screens. Particles in each size class were counted in gridded petri dishes under a stereomicroscope at 50–100× magnification. Charcoal concentration (number of particles cm^{-3}) from the two size fractions showed similar trends and were combined. Charcoal concentrations and deposition times were interpolated to the median sample resolution of each record (i.e., 20 yr cm^{-1}) to produce equally-spaced intervals within and between records. Charcoal accumulation rates (CHAR, particles cm^{-2} yr^{-1}) were determined by multiplying the interpolated charcoal concentrations (particles cm^{-3}) by the interpolated sedimentation rate (cm yr^{-1}) using CharAnalysis software (http://www.charanalsysis.googlepages.com; Higuera et al., 2008, Higuera et al., in revision).

To identify peaks in CHAR likely related to local fire occurrence, the CHAR time series was decomposed into two components: 1) a background component and 2) a peaks component. The background component represents long-term variations in charcoal production, secondary transport, sediment mixing, and sediment sampling (Long et al., 1998, Higuera et al., 2007) and was defined by a locally-weighted regression using the tricube weight function with a 700-yr window, robust to outliers (Cleveland, 1979; 5 robustness steps). The peaks component represents high-frequency variability around background and was defined as the residuals after the background component was subtracted. The peaks component can be further separated into two sub-components: non-fire-related variability in CHAR (i.e. analytical and natural noise; assumed to follow a normal or Gaussian distribution) and fire-related CHAR peaks (i.e., signal). A Gaussian mixture model was used to identify the noise component (Gavin et al., 2006, Higuera et al., 2008; Higuera et al., in revision), and the 95th percentile of this distribution was taken as the threshold value separating fire-related signal from noise in the peaks component (Higuera et al., 2008; Higuera et al., in revision). The procedure was done on each 700-yr, overlapping portion of the CHAR record, producing a unique threshold for each sample. The individual threshold values were smoothed with a 700-yr tricubic locally-weighted regression to produce the final threshold values for the record. Finally, all peaks exceeding the locally-defined threshold were screened using the original charcoal counts contributing to each peak. If the maximum count in a CHAR peak had a >5% chance of coming from the same Poisson-distributed population as the minimum charcoal count within the proceeding 75 years, then the “peak” was rejected (e.g., Charster user's guide, accessed March 2008, http://

Table 1
Uncalibrated and calibrated ^{14}C and ^{210}Pb ages for Sanger Lake

Depth (m)[a]	Predicted age (cal yr BP; med Prob.)[b,d]	Upper age range (cal yr BP)[c]	Lower age range (cal yr BP)[c]	^{14}C age BP	±	Material dated	Reference[e]
0.01	−48	−48	−47	–	–	Gyttja ^{210}Pb	USGS-Denver
0.02	−40	−40	−39	–	–	Gyttja ^{210}Pb	USGS-Denver
0.03	−31	−31	−30	–	–	Gyttja ^{210}Pb	USGS-Denver
0.04	−22	−23	−20	–	–	Gyttja ^{210}Pb	USGS-Denver
0.05	−13	−14	−11	–	–	Gyttja ^{210}Pb	USGS-Denver
0.06	−4	−6	−1	–	–	Gyttja ^{210}Pb	USGS-Denver
0.07	2	0	4	–	–	Gyttja ^{210}Pb	USGS-Denver
0.57	684	731	640	625	30	Twig	CAMS112965
0.79	699	747	655	1220	35	Needle	CAMS112995
1.415	714	763	670	1995	35	Needle	CAMS112966
1.64	2233	2293	2177	2215	35	Needles	CAMS119619
2.16	3001	3064	2947	2910	35	Wood	CAMS112967
2.42	3478	3533	3428	3205	35	Needle	CAMS112968
2.64	3979	4034	3921	3580	35	Wood	CAMS112969
3.25	5702	5757	5627	5035	35	Wood	CAMS118758
3.34	5955	6010	5881	5150	35	Leaf	CAMS112970
3.75	6992	7040	6940	6135	40	Wood	CAMS112971
3.96	7412	7452	7368	6845	50	Mazama Ash	Bacon, 1983
3.97	7430	7469	7386	6430	35	Needles	CAMS119619
4.26	7897	7942	7848	7005	35	Twig	CAMS118760
4.415	8144	8199	8085	7300	40	Wood	CAMS112972
4.775	8902	8983	8815	8060	45	Wood	CAMS112973
5.135	9901	10,000	9815	8795	45	Wood	CAMS112974
5.395	10,909	11,002	10,829	9455	35	cone scale	CAMS112996
5.4	10,953	11,046	10,873	9625	45	Gyttja	CAMS118761
5.58	11,810	11,892	11,734	10,060	40	Gyttja	CAMS118762
5.68	12,330	12,406	12,256	10,435	50	Gyttja	CAMS118763
5.83	13,143	13,220	13,071	11,460	70	Gyttja	CAMS118764
5.95	13,805	13,892	13,724	12,025	40	Gyttja	CAMS112994
6.23	Too old	Too old	Too old	15,720	510	Gyttja	CAMS112993

[a]Depth below mud surface.
[b]^{14}C calibrated ages derived using a bootstrapping approach based on the probability distribution function of all ^{14}C ages in the age-depth model (see Methods; Calib 5.0.2; Stuvier et al., 2005).
[c]95% confidence interval based on 10,000 runs.
[d]^{210}Pb dates were adjusted for the 53 years (the core was taken in 2003) since 1950 A.D. before being considered with the radiocarbon dates.
[e]^{210}Pb ages and errors from USGS-Denver.

geography.uoregon.edu/gavin/charster/Analysis.html). Statistical treatment of the charcoal records was done using the program CharAnalysis (PEH, available online at http://www.charanalysis.googlepages.com).

Fire episode frequency (number of fire episodes1000 yr^{-1}) was determined by smoothing the binary peak series with a tricubic locally-weighted regression to summarize long-term (i.e., millennial scale) trends. Peak magnitude (particles cm^{-2} peak^{-1}) represents the total accumulation of charcoal for all samples of a peak exceeding the threshold value, and may be related to fire size, fire intensity, and/or charcoal delivery (Whitlock et al., 2006; Higuera et al., 2007).

3.4. Pollen

Pollen analyses provided information on the regional and local vegetation history. Pollen was sampled every 50–100 years for the last 2000 years and every 100–200 years for the remainder of the Sanger Lake record. A total of 89 pollen samples were processed using methods of Bennett and Willis (2002). A *Lycopodium* tracer was added to calculate pollen concentration (grains cm^{-3}). Pollen grains were identified at magnifications of 500 and 1250×, and counts ranged from 300 to 530 terrestrial grains per sample, with at least 100 non-*Pinus* grains.

Pollen was identified to the lowest taxonomic level possible using reference collections, atlases (e.g., Moore and Webb, 1978; Kapp et al., 2000), and other publications (Hebda et al., 1988a,b; Jarvis et al., 1992). The assignment of pollen taxa was based on modern phytogeography. Haploxylon-type *Pinus* pollen was attributed to *Pinus monticola* but contributions from *P. lambertiana* (sugar pine) and/or minor amounts of *P. balfouriana* (fox tail pine) and *P. albicaulis* (whitebark pine) may also have been included. *Pinus* grains missing a distal membrane were identified as undifferentiated *Pinus*. *Abies* pollen grains were from *A. concolor*, *A. magnifica* and possibly *A. procera* (noble fir; although its range is limited in northern California and does not occur at either site today). *Picea* pollen was attributed to *P. breweriana* or *P. engelmannii* (Engelmann spruce). Cupressaceae grains probably come mostly from *Calocedrus decurrens* or *Chamaecyparis lawsoniana*, but *Juniperus occidentalis* (western juniper) and *Thuja plicata* are also in the region but not near the sites today. *Chrysolepis*-type grains were either from *C. chrysophylla* or *Lithocarpus densiflora*. *Quercus vaccinifolia*-type pollen were distinguished from *Q. garryana*-type based on coarseness of the sculpturing elements and differences in the apertures (Jarvis et al., 1992). *Ceanothus* grains were from *C. cuneatus* (buckbrush), *C. integerrimus* (deerbrush), *C. prostratus* (squaw carpet), *C. pumilus* (dwarf ceanothus), *C. thyrsiflorus* (blue blossom ceanothus), or *C. velutinus* (snowbrush ceanothus). Pollen grains that were broken, corroded, hidden or otherwise damaged were counted as 'Indeterminate', and those that were unidentifiable were counted as 'Unknown.'

Pollen percentages and accumulation rates (PAR; grains cm^{-2} yr^{-1}) were used to reconstruct past vegetation. Percentages of terrestrial upland taxa were based on a sum of pollen from all trees, shrubs, herbs, and pteridophytes. The pollen-percentage record was divided into five zones by use of a constrained cluster analysis (CONISS; Grimm, 1988). PAR were determined by dividing pollen concentrations by deposition time (yr cm^{-1}).

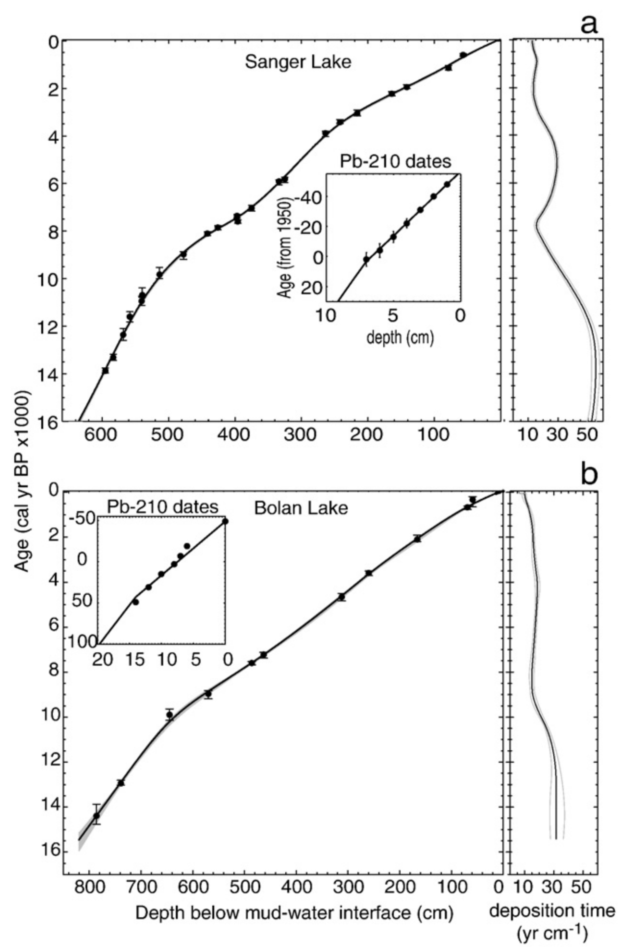

Fig. 2. Age-versus-depth curves and deposition time for (a) Sanger Lake and (b) Bolan Lake based on ^{14}C and ^{210}Pb dates, and tephrochronology. The gray band reflects the modeled range of dates and deposition times and the black line the 50th (i.e., median age) percentile of all runs. Circles and bars reflect the 50th, 2.5th (i.e., lower age) and 97.5th (i.e., upper age) percentiles of the probability distribution function of calibrated dates. See Table 1 and Table 2 for age information.

4. Results

The chronology, lithology, charcoal and pollen results for Sanger Lake and chronology, charcoal peak magnitude, and fire-episode frequency results for Bolan Lake are presented below. Lithology, charcoal (background CHAR) and pollen results for Bolan Lake are described in Briles et al. (2005).

4.1. Chronology

The Sanger Lake chronology was based on 23 ^{14}C AMS dates on terrestrial plant macrofossils and gyttja found in the long core and seven ^{210}Pb age determinations on the upper sediments of the short core. Mazama Ash, at 3.96 m depth, was assigned an age of 6845±50 ^{14}C BP (Bacon, 1983) and included to the chronology (Table 1; Fig. 2a). A date just below the Mazama Ash layer (3.97 m depth) yielded a younger radiocarbon date than the accepted age of the ash layer; however, the range of calibrated dates overlap, which suggest the dates could be in stratigraphic order. A radiocarbon date on inorganic clay at the bottom of the long core (6.23 m depth) yielded an anomalously old calibrated age (~19,000 cal yr BP), earlier than the timing of deglaciation in the Pacific Northwest (after 17,000 cal yr BP) (Clark and Gillespie, 1997; Porter and Swanson, 1998) and large laboratory error. The date was left out of the chronology.

A new age model was constructed for Bolan Lake, following the same methods described for Sanger Lake, in order to utilize the new radiocarbon calibration curve (IntCal04; Reimer et al., 2004) and the bootstrapping approach for determining an age model (Table 2; Fig. 2b). In most cases, the old chronology fell within the upper and lower confidence intervals; however between −49 and 2150 cal yr BP, the ages exceeded the lower confidence interval up to 60 years, between 6800 and 8000 cal yr BP up to 37 years, and between 11,000 and 13,250 cal yr BP up to 125 years. The new Bolan Lake age-depth model is used in this paper; however the new chronology did not substantially change the interpretations in Briles et al. (2005).

Table 2
Uncalibrated and calibrated ^{14}C and ^{210}Pb ages for Bolan Lake

Depth (m)[a]	Predicted age (cal yr BP; med Prob.)[b, d]	Upper age range (cal yr BP)[c]	Lower age range (cal yr BP)[c]	^{14}C age BP	±	Material dated	Reference[e]
6	−19	–	–	–	–	Gyttja ^{210}Pb	UWM
7	−7	–	–	–	–	Gyttja ^{210}Pb	UWM
8	3	–	–	–	–	Gyttja ^{210}Pb	UWM
10	15	–	–	–	–	Gyttja ^{210}Pb	UWM
12	31	–	–	–	–	Gyttja ^{210}Pb	UWM
14	49	–	–	–	–	Gyttja ^{210}Pb	UWM
0.59	523	564	452	267	46	Cone scale and needle	AA40215
0.71	670	719	589	708	41	Wood	AA40214
1.66	2057	2192	1982	2123	35	Leaf and charcoal	AA44436
2.6	3637	3717	3549	3354	39	Cone scale	AA44437
3.12	4603	4712	4496	4120	45	Wood	NSRL12159
4.63	7222	7280	7143	6290	45	Wood	NSRL12160
4.86	7583	7636	7517	6845	50	Mazama ash	Bacon, 1983
5.7	8854	8975	8717	8060	50	Wood	NSRL12161
6.45	10,204	10,369	10,045	8827	62	Wood	AA40217
7.39	12,895	13,023	12,796	11,010	65	Wood	NSRL12162
7.86	14,382	14,697	14,139	12,360	120	Gyttja	WIS2085

[a]Depth below mud surface.
[b]^{14}C calibrated ages derived using a bootstrapping approach based on the probability distribution function of all ^{14}C ages in the age-depth model (see Methods; Calib 5.0.2; Stuiver et al., 2005).
[c]95% confidence interval based on 10,000 runs. ^{210}Pb errors not specified by laboratory.
[d]^{210}Pb dates were adjusted for the 49 years (the core was taken in 1999) since 1950 A.D. before being considered with the radiocarbon dates.
[e]^{210}Pb ages based on concentration data provided by the center for Great Lake Studies, University of Wisconsin-Milwaukee (UWM; see Briles et al., 2005).

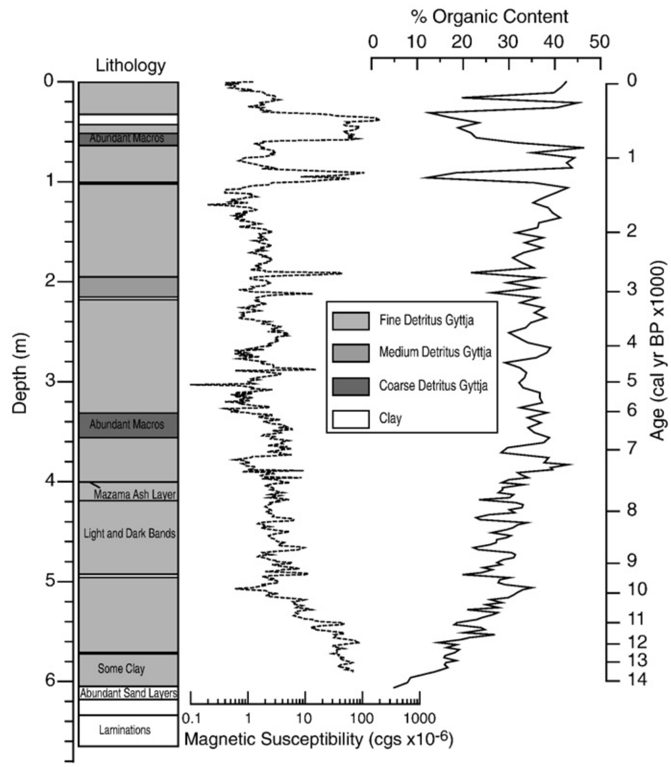

Fig. 3. Lithology, magnetic susceptibility (dashed line) and percent organic content (solid line) from Sanger Lake.

4.2. Lithology

The Sanger Lake long core contained two distinct lithological units (Fig. 3). The first unit (6.00 to 6.66 m depth; >14,200 cal yr BP) was an inorganic clay with sand layers (<4% organic matter, >60×10^{-6} cgs magnetic susceptibility values) that preserved little to no pollen and charcoal. The second unit (6 to 0 m depth; <14,200 cal yr BP) consisted of mainly fine-detritus gyttja with abundant pollen and charcoal. Between 6.00 to 5.16 m depth (14,200 and 10,000 cal yr BP), magnetic susceptibility decreased from 60 to 8×10^{-6} cgs and organic carbon content increased from 4 to 30%. Magnetic susceptibility between 5.16 and 1.06 m depth varied between 8 and 10×10^{-6} cgs. A 7 cm-thick clay layer was deposited from 0.42 to 0.36 m depth (380 and 470 cal yr BP), and occurred at approximately the same depth and thickness across the lake based on multiple gravity cores taken across the basin by Briles. Thin clay layers were also present at 1.01 m depth (1360 cal yr BP), 2.18 m depth (3030 cal yr BP), and 4.95 m depth (9340 cal yr BP). Organic carbon steadily increased between 6.00 and 3.76 m depth from 30 to 40% (10,000 to 7000 cal yr BP), dropped to 35% between 3.76 and 1.47 m depth (7000 to 2000 cal yr BP), and increased to 45% toward the top of the core.

4.3. Charcoal record

4.3.1. Sanger Lake

Fire activity at Sanger Lake since 14,500 cal yr BP fluctuated between 1.5 and 6.87 fire episodes 1000 yr^{-1} and background CHAR between 0.01 and 0.94 particles cm^{-2} yr^{-1} (Fig. 4). The late-glacial period (>10,400 cal yr BP) recorded the lowest background CHAR (<0.2 particles cm^{-2} yr^{-1}) and fire activity (1.5 to 3.7 fire episodes 1000 yr^{-1}). Peak magnitudes were small during this period (<9 particles cm^{-2} $peak^{-1}$).

Background CHAR increased from 0.2 to 0.84 particles cm^{-2} yr^{-1} between 10,400 and 6000 cal yr BP. Fire activity increased from 3.7 to 6.5 fire episodes 1000 yr^{-1} between 10,400 and 9200 cal yr BP and then decreased to 4.4 fire episodes 1000 yr^{-1} by 7200 cal yr BP. Peak

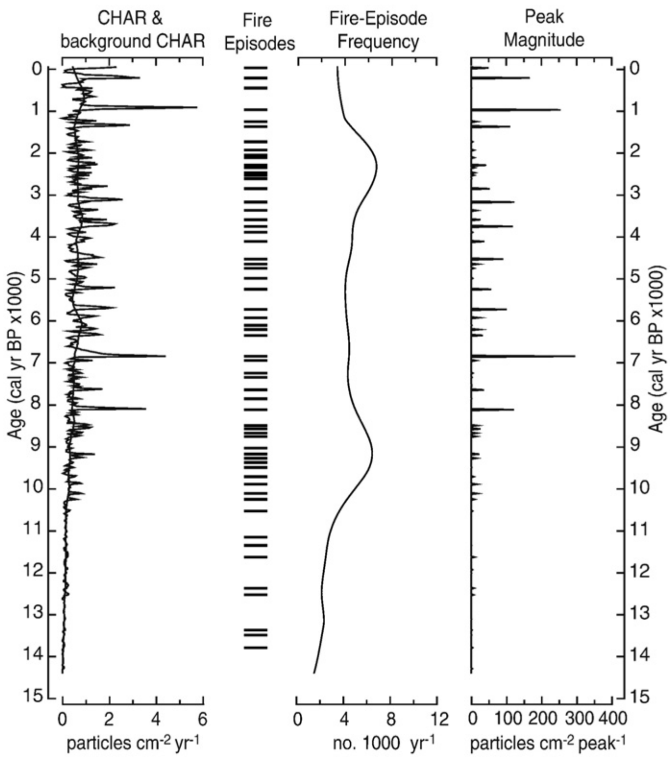

Fig. 4. Charcoal accumulation rates (CHAR) for the last 14,500 cal yr at Sanger Lake. Accumulation rates were decomposed into background CHAR (the slowly varying curve overlying the accumulation rate curve; window-width = 700 yr) and peaks or fire episodes. The fire-episode frequency shows the number of peaks 1000 yr^{-1}, based on a 2500 year smoothing window. Peak magnitude (particles cm^{-2}) measures fire size, fire intensity, and/or charcoal delivery.

magnitudes increased after 8450 cal yr BP to ~50 particles cm^{-2} $peak^{-1}$, ending with a large fire episode (>300 particles cm^{-2} $peak^{-1}$) at 6900 cal yr BP (the largest peak of the record that spanned several samples).

Background CHAR declined after 6000 cal yr BP, fluctuating between 0.6 and 0.8 particles cm^{-2} yr^{-1} until 1250 cal yr BP when it increased and reached the highest levels of the record at 660 cal yr BP (0.94 particles $cm^{-2}yr^{-1}$). Background CHAR then declined between 660 and the present to 0.45 particles $cm^{-2}yr^{-1}$. Fire activity continued to decline slightly between 7200 and 5300 cal yr BP to a 4.2 fire episodes 1000 yr^{-1} and then increased and reached the highest levels of the record by 2200 cal yr BP (6.9 fire episodes 1000 yr^{-1}). Fire frequency declined after 2200 cal yr BP to 3.5 episodes 1000 yr^{-1} and was comparable to fire frequencies of the late-glacial period. Peak magnitudes averaged ~100 particles between 6900 and 3000 cal yr BP, dropped to ~50 particles cm^{-2} $peak^{-1}$ between 3000 and 1250 cal yr BP, and increased to ~200 particles cm^{-2} $peak^{-1}$ between 1250 and the present.

4.3.2. Bolan Lake

Fire-episode frequency and background CHAR for Bolan Lake are described in full in Briles et al. (2005), however, fire-episode frequency is presented here again for purposes of comparing it with the Sanger Lake record in the Discussion section. Peak magnitudes were analyzed and presented below. Fire-episode frequency over the last 14,500 cal yr B.P. varied between 4 and 10 episodes 1000 yr^{-1}. Between 14,500 and 10,900 cal yr B.P., fire-episode frequency fluctuated between 3 and 7 episodes 1000 yr^{-1}, with the highest frequency at 13,000 cal yr B.P. and the lowest frequency at 14,000 and 11,500 cal yr B.P. (4 and 3 episodes 1000 yr^{-1}). Fire-episode frequency increased from 4 to 8 episodes 1000 yr^{-1} between 11,500 and 9200 cal yr B.P., declined to 7 episodes 1000 yr^{-1} between 9200 and 8500 cal yr B.P., and increased to 10 episodes 1000 yr^{-1}, the highest values of the record, by 7000 cal yr B.P. Fire-episode frequency steadily declined from 10 to 7 episodes 1000 yr^{-1} between 7000 and 3500 cal yr B.P., increased slightly from 7 to 8 episodes 1000 yr^{-1} between 3500 and 2500 cal yr B.P., decreased to 7 episodes 1000 yr^{-1} between 2500 and 1500 cal yr B.P. and then increased to 9 episodes 1000 yr^{-1} toward the present.

Peak magnitudes were small (<35 particles cm^{-2} $peak^{-1}$) between 14,000 and 11,800 cal yr BP, except for a large peak at 13,800 cal yr BP (380 particles cm^{-2} $peak^{-1}$). A mix of large (300 to >400 particles cm^{-2}

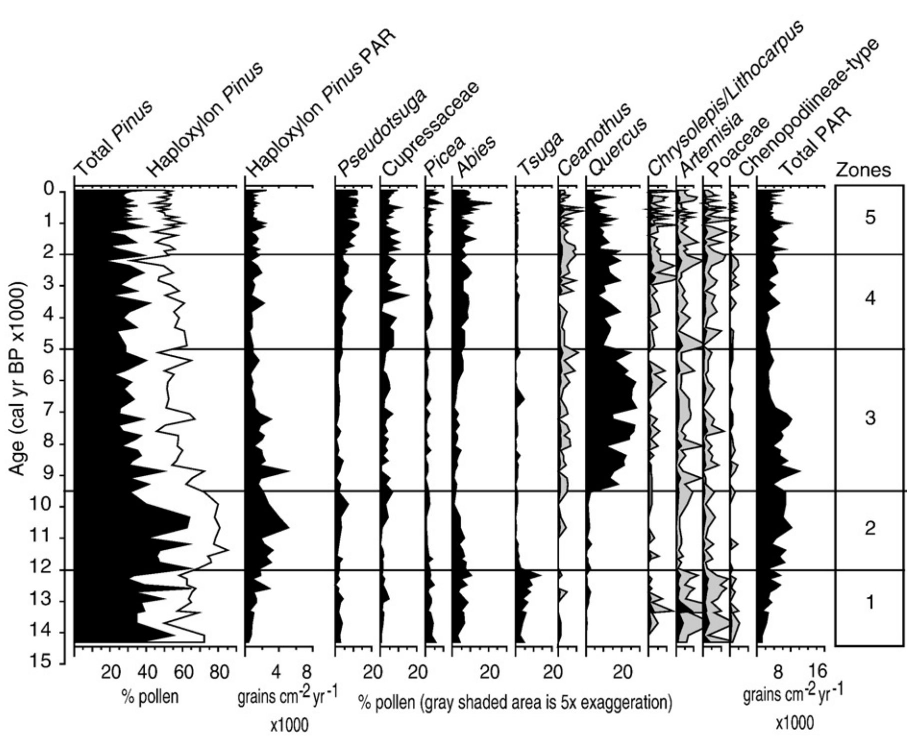

Fig. 5. Pollen percentages of select taxa, total pollen accumulation rate (PAR) and haploxylon *Pinus* PAR from Sanger Lake.

peak^{-1}) and small (1 to <70 particles cm^{-2} peak^{-1}) peak magnitudes occurred between 11,800 and 9500 cal yr BP. Small peaks (<100 particles cm^{-2} peak^{-1}) occurred between 9500 and 6000 cal yr BP. Between 6000 cal yr BP and the present the record was characterized by small-magnitude peaks (<50 particles cm^{-2} peak^{-1}) for 1000-year time spans and these were interrupted by large-magnitude peaks of >300 particles cm^{-2} peak^{-1}.

4.4. Sanger Lake pollen record

The Sanger Lake pollen record was divided in to five zones (Fig. 5):

Zone SA-1 (6.04–5.65 m depth; 14,200 to 12,000 cal yr BP) featured high percentages of haploxylon *Pinus*, *Tsuga*, *Picea* and increasing percentages of *Abies concolor*. Moderate percentages of *Artemisia*, Poaceae and Chenopodiineae and low but increasing pollen accumulation rates (PAR; 1000–3000 grains cm^{-2}yr^{-1}) suggest that the forest was initially open and became more closed (Fall, 1992; Davis et al., 1973; Ritchie and Lichti-Federovich, 1967). The forest composition was probably most similar to open forests of the *Tsuga mertensiana* Zone.

Zone SA-2 (5.65–5.01 m depth; 12,000 to 9600 cal yr BP) contained the highest percentages of haploxylon *Pinus* and high percentages of *Abies*. *Tsuga* dropped to low percentages and remained low for the rest of the record. *Pseudotsuga* and Cupressaceae percentages increased, especially between 9500 and 10,500 cal yr BP. *Artemisia*, Poaceae and Chenopodiineae percentages declined and PAR increased to the highest levels of the record (6000–8000 grains cm^{-2}yr^{-1}) suggesting that the forest became more closed than before (Ritchie and Lichti-Federovich, 1967; Davis et al., 1973; Fall, 1992). The pollen types represented in this zone come from taxa growing in the *Abies concolor* Zone today.

Zone SA-3 (5.65–3.05 m depth; 9600 to 5000 cal yr BP;) had high percentages of *Quercus* and low-to-moderate percentages of *Ceanothus*. Haploxylon *Pinus* percentages dropped to comparable amounts in Zone 1; however, PAR for the taxon dropped but remained higher than in Zone 1. The significantly increased percentages of *Quercus* likely resulted in an under representation of the haploxylon *Pinus* percentages in this zone as suggested by PAR. Cupressaceae percentages were the highest of the record. *Pseudotsuga* and *Abies* percentages were low. The forest composition was similar to present day Mixed-Evergreen forests ~500 m below the watershed today (Ritchie and Lichti-Federovich, 1967; Davis et al., 1973; Fall, 1992).

Zone SA-4 (3.05–1.49 m depth; 5000 to 2000 cal yr BP) was characterized by increasing percentages of *Abies* and *Pseudotsuga*. *Ceanothus* and *Chrysolepis*/*Lithocarpus* percentages peaked between 2000 and 3000 cal yr BP. Cupressaceae percentages remained comparable to those in Zone 3. Haploxylon *Pinus* PAR continued to decrease to 1000 grains cm^{-2}yr^{-1}, while percentages remained similar to Zone 3. *Quercus* percentages decreased through the zone. The forest during this time was similar to the Mixed-Conifer Zone located ~200 to 300 m downslope today (Solomon and Silkworth, 1986).

Zone SA-5 (1.49–0 m depth; 2000 cal yr BP to present) featured the highest percentages of *Pseudotsuga* and *Picea* of the record. *Pseudotsuga*, *Quercus*, *Ceanothus*, *Artemisia*, and Poaceae were high between 2000

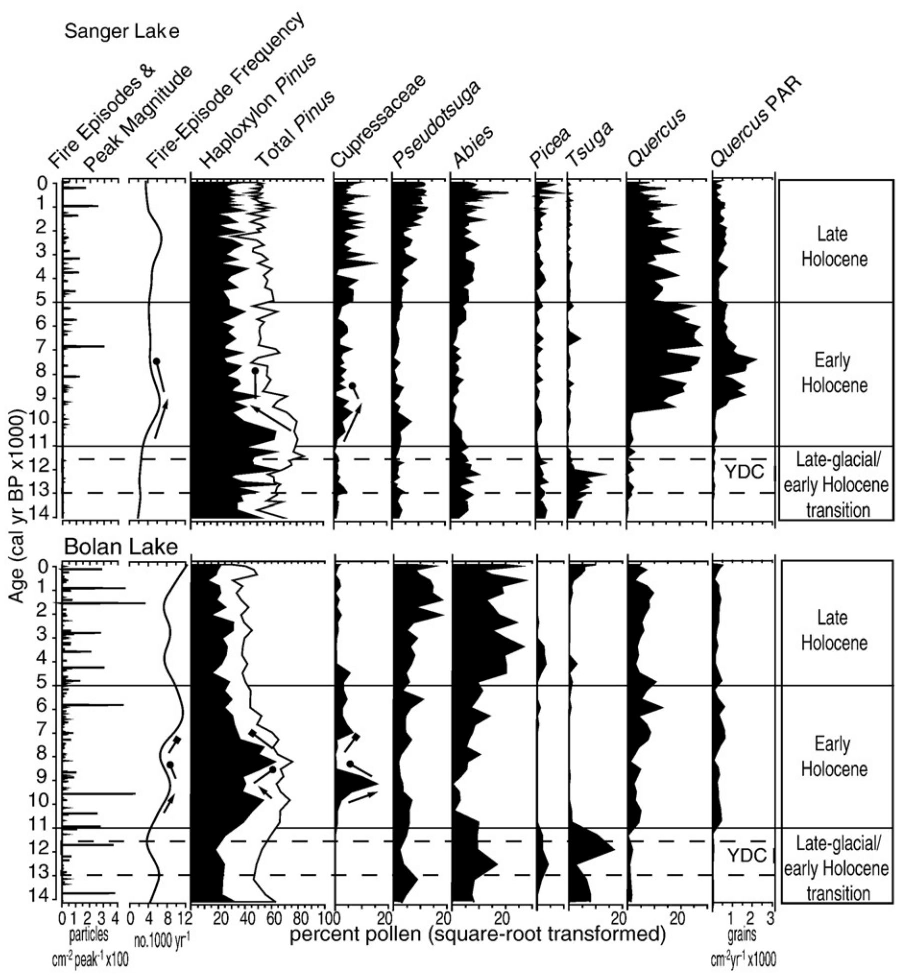

Fig. 6. Fire episodes, peak magnitude, fire frequency, and pollen percentages for Sanger and Bolan lakes. *Quercus* pollen accumulation rates (PAR) are also included. The arrows show the relationship between fire-episode frequency, Cupressaceae, and haploxylon *Pinus* (likely *Pinus monticola*) at the two sites. Increased fire-episode frequency (triangle and square arrows) is followed by a period of increased Cupressaceae and decreased *Pinus monticola*. The opposite occurs when fire-episode frequency decreases (circle arrow). The Younger Dryas chronozone (YDC) is defined by the dashed line.

and 1200 cal yr BP and then decreased thereafter. *Picea* and *Abies* had increased percentages between 1200 cal yr BP and present. The modern forest became established at Sanger Lake within the last 2000 cal yr.

5. Discussion

The vegetation and fire records of Sanger Lake and Bolan Lake are compared in the following section (Fig. 6). In addition, a brief overview is given on what is currently known about the regional climate history of the last 14,000 cal yr BP inferred from climate model simulations and ocean and terrestrial paleoclimate records (Bartlein et al., 1998; Barron et al., 2003; Vacco et al., 2005).

5.1. Late-glacial/early Holocene transition period (>11,000 cal yr BP)

Paleoclimate simulations for 14,000 cal yr BP suggest that increasing summer insolation resulted in summers that were warmer than before in the PNW, but still cooler and drier than present (Bartlein et al., 1998). Ocean core ODP 1019 (Barron et al., 2003), located at the same latitude as Sanger Lake and ~50 km offshore, recorded sea surface temperatures (SST) that were 1 °C less than the present day (12 °C) using alkenone-derived mean annual SST estimates between 15,000 and 13,000 cal yr BP. An abundance of diatoms between 14,600 to 12,900 cal yr BP from ODP 1019 suggests upwelling of colder bottom ocean waters (Barron et al., 2003). *Pinus* and *Artemisia* pollen found in ODP 1019 declined and *Alnus* increased from before, suggesting that conditions were becoming warmer and wetter on land.

Sanger and Bolan lakes were colonized by a subalpine parkland forest between 14,000 and 12,000 cal yr BP, and this vegetation was widespread across the region (Fig. 6; Daniels et al., 2005; Mohr et al., 2000). The lack of a tundra period prior to this forested period is consistent with relatively warm conditions following deglaciation. *Tsuga*, *Abies*, *Picea* and haploxlyon *Pinus* (likely *Pinus monticola*) were the dominant forest species. The gradual increase in pollen percentages of *Tsuga*, *Abies* and in PAR suggests a closing of the forest at this time. *Tsuga* would have been favored by deep spring snowpacks and a short mild growing season (Burns and Honkala, 1990). Fire-episode frequency and peak magnitudes were higher at Bolan Lake than at Sanger Lake at this time, suggesting that fires may have been larger and/or more intense at Bolan Lake and /or produced more charcoal.

Between 12,900 and 11,600 cal yr BP (i.e., during the Younger Dryas chronozone, Alley et al., 1993), alkenone-derived mean annual SST estimates from ODP 1019 abruptly dropped to <8 °C and diatom production decreased suggesting reduced coastal upwelling (Barron et al., 2003). After 11,600 cal yr BP, mean annual SSTs increased more than 5 °C within a 500-year period and diatom abundances remained low. Barron et al. (2003) attribute these changes to the Younger Dryas cool period (11,500 to 12,900 cal yr B.P.; Alley et al., 1993). This eastern Pacific cool event and subsequent abrupt warming event are recorded in ocean records to the north and south of ODP 1019 (Kienast and McKay, 2001; Mortyn et al., 1996). An isotopic speleothem record from the Oregon Caves National Monument suggests that land atmospheric temperatures dropped more than 3 °C after 13,000 cal yr BP for a 1200-year period and then abruptly increased (Vacco et al., 2005).

No distinctive or synchronous vegetation or fire change has been detected during the YD chronozone in the PNW region (Grigg and Whitlock, 1998; Mohr et al., 2000; Daniels et al., 2005). Bolan and Sanger lakes show increasing *Tsuga* suggesting that conditions were becoming warmer and wetter than before. *Tsuga* declined after 12,000 cal yr BP at Sanger Lake but was in greatest abundance at Bolan Lake until 11,500 cal yr BP. Haploxylon *Pinus* (and total *Pinus*) increased at Sanger Lake at 12,000 cal yr BP and around 500 years later at Bolan Lake. The fire regimes at the two sites were also different after 12,500 cal yr BP. Fire-episode frequency at Sanger Lake increased slowly and peak magnitudes were low through the period, whereas at Bolan Lake, frequency was high until 12,500 cal yr BP, declined to the lowest levels of the record at 11,500 cal yr BP and increased thereafter. Peak magnitudes also increased after 11,500 cal yr BP at Bolan Lake indicating that fires were large and/or intense. Increasing fire activity at Sanger Lake after 12,000 cal yr BP was likely responsible for the abundance of haploxylon *Pinus* (likely *Pinus monticola*). *P. monticola* is a seral species that relies on disturbances to remove competing vegetation for regeneration (Burns and Honkala, 1990).

Reduced upwelling that resulted in warmer conditions at Sanger Lake after 12,000 cal yr BP, is likely responsible for the loss of *Tsuga* and establishment of a forest with more *Pinus monticola* and increasing fire activity. Sanger Lake became more productive, as evidenced by increased organic content, whereas Bolan Lake remained relatively unproductive until 11,000 cal yr BP (Briles et al., 2005). At Bolan Lake, clastic minerals and the presence of pebbles in gyttja suggest more avalanche or glacial activity in the watershed. Therefore, the more inland location of Bolan Lake may have permitted cooler wetter conditions to persist 500 to 1000 years longer than at Sanger Lake.

5.2. Early and Middle Holocene (11,000 to 5,000 cal yr BP)

Paleoclimate simulations for 11,000 cal yr BP suggest that higher-than-present summer insolation in the early Holocene led to the expansion and intensification of the northeastern Pacific subtropical high pressure system and continental heating and drying in the Pacific Northwest (Bartlein et al., 1998). From 11,000 to 8200 cal yr BP, alkenone-derived mean annual SSTs temperatures from ODP 1019 were up to 1 °C above modern levels, and then decreased to 1 °C below modern levels between 8200 and 3300 cal yr BP (Barron et al., 2003). In addition, warm-water diatoms between 11,600 and 8200 cal yr BP, suggest a weak California Current and reduced upwelling. Cool-water diatoms increased between 8200 and 3300 cal yr BP, reflecting a stronger California Current and increased upwelling.

Major changes in vegetation and fire activity were registered at Bolan and Sanger lakes during the early Holocene (Fig. 6). Both sites show a decrease in the abundance of *Abies* at 11,000 cal yr BP and *Pseudotsuga* at 10,000 cal yr BP. *Abies* and *Pseudotsuga* occur in lowest abundance during the summer insolation maximum, between 10,000 and 9000 cal yr BP, which is not surprising since the species do best in wetter environments today. As summer insolation decreased, between 9000 and 5000 cal yr BP, *Abies* and *Pseudotsuga* increased in abundance responding to the cooler and wetter conditions than before. The changes in *Abies* during the early Holocene are similar to those found at other sites in the Klamath Mountains (Mohr et al., 2000; Daniels et al., 2005).

Understory shrubs, *Quercus* and *Ceanothus*, became abundant at Bolan and Sanger lakes and at other sites in the Klamath region (Mohr et al., 2000; Daniels et al., 2005). *Ceanothus* increased after 11,000 cal yr BP, and *Quercus* increased at Bolan Lake ca. 11,000 cal yr BP and at Sanger Lake ca. 9500 cal yr BP. *Ceanothus* species favor warm dry conditions and require fire to regenerate. *Quercus* is a shrub that does well in warm and especially dry conditions, has resinous leaves that carry fire from the understory into the forest canopy, and sprouts from the root crown following fire (Burns and Honkala, 1990). The presence of these species at both sites occurs during a period of high fire-episode frequency.

The delayed expansion of *Quercus* in the early Holocene at Sanger Lake, compared with Bolan Lake, is likely the result of slightly wetter conditions there compared with drier inland conditions resulting from intensified summer heating. Interestingly, PAR of *Quercus* increased abruptly and fire was frequent at Sanger Lake around 9200 cal yr BP, the insolation maximum. Both *Quercus* PAR and fire activity declined until 7000 cal yr BP, during a period when SSTs dropped and upwelling increased (Barron et al., 2003). In contrast, PAR of *Quercus* at Bolan Lake peaked ca. 7000 cal yr BP, when fire-episode frequency was highest, and decreased after 5500 cal yr BP, suggesting that warm dry conditions and high fire activity persisted for a longer period at Bolan Lake.

The trade-offs between Cupressaceae (likely incense cedar) and haploxylon *Pinus* (likely *Pinus monticola*) recorded at Bolan Lake are less evident at Sanger Lake (Fig. 6). At Bolan Lake, haploxylon *Pinus* increased at 11,000 cal yr BP when fire-episode frequency was low, decreased between 10,000 and 9000 cal yr BP, and was replaced by Cupressaceae when fire-episode frequency increased. Haploxylon *Pinus* then increased between 9000 and 8000 cal yr BP at the expense of Cupressaceae, as fire-episode frequency decreased, and dropped after 8000 cal yr BP as Cupressaceae increased and fire-episode frequency increased. It was suggested by Briles et al. (2005) that centennial-scale climate variations and fire might be responsible for these variations (i.e., cooler climate and decreasing fire favored haploxylon *Pinus*, whereas a warmer climate and increasing fire maintained more Cupressaceae). At Sanger Lake, haploxylon *Pinus* was abundant between 11,000 and 10,000 cal yr BP when fires were infrequent but increasing, and Cupressaceae (likely incense cedar and/or Port-Orford cedar) was not abundant. After 10,000 cal yr BP, Cupressaceae increased slightly at the expense of haploxylon *Pinus* as fire frequency increased until 9200 cal yr BP. After 9200 cal yr BP, fire frequency and Cupressaceae decreased slightly with little change in haploxylon *Pinus* abundance. Unlike Bolan Lake, no additional trade-offs in the two species are recorded at Sanger Lake after 9200 cal BP. Apparently, the more xeric conditions and greater incidence of fire at Bolan Lake allowed the relationship between haploxylon *Pinus* and Cupressaceae to persist longer than at Sanger Lake. Given that there is a short-lived and subdued response of haploxylon *Pinus* and Cupressaceae at Sanger Lake, the trade-off in the two species at Bolan Lake and the associated changes in fire cannot be attributed to centennial-scale climate variations based on these two records alone.

5.3. Late Holocene (5000 cal yr BP to present)

Paleoclimate simulations for 6000 cal yr BP indicate that decreasing summer insolation likely resulted in cooler wetter summers than before and a weaker northeastern Pacific subtropical high-pressure system in the summer than previously (Bartlein et al., 1998). In the winter, increasing solar radiation resulted in warmer and likely wetter winters than before. Alkenone-derived mean annual SSTs from ODP 1019 were initially cool (~11 °C) at 5000 cal yr BP and then increased by 1 °C after 3300 cal yr BP (Barron et al., 2003). The abundance of *Sequoia* pollen found in the ocean sediments from ODP 1019 suggests more upwelling and increased fog production in spring and summer.

Abies and *Pseudotsuga* were found in abundance in the Sanger and Bolan records, and had very similar histories at the two sites through the late Holocene (Fig. 6). Between 5000 and present, *Abies* reached late-glacial abundances at both sites. *Pseudotsuga* reached its greatest abundance at both sites within the last 2500 years. This is consistent with gradual warming through the late Holocene and suggests more mesic conditions through the late Holocene. Fire-episode frequency also increased at both sites, approaching (Sanger Lake) or exceeding (Bolan Lake) frequencies of the early Holocene. The increase in *Pseudotsuga* in the last 2500 years is consistent with the high fire frequency and peak magnitudes at both sites.

Both sites show an abundance of haploxylon *Pinus*, *Pseudotsuga*, and *Quercus* between 2000 and 1200 cal yr BP, and a drop in abundance of these taxa and replacement of *Abies* after 1200 cal yr BP. Within the last 300 years, a significant increase in *Picea* occurred in the forest at Sanger Lake, whereas *Tsuga* increased at Bolan Lake, perhaps in response to Little Ice Age cooling (Taylor, 1995). The higher snowpack and proximity of high-elevation peaks around Bolan Lake may account for the increase in *Tsuga* instead of *Picea breweriana*. Today, the high peaks in the Bolan Lake watershed support more *Tsuga*, whereas Sanger Lake has a minor component of *Tsuga*, but abundant *Picea breweriana*. One of the longest periods without fire occurred in the last 1000 years at Sanger Lake, while at Bolan Lake fire activity declined slightly between 2500 and 1700 cal yr BP and then increased toward the present day. Sanger Lake also maintained an abundance of Cupressaceae (likely *Chamaecyparis lawsoniana*) over the last 5000 cal yr BP, while at Bolan Lake it was a minor component of the forest and more likely *Calocedrus decurrens*. A detailed macrofossil study is needed to determine the exact species in the watersheds. The abundance of *Picea breweriana*, Cupressaceae, and infrequent fires are likely due to Sanger Lake's more maritime climate. The increased abundances of *Sequoia* pollen within the last 5000 years in ODP 1019, especially in the last 1000 years, suggests an increase in wetter conditions than before, and may account for the drop in fire-episode frequency at Sanger Lake. However, at Bolan Lake, peak fire-episode frequency suggests that this shift to wet conditions was restricted to the coastal regions. In addition, within the last 5000 years, several clay layers and peaks in magnetic susceptibility at Sanger Lake may represent erosional episodes as a result of increased heavy precipitation events and/or fire events resulting in debris flows, and these were not apparent at Bolan Lake. Today, the southeast side of the Sanger Lake watershed has an active debris flow channel that terminates 100 m from the shore of the lake, suggesting that debris flows have occurred recently.

6. Conclusions

In this study, large-scale controls in climate, namely variations in solar insolation, have been shown to influence on postglacial vegetation and fire activity. For example, the abundance of forest taxa, such as *Abies* and *Pseudotsuga*, showed similar trends at Sanger Lake and Bolan Lake when conditions were cooler and wetter than today during the late-glacial/early Holocene transition period. These species were reduced to their lowest abundances during the early Holocene when conditions were warmer and drier than present. Both sites also experienced peak fire frequency when summer insolation was higher than today ~9000 cal yr BP. Both *Abies* and *Pseudotsuga* increased in abundance, comparable to the late-glacial/early Holocene transition, as climate conditions became cooler and wetter than before in the late Holocene. In the last 2500 years, both sites recorded synchronous increases in *Pseudotsuga* and high fire frequency.

It is also clear that different microclimates at Sanger and Bolan lakes account for asynchronous responses and different sensitivities of species to these large-scale climate changes. For example, reduced costal upwelling and warmer SSTs after 12,000 cal yr BP resulted in the registration of warmer temperatures 1000 years earlier at Sanger Lake than at Bolan Lake. These warmer conditions at Sanger Lake resulted in the loss of *Tsuga*, *Picea*, *Artemisia*, and Poaceae and the early establishment of *Pinus monticola*. Later, trade-offs between Cupressaceae and haploxylon *Pinus,* that were associated with changes in fire-episode frequency, were strongly evident at Bolan Lake between 11,000 and 7000 cal yr BP, but they were shorter-lived and subdued at Sanger Lake (occurring between 11,000 and 9000 cal yr BP). It is likely that the warmer drier conditions at Bolan Lake increased the flammability of the vegetation, while the more mesic setting at Sanger Lake, resulting from increased ocean upwelling and coastal fog production, reduced flammability and fire occurrence. Increased spring and summer coastal upwelling and warmer winter conditions than before, created conditions at Sanger Lake that were wetter and milder than at Bolan Lake during the last 1000 years, and resulted in fewer fires at Sanger Lake than at Bolan Lake. Endemic species, *Picea breweriana* and *Chamaecyparis lawsoniana*, have likely been in the Sanger Lake watershed since the last ice age, whereas at Bolan Lake conditions were drier, and their presence was sporadic and short-lived. The drier conditions at Bolan Lake relative to those at Sanger Lake were persistent through the Holocene, with Sanger Lake supporting fewer fires with smaller peak magnitudes, and Bolan Lake registering more fires and larger peak magnitudes. However, both sites record high fire frequency ~9200 cal yr BP and 2500 cal yr BP.

It is becoming increasingly apparent that local controls can have a strong influence on vegetation and fire history in mountainous regions and account for differences in closely-spaced sites that experienced the same large-scale controls. In a similar comparison of the vegetation history along a steep coastal-to-inland moisture gradient on Vancouver Island, British Columbia, Brown et al. (2006) found dry conditions were registered inland during the early Holocene, while more coastal sites remained wet. Fire history reconstructions from two closely-spaced sites in British Columbia showed asynchronous patterns in fire episodes and different fire intervals in the middle Holocene, but more synchrony in the late Holocene (Gavin et al., 2006). The temporal differences in fire activity were attributed to shifts in the importance of local controls (i.e., aspect and topography) versus large scale controls under different configurations of regional climate. A similar comparison of two sites with different aspects and elevations in the eastern Klamath Mountains showed that a high elevation site with a north-facing aspect (Crater Lake) supported a more mesic forest through the Holocene than a lower elevation site with a south-facing aspect (Bluff Lake) (Mohr et al., 2000).

The comparison of Bolan and Sanger lakes vegetation and fire history in the Siskiyou Mountains suggests delays in the response of vegetation and fire response to long-term climate change can be on the order of centuries to millennia. Periods of contrasting vegetation and fire regimes in the Siskiyou Mountain region need further study to better evaluate how local factors (i.e., topography, aspect, ocean, edaphic controls) either enhance or suppress regional climate patterns on multiple time scales.

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References

Agee, J.K., 1993. Fire Ecology of Pacific Northwest Forests. Island Press, Washington, D.C.
Alley, R.B., Meese, D.D., Shuman, C.A., 1993. Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas event. Nature 362, 527–529.
Bacon, C.R., 1983. Eruptive history of Mount Mazama and Crater Lake Caldera, Cascade Range, U.S.A. Journal of Volcanology and Geothermal Research 18, 57–115.
Barron, J.A., Heusser, L., Herbert, T., Lyle, M., 2003. High-resolution climate evolution of coastal northern California during the past 16,000 years. Paleoceanography 18, 1020–1029.
Bartlein, P.J., Anderson, K.H., Anderson, P.M., Edwards, M.E., Mock, C.J., Thompson, R.S., Webb, R.S., Webb III, T., Whitlock, C., 1998. Paleoclimate simulations for North America over the past 21,000 years: features of the simulated climate and comparisons with paleoenvironmental data. Quaternary Science Reviews 17, 549–585.
Bennett, K.D., Willis, K.J., 2002. Pollen. In: Smol, J.P., Birks, H.J.B., Last, W.M. (Eds.), Tracking Environmental Change Using Lake Sediments. Terrestrial, Algal, and Siliceous Indicators, vol. 3. Kluwer Academic Publishers, Dordrecht, pp. 5–32.
Briles, C., Whitlock, C., Bartlein, P.J., 2005. Postglacial vegetation, fire and climate history of the Siskiyou Mountains, Oregon, USA. Quaternary Research 64, 44–56.
Brown, K.J., Fitton, R.J., Schoups, G., Allan, G.B., Wahl, K.A., Hebda, R.J., 2006. Holocene precipitation in the coastal temperate rainforest complex of southern British Columbia, Canada. Quaternary Science Reviews 25, 2762–2779.
Burns, R.M., Honkala, B.H., 1990. Silvics of North America: 1. Conifers; 2. Hardwoods. Agriculture Handbook 654, vol. 2. U.S. Department of Agriculture, Forest Service, Washington, DC.
Clark, D.H., Gillespie, A.R., 1997. Timing and significance of late-glacial and Holocene cirque glaciation in the Sierra Nevada, California. Quaternary International 38/39, 21–38.
Cleveland, W.S., 1979. Robust locally weighted regression and smoothing scatterplots. Journal of the American Statistical Association 74, 829–836.
Daniels, M.L., Anderson, R.S., Whitlock, C., 2005. Vegetation and fire history since the Late Pleistocene from the Trinity Mountains, northwestern California, USA. The Holocene 15, 1062–1071.
Davis, M.B., Brubaker, L.B., Webb III, T., 1973. Calibration of absolute influx. In: Birks, H.J.B., West, R.G. (Eds.), Quaternary Plant Ecology. John Wiley and Sons, New York, pp. 109–116.
Dean, W.E., 1974. Determination of carbonate and organic matter in calcareous sediments by loss on ignition comparison to other methods. Journal of Sedimentary Petrology 44, 242–248.
DellaSala, D.A., Reid, S.R., Frest, T.J., Strittholt, J.R., Olson, D.M., 1999. A global perspective on the biodiversity of the Klamath-Siskiyou ecoregion. Natural Areas Journal 19, 300–319.
Donato, D.C., Fontaine, J.B., Campbell, J.L., Robinson, W.D., Kauffman, J.B., Law, B.E., 2005. Post-wildfire logging hinders regeneration and increases fire risk. Science 311, 352.
Fall, P., 1992. Spatial patterns of atmospherical pollen dispersal in the Colorado Rocky Mountains, USA. Review of Palaeobotany and Palynology 74, 293–313.
Franklin, J.F., Dyrness, C.T., 1988. Natural Vegetation of Oregon and Washington. OSU Press, Oregon State University, Corvallis, Oregon.
Gavin, D.G., Hu, F.S., Lertzman, K., Corbett, P., 2006. Weak climatic control of stand-scale fire history during the late Holocene. Ecology 87, 1722–1732.
Gedye, S.J., Jones, R.T., Tinner, W., Ammann, B., Oldfield, F., 2000. The use of mineral magnetism in the reconstruction of fire history: a case study from Lago di Origlio, Swiss Alps. Palaeogeography, Palaeoclimatology, Palaeoecology 164, 101–110.
Grigg, L.D., Whitlock, C., 1998. Late-glacial vegetation and climate change in Western Oregon. Quaternary Research 49, 287–298.
Grimm, E.C., 1988. Data analysis and display. In: Huntley, B., WebbIII III, T. (Eds.), Vegetation History. Kluwer Academic, Dordrecht, Netherlands, pp. 43–76.
Hebda, R.J., Chinnappa, C.C., Smith, B.M., 1988a. Pollen morphology of the Rosaceae of Western Canada, I. *Agrimonia* to *Crataegus*. Grana 27, 5–113.
Hebda, R.J., Chinnappa, C.C., Smith, B.M., 1988b. Pollen morphology of the Rosaceae of Western Canada, II. *Dryas*, *Fragaria*, *Holodiscus*. Canadian Journal of Botany 66, 5–113.
Hickman, J.C. (Ed.), 1993. The Jepson Manual: Higher Plants in California. University of California Press, Berkeley.
Higuera, P.E., Peters, M.E., Brubaker, L.B., Gavin, D.G., 2007. Understanding the origin and analysis of sediment charcoal records with a simulation model. Quaternary Science Reviews 26, 1790–1809.
Higuera, P.E., Brubaker, L.B., Anderson, P.M., Brown, T.A., Kennedy, A.T., Hu, F.S., 2008. Frequent fires in ancient Shrub Tundra: implications of paleo-records for Arctic environmental change. PLoS ONE 3, e0001744.
Higuera, P.E., Brubaker, L.B., Anderson, P.M., Hu, F.S., Brown, T.A., in revision. Vegetation mediated impacts of past glacial climatic change on fire regimes in the south central Brooks Range, Alaska. Ecology.
Jarvis, D.I., Leopold, E.B., Liu, Y., 1992. Distinguishing the pollen of deciduous oaks, evergreen oaks and certain rosaceous species of southwestern Sichuan Province, China. Review of Palaeobotany and Palynology 75, 259–271.
Kapp, R.O., Davis, O.K., King, J.E., 2000. Pollen and Spores. The American Association of Stratigraphic Palynologists. Texas A&M University, College Station, Texas.
Kaufman, D.S., Porter, S.C., Gillespie, A.R., 2004. Quaternary alpine glaciation in Alaska, the Pacific Northwest, Sierra Nevada, and Hawaii. In: Gillespie, A.R., Porter, S.C., Atwater, B.F. (Eds.), The Quaternary Period in the United States. Elsevier, Amsterdam, pp. 77–104.
Kienast, S.S., McKay, J.L., 2001. Sea surface temperatures in the subarctic northeast Pacific reflect millennial-scale climate oscillations during the last 16 kyrs. Geophysical Research Letters 28, 1563–1566.
Long, C.J., Whitlock, C., Bartlein, P.J., Millspaugh, S.H., 1998. A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study. Canadian Journal of Forestry 28, 774–787.
Mohr, J.A., Whitlock, C., Skinner, C.N., 2000. Postglacial vegetation and fire history, Eastern Klamath Mountains, California. The Holocene 10, 587–601.
Moore, P.O., Webb, J.A., 1978. An Illustrated Guide to Pollen Analysis. John Wiley and Sons, New York.
Mortyn, P.G., Thunell, R.C., Anderson, D.M., Stott, L.D., Le, J., 1996. Sea surface temperature changes in the southern California borderlands during the last glacial-interglacial cycle. Paleoceanography 11, 415–430.
Porter, S.C., Swanson, T.W., 1998. Radiocarbon age constraints on rates of advance and retreat of the Puget Lobe of the cordilleran ice sheet during the last glaciation. Quaternary Research 50, 205–213.
Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, F.G., Manning, S.W., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. IntCal04 terrestrial radiocarbon age calibration, 26–0 ka BP. Radiocarbon 46, 1029–1058.
Ritchie, J.C., Lichti-Federovich, S., 1967. Pollen dispersal phenomena in Arctic-subarctic. Canada. Review of Paleobotany and Palynology 3, 255–266.
Skinner, C.N., Taylor, A.H., Agee, J.K., 2006. Fire in the Klamath Mountains bioregion. In: Sugihara, N.S., van Wagtendonk, J.W., Fites-Kaufmann, J., Shaffer, K., Thode, A. (Eds.), Fire in California ecosystems. University of California Press, Berkeley, pp. 170–194.
Shafer, S.H., Bartlein, P.J., Whitlock, C., 2005. Understanding the spatial heterogeneity of global environmental change in mountainous regions. In: Huber, U.M., Bugmann, H.K.M., Reasoner, M.A. (Eds.), Global change and mountain regions: an overview of current knowledge. Kluwer, pp. 21–31.
Solomon, A.M., Silkworth, A.B., 1986. Spatial patterns of atmospheric pollen transport in a montane region. Quaternary Research 25, 150–162.
Stuiver, M., Reimer, P.J., Reimer, R.W., 2005. CALIB 5.0. [WWW program and documentation].

Taylor, A.H., 1995. Forest expansion and climate change in the mountain hemlock (*Tsuga mertensiana*) zone, Lassen Volcanic National Park, California, USA. Arctic & Alpine Research 27, 207–216.
Taylor, A., Skinner, C.N., 1998. Fire history and landscape dynamics in a late-successional reserve, Klamath Mountains, California, USA. Forest Ecology and Management 111, 285–301.
Taylor, A.H., Skinner, C.N., 2003. Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. Ecological Applications 13, 704–719.
Telford, R.J., Heegaard, E., Birks, H.J.B., 2004. All age-depth models are wrong: but how badly? Quaternary Science Reviews 23, 1–5.
USDA Forest Service, 2004. The Healthy Forests Initiative and Healthy Forests Restoration Act: Interim Field Guide. Department of the Interior and Bureau of Land Mangement. FS-799.
Vacco, D.A., Clark, P.U., Mix, A.C., Cheng, H., Edwards, R.L., 2005. A speleothem record of Younger Dryas cooling, Klamath Mountains, Oregon, USA. Quaternary Research 64, 249–256.
West, G.J., 1989. Late Pleistocene/Holocene vegetation and climate. In: Basgall, M.E., Hildebrandt, W.R. (Eds.), Prehistory of the Sacramento River Canyon, Shasta County, California. Center for Archaeological Research, Davis, California, pp. 36–55.
Whitlock, C., Larsen, C.P.S., 2001. Charcoal as a fire proxy. In: Smol, J.P., Birks, H.J.B., Last, W.M. (Eds.), Tracking Environmental Change Using Lake Sediments. Terrestrial, Algal, and Siliceous indicators, vol. 3. Kluwer Academic Publishers, Dordrecht, pp. 75–97.
Whitlock, C., Bianchi, M.M., Bartlein, P.J., Markgraf, V., Walsh, M., Marlon, J.M., McCoy, N., 2006. Postglacial vegetation, climate, and fire history along the east side of the Andes (lat 41–42.5 S), Argentina. Quaternary Research 66, 187–201.
Whittaker, R.H., 1960. Vegetation of the Siskiyou Mountains, Oregon and California. Ecological Monographs 30, 279–338.
Wright Jr., H.E., Mann, D.H., Glaser, P.H., 1983. Piston cores for peat and lake sediments. Ecology 65, 657–659.