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Reconstructing fire regimes with charcoal from small-hollow sediments: a calibration with tree-ring records of fire

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Abstract: Interpretations of charcoal records from small hollows lack a strong theoretical and empirical foundation, and thus their potential for providing useful fire-history records is unclear. To evaluate this potential, we examined charcoal records in ^{210}Pb-dated cores from 12 small hollows and looked for evidence of 20 local fires reconstructed with tree-ring records from the surrounding forest. Using all charcoal > 0.15 mm wide we established an optimum threshold that identified charcoal peaks corresponding to known fires while minimizing charcoal peaks identified that were not associated with known fires (i.e., false positives). This threshold detected four of four high-severity fires, five of 10 moderate-severity fires, and three of six low-severity fires. Analysis of larger charcoal alone (> 0.50 mm wide) yielded nearly identical temporal patterns and detection rates, but four false positives were identified, twice as many as identified using all charcoal > 0.15 mm wide. Charcoal peak magnitude was highly variable within severity classes: although half of the low- and moderate-severity fires left no detectable peaks, others left peaks larger than some high-severity fires. Our results suggest that fire detection depends strongly on fire severity and that fine-scale spatial patterns of lower-severity burns play an important role in determining the charcoal signature of these events. High detection rates for high-severity fires and low false-positive rates indicate that charcoal records from small hollows will be most useful in systems where fires are large, severe and infrequent.

Key words: Palaeoecology, small hollows, fire history, charcoal, tree rings, calibration.

Introduction

Analysis of fossil pollen from small-hollow records has become a widely used method for studying stand-level vegetation changes at centennial to millennial timescales (Heide, 1984; Bradshaw, 1988; Foster and Zebryk, 1993; Björkman and Bradshaw, 1996; Davis *et al.*, 1998; Parshall, 1999; Hannon *et al.*, 2000; McLachlan *et al.*, 2000; Parshall and Calcote, 2001; Fujikawa, 2002). Pollen-based vegetation interpretations from these records are well supported by both theoretical and empirical research on the relationships between pollen deposition in small hollows and the composition of surrounding vegetation (Bradshaw, 1988; Chen, 1988; Jackson and Wong, 1994; Sugita, 1994; Calcote, 1995, 1998; Parshall and Calcote, 2001). In contrast, interpretations of charcoal from small-hollow records (Foster and Zebryk, 1993; Björkman and Bradshaw, 1996; Bradshaw *et al.*, 1997; Davis *et al.*, 1998; Hannon *et al.*, 2000; Niklasson *et al.*, 2002) lack a strong empirical foundation. The currently poor understanding of charcoal records from small hollows limits their use for studying ecological history in systems where fire is important. Like vegetation, fire regimes are often controlled by site-specific factors, such as topography and aspect (e.g., Camp *et al.*, 1997; Heyerdahl *et al.*, 2001; Gavin *et al.*, 2003; Taylor and Skinner, 2003), but we currently do not know how to accurately interpret charcoal from small hollows to provide stand-scale fire histories.

Interpretations of fire history from lacustrine charcoal records have benefited considerably from comparisons between tree-ring or historical records of fire and identifiable charcoal peaks (Clark, 1990; MacDonald *et al.*, 1991; Millspaugh and Whitlock, 1995; Tinner *et al.*, 1998; Pitkänen *et al.*, 1999, Laird and Campbell, 2000; Gavin *et al.*, 2003; Lynch *et al.*, 2003). However, comparable studies are lacking for small hollows. No calibration has systematically assessed how small-hollow sediments record fires, and thus their potential for providing ecologically meaningful records of fire history remains to be seen.

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In this study, we compare fire histories inferred from tree-ring records to ^{210}Pb-dated charcoal records from adjacent small hollows to calibrate and test a method for identifying fires from charcoal peaks in small-hollow sediments. Our study takes place in a Douglas-fir–western hemlock–lodgepole pine ecosystem in the Pacific Northwest, USA, and we specifically evaluate: (1) the effects of varying charcoal threshold values on fire detection and false-positive rates; (2) the potential for inferring fire severity from the sediment charcoal records, and (3) the accuracy of using >0.15 mm wide charcoal as compared to >0.50 mm wide charcoal to detect fires. As such, this is the first multisite calibration of small-hollow charcoal records with tree-ring records of fires.

Methods

Study area

The study area is an 800 ha region of Moran State Park on Orcas Island, one of the San Juan Islands of northwestern Washington, USA (48°39′N, 122°50′W; Figure 1). The San Juan Islands are located in the rain shadows of mountains on the Olympic Peninsula and Vancouver Island. Mean annual rainfall is 72 cm (70% falling between October and March), and mean January and July temperature is 4°C and 15°C, respectively (Olga, WA, 1971–2000; US National Climatic Data Center, Asheville, North Carolina). Forests fall at the dry end of the *Tsuga heterophylla* zone defined by Franklin and Dyrness (1988). The fire regime is similar to those in mesic to dry Douglas-fir forests, with high- and mixed-severity fires occurring approximately every 100 years (Agee, 1993: 210–11). Forest hollows 5–20 m in diameter are abundant throughout Moran State Park and retain standing water from approximately October to June. The forests in the study area have been protected since the establishment of the state park in 1922 and were not commercially cut before that time.

Two regions within Moran State Park were used for the calibration of small-hollow charcoal records with recent fire history. Mount Constitution is a 650 m high plateau currently supporting stands dominated by lodgepole pine (*Pinus contorta* var. *murrayana*), Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) and western hemlock (*Tsuga heterophylla*). Mount Pickett is slightly lower (300–500 m in elevation) and has variable topography. It is dominated by Douglas-fir and western hemlock, with occasional lodgepole pine, red alder (*Alnus rubra*) and western red cedar (*Thuja plicata*). Western white pine (*P. monticola*) and Sitka spruce (*Picea sitchensis*) are present in minor amounts in both study areas (< 5% basal area).

Tree-ring records of fire history

Fire histories for each site were based on (1) age structures developed from estimated ages of living trees and (2) fire scars from Douglas-fir trees. Age structures were used to identify stand establishment dates and distinct age classes. In Pacific Northwest forests cohort establishment is typically linked to a disturbance event, often fire (Agee, 1993). In the case of high-severity fires, where all trees are killed, age classes are often the only evidence of the event remaining in the modern vegetation (Agee, 1993). Using age structures also allowed us to infer disturbance severity by quantifying the number of trees predating (and thus surviving) a disturbance event. However, age structures alone provide a minimum age of a disturbance, and they do not record the type of disturbance initiating a cohort.

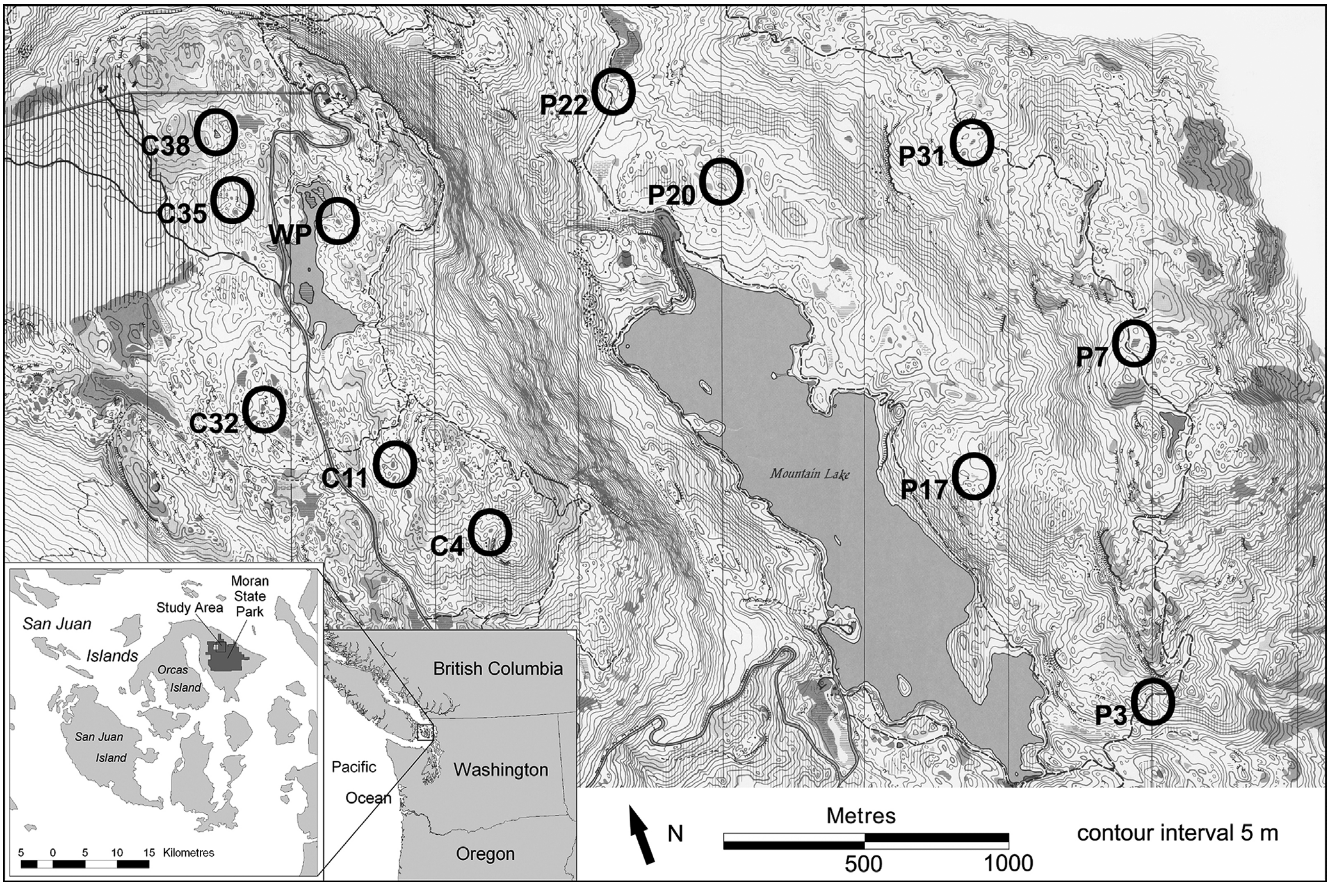

Figure 1 Moran State Park, on Orcas Island, in the San Juan Islands of northwestern Washington, USA. Black circles indicate study sites; small hollows are located at the centre of each circle, and tree-ring records represent the area within each circle. Detailed map produced by and used with permission from the Cascade Orienteering Club, Seattle, WA.

Fire scars from Douglas-fir trees, which can survive fires of moderate intensities (Agee, 1993), were coupled with age structures to obtain unambiguous evidence and precise dates of past fires.

Using a detailed topographic map (Cascade Orienteering Club, Seattle, WA) 12 small hollows were selected from both study regions to span a range of fire severities and estimated times since the last fire (Higuera, 2002). The species, diameter at breast height (DBH, 1.34 m), and location of all trees ≥ 5 cm DBH were recorded from within eight belt transects, each 2–6 m wide, extending 55 m from the edge of the hollow in the cardinal and subcardinal directions. The spatial scale of this sampling (≈ 1.25 ha) was designed to reconstruct a stand-level fire history compatible with our best understanding of the spatial scale of vegetation records (≈ 0.8–3 ha; Sugita, 1994; Calcote, 1995; 1998) and charcoal records (≈ 0.3 ha.; Patterson *et al.*, 1987) from small-hollow sediments.

To obtain representative age structures at each of the 12 sites, trees from the original survey were stratified into 10 cm size classes, and a subset for each species and size class was randomly selected for increment coring. Because many hollows are surrounded by a fringe of young trees that appear unassociated with fires, we only included trees from 5–55 m in these samples. Cores were taken from 30–40 trees per site from as close to the root crown as possible (average height = 32 cm, range = 0–150 cm) until a core reached as close to the pith as possible (average distance to pith = 4 mm, range = 0–87 mm). Fire scars from Douglas-fir trees were sampled opportunistically with an increment borer using the methods described by Barrett and Arno (1988).

Tree cores were mounted and fine sanded following the methods of Stokes and Smiley (1968), and rings were counted under a stereomicroscope at ×10–40. Crossdating was done using the 'list' method described by Yamaguchi (1990). A subsample of 35 Douglas-fir trees was also crossdated using the computer program COFECHA (Holmes, 1998). The dating of these samples was never adjusted by more than five years. When the pith was not reached on samples used for ageing, the number of missing rings was estimated using a transparency of ring widths equivalent to the 10 innermost rings of the sample (Villalba and Veblen, 1997). The number of years for a tree to reach core height was estimated based on the average width of the 10 innermost rings. When average inner-ring widths were ≥ 0.50 mm, a height growth rate of 10 cm/yr was assumed; otherwise a height growth rate of 5 cm/yr was assumed (modified from Agee, 1993: 86).

Using the estimated germination dates, age structures for each site were constructed by plotting the percentage of each species germinating in a given decade. At each site, exact fire dates were identified by the presence of on-site fire scars or by distinct age classes that were contemporary with fire scars at other sites. The fire severity at each site was estimated based on the proportion of surviving trees over the 1.25 ha sampling area (Morrison and Swanson, 1990; Agee, 1998). A fire with no trees predating the event was classified as high severity. Moderate-severity fires were those in which $\leq 25\%$ of the trees predated the fire, and low-severity fires were those with $> 25\%$ of the trees predating the fire. These definitions of fire severity refer to burning that occurred within 55 m of the hollow, as any individual fire burned with varying severity in different portions of its extent. At sites that burned twice, this classification system may overestimate the severity of the older fire, because the more recent fire may have killed trees that survived the older fire. The tree-ring record extends into the 1600s at some sites. However, only the period from 1800 to 2000 was used to infer fire timing and severity to avoid errors associated with a fading record (see Johnson *et al.*, 1994).

Small-hollow sediment sampling

Sediment cores were collected from the centre of each hollow using a 7.62 cm diameter, 50 cm long modified Gavin sampler (Gavin, 2000) in August and September 2000. Cores were described in the field, wrapped in polyvinylidene chloride film (Saran Wrap™) and aluminum foil, transported in polyvinyl chloride (PVC) tubes, and stored in the laboratory at approximately 3°C.

Sediment cores were sectioned continuously at 0.25 cm increments using a custom-made sampling device. Subsamples of 3 cm^3 were taken from each increment for charcoal analysis. Charcoal subsamples were soaked in a 10% sodium metaphosphate solution for 72 hours to disaggregate the sediment and then gently washed through 0.500 and 0.150 mm sieves with water. Samples were bleached with 8% hydrogen peroxide for 8 hours to aid in charcoal identification (Rhodes, 1998), and all charcoal pieces were counted at × 10–40 using a stereomicroscope. Theoretical and empirical studies indicate that charcoal > 0.10 mm wide ('sieved charcoal') represents fires occurring within 10^1–10^2 m from the edge of a collecting basin (Clark, 1988; Clark and Royall, 1996; Whitlock and Millspaugh, 1996; Clark *et al.*, 1998; Blackford, 2000; Laird and Campbell, 2000; Carcaillet *et al.*, 2001b; Gardner and Whitlock, 2001; Gavin *et al.*, 2003). However, there remains speculation as to the value of charcoal in larger size classes. For example, a study by Ohlson and Tryterud (2000) suggests that the presence of charcoal > 0.50 mm wide provides evidence of fires within 1 m of a collecting site (see also Tryterud, 2003). We analysed charcoal in two size classes separately in 11 of our 12 sites: 0.15–0.50 mm wide and 0.50–50 mm wide (hereafter referred to as '0.15–0.50 mm size class' and '0.50–50 mm size class'). After observing that the two size classes showed nearly identical patterns, we pooled all charcoal > 0.15 mm wide (hereafter referred to as 'pooled size class') and performed the same analyses as for the individual size classes.

^{210}Pb based sediment chronologies

Measurements of ^{210}Pb were performed by Flett Research Ltd (Manitoba, Canada; http://www.flettresearch.ca) on 10–14 samples from the upper 20–25 cm of each core, and the constant rate of supply (CRS) model was used to develop chronologies (Oldfield and Appleby, 1984; Binford, 1990). The CRS model assumes a constant rate of supply of unsupported ^{210}Pb to the sediments and is advantageous over other models because it does not assume a constant sediment accumulation rate. However, with the CRS model small changes in the estimated background level of ^{210}Pb can cause large changes in the estimated age of sediments older than ≈ 100 years (Binford, 1990).

Age assignments and the estimation of background levels of ^{210}Pb follow the methods described by Binford (1990). Errors associated with age models incorporate errors arising from natural variation, the statistical nature of measuring radioactivity, and the estimation of the background ^{210}Pb levels (Binford, 1990). In all ^{210}Pb chronologies first-order errors increase exponentially with increasing age estimates. Also, the amount of ^{210}Pb in the top layers of sediment controls the maximum age of a ^{210}Pb chronology and the magnitude of associated errors. Assuming a constant sediment accumulation rate for the lowermost sediments, we used the lowest two points of each chronology to assign dates to sediment below that level. These dates are subject to all the sources of error inherent in ^{210}Pb dating, plus the assumption of a constant sediment accumulation rate. Extrapolated dates start at ages older than 1850 at half of the sites, and between 1850 and 1900 at the other half. Our earliest tree-ring dated fires occur in the 1820s.

Identification of fires from charcoal records

Charcoal concentrations ($\#\cdot\text{cm}^{-3}$) were converted into charcoal accumulation rates (CHAR, $\#\cdot\text{cm}^{-2}\cdot\text{yr}^{-1}$) using sediment accumulation rates derived from the ^{210}Pb chronologies. The CHAR of each 0.25 cm sample was smoothed using a two-sample (0.5 cm) running average for the entire record to partially account for sediment mixing and nonhorizontal stratigraphy. With the smoothing, 0.5 cm sections typically represent ≤ 10 years.

In general, the CHAR of any sample represents charcoal from one or more of four sources: airborne fallout from local fires, airborne fallout from distant fires, secondary deposition not associated with current fire activity (e.g., slope wash, redeposition, sediment mixing) and noise (natural and analytical) (Patterson *et al.*, 1987; Clark and Royall, 1995; Clark *et al.*, 1996; Whitlock and Anderson, 2003). The terms ‘local’ and ‘distant’ are both widely used in the literature and ambiguous, but they generally refer to fires within (local) or beyond (distant) 10^1–10^2 m of a collecting basin. The goal of CHAR analysis is to isolate the signal of current local fires from the other sources of charcoal input. This is achieved by decomposing CHAR records into two components, termed ‘background’ and ‘peak’ (Clark and Royall, 1996; Clark *et al.*, 1996; Clark and Patterson, 1997; Long *et al.*, 1998). The background component of CHAR records represents integrated charcoal from distant fires, charcoal from secondary deposition, and noise. In long records this component usually varies at centennial to millennial timescales and is estimated with a variety of smoothing techniques that remove long-term while preserving short-term trends in charcoal accumulation (e.g., Clark and Royall, 1996; Long *et al.*, 1998; Carcaillet *et al.*, 2001a; Gavin *et al.*, 2003). When the background component is removed, what remains is termed the peak component, which consists mainly of charcoal deposited by local fires (Clark and Royall, 1996; Clark *et al.*, 1996; Long *et al.*, 1998). Because both background and peak components can contain substantial noise, peaks are usually identified only when total CHAR exceeds some threshold above the estimated background (Long *et al.*, 1998; Carcaillet *et al.*, 2001a; Gavin *et al.*, 2003; Lynch *et al.*, 2003). Determining this threshold is the critical step in interpreting fire frequencies from sediment-charcoal records, as the threshold value determines the number of peaks interpreted as fires (or fire events). Few studies have the independent records of fire required to quantify the tradeoffs inherent to a chosen threshold (but see Clark, 1990, and Gavin *et al.*, 2003).

Due to the short length of the calibration period in this study (300 years), we used a single background estimate for each record. Because ideally this estimate is not affected by the extreme values of the charcoal peaks (Gavin *et al.*, 2003), we used the median CHAR of each series to estimate background CHAR. Each CHAR series was converted to a uniform, ‘1-year’ resolution by linear interpolation before the medians were calculated. Although the true resolution of the series is not annual, this step accounts for variable sampling intensity across time (see Long *et al.*, 1998).

Given that one of the goals of this study was to establish a calibration for evaluating charcoal records, we evaluated thresholds representing varying multiples of the background CHAR (i.e., median CHAR) to identify the value that maximized the number of recognized peaks corresponding to known fires while minimizing the number of peaks not associated with fires. This value is termed the ‘optimum threshold value’ because it maximizes the overall correspondence between the charcoal and tree-ring records of fire. To be considered a ‘charcoal peak’ CHARs had to exceed a given threshold for three samples and more than 10 consecutive years. Similarly, CHARs had to decrease below the threshold for three samples and more than 10 consecutive years before one peak was considered finished and another could begin.

The correspondence between charcoal and tree-ring records of fire was expressed in two ways: (1) detection rate, the proportion of fires associated with recognized charcoal peaks; and (2) false-positive rate, the proportion of recognized charcoal peaks not corresponding to tree-ring evidence of fires. Given tree-ring evidence of a fire, the detection rate represents the probability of detecting that fire using the sediment-charcoal record. Given a charcoal peak in the sediment record, the false-positive rate represents the probability that the peak does not correspond to a fire detected in the tree-ring record. The term ‘correspondence’ refers to any charcoal peak with an apex occurring within 20 years prior to and 30 years after a fire inferred from the tree-ring record. This window accounts for potential ^{210}Pb dating errors, sediment mixing and delayed charcoal transport (e.g., Whitlock and Millspaugh, 1996; Gavin *et al.*, 2003).

Results

Tree-ring records of fire history

Eleven fires were identified at nine sites from a total of 19 fire scars (Table 1). At these sites age structures showed distinct age classes representing pulses of recruitment following the date of fire scars (Figure 2). Ten additional fires were identified by a combination of age classes and off-site fire-scar dates (Table 1). The main fire years across all sites were 1823, 1836 and 1894. In total, age structures and fire scars recorded 21 local fires: four high-severity, 10 moderate-severity and seven low-severity

Table 1 Tree-ring fire-history records for all sites. Fires identified with fire scars are listed by year and followed by the sample size for fire scars (fs); fires identified by cohorts coincident with fire scars at other sites are listed by the decade

Inferred fire severity				
Site	High	Moderate	Low	Total
C11	1890s	–	–	–
C35	1820s	–	–	–
C4	1830s	1894 (fs = 2)	–	2
P17	1830s	1894 (fs = 2)	–	2
P22	–	1894 (fs = 2) 1836 (fs = 1)	–	2
P3	–	1830s 1890s	–	2
P20	–	1830s	1890s 1903 (fs = 2)	2*
P31	–	1823 (fs = 1)	1894 (fs = 2)	2
C38	–	1823 (fs = 3)	1890s	2
P7	–	1830s	1894 (fs = 2)	2
C32	–	–	1836 (fs = 1)	1
WP	–	–	1826 (fs = 1)	1
Total	4	10	6*	20

*Due to the proximity of the two low-severity fires at P20, they are interpreted as one event in 1894 for comparisons with charcoal records.

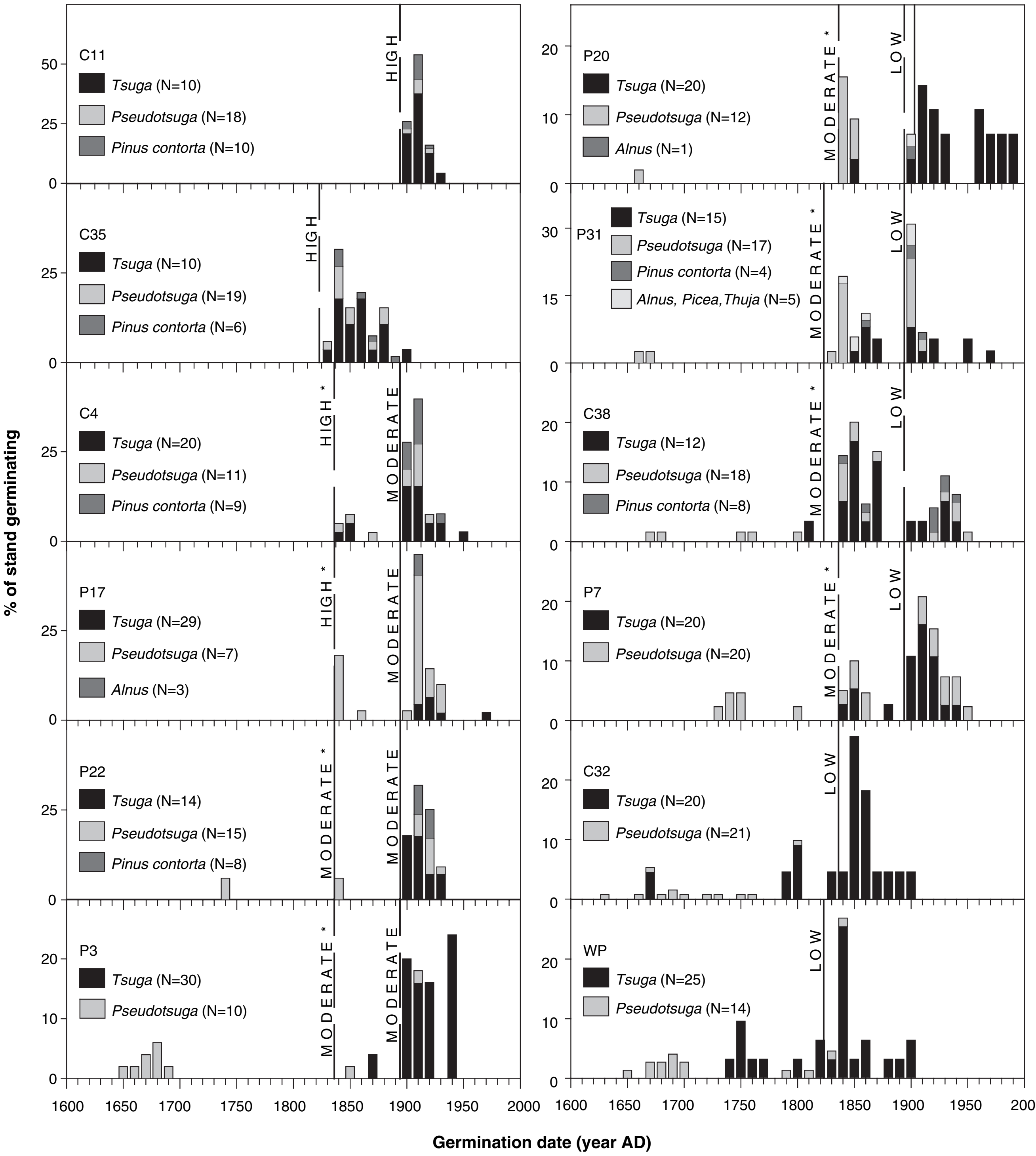

Figure 2 Age-class distributions of trees 55 m around each hollow used to infer fire history, with sample size for each species noted in each legend. Solid vertical lines represent on-site fire scars, and dashed vertical lines represent cohort-inferred fires that match fire-scar dates at other sites. Inferred fire severity is noted for each fire. An asterisk indicates a fire where severity classification is biased towards higher severities because of a more recent fire at that site; see methods for details. Sites are ordered from the upper left to the bottom right from high- to low-severity fires.

(Table 1; Figure 2). The 1894 and 1903 fires at P20 are interpreted as only one event in 1894 due to their close proximity in time, bringing the total number of fires analysed to 20 (Table 1). Eight sites recorded two fires, separated by 58–71 years, and moderate-severity fires occurred only at these sites.

Spatial patterns of tree ages frequently showed that trees surviving the most recent fire were unevenly distributed across the 1.25 ha sampling area (Higuera, 2002). For example, at sites P3 and P17 all trees surviving the 1894 fire were located within the southwestern and eastern half of the site, respectively (Figure 3). This suggests that although the 1894 fire was classified as moderate severity at this site, because more than 25% of the stand survived the fire, contiguous patches within the sampling area may have burned with higher or lower fire severity.

Sediment chronologies

^{210}Pb chronologies at most sites indicate 6–8 cm of sediment accumulation over the past 100 years (average rate 0.10 cm/yr; max 1.03 cm/yr at site C35; min 0.02 cm/yr at site

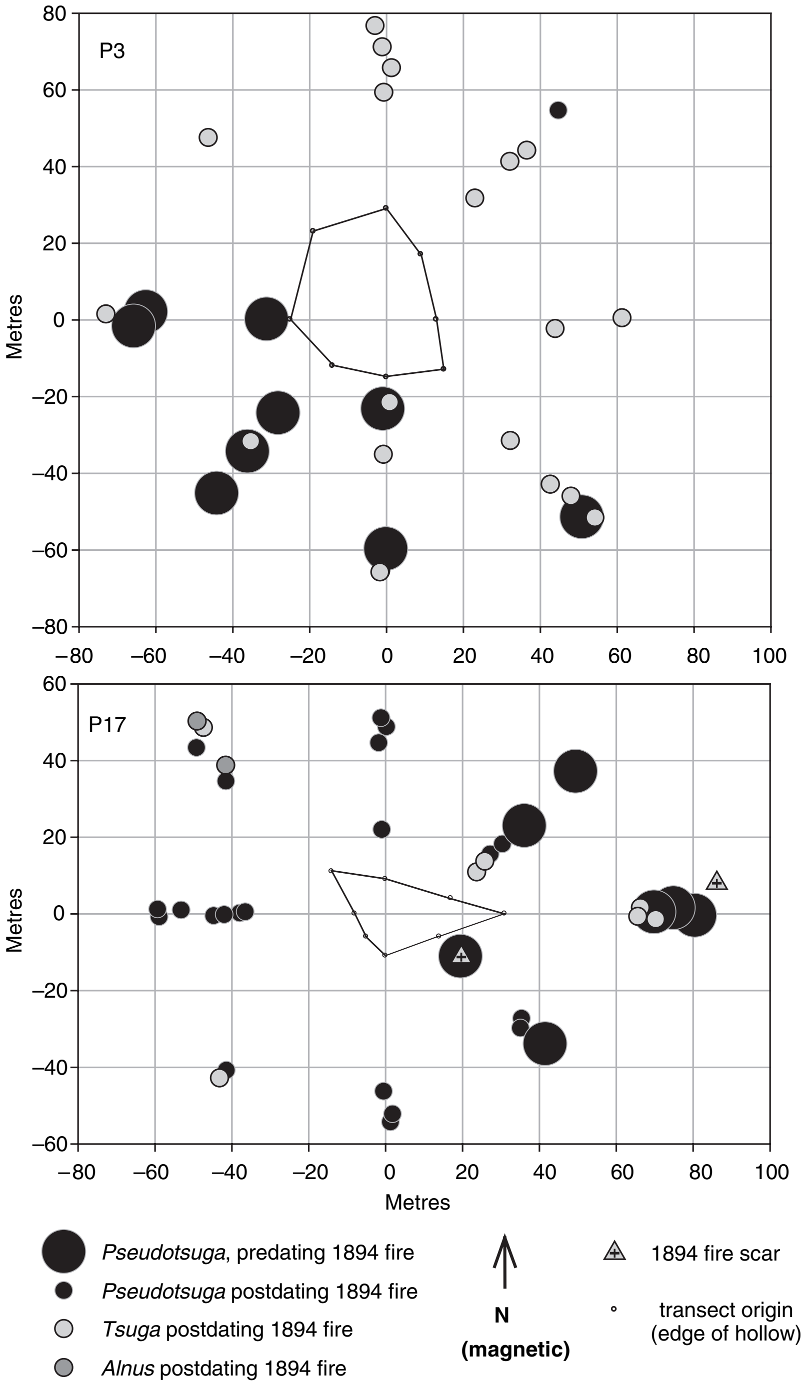

Figure 3 Map of transect origins and trees sampled for ages and fire scars at sites P3 and P17. The heterogeneous spatial pattern of Douglas-fir trees predating the 1894 fire suggests that this fire burned with higher severity on the northeastern and western half of sites P3 and P17, respectively.

C38; Figure 4). Error estimates of ^{210}Pb dates before 1900 vary widely (3 to >100 years) as a function of the standard deviation of original ^{210}Pb measurements. Standard deviations increase with depth because they are inversely related to ^{210}Pb content. Differences in total ^{210}Pb in different cores explain the large difference in standard deviations among sites.

With the exception of site C38, ^{210}Pb dating accuracy was high enough to distinguish sediment levels corresponding to the 1890s from the 1820–30s. At site C38 the estimated standard deviation at 7 cm was approximately 60 years, indicating that this depth could correspond to a date from 1834 to 1954.

Charcoal records

Charcoal accumulation was dominated by charcoal in the 0.15–0.50 mm size class, which typically accounted for more than 90% of charcoal pieces in each sample. Charcoal accumulation rates (CHARs) from the 0.15–0.50 mm and 0.5–50 mm size classes were highly correlated ($r^2_{\text{all sites combined}} = 0.72$, $p \ll 0.01$, $n = 738$) and exhibited nearly identical temporal patterns (Figure 5).

The highest detection rates were achieved using the pooled size class (0.15–0.50 mm+0.50–50 mm). Optimal threshold values for charcoal peak identification were between 1.63 and 1.75 times the median CHAR of a given record. Using thresholds below 1.63 resulted in a considerable increase in

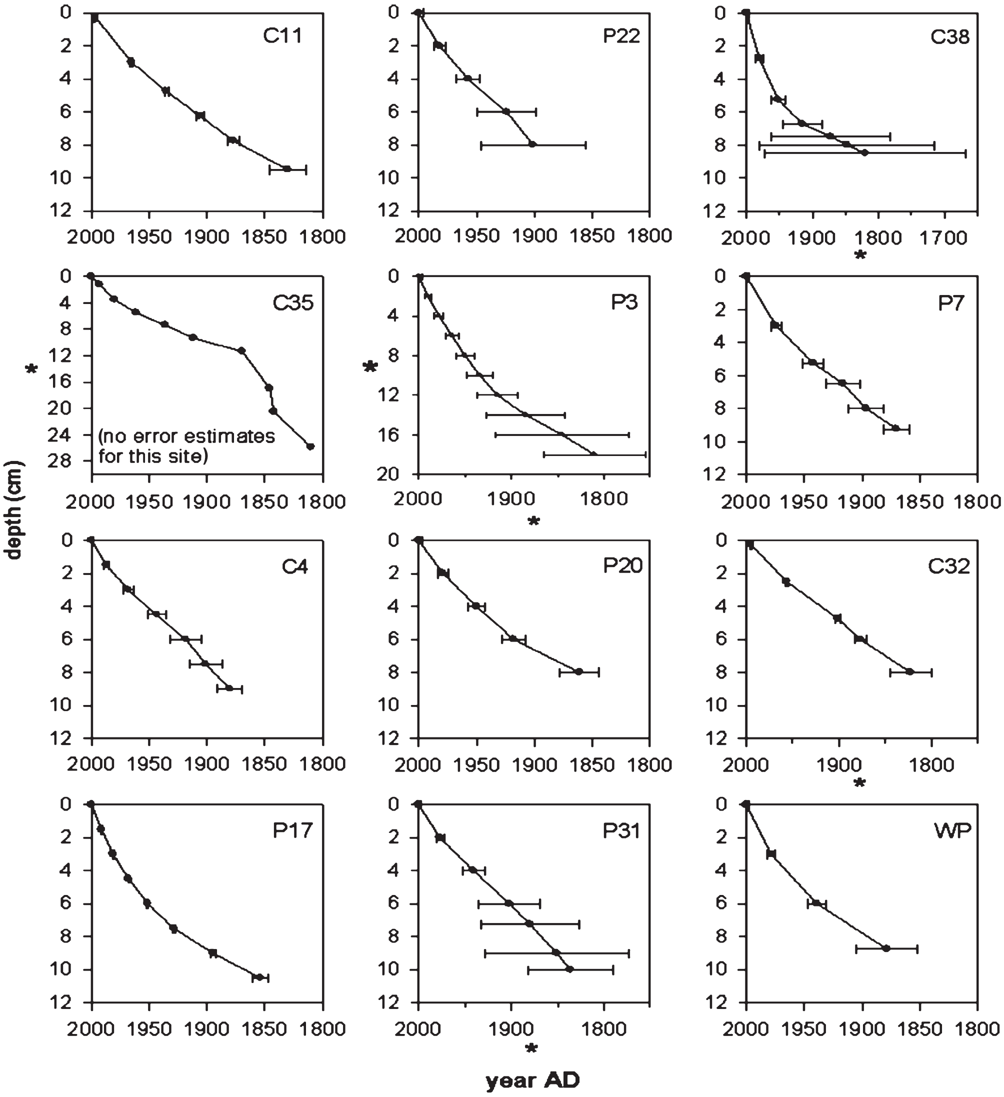

Figure 4 ^{210}Pb chronologies for all sites with one standard deviation indicated by error bars. * Note different scales on these axes. Error estimates for site C35 were not possible due to the high sediment accumulation rate at the bottom of this core.

false positives without increasing the number of true fires detected (Figure 6a). Thresholds above 1.75 resulted in decreased detection, particularly of low- and moderate-severity fires; detection rates for high-severity fires were robust for thresholds up to 3.25 (Figure 6b). Using a threshold of 1.75, the overall detection rate was 0.60. However, detection rates varied among high-, moderate- and low-severity fires (1.00, 0.50 and 0.50, respectively; Table 2). Six of the eight undetected fires occurred at sites with two fires (P3, P31, P17, C4, C38). Two charcoal peaks did not correspond to fires documented by tree-ring evidence (one at C32 and one at C38; Figure 5), yielding a false-positive rate of 0.14 (Table 3). Charcoal peaks using the pooled size class typically spanned 1–5 cm of sediment depth, corresponding to 10–119 years (average = 41, standard deviation = 34 years), and on average the maximum CHAR was reached 13 years after the tree-ring inferred fire date (standard deviation = 16 years; Figure 5).

The results for the 0.15–0.50 mm size class were virtually identical to those for the pooled data (0.15–50 mm) and will not be discussed further (Tables 2 and 3). For the 0.5–50 mm size class, optimum threshold values were between 1.88 and 2.5 times the median CHAR of a given record (Figure 7a), higher than with the pooled size class. Using a threshold in this range, the overall detection rate was the same as with the pooled size class (0.60). However, the detection rates for fires of varying severity differed: 1.0, 0.67 and 0.20 for high-, moderate- and low-severity fires, respectively (Figure 7b; Table 2). The most important difference between the 0.5–50 mm size class and the pooled size class was in the false-positive rate: the false-positive rate for the 0.5–50 mm analysis was 0.27, almost double the 0.14 observed in the pooled analysis (Table 3).

The magnitude of CHAR peaks varied widely among sites, from <10 to >300 pieces$\cdot$cm$^{-2}\cdot$year^{-1} at C11 and C35, respectively (Figure 5). Although high-severity fires always produced distinct CHAR peaks, low- and moderate-severity fires often produced CHAR peaks as large as those produced by high-severity fires (Figure 5). This variability in charcoal deposition between fire severity classes eliminated any predictable relationship between charcoal peak magnitude and fire severity (Higuera, 2002).

Discussion

Reconstructing fire regimes using sediment charcoal records requires an understanding of their accuracy and precision: how well does a record detect fires, what biases does a record have, and how often does a record lead to false conclusions about past fires? By quantifying the correspondence of our small-hollow and tree-ring records of fires in terms of detection and false-positive rates, our results provide answers to these questions for some Douglas-fir–western hemlock–lodgepole pine forests in northwestern Washington, USA. This study also adds to a small but growing pool of empirical data that helps improve interpretations of all sediment-charcoal records.

Two methodological issues must be considered when interpreting the sediment and tree-ring records from this study. First, interpreting fire severity from tree age structures involves assumptions of tree survival and prefire tree densities that make boundaries between severity classes inherently ambiguous (Morrison and Swanson, 1990; Agee, 1993). While the distinction between low- and high-severity fires is accurate, some fires in the moderate-severity class may have been more similar to low- or high-severity fires. Also, at sites with two fires, the severity of the earliest fire could be overestimated due to mortality caused by the more recent fire. However, because tree diameter is a major factor influencing fire survival (Agee, 1993), trees large enough to survive one fire should survive a fire of similar severity ≈ 60–70 years later. In our data set this potential but minor source of error applies to five moderate- and two high-severity fires.

A second methodological issue is the potential errors in ^{210}Pb dating that may be inherent to dating small-hollow sediments. For example, the drying of small-hollow sediments in summer months may facilitate downcore movement of ^{210}Pb, which would lead to an underestimation of age at any given depth (Robert Flett, personal communication). This process may explain why site C32 does not detect an 1836 fire yet contains a distinct charcoal peak in the 1890s, when no fire occurred there (i.e., a false positive); downward movement of ^{210}Pb at this site could lead to an erroneously young date for a charcoal peak that actually corresponded to the 1836 fire. Because a site 400 m away (C11) burned in the 1890s, it is just as reasonable to interpret this false positive as a result of extralocal charcoal production (>55 m from the hollow).

Our overall interpretations should be robust to few or minor dating errors, given the analysis of 20 fires across 12 sites. As our study is one of the first to use ^{210}Pb methods to date small-hollow sediments, further research is needed to address the likelihood of potential errors in these sedimentary environments.

Detecting fire occurrence and severity

Our study suggests that high-severity fires consistently leave distinct evidence in small hollow charcoal records, while moderate- and low-severity fires leave inconsistent evidence. These results are in agreement with conceptual models of charcoal analysis, which emphasize the importance of charcoal production and transport processes in determining the amount of charcoal reaching a sedimentary basin (Patterson *et al.* 1987; Clark, 1988; MacDonald *et al.*, 1991; Whitlock and Anderson, 2003). For a given set of weather conditions the amount of charcoal deposited at a sampling point will increase as charcoal production increases and the distance to a fire decreases. In this context, it is easy to understand why high-severity fires would consistently produce detectable peaks in nearby small hollows. First, high-severity fires consume more vegetation (Agee, 1993; Sandberg *et al.*, 2002) and produce more charcoal than lower severity fires (Pitkänen *et al.*, 1999). Secondly, since we define high-severity fires as those that leave no surviving trees, they burn all or nearly all the area near a hollow. The distance from the edge of the fire to the centre of the hollow, therefore, is inevitably short, increasing the probability of significant charcoal deposition. Finally, high-severity fires are more likely to occur in association with high winds and large updrafts (Turco *et al.*, 1983; Agee, 1993; Sandberg *et al.*, 2002), which would also lead to more widespread charcoal deposition across a landscape (Clark, 1988).

Moderate- and low-severity fires produced less consistent signals than high-severity fires. Differences in charcoal production seem unlikely to account for much of this inconsistency: if charcoal production were the main factor determining deposition in small hollows, then one would expect moderate- and low-severity fires to produce smaller peaks than high-severity fires. However, while some moderate- and low-severity fires produced small peaks or none at all, others produce peaks larger than those left by some high-severity fires ($> \times 10$ the background level; see Figure 5). It seems more likely that the variation in peak height is due to controls over charcoal transport, specifically the distance between the fire and the hollow. Fires in our study area, as in many western North American forests, burn with high spatial heterogeneity, resulting in intermixed patches of low, moderate and high fire severity (Morrison and Swanson, 1990; Agee, 1993). Some burn patches might stop well short of the hollow boundary (e.g., sites P3 and P17, Figure 3), while others might reach the edge of, or even burn over, the hollow. Coupled with relatively short transport distances due to weaker winds and less buoyant smoke plumes (Sandberg *et al.*, 2002), the patchy spatial patterns of low- and moderate-severity fires could easily explain the observed variations in peak heights. Undoubtedly, there are more variables at play, such as fuel loads, topography and wind, but our records suggest that fire heterogeneity is an important variable determining if a fire is detected in sediment-charcoal records.

Our fire-detection rates add empirical support to interpretations made by Niklasson *et al.* (2002), who suggest that charcoal records from small hollows can 'easily overlook mild fires'. However, we had a substantially higher detection rate for low- and moderate-severity fires than Niklasson *et al.* did (50% verses 8%, respectively), possibly for two reasons. First, these studies took place in forests with fundamentally different fire regimes. Niklasson *et al.* (2002) believe that most fires in their tree-ring records were small, of low severity, and set by humans. This contrasts to the low-severity fires that burned in our study area, which we know were part of a larger complex of fires that burned with variable severity and with high spatial heterogeneity. It is likely that the fires in the Niklasson *et al.* (2002) study were on the low end of the (theoretical) spectrum of low-severity fires, whereas the low-severity fires in our study included a broader portion of this spectrum and eventually merged into moderate-severity fires. Secondly, we used a much larger sample size for charcoal analysis (3 cm^3 of sediment per sample verses 0.2–0.4 cm^3 in the Niklasson *et al.* study) and found charcoal throughout the records, making it unlikely that undetected fires were a consequence of insufficient sampling. While we also conclude that small hollows are biased against detecting lower-severity fires, our results suggest that in some systems roughly half of these fires can still produce detectable charcoal peaks in small-hollow sediments.

Detecting fire timing

Inferred fire dates differed among tree-ring and charcoal records. Most charcoal peaks spanned 20–30 years and fell within two decades of the fire date assigned by tree rings, with a tendency for charcoal peaks to lag the fire date (Figure 5). For example, the apex of the charcoal peak representing the 1890s fire at site C11 was 36 years after the fire date, and the charcoal peak associated with the 1830s moderate-severity fire at site C38 occurred in the 1850s. Some error is expected

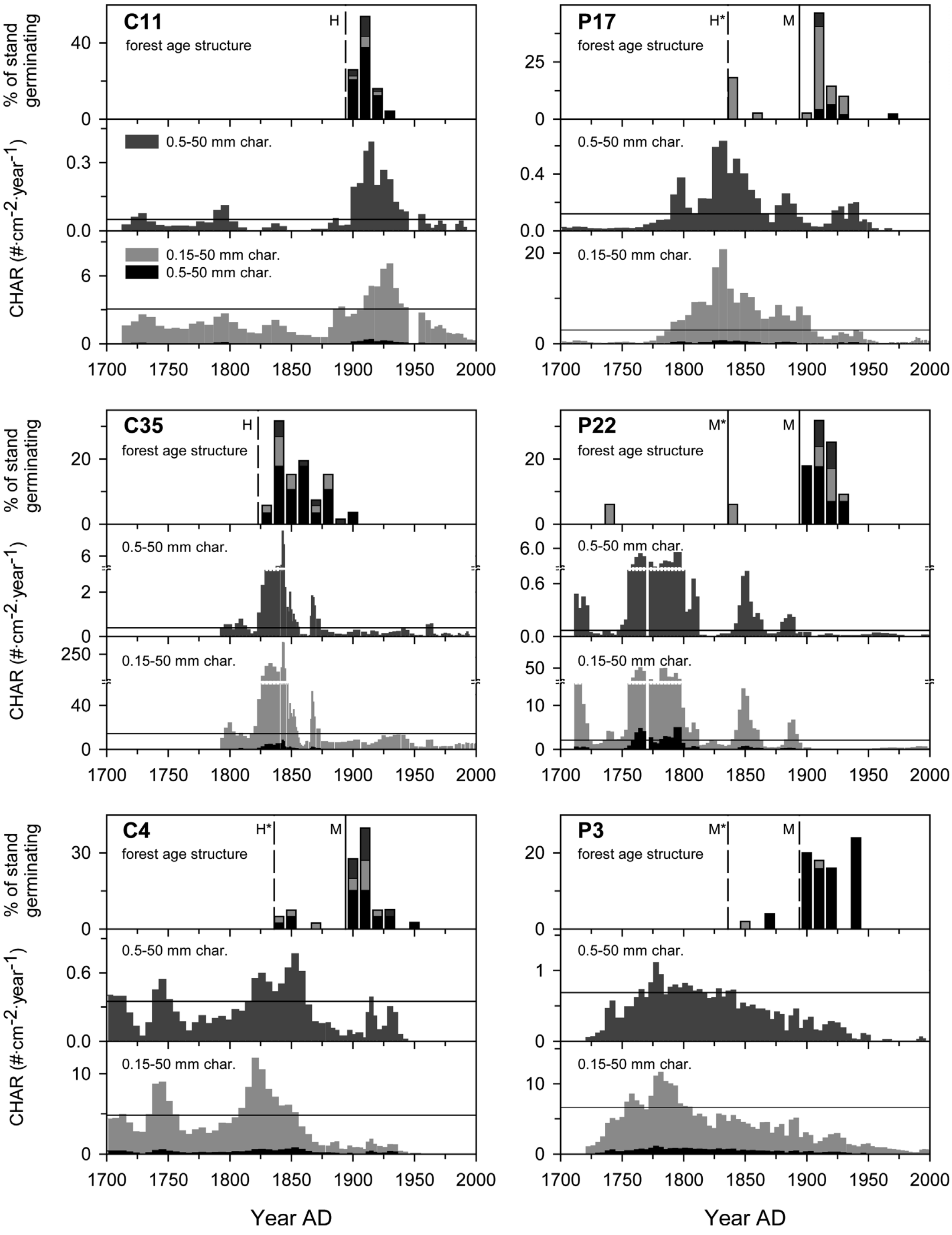

Figure 5 Age-class distributions, inferred fire timing and severity, and charcoal accumulation rates (CHARs) for all sites. The upper panel for each site is the modern age structure of trees 55 m around each hollow, with details described in Figure 2. The middle panel for each site is the CHARs for the 0.50–50 mm size class. The lower panel for each site is the CHARs for the pooled size classes: 0.15–0.50 mm size class (dark grey bars); 0.50–50 mm size class (black bars, very small values). The threshold values for peak identification in the CHAR records are represented by horizontal lines. Sites are ordered from the upper left to the bottom right from high- to low-severity fires.

because of the varying accuracies of dating methods. Fire dates based on fire scars should have annual resolution while decadal resolution is more likely for those based on age structures. In contrast, ^{210}Pb chronologies could be inaccurate by several decades.

Taphonomic processes also affected the ability to infer precise fire dates from our records. Sediment mixing certainly occurred and may partially explain the multidecade breadth of charcoal peaks. However, mixing does not account for a temporal lag in peaks, because mixing alone would keep sediments centred on the fire date. Secondary charcoal input in lake sediments may last several decades after a fire (Whitlock and Millspaugh, 1996; Gavin *et al.*, 2003), and this could occur in small hollows as well. The temporal lags observed in this study, however, may also result from depositional processes unique to small hollows. For example, the smaller basin area of small hollows results in a larger probability of large charcoal pieces reaching its centre. When large charcoal pieces (> 5 mm diameter) fall directly on a hollow during a fire, they contribute mass to an area above the surface of the hollow. As material accumulates around these charcoal pieces, they are surrounded by younger sediments, creating a stratigraphy in which the charcoal peak lags the actual fire date by several millimetres (or several years to decades).

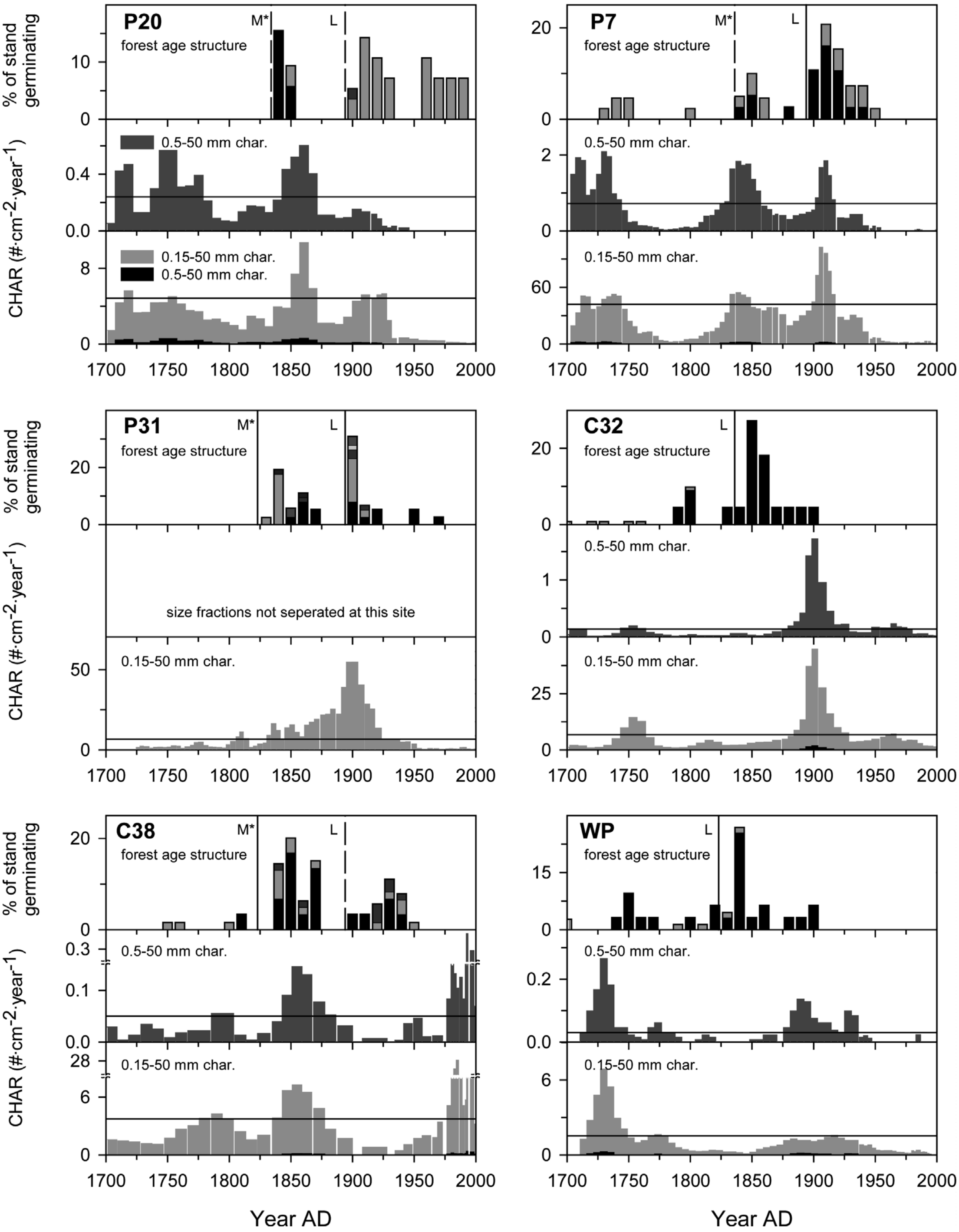

Figure 5 (*Continued*)

False inferences of fire

Charcoal peaks in the absence of local fire were rare in our records, giving us confidence that most charcoal peaks represent fires. The false positives that did occur may have resulted from several processes, including transport of charcoal from distant fires due to strong winds (Clark, 1988; Gardner and Whitlock, 2001) and secondary charcoal input. Strong winds may explain a false positive identified at site C32 in the 1890s (Figure 5), because, although there was no tree-ring evidence for fire within 55 m of the hollow, fires were burning with high severity ≤400 m away (e.g., at site C11, Figure 2). However, the absence of a peak earlier in the C32 record, when tree-ring evidence indicates a low-severity fire, makes a precise interpretation difficult. As a mechanism for causing false positives, secondary charcoal transport may be more important in small hollows than in lakes because hollows have a larger perimeter to surface area ratio; i.e., a greater proportion of the hollow is close to or overhung by trees that could easily contribute charcoal to the hollow surface long after a fire event. We suspect this process created the false positive at site C38, because we are very confident this site has not burned since the turn of the twentieth century (Figure 2; personal observation).

Tradeoffs with charcoal size classes

While each charcoal size class correctly identified the same number of fires (Table 2), the 0.50–50 mm size class displayed more charcoal peaks in the absence of fires (i.e., false positives; Table 3). The low frequency of 0.50–50 mm charcoal relative to 0.15–0.50 mm charcoal results in fewer particles counted for

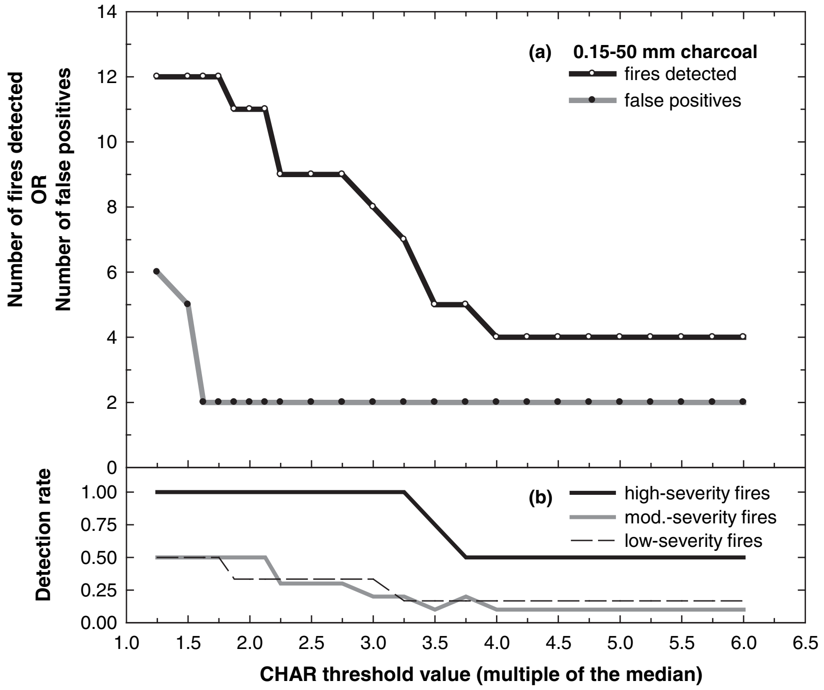

Figure 6 (a) Total number of fires detected and false positives as a function of the threshold value used for charcoal peak identification for the pooled size class (0.15–0.50 mm + 0.50–50 mm size classes). Optimum threshold values, which maximize the number of fires detected while minimizing the number of false positives, are between 1.63 and 1.75. (b) Detection rates stratified by fire severity illustrate the different sensitivities of each fire-severity class to a varying range of thresholds.

the 0.50–50 mm size class. This leads to higher variability in counts when equal volumes of sediment are analysed (see also Whitlock and Millspaugh, 1996). The high variability associated with small charcoal counts increases the probability that random factors will create a peak in the absence of fire. Like Ohlson and Tryterud (2000) we frequently found charcoal > 0.50 mm associated with fire. However, our finding of high false-positive rates in the 0.50–50 mm size class suggests that their conclusion that 'the occurrence of charcoal particles ≥ 0.50 mm in forest soils is a solid and reliable evidence for local fire...' does not hold as well for small-hollow sediments. By reducing the probability of false positives, the analysis of all charcoal > 0.15 mm wide, on a per volume basis, produced more accurate records of past fire occurrence than the analysis of charcoal > 0.50 mm wide.

Conclusions

Our study has several important implications for reconstructing fire regimes with small-hollow sediments. First, our results indicate that small hollows accurately record high-severity fires

Table 2 Contingency table for tree-ring–charcoal relationships for fires from AD 1800–2000

Inferred fire severity	Tree-ring fire	Charcoal peak presence/absence (+/−)			Fire detection rates		
		0.15–0.5 mm	0.5–50 mm	0.15–50 mm	0.15–0.5 mm	0.5–50 mm	0.15–50 mm
High	P17	+	+	+	1.0	1.0	1.0
	C4	+	+	+			
	C11	+	+	+			
	C35	+	+	+			
Moderate	P7	+	+	+	0.56*	0.67*	0.50
	P20	+	+	+			
	P22 (1)	+	+	+			
	P22 (2)	+	+	+			
	C38	+	+	+			
	P3 (1)	−	−	−			
	P3 (2)	−	−	−			
	P17	−	+	−			
	P31	NA*	NA*	−			
	C4	−	−	−			
Low	P7	+	+	+	0.40*	0.20*	0.50
	P20	+	+	+			
	P31	NA*	NA*	+			
	C32	−	−	−			
	C38	−	−	−			
	WP	−	−	−			

*Site P31 is not included in the 0.15–0.5 mm and 0.5–50 mm analysis because size classes were not separated at this site.

Table 3 False-positive rates for each size class analysed. The false-positive rate is the number of charcoal peaks identified not corresponding to tree-ring dated fires, divided by the total number of peaks identified

Charcoal size class analysed	No. of peaks identified	No. of false positives	False-positive rate*
0.15–0.5 mm	13	2	0.15
0.5–50 mm	15	4	0.27
0.15–50 mm	14	2	0.14

*For the 0.15–0.5 mm and the 0.5–50 mm analysis, only 11 sites were used, automatically reducing the number of peaks identified by one.

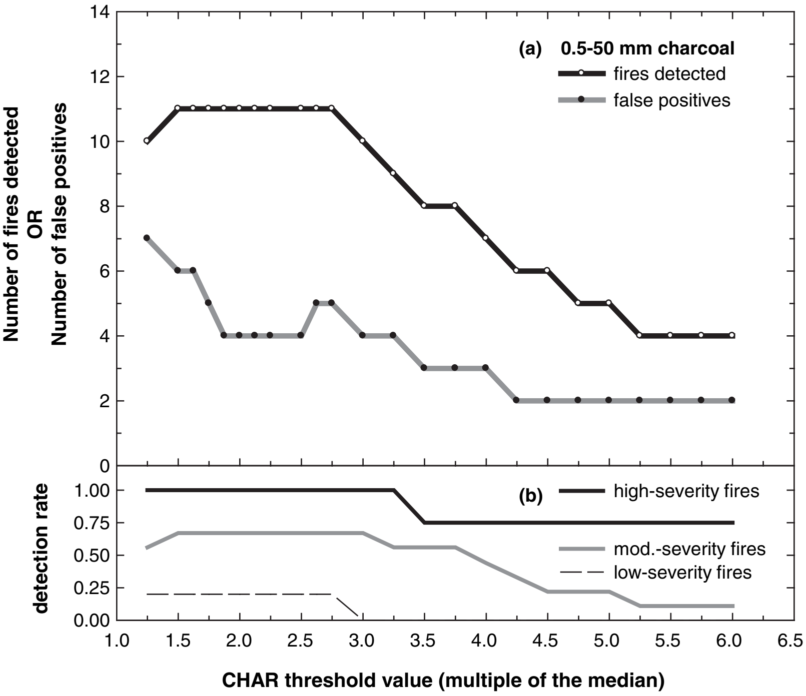

Figure 7 Same information as displayed in Figure 6, but for charcoal from the 0.50–50 mm size class. Optimum threshold values are between 1.88 and 2.50. See Figure 6 for details.

but miss many moderate- and low-severity fires. Secondly, the pattern of this bias suggests that detecting a fire in a sediment record may depend strongly on fine-scale spatial patterns of burning. When fires burn in patches of varying severities, small fires of low severity may or may not be detected, depending on their proximity to the hollow and the proportion of the surrounding landscape affected. Thirdly, slow sediment accumulation, sediment mixing and secondary charcoal input in small hollows limit the possibility of detecting individual fires closely spaced in time (e.g., < 60–70 years in this study).

Our overall results call into question the use of thresholds for identifying individual fires in mixed-severity fire regimes. While we can predict that most high-severity fires and approximately half of the lower-severity fires would be detected in a sediment record, it is not possible to determine the number of fires that actually occurred, or the proportion of high-, moderate- and low-severity fires. While our results are specific to small hollows, many of the mechanisms we identify as important controls of fire detection also apply to charcoal records from lake sediments. It is likely that detection rates in all sediment charcoal records vary with fire size, severity and proximity. Given the limitations we identify, small hollow charcoal records would be most useful in forests where fires are large and intense and fire frequency is low (e.g., high-severity fire regimes; see Agee, 1998). In these systems, one can capitalize on the accuracies of small-hollow charcoal records to generate long-term records of fire history unattainable by other means.

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References

Agee, J.K. 1993: *Fire ecology of Pacific Northwest forests.* Washington, DC: Island Press.

—— 1998: The landscape ecology of western forest fire regimes. *Northwest Science* 72, 24–34.

Barrett, S.W. and **Arno, S.F.** 1988: Increment-borer methods for determining fire history in coniferous forests. USDA Forest Service General Technical Report, INT-244.

Binford, M.W. 1990: Calculation and uncertainty analysis of ^{210}Pb dates for PIRLA project lake sediment cores. *Journal of Paleolimnology* 3, 253–67.

Björkman, J. and **Bradshaw, R.** 1996: The immigration of *Fagus sylvatica* L. and *Picea abies* (L.) Karst. into a natural forest stand in southern Sweden during the last 2000 years. *Journal of Biogeography* 23, 235–44.

Blackford, J.J. 2000: Charcoal fragments in surface samples following a fire and the implications for interpretation of subfossil charcoal data. *Palaeogeography, Palaeoclimatology, Palaeoecology* 164, 33–42.

Bradshaw, R.H.W. 1988: Spatially-precise studies of forest dynamics. In Huntley, B. and Webb, T. III, editors, *Vegetation history*, Dordrecht: Kluwer, 725–51.

Bradshaw, R.H.W., Tolonen, K. and **Tolonen, M.** 1997: Holocene records of fire from the boreal and temperate zones of Europe. In Clark, J.S. Cachier, H., Goldammer, J.G. and Stocks, B.J., editors, *Sediment records of biomass burning and global change*, New York: Springer, 347–65.

Calcote, R. 1995: Pollen source area and pollen productivity: evidence from forest hollows. *Journal of Ecology* 83, 591–602.

—— 1998: Identifying forest stand types using pollen from forest hollows. *The Holocene* 8, 423–32.

Camp, A., Oliver, C., Hessburg, P. and **Everett, R.** 1997: Predicting late-successional fire refugia pre-dating European settlement in the Wenatchee Mountains. *Forest Ecology and Management* 95, 63–77.

Carcaillet, C., Bergeron, Y., Richard, P.J.H., Fréchette, B., Gauthier, S. and **Prairie, Y.T.** 2001a: Change of fire frequency in the eastern Canadian boreal forests during the Holocene: does vegetation composition of climate trigger the fire regime? *Journal of Ecology* 89, 930–46.

Carcaillet, C., Bouvier, M., Fréchette, B., Larouche, A.C. and **Richard, P.J.H.** 2001b: Comparison of pollen-slide and sieving methods in lacustrine charcoal analyses for local and regional fire history. *The Holocene* 11, 467–76.

Chen, Y. 1988: Pollen source and distribution in a forest hollow in Sylvania, Michigan, USA. *Pollen et Spores* 30, 95–110.

Clark, J.S. 1988: Particle motion and the theory of charcoal analysis: source area, transport, deposition, and sampling. *Quaternary Research* 20, 67–80.

—— 1990: Fire and climate change during the last 750 yr in northwestern Minnesota. *Ecological Monographs* 60, 135–59.

Clark, J.S. and **Patterson, W.A.** 1997: Background and local charcoal in sediments: scales of fire evidence in the paleorecord. In Clark, J.S., Cachier, H., Goldammer, J.G., and Stocks, B.J., editors, *Sediment records of biomass burning and global change*, New York: Springer, 23–48.

Clark, J.S. and **Royall, P.D.** 1995: Particle-size evidence for source areas of charcoal accumulation in late Holocene sediments of Eastern North American Lakes. *Quaternary Research* 43, 80–89.

—— 1996: Local and regional sediment charcoal evidence for fire regimes in presettlement north-eastern North America. *Journal of Ecology* 84, 365–82.

Clark, J.S., Lynch, J., Stocks, B. and **Goldammer, J.G.** 1998: Relationships between charcoal particles in air and sediments in west-central Siberia. *The Holocene* 8, 19–29.

Clark, J.S., Royall, P.D. and **Chumbley, C.** 1996: The role of fire during climate change in an eastern deciduous forest at Devil's Bathtub, New York. *Ecology* 77, 2148–66.

Davis, M.B., Calcote, R.R., Sugita, S. and **Takahara, H.** 1998: Patchy invasion and the origin of a hemlock-hardwoods forest mosaic. *Ecology* 79, 2641–59.

Foster, D.R. and **Zebryk, T.M.** 1993: Long-term vegetation dynamics and disturbance history of a *Tsuga*-dominated forest in New England. *Ecology* 74, 982–98.

Franklin, J.F. and **Dyrness, C.T.** 1988: *Natural vegetation of Oregon and Washington*. Corvallis: Oregon State University Press.

Fujikawa, W.Y. 2002: A 7600-year vegetation and fire history of Mt Constitution, Orcas Island, Washington. USA. MS thesis, University of Washington, Seattle.

Gardner, J.J. and **Whitlock, C.** 2001: Charcoal accumulation following a recent fire in the Cascade Range, northwestern USA, and its relevance for fire-history studies. *The Holocene* 11, 541–49.

Gavin, D.G. 2000: Holocene fire history of a coastal temperate rainforest, Vancouver Island, British Columbia, Canada. PhD dissertation, University of Washington, Seattle.

Gavin, D.G., Brubaker, L.B. and **Lertzman, K.P.** 2003: An 1800-year record of the spatial and temporal distribution of fire from the west coast of Vancouver Island, Canada. *Canadian Journal of Forest Research* 33, 573–86.

Hannon, G.E., Bradshaw, R. and **Emborg, J.** 2000: 6000 years of forest dynamics in Suserup Skov, a seminatural Danish woodland. *Global Ecology and Biogeography* 9, 101–14.

Heide, K. 1984: Holocene pollen stratigraphy from a lake and small hollow in north-central Wisconsin, USA. *Palynology* 8, 3–20.

Heyerdahl, E.K., Brubaker, L.B. and **Agee, J.K.** 2001: Spatial controls of historical fire regimes: a multiscale example from the interior west, USA. *Ecology* 82, 660–78.

Higuera, P.E. 2002: Reconstructing fire regimes with charcoal and pollen from small hollows: a calibration with tree-ring records of fire. MS thesis, University of Washington, Seattle.

Holmes, R. 1998: Dendrochronological Program Library, version 3.0. Laboratory of Tree-ring Research, University of Arizona, Tucson.

Jackson, S.T. and **Wong, A.** 1994: Using forest patchiness to determine pollen source areas of closed-canopy pollen assemblages. *Journal of Ecology* 82, 89–99.

Johnson, E.A., Miyanishi, K. and **Kleb, H.** 1994: The hazards of interpretation of static age structures as shown by stand reconstructions in a *Pinus contorta-Picea engelmannii* forest. *Journal of Ecology* 82, 923–31.

Laird, L.D. and **Campbell, I.D.** 2000: High resolution palaeofie signals from Christina Lake, Alberta: a comparison of the charcoal signals extracted by two different methods. *Palaeogeography, Palaeoclimatology, Palaeoecology* 164, 111–23.

Long, C.J., Whitlock, C., Bartlein, P.J. and **Millspaugh, S.H.** 1998: A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study. *Canadian Journal of Forest Research* 28, 774–87.

Lynch, J.A., Clark, J.S., Bigelow, N.H. and **Edwards, M.E.** 2003: Geographic and temporal variations in fire history in boreal ecosystems of Alaska. *Journal of Geophysical Research* 108, 1–17.

MacDonald, G.M., Larsen, C.P.S., Szeica, J.M. and **Moser, K.A.** 1991: The reconstruction of boreal forest fire history from lake sediments: a comparison of charcoal, pollen, sedimentological, and geochemical indices. *Quaternary Science Reviews* 10, 53–71.

McLachlan, J.S., Foster, D.R. and **Menalled, F.** 2000: Anthropogenic ties to late-successional structure and composition in four New England hemlock stands. *Ecology* 81, 717–33.

Millspaugh, S.H. and **Whitlock, C.** 1995: A 750-year fire history based on lake sediment records in central Yellowstone National Park, USA. *The Holocene* 5, 283–92.

Morrison, P.H. and **Swanson, F.J.** 1990: *Fire history and pattern in a Cascade Range landscape.* USDA Forest Service General Technical Report PNW-GTR-254. Portland, Oregon: Pacific Northwest Research Station.

Niklasson, M., Lindbladh, M. and **Björkman, L.** 2002: A long-term record of *Quercus* decline, logging, and fires in a southern Swedish *Fagus-Picea* forest. *Journal of Vegetation Science* 13, 765–74.

Ohlson, M. and **Tryterud, E.** 2000: Interpretation of the charcoal record in forest soils: forest fires and their production and deposition of macroscopic charcoal. *The Holocene* 10, 519–25.

Oldfield, F. and **Appleby, P.G.** 1984: Empirical testing of ^{210}Pb models for lake sediments. In Hanworth, E.Y. and Lunds, J.W.G., editors, *Lake sediments and environmental history: studies in paleolimnology and palaeoecology in honour of Winifred Tutin*, Minneapolis: University of Minnesota Press, 93–124.

Parshall, T. 1999: Documenting forest stand invasion: fossil stomata and pollen in forest hollows. *Canadian Journal of Botany* 77, 1529–38.

Parshall, T. and **Calcote, R.** 2001: Effect of pollen from regional vegetation on stand-scale forest reconstruction. *The Holocene* 11, 81–87.

Patterson, W.A., Edwards, K.J. and **Maguire, D.J.** 1987: Microscopic charcoal as a fossil indicator of fire. *Quaternary Science Reviews* 6, 3–23.

Pitkänen, A., Lehtonen, H. and **Huttunen, P.** 1999: Comparison of sedimentary microscopic charcoal particle records in a small lake with dendrochronological data: evidence for the local origin of microscopic charcoal produced by forest fires of low intensity in eastern Finland. *The Holocene* 9, 559–67.

Rhodes, A.N. 1998: A method for the preparation and quantification of microscopic charcoal from terrestrial and lacustrine sediment cores. *The Holocene* 8, 113–17.

Sandberg, D.V., Ottmar, R.D., Peterson, J.L. and **Core, J.** 2002. *Wildland fire in ecosystems: effects of fire on air.* USDA Forest Service General Technical Report. RMRS-GTR-42-vol. 5. Odgen, UT: Rocky Mountain Research Station.

Stokes, M.A. and **Smiley, T.L.** 1968: *Tree-ring dating* Chicago: University of Chicago Press.

Sugita, S. 1994: Pollen representation of vegetation in Quaternary sediments: theory and method in patchy vegetation. *Journal of Ecology* 82, 881–97.

Taylor, A.H. and **Skinner, C.N.** 2003: Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. *Ecology* 13, 704–19.

Tinner, W., Conedera, M., Ammann, B., Gäggeler, H., Gedye, S., Jones, R. and **Sägesser, B.** 1998: Pollen and charcoal in lake sediments compared with historically documented forest fires in southern Switzerland since AD 1920. *The Holocene* 8, 31–42.

Tryterud, E. 2003: Forest fire history in Norway: from fire-disturbed pine forests to fire-free spruce forests. *Ecography* 26, 161–70.

Turco, R.P., Toon, O.B., Ackerman, T.P., Pollack, J.B. and **Sagan, C.** 1983: Nuclear winter: Global consequences of multiple nuclear explosions. *Science* 222, 1283–92.

Villalba, R. and **Veblen, T.T.** 1997: Improving estimates of total tree ages based on increment core samples. *Ecoscience* 4, 534–42.

Whitlock, C. and **Anderson, R.S.** 2003: Fire history reconstructions based on sediment records from lakes and wetlands. In Veblen, T.T., Baker, W.L., Montenegro, G., and Swetman, T., editors, *Fire and climatic change in temperate ecosystems of the western Americas*, New York: Springer, 3–31.

Whitlock, C. and **Millspaugh, S.H.** 1996: Testing the assumptions of fire-history studies: an examination of modern charcoal accumulation in Yellowstone National Park, USA. *The Holocene* 6, 7–15.

Yamaguchi, D.K. 1990: A simple method for cross-dating increment cores from living trees. *Canadian Journal of Forest Research* 21, 414–16.