Local and regional vegetation change on the northeastern Olympic Peninsula during the Holocene

J.S. McLachlan and L.B. Brubaker

Abstract: The postglacial vegetation history of the northeastern Olympic Peninsula was investigated at different spatial scales by comparing the pollen, macrofossil, and charcoal records from a low elevation lake (Crocker Lake) and a nearby forested swamp (Cedar Swamp). The regional pollen record from Crocker Lake revealed a parkland of coniferous species with divergent modern ecological tolerances, including *Pinus contorta*, *Picea sitchensis*, and *Abies lasiocarpa* during the late glacial period (~13 000 – 10 000 BP). Disturbance-adapted species such as *Alnus rubra* and *Pseudotsuga menziesii* dominated forests during the early Holocene (10 000 – 7000 BP). Modern forests containing mesic late-successional species such as *Tsuga heterophylla* and *Thuja plicata* were established during the late Holocene (7000 BP to present). During the late glacial period, the local vegetation at Cedar Swamp was dominated by *Alnus sinuata*. Hydrologic changes resulted in the establishment of a deep marsh during the early Holocene. Hydrosere succession from an open aquatic environment to a forested wetland and disturbance-mediated alternations between *Thuja plicata* and *Alnus rubra* characterized the local vegetation during the late Holocene. Throughout the Holocene, the vegetation of the northeastern Olympic Peninsula was governed by broad climatic and physiographic parameters at the regional scale and the effects of local geomorphologic constraints and disturbance history at the finer landscape scale.

Key words: fossil pollen, vegetation history, Olympic Peninsula, Quaternary.

Résumé : Les auteurs ont étudié l'histoire de la végétation post-glaciaire dans le nord-est de péninsule Olympique selon différentes échelles de temps, en comparant les pollens, les macrofosilles et les charbons, à partir d'un lac de basse altitude (lac Croker) jusqu'à une forêt marécageuse voisine (Cedar Swamp). Les données polliniques régionales du lac Croker révèlent la présence d'un parc forestier comportant des espèces conifériennes avec des tolérances écologiques modernes divergentes, incluant le *Pinus contorta*, le *Pinus sitchensis* et l'*Abies lasiocarpa* au cours de la fin de la période glaciaire (~13 000 – 10 000 ans AP). Des espèces adaptées aux perturbations, telles que l'*Alnus rubra* et le *Pseudotsuga menziesii*, ont dominé les forêts au cours de l'Holocène (10 000 – 7000 ans AP). Les forêts modernes contenant des espèces mésiques de fin de succession, telles que le *Tsuga heterophylla* et le *Thuja plicata*, se sont établies au cours de la fin de l'Holocène (7000 an AP jusqu'à présent). Au cours de la fin de la période glaciaire, la végétation locale à Cedar Swamp était dominée par l'*Alnus sinuata*. Des changements hydrologiques ont conduit à l'établissement d'un marais profond au début de l'Holocène. Vers la fin de l'Holocène une succession hydrosérique allant d'un environnement aquatique ouvert jusqu'à une forêt humide et des alternances liées à des perturbations entre le *Thuja plicata* et l'*Alnus rubra* ont caractérisé la végétation locale vers la fin de l'Holocène. Tout au long de l'Holocène, la végétation du nord-est de la péninsule Olympique a été déterminée par de grands paramètres climatiques et physiographiques à l'échelle régionale et par les effets des contraintes géomorphologiques et l'histoire des perturbations à l'échelle plus fine du paysage.

Mots clés : pollen fossile, histoire de la végétation, péninsule Olympique, quaternaire.
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Introduction

Recent studies have emphasized the importance of examining vegetation patterns and dynamics at multiple spatial scales (Urban et al. 1987; Wiens 1989; Graumlich and Davis 1993). Such a perspective often reveals a hierarchy of controlling environmental factors and processes (Wiens 1989) that can be used to generate theories of ecological organization across scales (Urban et al. 1987; Allen and Hoekstra 1992) and to predict future vegetation change (Delcourt et al. 1983). In the Pacific Northwest, the dominance of evergreen conifers at the broadest scale is thought to reflect the effects of moderate year-round temperatures with strongly seasonal precipitation (Waring and Franklin 1979; Lassoie et al. 1985). The distribution of major forest types within this region is the

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result of interactions between the predominantly westerly flow of marine air masses and the complex topography of the region. In western Washington, for instance, the distribution of lowland forest types is largely a function of the effects of the Coast and Olympic ranges, with mild rainy environments to the west of the mountains and drier more variable conditions in the Puget Lowlands (Franklin and Dryness 1973). At finer spatial scales, forest patterns are determined by interactions between the local geomorphological setting and disturbance history. The glacial and tectonic history of this region has created a diversity of landforms whose effects on substrate, aspect, and disturbance processes result in a complex mosaic of forest patches (Hemstrom and Franklin 1982; Swanson et al. 1990).

The current study examines how environmental controls of vegetation ranging from the landscape (10^4 m^2) to the regional (10^{10} m^2) scale have changed in a low elevation area of western Washington over the course of the Holocene. The study is based on differences in the spatial resolution of different fossil analyses employed. Two pollen records were interpreted as representing vegetation at two distinct spatial scales based on the principle that the area from which deposited pollen originates increases with the radius of the depositional basin (Jackson 1994). Crocker Lake is a moderate-sized lake (26 ha), which should sample pollen originating from up to several tens of kilometres away (Janssen 1984; Bradshaw and Webb 1985). Cedar Swamp is currently forested and should receive pollen predominantly from nearby vegetation (within 30 m), although some pollen may originate from regional sources (Janssen 1967; Jacobson and Bradshaw 1981). Comparison between the pollen records of these two sites should, therefore, allow the interpretation of broad regional patterns of vegetation change and finer scale vegetation dynamics at a specific site within that region. Plant macrofossils, which are generally deposited within 30 m of their origin (Dunwiddie 1983), provide confirmation of the local presence of several taxa. In addition, fossil charcoal was used to characterize the role of fire at both regional and local scales. For example, microscopic charcoal particles (diameter 12.5–50 μm) from Crocker Lake sediments should originate from the approximate source area of the pollen record (radius = 10–30 km), whereas macroscopic charcoal (diameter >425 μm) probably represents fire activity at a much finer spatial scale (cf. Clark 1988).

Long-term changes in the vegetation of western Washington and adjacent British Columbia were previously investigated through fossil pollen records in lake and peat deposits in the Puget Lowlands and the coastal Olympic Peninsula (Fig. 1). Since these types of records reflect vegetation on scales of 100 to 1000 km^2 (Bradshaw 1988), the primary emphasis of previous work was on understanding climatically driven changes in vegetation at relatively coarse spatial scales. The two studies examining long-term vegetation histories at finer spatial scales (Dunwiddie 1986; Sugita 1990) do not span the entire Holocene.

The postglacial vegetation history of the northeastern Olympic Peninsula has never been fully investigated at any spatial scale. Its position in the rainshadow of the Olympic Mountains suggests that large-scale climatic fluctuations may have affected the area differently than other regions in western Washington. This appears to have been true for the late glacial period (13 000 to 10 000 BP) when the only previous fossil pollen study of the area indicates a considerably drier vegetation type than at low elevations in coastal areas or the Puget Lowland (Peterson et al. 1983). However, nothing is currently known of the subsequent vegetation history of the area or of long-term variations in landscape scale vegetation dynamics.

Site descriptions

Crocker Lake (48°56′00″N, 122°52′30″W) and Cedar Swamp (informal name; 47°54′45″N, 122°52′30″W) are located at 60 m elevation in an area of low hills in the rainshadow of the Olympic Mountains (Fig. 1). This area was glaciated by the Puget Lobe of the Cordilleran Ice Sheet during the Vashon Stade of the Fraser Glaciation (Waitt and Thorson 1983). Both sites are within the Leland Creek spillway, which drained proglacial Lake Leland sometime before 13 000 BP (Thorson 1980) and probably originated in the dead-ice topography formed in the aftermath of this event. The area lies within the *Tsuga heterophylla* zone, a vegetation zone dominated by *Pseudotsuga menziesii*, *Tsuga heterophylla*, and *Thuja plicata* in pre-Euroamerican settlement times (Franklin and Dyrness 1973). Current vegetation is characterized by extensive stands of second-growth *Pseudotsuga menziesii* and *Alnus rubra* resulting from the intensive forestry practiced in the surrounding landscape. Drought-tolerant species such as *Pseudotsuga menziesii*, *Rhododendron macrophyllum*, and *Holodiscus discolor* are more abundant in this area than in moister parts of the *Tsuga heterophylla* zone (Henderson et al. 1989). At Sequim, 20 km to the northwest, continuous forests are replaced by open prairies because of low precipitation and coarse soils (Fowler and Wheeting 1941).

Crocker Lake (26 ha lake, ~6 m deep) is a kettle lake with a flat bottom. It is fed by a small stream that drains neighboring foothills of the Olympic Mountains and drains into the Strait of Juan de Fuca via Snow Creek. A thin margin of *Typha latifolia* surrounds the lake.

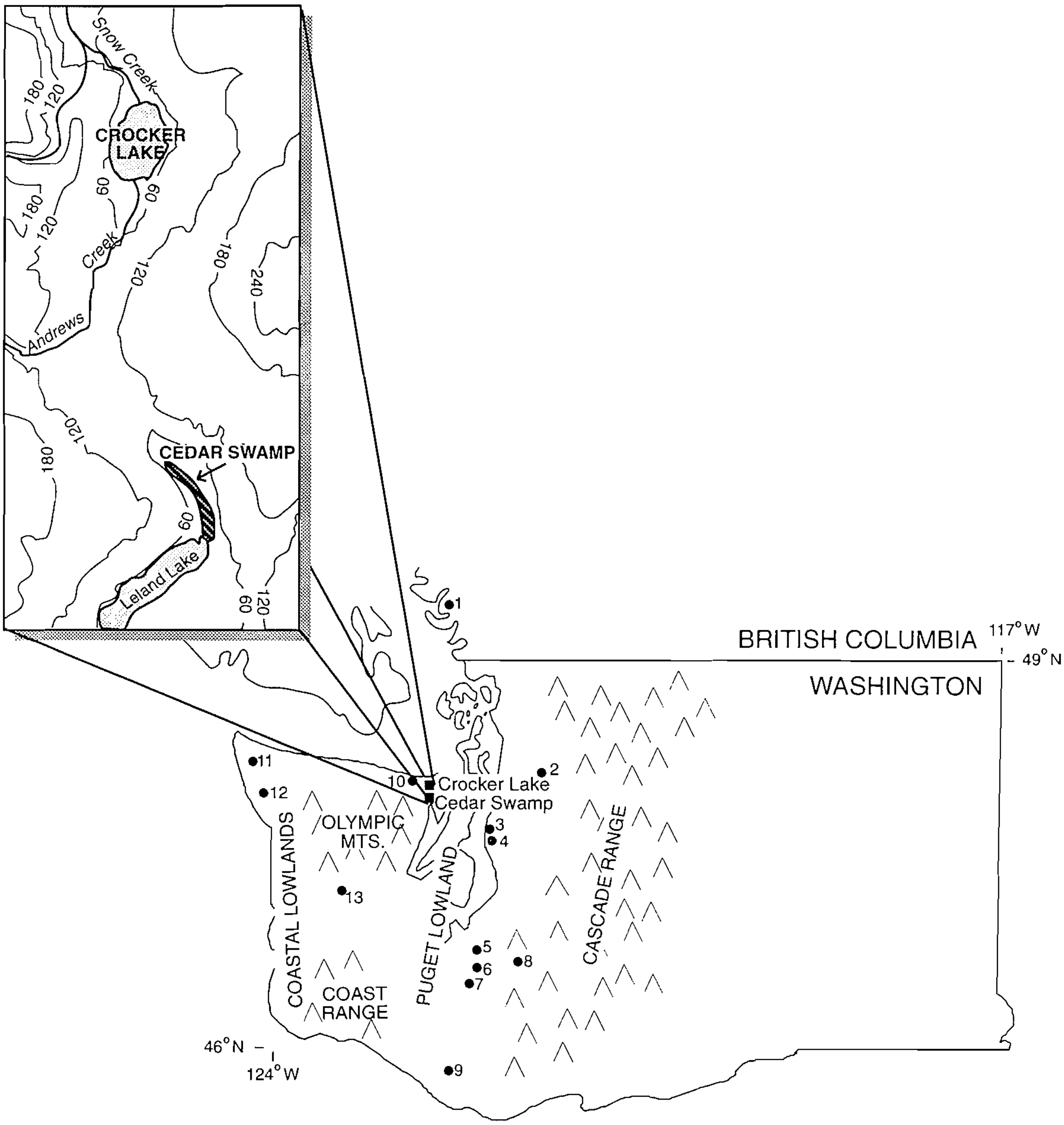
Cedar Swamp is a riparian swamp (~10 ha) located in a flat seepage area that drains into Leland Lake 3 km south of Crocker Lake. Hydrologically, the swamp grades gently from a wet meadow to areas with >1 m of standing water in the winter. The swamp is currently forested with second growth *Alnus rubra* and *Thuja plicata*, which are replacing a clear-cut stand of larger *Thuja plicata*, *Alnus rubra*, and *Tsuga heterophylla*. Understory species at the site include *Rubus spectabilis*, *Maianthamum dilatatum*, and *Spiraea* sp. *Lysichitum americanum*, *Carex* spp., and *Nuphar polysepalum* occupy progressively deeper aquatic areas, although trees grow on small topographic irregularities in even the deepest part of the swamp.

Methods

Pollen, macrofossils, and charcoal

A 5-cm diameter modified Livington piston sampler (Wright 1967) was used to retrieve a 1181-cm sediment core from the center of Crocker Lake and a 998-cm sediment core from a central location in Cedar Swamp (47 cm of standing water). The top 27 cm of the Cedar Swamp sediments were disturbed during coring and not analyzed. The two cores were extruded and described in the field, wrapped in plastic wrap and alu-

Fig. 1. Location of Crocker Lake Cedar Swamp and the sites mentioned in the text. 1, Marian and Surprise Lakes (Matthewes 1973); 2, Kirk Lake (Cwynar 1986); 3, Hall Lake (Tsukada et al. 1981); 4, Lake Washington (Leopold et al. 1982); 5, Nisqually Lake (Hibbert 1979); 6, Mineral Lake (Tsukada et al. 1981); 7, Davis Lake (Barnosky 1981); 8, Jay Bath (Dunwiddie 1986); 9, Battleground Lake (Barnosky 1985); 10, Manis Mastodon site (Peterson et al. 1983); 11, Wentworth Lake (Heusser 1973); 12, Bogachiel River site (Heusser 1978); 13, Zenkner Valley section (Heusser 1977). Elevation in metres.



minum foil, and transported to the University of Washington where they were stored at 4°C.

In the upper 300 cm of the Cedar Swamp core, 1-m core lengths were compressed somewhat during coring. Since there are no obvious inconsistencies in the pollen record corresponding to the ends of these cores, we assumed that there are no hiatuses in the record and adjusted the depths of the compressed samples to correspond to the original 1-m drive lengths. Because the nature of such core compression is uncertain, however, no interpretations were made across the transition between <1 m core lengths.

One-millilitre subsamples were removed from these cores at 10- to 30-cm intervals for pollen processing. These samples were also used for microscopic charcoal analysis and determination of organic carbon content by percent dry weight loss on ignition (LOI) at 550°C on the Crocker Lake core. Tablets of exotic *Lycopodium* spores were added to the pollen samples to determine pollen concentration and accumulation rates. The standard pollen processing procedures of Faegri and Iverson (1989) were used, with the addition of a sieving step for inorganic samples (7-μm Nitex filter). A minimum of 300 terrestrial pollen grains were identified at 400× and 1000× at each level. Pollen percentages were based on the total terrestrial pollen sum. Ratios of *Alnus*

Table 1. Dating chronology from Crocker Lake and Cedar Swamp.

Depth (cm)	Material dated	Radiocarbon age (BP ± 1 SD)	Sample code	Used in study?
		Crocker Lake		
0	Sediment surface	0	—	Yes
200–210	Bulk sediment	1780±70	Beta-60299	Yes
450–60	Bulk sediment	4760±130	Beta-60300	Yes
601–611	Bulk sediment	7530±130	Beta-60301	No
613	Pollen	6960±60	—	Yes
800–810	Bulk sediment	9830±140	Beta-60302	Yes
950–960	Bulk sediment	11540±240	Beta-60303	Yes
1174	Wood (AMS date)	10420±60	Beta-70546	No
		Cedar Swamp		
0	Sediment surface	0	—	Yes
166–176	Leaves (AMS date)	5300±60	Beta-70547	Yes
240–250	Bulk sediment	6650±140	Beta-64285	Yes
260	Mazama ash layer*	6960±60	—	Yes
480–490	Bulk sediment	8540±130	Beta-64286	Yes
783–793	Bulk sediment	8380±300	Beta-64287	No
783–793	Leaves (AMS date)	9830±60	Beta-70548	Yes
987–997	Leaves (AMS date)	11340±60	Beta-70549	Yes

*Based on AMS date of Mazama ash layer at Crocker Lake (613 cm).

sinuata to *Alnus rubra* and haploxylon to diploxylon types for *Pinus* pollen were determined based on at least 25 grains per level. Pollen zones were delineated for both percentage diagrams by visual inspection. Microscopic charcoal fragments (longest axis 12.5–50 μm) were counted along evenly spaced transects on pollen slides until a total of at least 50 exotic *Lycopodium* spores were encountered. Counts are expressed as particle accumulation rates (PARs; no. of particles/($cm^2 \cdot$ year) in the pollen diagram.

For the Crocker Lake core, plant macrofossils and macroscopic charcoal particles (>425 μm) were removed from a ~2 mm thick strip of sediment sampled continuously along the length of the core and divided into sections representing ~500-year deposition periods. For the Cedar Swamp core, plant macrofossils were removed from thirteen 10 cm long half-core segments subsampled evenly along the core and macroscopic charcoal was sampled as at Crocker Lake. All samples were soaked overnight in a 10% KOH solution, sieved at 425 μm, and identified at 10×. Pinaceae and Cupressaceae needle fragments and selected seeds were identified using modern reference collections at the University of Washington Herbarium and published keys (USDA Forest Service 1948; Dunwiddie 1985). Macroscopic charcoal particles were tallied for each 500-year period and are expressed as PARs.

Core chronologies

Sediment ages for the Crocker Lake core (Table 1) were based on five conventional ^{14}C dates of bulk sediments, one AMS ^{14}C date of a piece of wood (117 cm), and the age of the Mount Mazama tephra layer as determined by AMS ^{14}C dating of concentrated pollen extracted from the 2.5 cm directly below the tephra layer (Brown 1994). The AMS ^{14}C date of the wood (10 420 ± 60 BP; Table 1) is >2500 years younger than the age of glacial ice recession from this area (Thorson 1980; Waitt and Thorson 1983). Although basal radiocarbon dates originating in dead-ice terrain have been known to postdate glacial retreat by thousands of years (Porter and Carson 1971), the inconsistency of this date with dates from overlying sediments (Table 1) suggests that it is anomolous. It was therefore not used to establish chronology. Since no reliable dates were available from the bottom 2.5 m of the core and changes in sediment composition suggest a likely change in sedimentation rates during this period, the basal age of this core is not known. Consequently, accumulation rates of fossil material during this period were not calculated. The date of concentrated pollen from immediately below the Mount Mazama tephra layer (6900 ± 60 BP) corresponds with the generally accepted age of 6700–7000 BP (Sarna-Wojcicki et al. 1983) for this tephra but is almost 600 years younger than the bulk date from nearly the same sediment layer. This discrepancy suggests that some of the bulk sediment dates from this core may be influenced by old carbon from carbonaceous Tertiary bedrock in the headwaters of Anderson Creek. Since additional dates would be needed to substantiate a hard water effect, no adjustments in the bulk sediment dates were made, other than the substitution of the concentrated pollen date for the bulk date at the same depth. Sedimentation rates were determined based on linear interpolation through the sediment surface (= 0 BP) and all but the two anomolous dates discussed above.

The Cedar Swamp core was dated using three conventional ^{14}C dates of bulk sediments, three AMS ^{14}C dates of seeds, and leaf fragments and the Mount Mazama tephra layer. The bulk sedimentation date at 783–793 cm resulted in a dating reversal (Table 1), possibly due to root penetration by younger plants. An AMS date of dicot leaf fragments at the same depth was therefore determined and substituted for this date. The other dates obtained for the Cedar Swamp core are thought to be reliable.

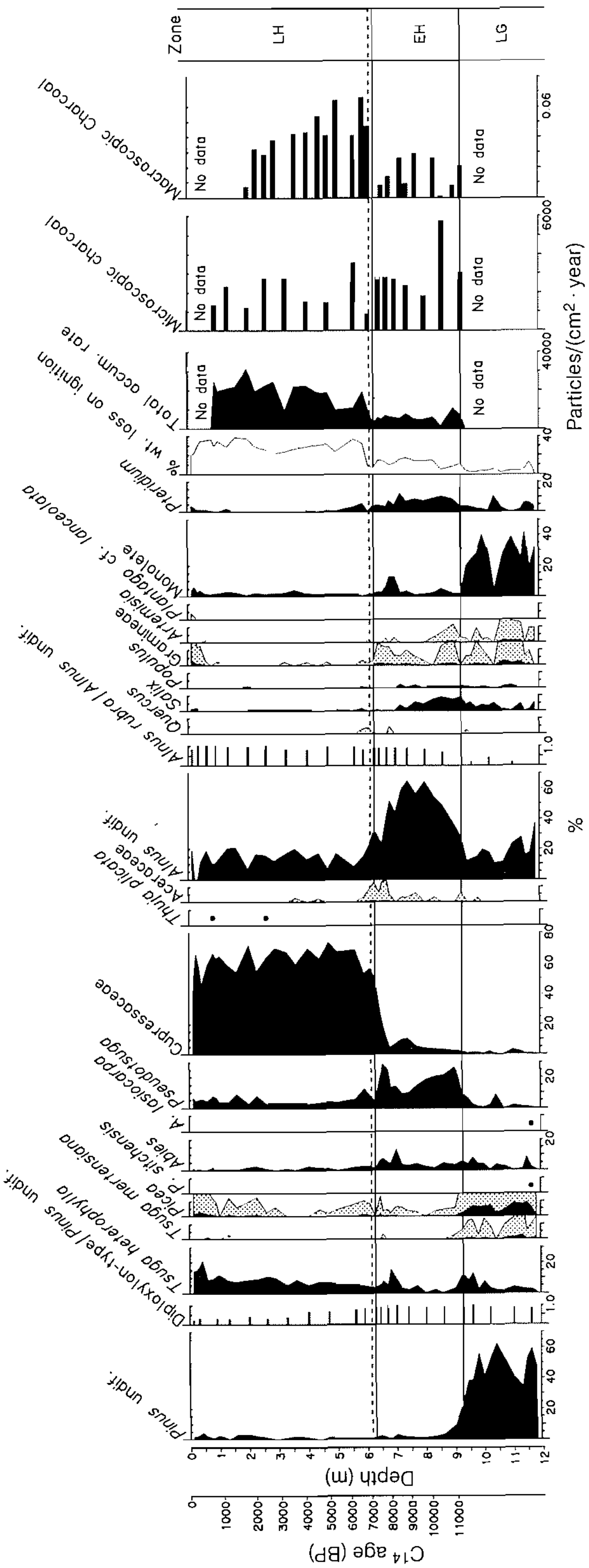


Fig. 2. Pollen percentage diagram for Crocker Lake. Dots mark the stratigraphic position of macrofossils. Stippled areas indicate percentage × 10.

Results

Sediment stratigraphy

The basal sediments of the Crocker Lake core are composed of inorganic silt (LOI <7%) (Fig. 2), which grades into fine detritus gyttja (LOI ~15%) at ~ 930 cm. Organic content increases abruptly to >30% near the Mount Mazama tephra layer (614 cm) and decreases to <25% at ~90 cm, corresponding to an increase in pollen of herbaceous species associated with European settlement. The entire Cedar Swamp core is composed of fibric sedge peat, except for the basal 10 cm, which are composed of glacial clay and sand layers. A layer of charred peat appears in the core at 970–980 cm.

Pollen and macrofossil stratigraphy

Crocker Lake

The late glacial pollen zone (LG; > 11 000 BP; Fig. 2) is dominated by diploxylon pine (assumed to be *Pinus contorta*). Other conifers representative of this zone include *Picea* (macrofossils indicate *Picea sitchensis*), *Abies* (macrofossils indicate *Abies lasiocarpa*), *Tsuga mertensiana*, and *Tsuga heterophylla*. *Alnus sinuata*, *Salix*, and *Populus* are the most common deciduous tree and shrub taxa. Common herb taxa include Cyperaceae and an unknown fern (monolete spore). Although pollen concentration is relatively low (>27 000 grains/cm^3), total PARS are unknown because of the lack of chronological control for this period.

The early Holocene pollen zone (EH; 11 000 to 7000 BP) is characterized by high percentages of *Alnus rubra* and *Pseudotsuga menziesii*. Other pollen and spore types with relatively high percentages in this zone include *Abies*, *Acer*, Gramineae, and *Pteridium aquilinum*. As *Alnus rubra* pollen percentages decrease during the transition to the late Holocene, minor peaks occur in the percentages of *Abies*, *Tsuga heterophylla*, *Pseudotsuga menziesii*, and *Acer*. Total PARs during the early Holocene zone average 6000 grains/(cm^2 · year).

A sharp rise in Cupressaceae pollen (macrofossils indicate *Thuja plicata*) coincides with a decrease in *Pseudotsuga menziesii*, *Alnus rubra*, and several other taxa at the beginning of the late Holocene zone (LH; 7000 to present). *Tsuga heterophylla* and Cupressaceae percentages are relatively high throughout this zone. A minor percentage increase in *Picea* accompanies a gradual shift in pine pollen for diploxylon (*Pinus* cf. *contorta*) to haploxylon (*Pinus* cf. *monticola*) type around 3000 BP. The period of Euroamerican settlement is indicated by an increase in Gramineae, the first appearance of *Plantago* cf. *lanceolata* and minor shifts in the relative abundance of *Tsuga heterophylla*, *Alnus rubra*, and Cupressaceae at ~90 cm. Total PARs increase to an average of 18 000 grains/(cm^2 · year) during the late Holocene.

Cedar Swamp

During the late glacial period, *Pinus* percentages in the late glacial pollen zone of Cedar Swamp (Fig. 3) are roughly half those at Crocker Lake, whereas *Alnus sinuata* percentages roughly double those of Crocker Lake. Percentages of *Picea* and *Tsuga heterophylla* are slightly lower at the swamp and *Salix* and Cyperaceae values are more variable but generally

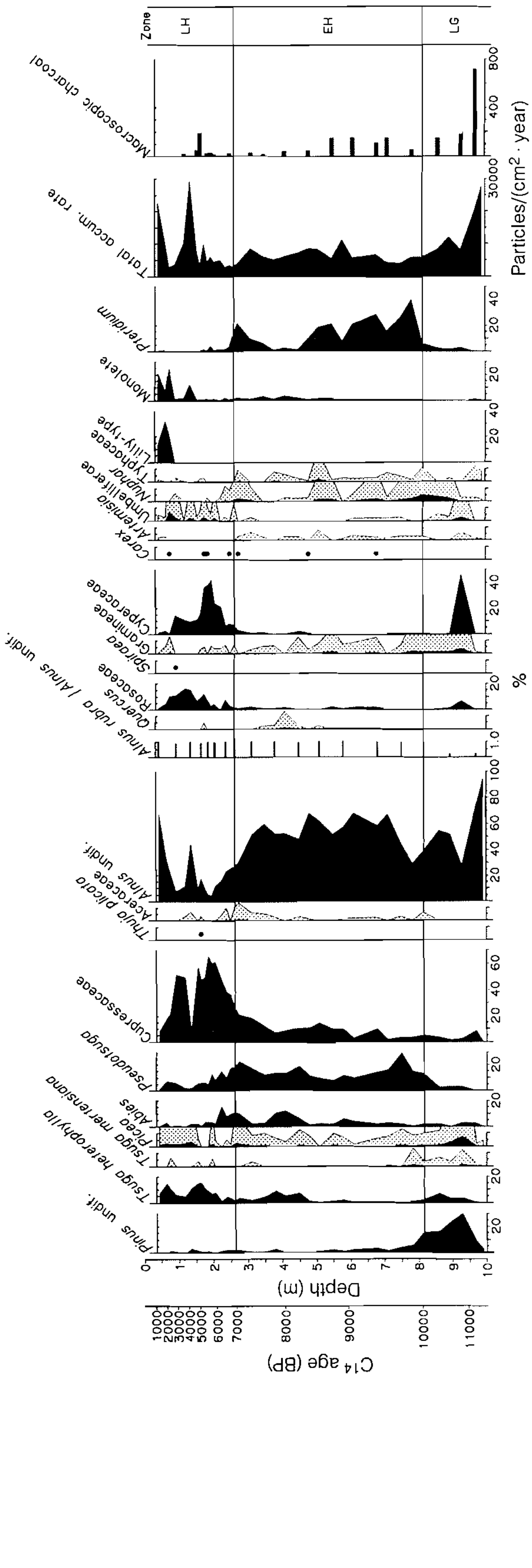


Fig. 3. Pollen percentage diagram for Cedar Swamp. Dots mark the stratigraphic position of macrofossils. Stippled areas indicate percentage ×10.

higher. Total PARs are initially high (28 000 grains/(cm^2 · year)) but rapidly decrease to less than 10 000 grains/(cm^2 · year).

Pollen percentages and total PARs at Cedar Swamp are similar to those of Crocker Lake during the early Holocene. Even the series of percentage peaks of tree species that characterizes the transition to the late Holocene pollen zone at Crocker Lake is apparent in the Cedar Swamp record. Cupressaceae pollen and *Pteridium aquilinum* spores, however, are slightly more abundant at the Swamp.

The late Holocene pollen record at the swamp has several features similar to those at Crocker Lake, such as relatively high Cupressaceae (macrofossils indicate *Thuja plicata*) and *Tsuga heterophylla* percentages and low *Pseudotsuga menziesii* and *Alnus rubra* percentages. However, several differences set these records apart. Pollen percentages are less constant at Cedar Swamp. In particular, sharp fluctuations in Cupressaceae and *Alnus rubra* pollen have no counterpart in the Crocker Lake record. Also, shrub and herb taxa such as *Salix*, Rosaceae (macrofossils indicate *Spiraea* cf. *douglasii*), Cyperaceae, and Umbelliferae are common in the Cedar Swamp record but not in the Crocker Lake record. PARs at Cedar Swamp are similar to those of the early Holocene (~8000 grains/(cm^2 · year)) with the exception of two brief spikes of greater than 20 000 grains/(cm^2 · year), which correspond to peaks in *Alnus rubra* percentages.

Charcoal stratigraphy

The early Holocene microscopic charcoal record from Crocker Lake begins with a peak in charcoal accumulation rates (5700 particles/(cm^2 · year); Fig. 2), but they immediately decline to a relatively constant rate of ~3000 particles/(cm^2 · year). Charcoal accumulation rates are generally lowest during the late Holocene, although fluctuations of up to 3500 particles/(cm^2 · year) occur. The macroscopic charcoal accumulation rates from Crocker Lake, by contrast, are unambiguously lower in the period before the Mazama ash layer than after it. Macroscopic charcoal accumulation rates at Cedar Swamp generally decrease over the course of the Holocene. The charcoal record is punctuated by sharp peaks in charcoal influx at 11 300 and 5100 BP.

Discussion

Crocker Lake record of regional vegetation

Late glacial period (LG: > 11 000 BP)

In the few thousand years following deglaciation, a mixture of species currently found in subalpine regions of both continental (*Pinus contorta*, *Abies lasiocarpa*) and maritime (*Tsuga mertensiana*) climates as well as in low elevation maritime regions (*Picea sitchensis*, *Tsuga heterophylla*) characterized the vegetation in the Crocker Lake area. Low total pollen influx and the presence of herbaceous taxa indicative of open conditions (Gramineae, *Artemisia*) suggest that trees formed relatively open woodlands or scattered clumps within partially forested landscapes. While similar forest types characterized late-glacial vegetation throughout much of the Puget Lowland (Mathewes 1973; Tsukada et al. 1981; Barnosky 1981; Cwynar 1986), open herb and shrub communities existed only 20 km northwest of the site (Peterson et al. 1983), indicating that physiographic parameters in the late-glacial period resulted in a distribution of forest types similar to that of today.

Early Holocene period (EH: 11 000 to 7000 BP)
At the beginning of the early Holocene, tree species common in the late glacial decreased in abundance and were replaced by a new assemblage of species characteristic of warmer and drier conditions. Upland communities may have resembled the relatively open *Pseudotsuga menziesii* communities found today in central Oregon and on dry and fire-prone sites throughout the Puget Lowland (Franklin and Dyrness 1973). The combination of higher percentages of pollen and spores from taxa indicating open environments, such as *Pseudotsuga menziesii*, *Pteridium aquilinum*, *Artemisia*, and Gramineae, with relatively inorganic sediments and low total PARs suggest the presence of a more open environment with relatively high erosion rates and low pollen productivity. The abundant *Alnus rubra* pollen of this period is likely to have originated primarily from riparian populations as this species is subject to water stress on droughty upland sites (Pezeshki and Hinckley 1988). Early Holocene pollen spectra are interpreted as indicating dry conditions throughout the Pacific Northwest (Whitlock 1993) that have been attributed to the effects of relatively severe summer droughts (Tsukada et al. 1981; Barnosky 1985).

Late Holocene period (LH: 7000 BP to present)
Forests characteristic of presettlement low elevation landscapes were probably established at Crocker Lake ~7000 BP when mesic late successional species such as *Thuja plicata* and *Tsuga heterophylla* increased in abundance. Total pollen accumulation rates reached their highest levels at this time, probably indicating the establishment of closed forests. Similar changes occur in pollen records throughout low elevations in western Washington around this time (e.g., Barnosky 1981; Tsukada et al. 1981; Cwynar 1986) and are thought to be due to the establishment of modern temperature and moisture regimes.

Minor shifts in tree taxa, such as the gradual increase in *Picea sitchensis* and the replacement of *Pinus contorta* by *Pinus monticola* beginning around 3000 BP, may indicate a regional cooling trend that has been observed in high elevation glacial and vegetation records (Crandell and Miller 1974; Dunwiddie 1986) but is not well documented at low elevations. As in other low elevation pollen records from the Pacific Northwest, forest clearance by Euroamerican settlers is marked by an increase in disturbance-adapted species such as Gramineae and *Plantago* cf. *lanceolata*. These changes represent perhaps the strongest perturbations in regional forests since the establishment of modern low-elevation forest types 7000 years ago.

Vegetation history at Cedar Swamp

Late glacial shrub–scrub wetland
The strong representation of *Alnus sinuata* and Cyperaceae in the Cedar Swamp record prior to 10 000 BP suggests that the site was vegetated and received a largely local pollen signal during the late glacial period. It may have been dominated by *Alnus sinuata* thickets analogous to modern shrub communities found in frequently disturbed sites at higher elevations in the Northwest (Franklin and Dyrness 1973). Coniferous species that characterized the regional landscape may have been restricted to upland sites. The relatively low percentage of diploxylon pine pollen during this period, for example, suggests that *Pinus contorta* was not a component of the local wetland vegetation even though it can thrive on poorly drained soils (Minore 1979). Overall, differences between wetland environments such as Cedar Swamp and the upland matrix may have had important consequences at the landscape level. For example, on modern boreal and alpine landscapes, shrubby pockets of *Alnus sinuata* perform important ecological functions such as providing habitat for wildlife in otherwise open coniferous environments (Mitchell 1967); the shrub–scrub wetland at Cedar Swamp likely performed similar functions on the late glacial landscape.

Early Holocene deep marsh
The rise in *Nuphar* pollen around 10 500 BP is the first indication of a shift to wetter conditions at Cedar Swamp. During the early Holocene, elevated percentages of the pollen of aquatic species such as *Typha* and *Nuphar* indicate that the site was submerged for most or all of the year (Spence 1982) and probably too wet to sustain woody plants. The overall similarity between the terrestrial pollen assemblages at Cedar Swamp and Crocker Lake during the early Holocene suggests that the openness of the Cedar Swamp site resulted in it collecting pollen primarily from the same regional source area as Crocker Lake.

The reason for moister local conditions during a dry climatic period is not known, although such conditions may have resulted from a combination of climatic factors (e.g., the effects of shifting seasonality on hydroperiod), local hydrologic factors (e.g., impeded drainage), and (or) other factors leading to changes in the overall balance between the height of the water table and peat accumulation (Clymo 1991).

Late Holocene transition to forested swamp
Increases in Cyperaceae, Umbelliferae, and *Thuja plicata* (based on macrofossil identification) around 7500 BP and contemporaneous decreases in aquatic taxa such as *Typha* and *Nuphar* indicate the return of terrestrial vegetation to the site. In some respects, vegetation development during the late Holocene represents a classical example of hydrosere succession (Cooper 1913; Walker 1970) with a shift from aquatic taxa to emergent herbs such as the Cyperaceae (6000 BP) to woody shrubs such as *Spiraea* (Rosaceae pollen type) and *Salix* (3500 BP). However, sharp fluctuations in the pollen of *Alnus rubra* and *Thuja plicata*, indicate that trees were present at the site throughout this succession, suggesting that topographic irregularities permitted the coexistence of forest vegetation within the context of gradual wetland terrestrialization.

Disturbance drivers of vegetation change

Trends in microscopic charcoal accumulation at Crocker Lake are interpreted here as broadly indicative of changes in fire activity in the region surrounding the two sites. The decline in accumulation rates between the early and late Holocene is consistent with the climatic and vegetation interpretations described above. Frequent fires may have been an important mechanism by which early Holocene summer drought resulted in open *Pseudotsuga menziesii* dominated forests.

The increase in accumulation rates of macroscopic charcoal at Crocker Lake between the early and late Holocene seems to conflict with the previous interpretation. Although factors governing charcoal production are complex and poorly understood (Patterson et al. 1987; Clark 1988), the increase in macroscopic charcoal accumulation rates at ~7000 BP may reflect a difference in the size of charcoal produced by the burning of different vegetation types. On the modern landscape, a shift from ground fires to intense crown fires accompanies the transition from open *Pseudotsuga menziesii* communities to old-growth *Tsuga heterophylla* – *Pseudotsuga menziesii* forests (Agee 1993). Similar changes in fire intensity may have accompanied the structural and compositional shift in dominant vegetation type at this time.

Because of potential changes in the source area of incoming charcoal associated with shifts between terrestrial and aquatic conditions at Cedar Swamp, we interpret the macroscopic charcoal record from this site conservatively, discussing only events that are likely to represent local fires. The pronounced peak in macroscopic charcoal and associated burnt peat fragments at the beginning of the Cedar Swamp record, for instance, indicate that a fire burned the surface of the wetland around 11 300 BP. Subsequent increases in *Alnus sinuata* and Cyperaceae pollen suggest that the persistence of these disturbance-adapted taxa may have been favored by fire as well as moist site conditions. Local fires of the type documented during the late glacial apparently did not occur during the early Holocene, presumably due to the shift to more aquatic conditions. A peak in charcoal accumulation rates at 5000 BP indicates that the site had become dry enough to permit a local fire, which appears to have resulted in the temporary replacement of *Thuja plicata* by *Alnus rubra*. While fires were probably the most important disturbance factor in upland areas during the late Holocene, the local charcoal record indicates only one major fire at the swamp during this period. A second local replacement of *Thuja plicata* by *Alnus rubra* around 2500 BP may have been due to flooding.

Vegetation dynamics across spatial and temporal scales

Fossil evidence employed in this study reveals vegetation history on the northeastern Olympic Peninsula at different spatial scales. Differences between the local wetland record of Cedar Swamp and the regional upland-dominated record of Crocker Lake provide some indication of the relative importance of environmental controls operating at different spatial scales and in different geomorphological settings. The trends observed at these sites, in the context of other lowland records in western Washington, suggest that the general hierarchy of environmental controls active today has remained more or less constant throughout the Holocene. At the broadest scale, climatic changes driven by factors such as the effect of changing seasonal insolation on atmospheric circulation patterns are responsible for the major postglacial vegetation changes in the Pacific Northwest (Whitlock 1993). Within this setting, the template of regional physiography determines broad vegetation patterns. Fossil pollen records from the region suggest that the distribution of major lowland forest zones has remained fairly constant during the Holocene. The Crocker Lake record, for example, shares most of the features of other long-term records from the Puget Lowland, indicating that the area currently occupied by low elevation *Tsuga heterophylla* zone forests maintained a uniform vegetation type during each climatic period since the recession of continental glaciers. The position of Crocker Lake in the Olympic rainshadow did not, therefore, set it apart from more mesic Puget Lowland sites even during the dry early Holocene, when other relatively dry areas, e.g., on droughty soils (Hibbert 1979) or at the margins of oak woodlands (Barnosky 1985), formed open savannahs.

Local environmental processes that are not detectable in regional records are apparent at Cedar Swamp. For example, the influence of changing water table depth on local site conditions probably had a more direct effect on the characteristics of wetland vegetation than did regional climate. While changing climate undoubtedly influences local water tables, the late Holocene record at Cedar Swamp indicates that hydrosere succession to a forested wetland occurred during a period of relatively stable climate. The autogenic processes of hydrosere succession are unique to wetland environments, however, and small-scale fossil studies of forests on more typical upland sites in the Pacific Northwest (Dunwiddie 1986; Sugita 1990) indicate that cycles of disturbance are generally the most important driver of local vegetation change during stable climatic periods.

The unusual geomorphological and hydrological setting of Cedar Swamp also influenced local disturbance regime. While fire has probably been the dominant disturbance factor in upland environments throughout the holocene, its role in the local environment of Cedar Swamp has apparently been more limited since the local pollen and charcoal record indicate few fires. Other than during the early Holocene, when local vegetation was primarily aquatic, hydrological changes, such as floods, may have been the primary disturbance agent at Cedar Swamp.

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