QUATERNARY RESEARCH 43, 370–381 (1995)

Postglacial Vegetation and Climate of the Cascade Range, Central Oregon

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Received December 15, 1994

Pollen data from two sites provide information on the postglacial vegetation and climate history of the Cascade Range. Indian Prairie in the western Cascade Range was colonized by subalpine forests of *Pinus*, *Picea*, and *Tsuga* and open meadows prior to ca. 12,400 ^{14}C yr B.P. The treeline lay 500 to 1000 m below its modern elevation and conditions were cooler than at present. From ca. 12,400 to ca. 9950 ^{14}C yr B.P. *Abies* became important and the forest resembled that presently found at middle elevations in the western Cascade Range. The pollen record implies a rise in treeline and warmer conditions than before. From ca. 10,000 to 4000–4500 ^{14}C yr B.P., conditions that were warmer and effectively drier than today led to the establishment of a closed forest composed of *Pseudotsuga*, *Abies*, and, at lower elevations, *Quercus* and *Corylus*. During this period, Gold Lake Bog in the High Cascades was surrounded by closed forest of *Pinus* and *Abies*. The early-Holocene pollen assemblages at both Indian Prairie and Gold Lake Bog lack modern analogues, and it is likely that greater-than-present summer radiation fostered unique climatic conditions and vegetation associations at middle and high elevations. In the late Holocene, beginning ca. 4000–4500 ^{14}C yr B.P., cooler and more humid conditions prevailed and the modern vegetation was established. A comparison of these sites with others in the Pacific Northwest suggests that major patterns of vegetational change at individual sites were a response to large-scale changes in the climate system that affected the entire region. ©1995 University of Washington.

INTRODUCTION

The Pacific Northwest has experienced dramatic environmental changes in the past 20,000 yr as the region shifted from glacial to interglacial conditions. The regional changes are ascribed to large-scale changes in the global climate system caused by variations in the size of the Laurentide ice sheet and the seasonal cycle of solar radiation. These hemispheric and continent-wide climate controls affected temperature and precipitation gradients within the region, as well as the location and intensity of atmospheric circulation features. A series of biological responses to the climate changes included species range adjustments, creation and dissolution of plant communities, and broad shifts in the composition of biomes (Whitlock, 1992; Thompson *et al.*, 1993).

Our understanding of the vegetational response to environmental changes in the Pacific Northwest is drawn largely from pollen records obtained from the lowlands of western Washington, southwestern British Columbia, and western Oregon (Whitlock, 1992 and references therein; Hebda, 1995; Worona and Whitlock, 1995). The vegetation history of the Cascade Range, in contrast, stands out as an area that has received little study. Despite the large number of natural wetlands suitable for paleoecologic investigations, only the late-Holocene vegetation history of Mt. Rainier has been described (Dunwiddie, 1986). The Mt. Rainier data suggest the development of modern forest associations in the past 4000 yr, but they tell little about antecedent conditions or the nature of past vegetation along the main Cascade crest. In the absence of mountain records, information on the environmental history of the Cascade Range rests largely on inferences drawn from paleoecologic data in adjacent lowlands.

In this paper, we extend the coverage of paleoecologic sites in the Cascade Range by reporting on pollen records from Indian Prairie (Latitude 44°38′N, Longitude 122°34′30″ W, elevation 988 m) and Gold Lake Bog (Latitude 43°39′N, Longitude 122°02′30″ W, elevation 1465 m) in central Oregon. These data disclose the vegetational and climatic history of middle and high elevations during the past 14,000 yr and help elucidate the response of mountain forests to the suite of postglacial environmental conditions that affected the Pacific Northwest.

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0033-5894/95 $6.00

MODERN SETTING AND STUDY SITES

The present-day diversity of vegetation and climate in the Pacific Northwest arises from an interplay between westerly maritime air masses and the north–south-trending Coast Range and Cascade Range. Winters west of the Cascade crest are cool and wet as a result of cyclonic storms generated from the Aleutian Low; summers, under the influence of the east Pacific Subtropical High, are dry. Within the Cascade Range, increases in precipitation and decreases in temperature with elevation have a direct bearing on the distribution of tree species (Franklin and Dyrness, 1988). The Willamette Valley (120–240 m elevation), on the west side of the Cascade Range, supports woodland of *Quercus garryana* (Oregon white oak), while *Pseudotsuga menziesii* (Douglas-fir); *Acer macrophyllum* (bigleaf maple), *Fraxinus latifolia* (Oregon ash), and *Alnus rubra* (red alder) are common in riparian settings. At higher elevations (250–1000 m), the *Tsuga heterophylla* Zone (Franklin and Dyrness, 1988) is dominated by *Pseudotsuga, T. heterophylla* (western hemlock), and *Thuja plicata* (western red cedar). *Abies grandis* (grand fir) and *Pinus monticola* (western white pine) are also present as minor components. The *Abies amabilis* Zone (1000–1500 m elevation) features closed forests of *A. amabilis* (Pacific silver fir), *T. heterophylla, Abies procera* (noble fir), *Pseudotsuga, Thuja,* and *P. monticola.* In the southern Cascade Range, *Pinus lambertiana* (sugar pine), *Abies magnifica* (California red fir), and at lower elevations *Abies concolor* (white fir) reach their northern limits. The highest-altitude forests comprise the *Tsuga mertensiana* Zone (1500–2000 m elevation). The dominants are *T. mertensiana* (mountain hemlock) and *A. amabilis,* but *Abies lasiocarpa* (subalpine fir), *A. procera, A. magnifica, Picea engelmannii* (Engelmann spruce), and *Chamaecyparis nootkatensis* (Alaska cedar) are also present. *Pinus contorta* (lodgepole pine), *P. monticola,* and *Pseudotsuga* occur in this zone as seral taxa after fire. Forest gives way to a parkland of tree islands and meadow communities at ca. 1900 m elevation. The upper limit of parkland is at ca. 2200 m elevation, above which lies alpine tundra (Franklin and Dyrness, 1988).

Indian Prairie is a ca. 17-ha fen located in a north-facing cirque valley of presumed late-Pleistocene age at the western edge of the Cascade Range (Fig. 1). The fen is seasonally flooded by snow melt in spring and fed by ground water and Indian Prairie Creek in summer. Indian Prairie lies below the upper limit of the *Tsuga heterophylla* Zone. The surrounding forest has been extensively logged and adjacent hillslopes are covered with second-growth forests of *Pseudotsuga* and *A. procera. Pseudotsuga, T. heterophylla, A. amabilis, A. procera,* and *Taxus brevifolia* (western yew) are common on unlogged slopes. The understory contains *Polystichum munitum* (swordfern), *Rhododendron macrophyllum* (Pacific rhododendron), *Acer circinatum* (vine maple), *Berberis nervosa* (Oregon grape), *Chimaphila umbellata* (little prince's pine), *Vaccinium* spp. (huckleberry), *Rubus* spp. (blackberry), and *Ribes* spp. (gooseberry). *Alnus sinuata* (Sitka alder) grows along the banks of Indian Prairie Creek, and the fen supports *Carex* spp. (sedge), *Salix* spp. (willow), *Poaceae* spp. (grass), and other wetland herbs.

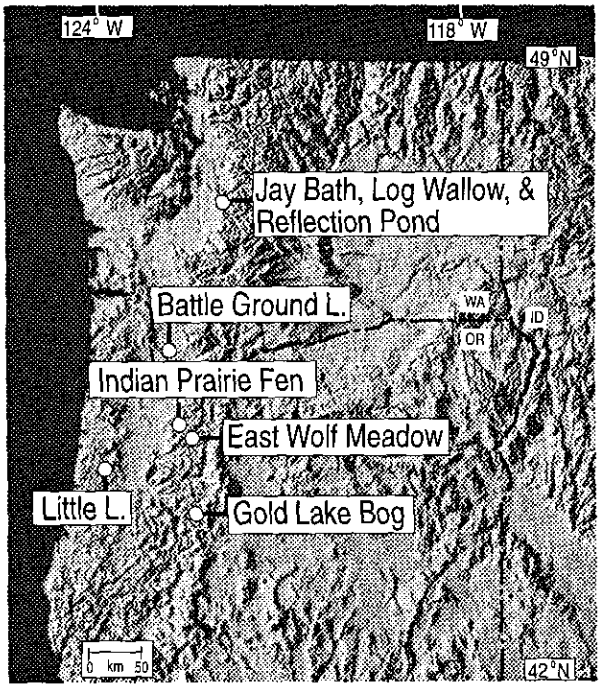


FIG. 1. Map showing location of fossil pollen sites discussed in text.

Gold Lake Bog is a 600-ha bog located at the northeast side of Gold Lake in a glacial trough of late-Pleistocene age (Fig. 1). Salt Creek flows through the bog and into the lake. Gold Lake Bog lies in the transition between the *Abies amabilis* and *Tsuga mertensiana* zones (Franklin, 1972; Franklin and Dyrness, 1988). Upland forests consist of *Pseudotsuga, T. mertensiana, Pinus monticola, Pinus contorta,* and *A. amabilis.* The understory is dominated by *Vaccinium* spp., *Amelanchier alnifolia* (Saskatoon serviceberry), *Acer circinatum, Sorbus sitchenisis* (Sitka ash), and *Rhododendron macrophyllum.* The *Sphagnum* bog supports *Picea engelmannii, Abies lasiocarpa, Betula glandulosa* (bog birch), *Alnus sinuata, Salix geyeriana, Spiraea douglasii* (spirea), and *Kalmia microphylla* (bog laurel). In 1965 Gold Lake Bog was designated a Research Natural Area to protect rare wetland plants that grow there.

METHODS

Sediment cores were recovered from Indian Prairie and Gold Lake Bog with a square-rod piston sampler (Wright *et al.*, 1983). Cores were extruded in the field and wrapped in cellophane and aluminum foil. In the laboratory, cores were sliced longitudinally, and the lithology was described. Samples of 1 cm^3 were taken at 20-cm intervals for loss-on-ignition analysis to estimate the percent of organic matter and carbonates in the sediment. Weight-loss after burning the samples for 2 hr at 550°C was used to determine percent of organic matter. There was negligible weight loss after 2 hr at 900°C, which implies little or no carbonates (Dean, 1974).

Samples of 1 cm^3 were taken at 10-cm intervals for pollen analysis and prepared by standard techniques (Faegri *et al.*, 1989). Tablets of *Lycopodium* spores were added to the pollen samples in a known quantity to permit calculation of pollen concentrations (grains/cm^3). Pollen residues were stored in silicone oil.

Pollen was identified to the lowest taxonomic level possible at magnifications of 500 and 1250× by comparison with reference material and published atlases. Grains that were corroded, degraded, broken, or hidden were placed in the "Indeterminate" category. Pollen grains that were in good condition but could not be identified with available reference material were considered "Unknown." At least 300 terrestrial pollen and spores were counted for each level, except where pollen concentration was exceptionally low.

The assignment of particular pollen taxa was based on modern phytogeography. Haploxylon-type pine was assigned to *Pinus albicaulis*, *P. monticola*, or *P. lambertiana*. Diploxylon-type pine pollen was probably from *P. contorta*, although *P. ponderosa* (ponderosa pine) may also have been a contributor. *Pinus* grains that lacked a distal membrane were identified as undifferentiated *Pinus*, and it was assumed that these grains were composed of diploxylon-type and haploxylon-type pine in the same proportion as in the identified *Pinus* grains.

With respect to other tree and shrub taxa, *Abies* pollen may have come from *A. amabilis*, *A. concolor*, *A. grandis*, *A. lasiocarpa*, *A. magnifica*, or *A. procera*. *Picea* pollen grains were attributed to *P. engelmannii* on the assumption that postglacial conditions were unsuitable for the coastal *P. sitchensis* (Sitka spruce) in the Cascade Range. *Pseudotsuga*-type pollen grains were assigned to *Pseudotsuga*, because *Larix* (larch) is primarily an Upper Columbia River Basin species (Fowells, 1965) and probably has not grown in western Oregon in postglacial time. Cupressaceae pollen was ascribed largely to *Thuja plicata*, although *Chamaecyparis nootkatensis*, *Calocedrus decurrens* (incense cedar), and *Juniperus communis* (common juniper) may have also been sources of the pollen. Unfortunately, the preservation of *Alnus* pollen at Indian Prairie and Gold Lake Bog was not good enough to discriminate between *A. sinuata*-type and *A. rubra*-type, as other studies have done (Barnosky, 1985; Worona and Whitlock, 1995). *Artemisia* pollen is either from alpine wormwoods (e.g., *A. scopulorum*, *A. norvegica*, *A. trifurcata*) or sagebrushes (e.g., *A. tripartita*, *A. tridentata*, *A. arbuscula*) (Hitchcock and Cronquist, 1973).

Pollen percentages and accumulation rates were used to reconstruct past vegetation. The denominator for terrestrial taxa percentages was the sum of all terrestrial upland taxa, including trees, shrubs, herbs, and pteridophytes. Because *Alnus*, *Salix*, and Cyperaceae grow on the local wetlands of both sites, these taxa were excluded from the terrestrial pollen sum. The denominator for the percentage of riparian, fen, and aquatic taxa (designated "Other taxa" on the pollen diagrams) was the sum of all pollen and spores, including wetland and aquatic types. Pollen concentrations (grains/cm^3) and deposition times (calibrated yr/cm) were used to calculate pollen accumulation rates (grains/cm^2/yr), which served as a general indicator of vegetational formation (Davis *et al.*, 1973; Fall, 1992).

LITHOLOGY AND CHRONOLOGY

Two cores were taken from Indian Prairie within 2 m of each other. Core 92A (7.93 m long) was the primary one for analysis, and core 92B (7.5 m long) was used to fill in gaps in recovery and provide a continuous stratigraphic record. Changes in lithology and organic content were used to define lithologic units. The lowest unit (7.31–7.93 m depth) consisted of inorganic silty clay with alternating light and dark layers (<4% organic content). These layers may represent seasonal sedimentation in a lake fed by glacial meltwater. Sediment from 3.36–7.31 m depth had a higher organic content (18.6–89.0%) than sediments below, and the lithology changed from fine detritus gyttja at the bottom to decomposed peat. This lithologic transition probably occurred as the site changed from lake to swamp. A 2-cm-thick volcanic ash layer found at 3.35 m depth was ascribed to the eruption of Mount Mazama in southwestern Oregon (layer O), ca. 6845 ± 150 ^{14}C yr B.P. (Bacon, 1983). The ash layer was overlain by 1.6 m of coarse detritus gyttja (55.2–87.8% organic content). The upper 3.34 m consisted of sedge peat and marked the development of the modern fen.

Three cores were taken from Gold Lake Bog. Core 92B (6.49 m long) was the primary core, and samples were taken from cores 92A (3.75 m long) and 92C (1.0 m long) as needed to fill in gaps. The lowest unit (5.14–6.42 m depth) consisted of alternating layers of sand and silty clay of low organic content (1.1–9.3%). These layers increased in thickness toward the top of the unit and were attributed to seasonal deposition during a glacial meltwater phase. The overlying sediment (4.25–5.14 m depth) consisted of alternating layers of fine and medium detritus gyttja that suggested fluctuations in water depth during a productive lake phase. A thick pumiceous tephra present from 2.63–3.25 m depth was assumed to be layer

O. The overlying 2 m of sediment (0.55–2.63 m depth) consisted of silt and medium and coarse detritus gyttja (17.4–21.9% organic content), which was probably deposited in a shallow lake. The upper 55 cm of *Sphagnum* peat (>52% organic content) accumulated when the modern bog developed.

Uncalibrated radiocarbon dates (^{14}C yr B.P.) and calibrated ages (cal yr B.P.) from Indian Prairie and Gold Lake Bog are listed in Table 1. Calibrated ages were determined with the program of Stuiver and Reimer (1993) and the most likely ages are noted in parentheses. Linear interpolation of the uncalibrated and calibrated radiocarbon ages was used to construct age-versus-depth relations for each site (Fig. 2). The inferred basal age was calculated based on extrapolation of the linear regression of the two stratigraphically lowest ages. One date (8710 ^{14}C yr B.P.) from Gold Lake Bog seemed to be an outlier, and it was not used in the regression. The anomalously young age may have been a result of the introduction of modern carbon in groundwater, contamination in the laboratory during sampling, or bioturbation. Deposition times for pollen accumulation rates were calculated from the calibrated age-versus-depth relation, but to facilitate

TABLE 1

Uncalibrated Radiocarbon Dates and Calibrated Ages from Indian Prairie and Gold Lake Bog

Depth (m)^{a}	Material dated	Uncalibrated ^{14}C age (^{14}C yr B.P.)	Lab number	Calibrated age (cal yr B.P.)^{b}
		INDIAN PRAIRIE		
Core 92A				
1.76–1.86	Wood	2880 ± 60	Beta-60639	3075, (2971^{c}), 2883
2.30–2.40	Lake sediment	4950 ± 60	Beta-62266	5738, (5568^{c}), 5612
3.32–3.34	Mazama tephra O	6850 ± 50^{d}		7664, (7631^{c}), 7578
5.01–5.09	Lake sediment	8770 ± 80	Beta-60640	9588, (9684, 9714^{c}, 9731), 9745, 9841, 9889
5.90–6.00	Lake sediment	9830 ± 70	Beta-62267	11,007, (10,994^{c}), 10,970
Core 92B				
7.15–7.25	Lake sediment	12,300 ± 110	Beta-60641	14,583, (14,371^{c}), 14,180
		GOLD LAKE BOG		
Core 92B				
1.30–1.40	Lake sediment	3970 ± 90	Beta-60636	4287, (4415^{c}), 4527
1.85–1.95	Lake sediment	4870 ± 90	Beta-62264	5489, (5589^{c}), 5705
2.52–2.92	Mazama tephra O	6845 ± 50^{c}		7664, (7631^{c}), 7578
Core 92A				
3.87–3.98	Lake sediment	8500 ± 80	Beta-60637	9398, (9456, 9474^{c}, 9480), 9499
4.84–4.94	Lake sediment	9300 ± 70	Beta-62265	10,148, (10,224, 10,240^{c}, 10,294), 10,365
4.94–5.04	Lake sediment	8710 ± 80^{e}	Beta-60638	9529, (9648, 9777^{c}, 9783) 9856

[a] Depth below mud surface.

[b] Based on Stuiver and Reimer (1993).

[c] Calibrated ages used in age-vs-depth model (Fig. 2).

[d] Based on Bacon (1983).

[e] Possibly contaminated, age not used in the age-vs-depth model (Fig. 2).

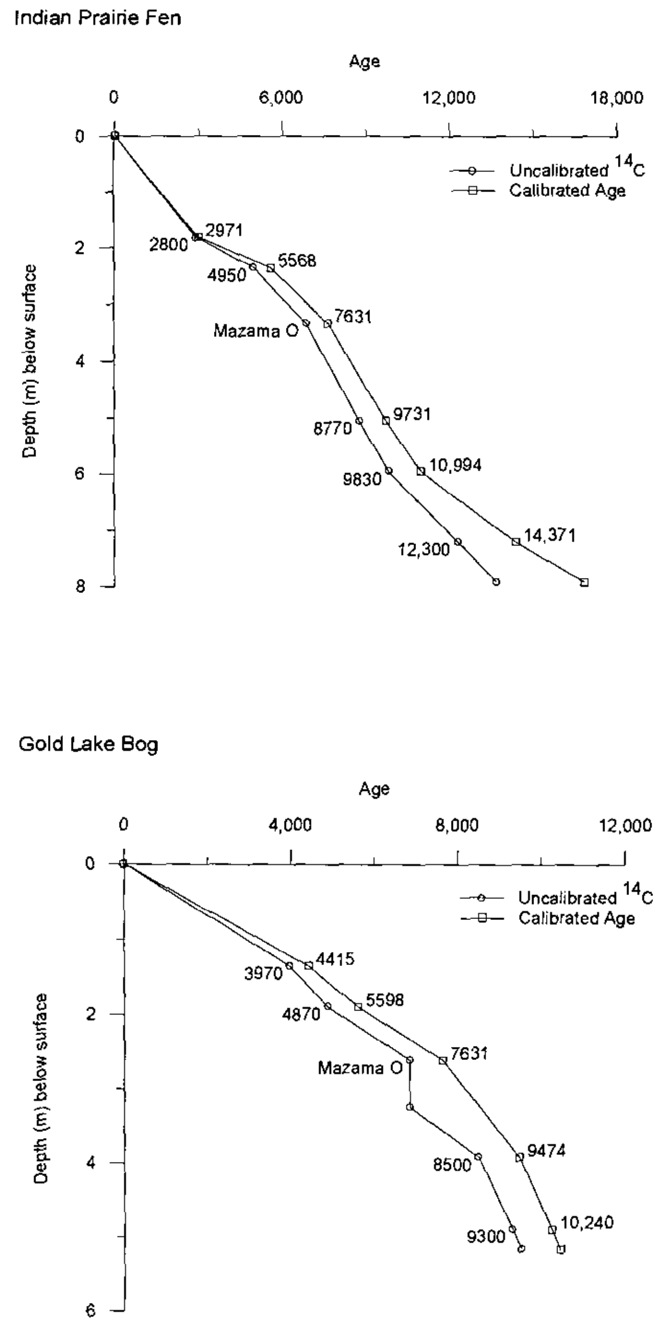


FIG. 2. Age-vs-depth curves for Indian Prairie and Gold Lake Bog. Numbers are calibrated and uncalibrated radiocarbon ages and are listed in Table 1.

comparison with other paleoenvironmental records the remainder of the discussion uses uncalibrated radiocarbon ages.

THE POLLEN RECORDS

Indian Prairie

The Indian Prairie record was divided into four local pollen zones by use of constrained cluster analysis (CONISS; Grimm, 1988): IP-1 (*Pinus–Picea–Artemisia*), IP-2 (*Abies*), IP-3 (*Pseudotsuga*-type–*Abies–Quercus–Dryopteris*-type), and IP-4 (*Tsuga heterophylla–Abies*–Cyperaceae). Features of these zones are described in Table 2 (see also Fig. 3).

The pollen assemblages of IP-1 (ca. 13,700–12,400 ^{14}C yr B.P.) indicate a period of subalpine forest and meadow at Indian Prairie. Pollen accumulation rates fall within the range of those from present-day subalpine parkland (Fall, 1992), and high percentages of *Pinus, Picea, Tsuga mertensiana, Artemisia,* Poaceae, and herbs are similar to modern pollen spectra from Mt. Hood (Heusser, 1978). *Picea* pollen is attributed to *P. engelmannii, Pinus* pollen is probably from some combination of *P. contorta, P. albicaulis,* or *P. monticola. Abies* pollen is tentatively assigned to *A. lasiocarpa* or *A. amabilis. Artemisia* pollen is ascribed to alpine species, although sagebrush (e.g., *A. tridentata vaseyana*) may also have been present in dry areas. *Polygonum bistortoides*-type pollen, which is present in low amounts, is diagnostic of subalpine parkland and alpine environments (Heusser, 1978; Whitlock, 1993). The lithologic record indicates that the lake was unproductive and had little or no fen development.

The assemblages within IP-2 (ca. 12,400–9950 ^{14}C yr B.P.) most closely resemble the modern pollen rain of the *Abies amabilis* Zone, which is characterized by high percentages of *Abies* and low percentages of *Picea, Tsuga mertensiana, Tsuga heterophylla,* haploxylon-type pine and nonarboreal taxa (Barnosky, 1981). Modern samples,

TABLE 2
Description of Key Features in the Indian Prairie Pollen Record

Pollen zone	Depth (m)	Age (^{14}C yr B.P.)	Description
IP-4	0.22–2.00	0–4000	High percentages of *Tsuga heterophylla* (23.3–46.6%); *Abies* and *Pseudotsuga*-type well represented (<28% and <13.8%); Cupressaceae, *Fraxinus latifolia*-type, *Quercus, Corylus, Sambucus, Rhamnus, Arceuthobium, Acer macrophyllum*-type, Rosaceae, and Ericaceae in trace amounts (<2%); Poaceae (<16%) and Cyperaceae (<35%) abundant at top. Total accumulation rate of terrestrial pollen and spores: 1000–12,200 grains/cm^2/yr.
IP-3	2.10–6.01	4000–9950	High percentages of *Pseudotsuga*-type (<23.6%), *Quercus* (<11.0%), *Corylus* (hazel) (<4.9%), *Dryopteris*-type (<58.3%), and *Alnus* (<50.4%); *Abies* in relatively high percentages (<20%); *Tsuga heterophylla* and *Fraxinus* in low percentages (<5%); nonarboreal taxa in moderate to high percentages (15–60%) including Poaceae, *Artemisia, Pteridium*-type (bracken fern), Tubuliflorae, Chenopodiineae, Ranunculaceae, Umbelliferae, *Galium* (bedstraw), Liliaceae, and Cruciferae; Cyperaceae (<10%) and *Lysichiton* (skunk cabbage) (<15%) in high amounts. Total accumulation rate of terrestrial pollen and spores: 600–16,000 grains/cm^2/yr.
IP-2	6.01–7.25	9950–12,400	*Abies* (18.3–49.7%) and *Alnus* (10.7–32.6%) higher than IP-1; *Pinus,* mostly haploxylon-type, (6.6–10.0%), *Tsuga mertensiana* (0.6–11.3%) and *T. heterophylla* (2.5–14.5%) abundant at the base of the zone, low in middle, and high near top; *Pseudotsuga*-type and Cupressaceae pollen in low amounts (5%); *Dryopteris*-type spores abundant (<24%); *Sambucus* (elderberry), *Rhamnus* (buckthorn), *Arceuthobium,* and Rosaceae in trace amounts (<2%); Tubuliflorae, *Thalictrum* (meadow-rue), other Ranunculaceae, Umbelliferae, *Artemisia,* and Poaceae <2%; *Isoetes* (quillwort) microspores <4.9%. Total accumulation rate of terrestrial pollen and spores: 2900–11,800 grains/cm^2/yr.
IP-1	7.25–7.93	12,400–13,680	High percentages of *Pinus* (≤28.9%), (mostly diploxylon-type at the base of the zone and haploxylon-type at the top), *Picea* (≤25.2%), *Tsuga mertensiana* (≤13.6%), and *Artemisia* (≤35.8%) and moderate percentages of Poaceae (from 5.8 to 14.1%). Increasing amounts of *Abies* (from 2.0 to 15.9%) and *Tsuga heterophylla* (from 1.7 to 6.2%). *Arceuthobium* (mistletoe), Ericaceae, and Rosaceae present (<3% each); *Alnus* percentages between 3.2 and 15.2%, and Cyperaceae from 2.3 to 6.6%. Other herbs, including *Polygonum bistortoides*-type (American bistort), *Galium,* Ranunculaceae, and Tubuliflorae, present in trace values (<2%). Total accumulation rate of terrestrial pollen and spores: 1900–6000 grains/cm^2/yr.

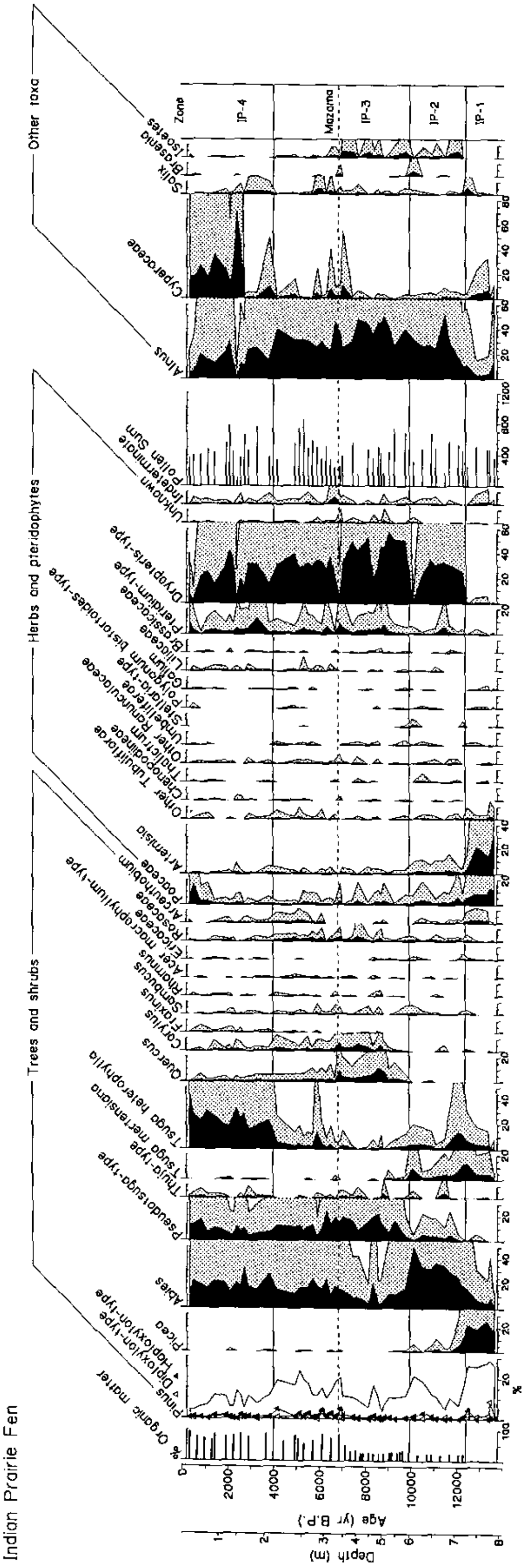


FIG. 3. Percentage pollen diagram for selected taxa at Indian Prairie. Percent organics is also shown. Shaded pattern on pollen curves is 5× exaggeration of black pattern.

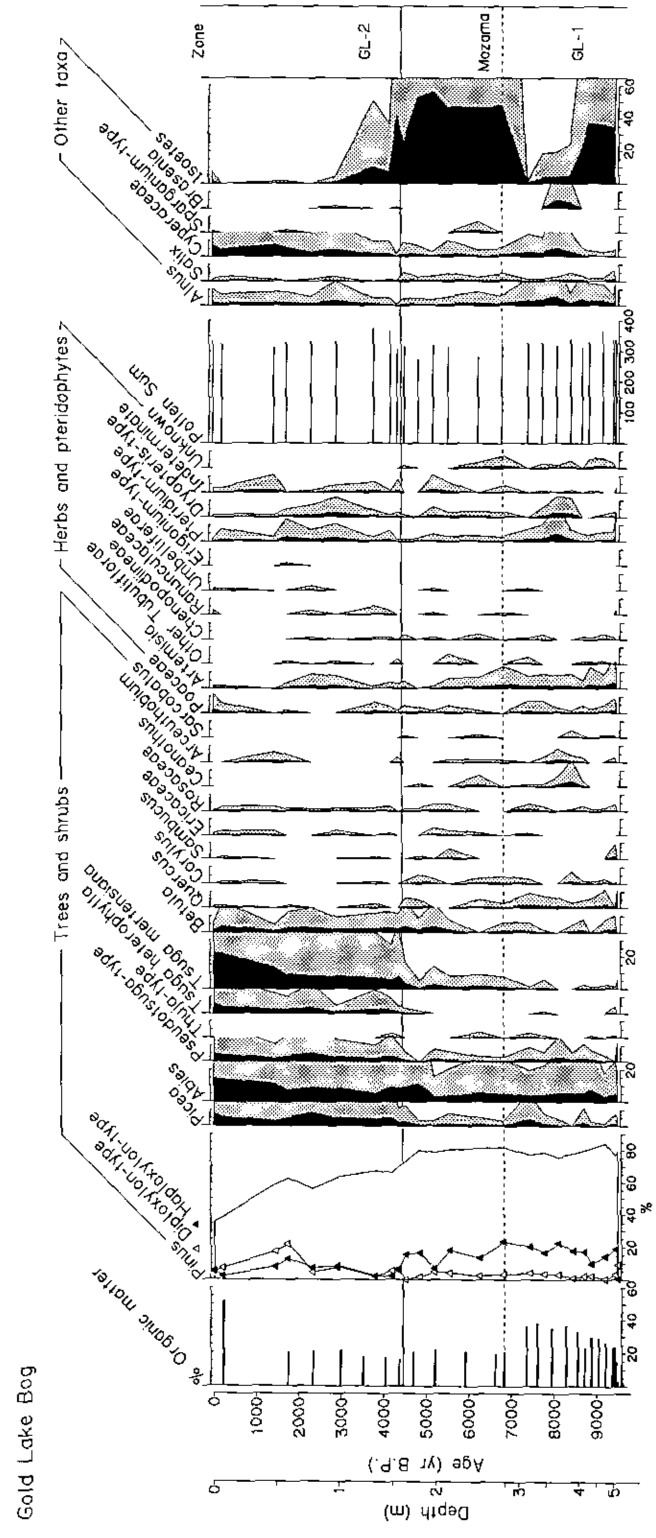


FIG. 4. Percentage pollen diagram for selected taxa at Gold Lake Bog. Percent organics is also shown. Shaded pattern on pollen curves is 5× exaggeration of black pattern.

however, feature higher percentages of *Artemisia* than those of IP-2. Pollen accumulation rates are higher than in the previous zone and fall within the range of those from present-day montane forest (Fall, 1992). The vegetation was probably a closed *Abies* forest, which implies a local treeline depression of 500 m. *Abies lasiocarpa* may have grown in the coldest settings, while *A. amabilis, A. procera,* or possibly *A. grandis* may have occupied warmer habitats (Fowells, 1965). *Alnus sinuata* was probably present in disturbed wet areas, such as avalanche paths and areas of prolonged snow accumulation (Franklin and Dyrness, 1988). *A. grandis* and *Alnus rubra* may have grown at lower elevations and along streams. *Dryopteris*-type spores were assigned to *Polystichum, Dryopteris,* and other ferns.

The high percentages of *Pseudotsuga, Alnus,* and *Quercus* in IP-3 (ca. 9950–4000 yr B.P.) resemble modern spectra from the Willamette Valley and seral forests within the lower *Tsuga heterophylla* Zone (Heusser, 1978). At Indian Prairie, *Pseudotsuga* was apparently the forest dominant, and *Tsuga* and *Abies* were less common than today. Stands of *Alnus* probably grew at the site and in other mesic habitats. Some of the *Alnus* pollen may also have been blown up from lower elevations, where *A. rubra* apparently was more widespread (Whitlock, 1992; Worona and Whitlock, 1995). High percentages of *Quercus* and *Corylus* pollen suggest an expansion of Willamette Valley vegetation to higher elevations, although these taxa probably did not reach the elevation of the site. The lithologic evidence suggests that the lake was becoming shallower and more productive during this period.

The period of IP-4 (ca. 4000 ^{14}C yr B.P. to present) marks the development of modern forest and fen. The assemblage matches present-day spectra from the western Cascade Range (Heusser, 1978), and pollen accumulation rates suggest a period of closed montane forest (Fall, 1992). *Tsuga heterophylla* joined *Pseudotsuga* and *Abies* to become an important component of the forest. High percentages of Cyperaceae and *Alnus* pollen and a lithologic change from coarse detritus gyttja to decomposed peat also occurred during IP-4 time. Apparently, formation of the fen coincided with the establishment of the modern *Tsuga–Pseudotsuga–Abies* forest.

Gold Lake Bog

The pollen record from Gold Lake Bog is divided into two local zones: GL-1 (*Pinus–Abies*) and GL-2 (*T. mertensiana–Abies–Picea*) (Table 3, Fig. 4). Pollen percentages and accumulation rates indicate that GL-1 (ca. 9500–4500 ^{14}C yr B.P.) was a period of montane or subalpine forest of *Pinus* and *Abies*. Haploxylon-type pine pollen may be from *P. albicaulis, P. monticola,* or *P. lambertiana*. Of these possibilities, *P. albicaulis* generally grows at the highest elevations and in dry settings today. It is associated with *Tsuga mertensiana, Picea engelmannii,* and *Abies lasiocarpa* in the northern Cascade Range and with *P. monticola* and *A. magnifica* in the southern Cascade Range (Franklin and Dyrness, 1988; Arno and Hoff, 1989). *P. monticola* is generally a low- to middle-elevation species in the Cascade Range. It favors full sunlight, grows best in well-drained soils, and is adapted to fire (Fowells, 1965; Agee, 1993). *P. lambertiana* is a middle-elevation species that reaches its northern limit in the southern Cascade Range. It is more

TABLE 3
Description of Key Features in Gold Lake Bog Pollen Record

Pollen zone	Depth (m)	Age (^{14}C yr B.P.)	Description
GL-2	0–1.65	0–4470	Increasing percentages of *Tsuga mertensiana* (3.5–22.3%), *Abies* (9.5–14.6%), and *Picea* (2.5–7.7%), *Pseudotsuga*-type (1.5–5.1%); highest values of diploxylon-type pine (22.9%); *Pinus* percentages decreasing from 73.1 to 35.7%, haploxylon-type pine dropping from 15.4 to 5.4%. *Betula, Alnus,* and *Salix* in low amounts (<4%). Herb and pteridophyte taxa present, including Poaceae (<2.4%), *Artemisia* (<1.8%), and *Pteridium* (<3%). *Isoetes* microspores decline from 42% to <2% at top. Total accumulation rate of terrestrial pollen and spores: 600–3500 grains/cm^2/yr.
GL-1	1.65–6.50	4470–9520	High percentages of *Pinus* (75.7–84.3%); diploxylon-type pine (<9%) greater than haploxylon-type pine (<1%) at base, haploxylon-type (<27%) greater than diploxylon-type pine (<5%) at top; *Abies* (<11.4%), *Picea* (<5%), *Pseudotsuga*-type (<3.2%), *Tsuga mertensiana* (<3%), and Cupressaceae (<1%) present; deciduous tree and shrub taxa including *Betula* (<5.3%), *Alnus* (<5.3%), *Salix, Ceanothus, Quercus, Corylus,* Rosaceae, *Sambucus,* and *Arceuthobium* in low amounts. *Artemisia* (<2.7%) and *Pteridium*-type (<4.7%) present; *Isoetes* microspores at base and top of zone (<56.6%); Cyperaceae pollen in low amounts (<5.3%). Total accumulation rate of terrestrial pollen and spores: 1100–9200 grains/cm^2/yr.

drought tolerant than *P. monticola* (Minore, 1979) and also well adapted to fire. Needle fragments of a five-needle pine were found at 3.35–3.45, 3.96–4.07, and 4.70–4.82 m depth in the core. They most closely resemble those of *P. monticola* or *P. lambertiana*. Needle remains of *Pinus contorta* (two-needle) were recovered at 3.65–3.75 and 4.60–4.70 m depth.

Based on the poor pollen representation of other subalpine associates, such as *Picea* and *Tsuga mertensiana*, it seems likely that *Pinus albicaulis* and *Abies lasiocarpa* were not major contributors to the pollen record in GL-1 time. The macrofossil data suggest that *Pinus* pollen came from *P. monticola* or *P. lambertiana* and *P. contorta*. The source of *Abies* pollen was probably some combination of *A. amabilis*, *A. procera*, *A. grandis*, *A. concolor*, or *A. magnifica*. The forest composition may also have shifted among these taxa in a manner that cannot be detected by pollen data. For example, a forest of *P. albicaulis* and *A. lasiocarpa* may have colonized the region soon after deglaciation, but as the climate warmed and soil development progressed, a mixed forest of *P. contorta*, *P. monticola*, *A. procera*, and *A. amabilis* may have become established. Unfortunately, it is difficult to characterize the vegetation when several species could have contributed to the *Pinus* and *Abies* pollen.

GL-2 (ca. 4500 ^{14}C yr B.P. to present) resembles modern spectra from the High Cascade Range (Heusser, 1978), and the accumulation rates are consistent with closed montane forest (Fall, 1992). After ca. 4500 ^{14}C yr B.P., the role of *Pinus* in the forest diminished, whereas that of *Tsuga mertensiana*, *Picea*, *Abies*, *Pseudotsuga*, and *Tsuga heterophylla* increased. A substantial rise in *T. mertensiana* percentages ca. 2000 ^{14}C yr B.P. suggests that mountain hemlock expanded its range most dramatically in the past 2 millennia.

ENVIRONMENTAL RECONSTRUCTION

The vegetation history at Indian Prairie and Gold Lake Bog traces the development of Cascade forests following deglaciation and their modification in the Holocene (Fig. 5). A comparison of this history with reconstructions derived from other records in western Washington and Oregon provides new insights into the broad vegetational responses to regional environmental changes (Fig. 6). As points of comparison, sites on Mt. Rainier—Jay Bath, Log Wallow, and Reflection Pond—(Dunwiddie, 1986) reconstruct the vegetation history at high altitudes in central Washington; Battle Ground Lake provides information on Holocene vegetation in the southern Puget Trough (Barnosky, 1985); a late-Holocene record from East Wolf Meadow comes from the western Cascade Range, Oregon (A. S. Gottesfeld and L. M. J. Gottesfeld, unpublished data); and pollen data from Little Lake disclose conditions in the central Coast Range of Oregon (Worona and Whitlock, 1995).

Late-glacial Interval (ca. 14,000–10,000 ^{14}C yr B.P.)

Between ca. 13,700 and ca. 12,400 ^{14}C yr B.P., a subalpine forest of *Picea*, *Pinus*, and *Tsuga mertensiana* and meadows grew in the vicinity of Indian Prairie. The similarity of this vegetation to present-day associations in the modern *T. mertensiana* Zone (Franklin and Dyrness, 1988) suggests a depression of treeline by 500–1000 m (Fig. 5). Based on a modern environmental lapse rate of 6°C/km (Barry, 1992), mean annual temperature was at least 3°C lower than at present. From ca. 12,400 to ca. 9950 ^{14}C yr B.P., a closed forest composed of *Abies lasiocarpa*, *A. amabilis*, *A. procera*, and/or *A. grandis* developed near Indian Prairie. *Tsuga mertensiana*, *T. heterophylla*, and *Pinus* were minor elements of the forest. These taxa co-occur today in the *Abies amabilis* Zone (Franklin and Dyrness, 1988), which suggests a treeline depression of about 500 m at Indian Prairie (Fig. 5). Mean annual temperature was 1–3°C lower than at present and conditions were wetter than before (Minore, 1979).

The presence of inorganic laminated sediments, barren of pollen, at the base of Gold Lake Bog suggests deposition in a periglacial environment prior to ca. 9500 ^{14}C yr B.P. The sediments may have been laid down during the Sumas Stade of the Fraser Glaciation (i.e., Canyon Creek advance of the Cabot Creek Glaciation; Scott, 1977), which occurred between ca. 11,500 and 10,000 ^{14}C yr B.P. Regional snowline in the central Cascade Range was ca. 700–750 m lower then than at present (Scott, 1977).

In the southern Puget Trough, an open forest of *Picea engelmannii*, *P. sitchensis*, *Abies grandis* or *A. amabilis*, and *Tsuga mertensiana* was present at Battle Ground Lake from 15,000 to ca. 11,200 ^{14}C yr B.P. (Barnosky, 1985), and the climate was cooler and wetter than today. Between ca. 11,200 and ca. 10,000 ^{14}C yr B.P., *Tsuga heterophylla*, *P. sitchensis*, *Pseudotsuga*, *A. grandis* or *A. amabilis*, *Populus* (cottonwood), and *Alnus* grew in the lowlands. This mixture of montane and subalpine species has no modern counterpart, but one can imagine that high-elevation species survived in the moist north-facing slopes around Battle Ground Lake, while the low-elevation species colonized disturbed and drier areas (Whitlock, 1992).

The lowlands of the central Oregon Coast Range were covered by closed forest of *Picea* (probably *P. engelmannii* and *P. sitchensis*), *Pinus contorta*, *Abies*, and perhaps *Tsuga mertensiana* between ca. 14,000 and ca. 13,500 ^{14}C yr B.P. (Worona and Whitlock, 1995). From ca. 13,500 to ca. 10,000 ^{14}C yr B.P., the vegetation was dominated by *Pinus*, *Abies*, *Tsuga*, *Pseudotsuga*, and *Alnus rubra*, implying warmer conditions than before.

Both high- and low-elevation records in the region suggest that late-glacial temperatures were at least 3°C lower than at present. A shift toward warmer and effectively wetter conditions at the end of the late-glacial period

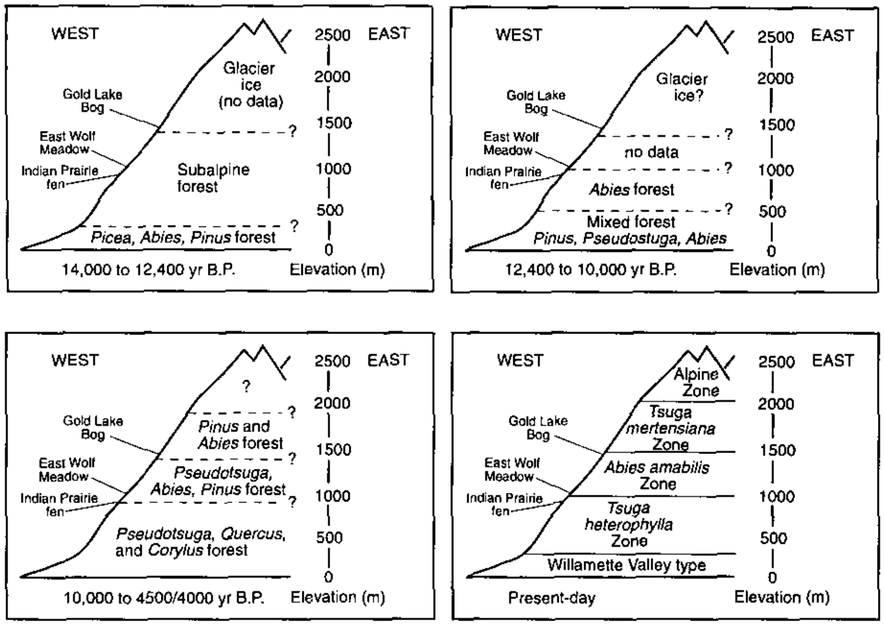
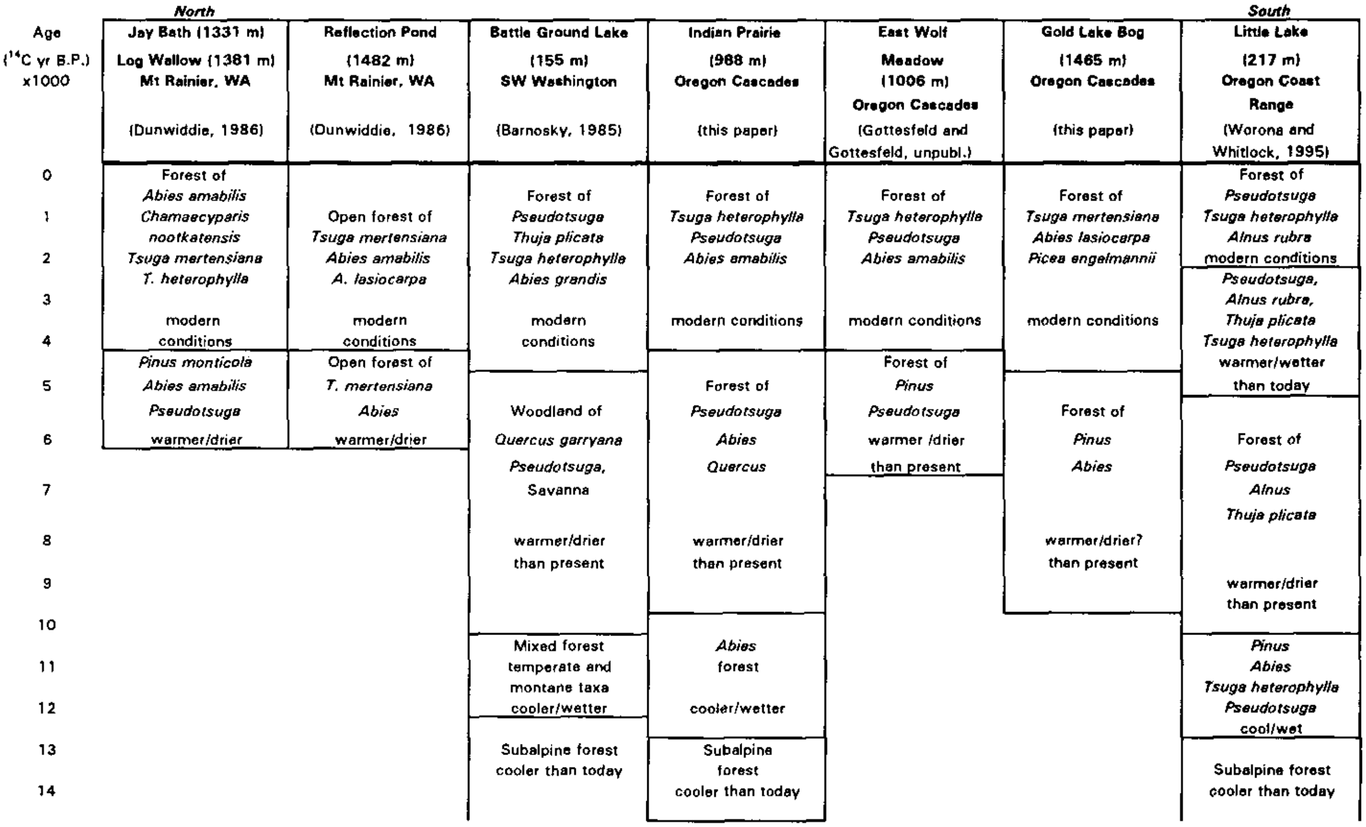


FIG. 5. Environmental reconstruction of western Cascade Range of Oregon for the past 14,000 yr.

seems to have occurred at slightly different times. At Indian Prairie warming is registered as early as ca. 12,400 ^{14}C yr B.P., at Battle Ground Lake it occurred at ca. 11,200 ^{14}C yr B.P., and at Little Lake it took place at ca. 13,500 ^{14}C yr B.P. The climatic amelioration registered at Indian Prairie and Little Lake is concurrent with that at Mineral Lake (Tsukada *et al.*, 1981) and Davis Lake (Barnosky, 1981) in the central Puget Trough. At Battle Ground Lake the shift is later, perhaps because cool air that was advected down the Columbia River Gorge prolonged glacial conditions at this site.

The registration of cool, humid conditions in the fossil



	North						*South*
Age (^{14}C yr B.P.) x1000	**Jay Bath (1331 m)** **Log Wallow (1381 m)** **Mt Rainier, WA** (Dunwiddie, 1986)	**Reflection Pond** **(1482 m)** **Mt Rainier, WA** (Dunwiddie, 1986)	**Battle Ground Lake** **(155 m)** **SW Washington** (Barnosky, 1985)	**Indian Prairie** **(988 m)** **Oregon Cascades** (this paper)	**East Wolf** **Meadow** **(1006 m)** **Oregon Cascades** (Gottesfeld and Gottesfeld, unpubl.)	**Gold Lake Bog** **(1465 m)** **Oregon Cascades** (this paper)	**Little Lake** **(217 m)** **Oregon Coast Range** (Worona and Whitlock, 1995)
0	Forest of *Abies amabilis* *Chamaecyparis nootkatensis* *Tsuga mertensiana* *T. heterophylla* modern conditions	Open forest of *Tsuga mertensiana* *Abies amabilis* *A. lasiocarpa* modern conditions	Forest of *Pseudotsuga* *Thuja plicata* *Tsuga heterophylla* *Abies grandis* modern conditions	Forest of *Tsuga heterophylla* *Pseudotsuga* *Abies amabilis* modern conditions	Forest of *Tsuga heterophylla* *Pseudotsuga* *Abies amabilis* modern conditions	Forest of *Tsuga mertensiana* *Abies lasiocarpa* *Picea engelmannii* modern conditions	Forest of *Pseudotsuga* *Tsuga heterophylla* *Alnus rubra* modern conditions
1							
2							*Pseudotsuga,* *Alnus rubra,* *Thuja plicata* *Tsuga heterophylla* warmer/wetter than today
3							
4	*Pinus monticola* *Abies amabilis* *Pseudotsuga* warmer/drier	Open forest of *T. mertensiana* *Abies* warmer/drier		Forest of *Pseudotsuga* *Abies* *Quercus* warmer/drier than present	Forest of *Pinus* *Pseudotsuga* warmer /drier than present		
5			Woodland of *Quercus garryana* *Pseudotsuga,* Savanna warmer/drier than present			Forest of *Pinus* *Abies* warmer/drier? than present	Forest of *Pseudotsuga* *Alnus* *Thuja plicata* warmer/drier than present
6							
7							
8							
9							
10			Mixed forest temperate and montane taxa cooler/wetter	*Abies* forest cooler/wetter			*Pinus* *Abies* *Tsuga heterophylla* *Pseudotsuga* cool/wet
11							
12			Subalpine forest cooler than today				
13				Subalpine forest cooler than today			Subalpine forest cooler than today
14							

FIG. 6. Summary of postglacial vegetation history and inferred climate for selected sites in the Pacific Northwest.

record compares well with paleoclimate model simulations of the late-glacial period (Thompson *et al.*, 1993). Model simulations for 12,000 ^{14}C yr B.P. suggest that the jet stream lay at the latitude of Oregon, north of its full-glacial position. The stronger jet increased the frequency and intensity of winter storms in Oregon and Washington; while lower-than-present sea-surface temperatures and the protracted influence of the North American ice sheets maintained cool conditions in the Pacific Northwest.

Percentage increases in *Pinus, Tsuga mertensiana, Abies,* and *Tsuga heterophylla* at Indian Prairie correspond in time with a peak in *Picea* and *Pinus* percentages between ca. 11,000 and ca. 10,000 ^{14}C yr B.P. at Little Lake (Worona and Whitlock, 1995). Both signals may be evidence of Younger Dryas-age cooling, which has been detected at some coastal Pacific Northwest sites (Mathewes, 1993; Engstrom *et al.*, 1990), but not at others, e.g., Battle Ground Lake (Whitlock, 1992). Additional data are needed south of the Cordilleran ice sheet to determine the expression of late-glacial climatic oscillations at these and other sites in the Pacific Northwest.

Early Holocene (ca. 10,000–5000 ^{14}C yr B.P.)

Conditions were generally warmer and drier than present in the early Holocene at all elevations and latitudes (Fig. 6). Species shifted their upper limits upslope by 250–500 m elevation, and the distribution of xerophytic vegetation was more widespread in the region than at present. At Jay Bath and Log Wallow on Mt. Rainier, the forest was composed of *Pinus monticola, P. contorta, Abies amabilis, A. lasiocarpa, A. procera, Pseudotsuga,* and *Alnus sinuata* from ca. 6000 to 5000–4000 ^{14}C yr B.P. (Dunwiddie, 1986). Apparently, the upper limits of many species lay at higher elevations than at present. At Reflection Pond on Mt. Rainier, the occurrence of *Tsuga mertensiana, A. amabilis,* and *A. lasiocarpa* above their present range between ca. 6000 and 4000 ^{14}C yr B.P. is also evidence of warmer-than-present conditions (Dunwiddie, 1986).

The record from Battle Ground Lake suggests a savanna or woodland of *Quercus* and *Pseudotsuga* in the southernmost Puget Trough from ca. 9000 to ca. 4500 ^{14}C yr B.P. (Barnosky, 1985). This site provides evidence of a northward expansion of the Willamette Valley type vegetation into southwestern Washington. At Little Lake a closed forest of *Pseudotsuga,* with *Alnus rubra* in disturbed and riparian settings, occurred between ca. 10,000 and ca. 5000 ^{14}C yr B.P. (Worona and Whitlock, 1995). At both Little Lake and Battle Ground Lake, the poor record of mesophytic taxa during the early Holocene indicates that summer drought was more intense than at present. Fire frequency was probably higher under this climatic regime, which also would have favored *Pseudotsuga, Quercus,* and *Alnus* as seral codominants.

A closed forest of *Pseudotsuga* and *Abies* was present near Indian Prairie from ca. 10,000 to ca. 4000 ^{14}C yr B.P. A combination of warmer conditions and frequent fires would have reduced the role of *Abies* compared to the preceding period (Agee, 1993). The pollen data indicate that *Quercus* and *Corylus* extended their range upslope by as much as 500 m (Fig. 5), which is further evidence of summer drought. Evidence from East Wolf Meadow suggests the occurrence of a closed forest of *Pinus* and *Pseudotsuga* from ca. 6750 to ca. 4000 ^{14}C yr B.P. (A. S. Gottesfeld and L. M. J. Gottesfeld, unpublished data). *Pinus* and *Abies* were more widespread at higher elevations near Gold Lake Bog from ca. 9500 to ca. 4500 ^{14}C yr B.P. (Fig. 6). The early-Holocene assemblages at both East Wolf Meadow and Gold Lake Bog seem to have no modern analogue in the region, but the coverage of modern pollen samples in the Pacific Northwest is uneven. Additional samples from the southern Cascade Range and the mountain ranges of the interior Pacific Northwest, for example, might identify vegetation types that produce high percentages of haploxylon-type and diploxylon-type pine, *Pseudotsuga,* and *Abies.*

In the Pacific Northwest, solar radiation values were about 8% higher in summer and 10% lower in winter in the early Holocene (Kutzbach and Guetter, 1986; Kutzbach *et al.*, 1993). The direct effects of greater-than-present summer radiation in the Pacific Northwest included higher temperatures and decreased effective moisture. Increased summer radiation also resulted in a strengthening of the east Pacific Subtropical High pressure system (Barnosky *et al.*, 1987; Whitlock, 1992; Thompson *et al.*, 1993). These no-analogue climatic conditions provide another explanation for the unusual communities at Indian Prairie, Gold Lake Bog, and East Wolf Meadow in the early Holocene.

Late Holocene (ca. 5000 ^{14}C yr B.P.–Present)

The late Holocene marks the introduction of the present-day climate and the establishment of modern vegetation types and fire regimes (Fig. 6). Paleoclimate model simulations of late Holocene conditions imply that cool humid conditions developed as summer radiation decreased and the east Pacific Subtropical High weakened (Thompson *et al.*, 1993). At Jay Bath and Log Wallow, *Abies amabilis, Chamaecyparis nootkatensis, Tsuga mertensiana,* and *Tsuga heterophylla* grew together after ca. 3400 and ca. 3700 ^{14}C yr B.P. (Dunwiddie, 1986). At Reflection Pond, an open forest of *Abies lasiocarpa* and scattered *A. amabilis* and *T. mertensiana* was present after ca. 3700 ^{14}C yr B.P. (Dunwiddie, 1986). Modern vegetation types became established in the southern Puget Trough at Battle Ground Lake at ca. 4500 ^{14}C yr B.P. when forests of *Pseudotsuga, Thuja plicata,* and *Abies grandis* replaced woodland and savanna (Barnosky, 1985). In the central Oregon Coast Range, *Pseudotsuga, T. heterophylla, T. plicata,* and *Alnus* grew near Little Lake at about 5500 ^{14}C yr B.P. (Worona and Whitlock, 1995). In the western Cascade Range, a closed forest of *T. heterophylla, Pseudotsuga,* and *Abies* formed at ca. 4000 ^{14}C yr B.P. at Indian Prairie. In the High Cascade Range, *T. mertensiana, Picea engelmannii,* and *A. lasiocarpa* dominated the vegetation around Gold Lake Bog after ca. 4500 ^{14}C yr B.P. (Fig. 5).

In the past 2000 yr, *Thuja plicata* has become less abundant than *Pseudotsuga* at Little Lake, which coincides with charcoal evidence of increased fire frequency (C. Long, unpublished data). Conversely, at Gold Lake Bog, an expansion of *T. mertensiana* and *Abies* implies development of mature forest and longer fire return intervals (Agee, 1993). The timing of the appearance of modern conifer forests apparently varies from site to site as a consequence of differences in local climate, elevation, site aspect, and fire regime.

CONCLUSIONS

The vegetation history of the Cascade Range and adjacent regions shows clear responses to two large-scale changes in the climate system during the past 14,000 yr. First, initial warming is attributed to changes in atmospheric circulation during the wastage of the Laurentide ice sheet, most notably the northward shift of the jet and the weakening of the glacial anticyclone. In the southern Cascade Range, warming resulted in deglaciation by ca. 14,000 ^{14}C yr B.P. and forestation of the region occurred shortly thereafter. The absence of a tundra period at either Indian Prairie or Gold Lake Bog suggests that conditions had warmed considerably by the time the lakes formed. Indian Prairie contains evidence of a climatic reversal superimposed on this warming trend. Additional high-resolution studies are needed to delineate the spatial and temporal extent of this cooling and determine whether it corresponds to the Younger Dryas event.

Second, the pollen records consistently register evidence of a warmer, effectively drier period between ca. 10,000–9500 and 5000–4500 ^{14}C yr B.P. In the Cascade Range, this is evidenced by an upward shift in species ranges and the formation of no-analogue communities. Elsewhere in the Pacific Northwest, the early Holocene is characterized by a rise in treeline, an expansion of xerophytic communities, and increased fire frequency (Whitlock, 1992; Hebda, 1995). The early Holocene conditions are attributed to the direct effects of increased summer radiation, i.e., higher summer temperatures and decreased effective moisture, and also to the indirect effect of a strengthened east Pacific Subtropical High (Thompson *et al.*, 1993).

A trend toward cooler, more-humid conditions in the late Holocene promoted the expansion of mesophytic vegetation. In the Cascade Range, pollen data from Indian Prairie and Gold Lake Bog suggest that modern vegetation and climate have been present for the past 4000 to 5000 yr. This observation does not imply that vegetation has been stable over this time period or that plant communities at the beginning of the late Holocene were necessarily identical to those at present. Undoubtedly, the relative abundance of species and the composition of communities have varied as a result of species' differential sensitivies to short-term climate events (e.g., Little Ice Age), changes in disturbance regime, and soil development. These factors continue to shape the pattern of plant communities and stand ages that characterize the forest mosaic within modern vegetation zones.

It is interesting that the modern vegetation has existed for about the same span of time as other vegetation types in the Holocene. At Indian Prairie, late-glacial subalpine forest formed ca. 14,000 ^{14}C yr B.P. and persisted for ca. 2000 yr. *Abies* forest succeeded and was present for the next 2000 yr. Early Holocene forests of *Pseudotsuga* and *Abies* and expanded savanna in the lowlands lasted about 5000 yr. At Gold Lake Bog, mixed forest of *Pinus* and *Abies* was present in the early Holocene and endured for ca. 5000 yr (although more changes in the vegetation may have occurred than the pollen record can detect).

The duration of the modern vegetation types is striking, however, when compared with the remarkable age of individual trees within the forests. *Pseudotsuga, Tsuga, Thuja, Picea,* and *Abies,* for example, live hundreds of years in the old-growth forests of the western Cascade Range. Forest associations within the *Abies amabilis* or the *Tsuga heterophylla* zones today have existed for about 10 generations of the dominant species. Efforts to preserve and protect old-growth forests should recognize the relatively short history of present-day communities. Assessing the range of ecosystem processes required to sustain this vegetation requires an understanding of their sensitivity to environmental changes occurring over several millennia.

ACKNOWLEDGMENTS

We thank D. P. Adam, P. J. Bartlein, J. A. Mohr, and M. A. Worona for comments on the manuscript. D. Dawson helped with plant macrofossil analysis. F. Swanson, A. S. Gottesfeld, and L. M. J. Gottesfeld provided us with unpublished data from East Wolf Meadow. This research was supported by grants from NSF Climate Dynamics Program (ATM-9096230, ATM-9307201) to C. Whitlock.

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