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Soil and sedimentary charcoal evidence for Holocene forest fires in an inland temperate rainforest, east-central British Columbia, Canada

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Abstract: Accelerator radiocarbon dating of 147 charcoal samples recovered from colluvial and alluvial fan deposits at 29 sites was used to reconstruct the Holocene fire history of an inland temperate rainforest watershed in east-central British Columbia (BC), Canada. Radiocarbon dates ranged from 182 to 9558 cal. yr BP, with prominent peaks in the probability distribution of calibrated dates at *c*. 7100, 3900, 2300, 1600 and 250–1000 cal. yr BP. The inferred median fire return interval (FRI) was 800–1200 cal. yr, depending on the extent of inbuilt age errors resulting from charring of wood pre-dating actual fire ages. This FRI is likely an overestimate, as less severe events may not have created sufficient erosion and slope instability to preserve a record of charcoal in buried soils and slope deposits. Median time since fire was 467 cal. yr based on ages of the uppermost charcoal found at each site, but the severity of heart-rots in the dominant redcedars (*Thuja plicata* Donn ex D. Don) prevented independent confirmation of stand ages by dendrochronology. Sites with multiple charcoal-containing layers having similar radiocarbon ages can be explained with reference to contemporary post-fire mass-wasting processes. Peaks in fire-related sedimentation probability coincided broadly with periods of higher fire frequency *c*. 600–1000, 1300–2400 and 3500–4500 cal. yr BP inferred from sedimentary charcoal records at subalpine sites in southwestern BC. Correspondence with fire records from more distant sites in northwestern North America was less clear.

Key words: Fire, soil charcoal, radiocarbon dating, temperate rainforest, colluvium, alluvial fans, Holocene, British Columbia, Canada.

Introduction

Recent interest in the management and conservation of coastal temperate rainforests in northwestern North America (Schoonmaker *et al.*, 1997) has stimulated research on the biodiversity, palaeoecology, and natural disturbance regimes of this region (Lawford *et al.*, 1996; Lertzman *et al.*, 1996; Brown and Hebda, 2002; Gavin *et al.*, 2003a,b; Newmaster *et al.*, 2003). Approximately 500 km inland, a much less-studied rainforest type occurs at low elevations on the windward slopes of the Columbia and Rocky Mountains (51°–54°N) and corresponds to the northern wetter and cooler subzones of the Interior Cedar-Hemlock (ICH) biogeoclimatic zone of British Columbia (BC), Canada (Ketcheson *et al.*, 1991) (Figure 1). This inland rainforest shares the dominant tree species of western redcedar (*Thuja plicata* Donn ex D. Don) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) with its coastal counterpart, but occurs in a globally rare climatic

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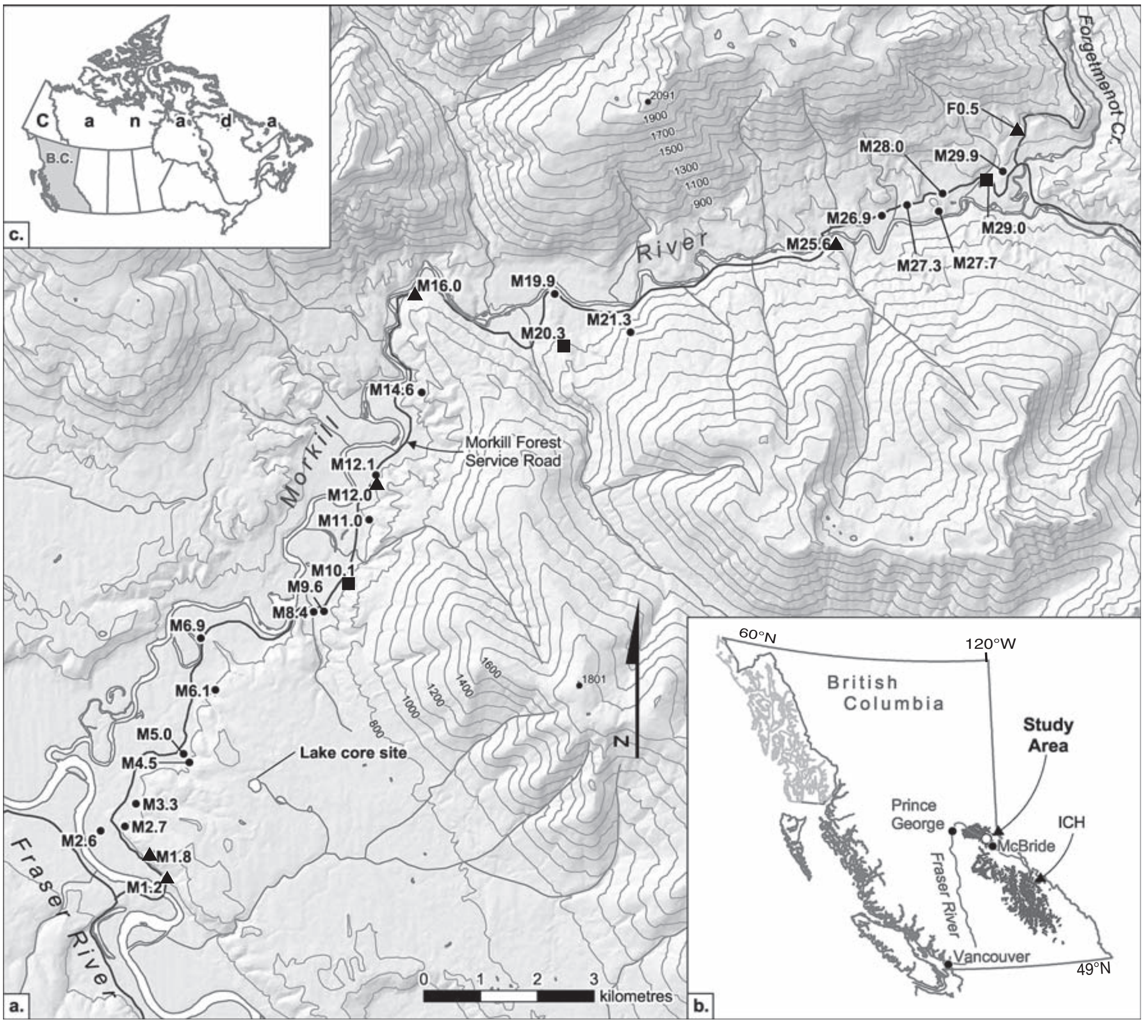

Figure 1 Locations of soil charcoal sampling sites in (a) the Morkill River valley in relation to (b) the inland rainforest portion (shaded) of the Interior Cedar-Hemlock (ICH) zone in (c) British Columbia, Canada. Site locations were designated by km distance along the Morkill (M) or Forgetmenot (F) access roads, with spot elevations and contours in m above sea level (100 m contour interval). Deposit types at each sampling site are indicated: colluvial toeslope, solid circles; fan, solid triangles; slide, earthflow or debris flow lobe, solid squares

combination of continentality and humidity (Arsenault and Goward, 2000).

Stand-initiating fires in the ICH have return intervals of at least 250 years (BC Ministry of Forests, 1995), but there is likely much spatial variability in fire regimes in complex mountainous landscapes. The inland rainforests are likely more susceptible to fire, wind, insects and avalanches than their coastal counterparts, resulting in a smaller proportion of stands in the oldest age-classes. The most ancient stands are restricted to topographically protected sites where trees may be over 800 years old (Arsenault, 1998; Arsenault and Goward, 2000). Research on natural disturbance processes in the BC inland rainforest has been hampered by the limited utility of dendrochronology. Western redcedars are usually the largest trees in these forests, but virtually all boles older than 200 years contain extensive heartwood decay (Buckland, 1946) and usually have only a thin outer shell of sound wood.

Other palaeoenvironmental evidence of disturbance history is lacking, with no published studies of pollen and charcoal in lake sediments from the inland rainforest in east-central BC. In coastal BC and the western USA, radiocarbon dating of charcoal preserved in soils and surficial deposits has provided important insights into Holocene fire regimes and their geomorphic consequences, but this technique has not been used in interior BC. In Yellowstone National Park, USA, Meyer *et al.* (1992, 1995) used dated charcoal and observations of modern post-fire processes (Meyer and Wells, 1997) to reconstruct the Holocene history of fire-related sedimentation on alluvial fans. Links were suggested between these local geomorphic processes and regional and hemispheric climatic changes, with reduced fire activity during cooler periods (Meyer and Pierce, 2003). This approach was extended to the lower-elevation ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Lawson) forests of central Idaho, where alluvial fan deposits recorded fire-related sedimentation events of varying severity (Meyer and Pierce, 2003).

In wet low-elevation and subalpine forests of coastal BC, radiocarbon dating of soil charcoal has been used to estimate the time since the last fire, as well as fire return intervals (Lertzman *et al.*, 2002; Gavin *et al.*, 2003a,b; Hallett *et al.*, 2003). Geomorphically stable sites were sought in order to avoid age versus depth inversions in successive charcoal dates (Hallett *et al.*, 2003), but charcoal can be also redistributed within soils by faunal burrowing, treethrow and freeze-thaw action (Carcaillet, 2001). Radiocarbon dating of soil charcoal enables site-specific investigations of fire history (Carcaillet, 1998) and soil disturbance frequency (Gavin, 2003).

These studies documented the long fire return intervals in BC coastal forests, identified landform and climatic controls on fire activity and refined soil charcoal research methods. In particular, Gavin (2001) recognized the inherent problem of 'inbuilt ages' resulting from charring of woody material considerably older than the actual time since fire. This limitation is important in ecosystems with long-lived trees and abundant coarse woody debris, as in both coastal and inland rainforests in BC (Feller, 2003). For a Vancouver Island coastal rainforest, Gavin (2001) compared stand ages, estimated by dendrochronology, with soil charcoal radiocarbon dates, and found inbuilt ages of 30–610 years (95% confidence interval) that usually placed the actual fire date outside the 2 σ confidence interval of the calibrated date.

We present evidence from radiocarbon-dated soil charcoal that fire has been an important Holocene geomorphic influence in a watershed in the heart of the inland rainforest of east-central BC.We first report on local geomorphic controls of charcoal deposition and preservation, and then compare the reconstructed history of fire activity with results from elsewhere in western North America, in relation to broader Holocene climatic changes.

Study area

This study focuses on the Morkill River watershed in the wet, cool variant (ICHwk3) of the ICH biogeoclimatic zone (Meidinger *et al.*, 1988) in the upper Fraser River watershed (Figure 1). Mean annual precipitation for this area is 1006 mm and mean annual temperature is +3.1°C, with May–September mean values of 402 mm and +10.8°C, respectively (Meidinger *et al.*, 1988). Except for riparian areas dominated by hybrid white spruce (*Picea engelmannii* × *glauca*) and black cottonwood (*Populus balsamifera* ssp. *trichocarpa* (T. & G.) Brayshaw), this moist climate supports dense redcedar-hemlock forests in the lower 30 km of the Morkill River valley between 700 and 1350 m elevation. Redcedars often exceed 1 m in diameter in the remaining old-growth stands, but heart-rots are present in virtually all boles, making dendrochronological methods impractical for estimating stand ages. Although Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) is long-lived and has more complete ring sequences than other ICH tree species, it occurs too sporadically to be useful in estimating stand ages in this area.

During deglaciation, meltwater lakes occupied the lower Morkill River valley, depositing clayey to sandy sediments that remain as dissected terraces between 800 and 1300 m elevation (Froese, 1998; Froese and Cruden, 2001). A basal radiocarbon date of 10 830 cal. yr BP (AA46035) from a small lake on the lowest glaciolacustrine terrace (Figure 1) provides a minimum age for drainage of the final meltwater lake phase. Deep gullying of the steep (up to 70°) 50–150 m high glaciolacustrine terrace scarps has built numerous alluvial fans on the Holocene terraces of the Morkill River. These scarps have been further modified by landslides that originate as shallow (< 1 m deep) earth slides after disruption of the forest root mat (Froese and Cruden, 2001). On silty materials, these failures can be enlarged by earth flows that deliver repeated sediment pulses to alluvial fans via gullies (Froese and Cruden, 2001). Thus, the toeslopes of the glaciolacustrine terrace scarps consist of a 5–35° apron of interfingering colluvial and alluvial fan deposits.

Methods

Given the importance of the forest root mat in preventing slope instability and erosion, we hypothesized that infrequent severe forest fires were the major trigger of toeslope aggradation in the lower Morkill River watershed during the Holocene. Our approach was to combine observations of contemporary post-fire slope processes with a systematic search for datable evidence of fire-related sedimentation. We also conducted a reconnaissance of five road-accessible ICH watersheds within 40 km of our main study area, between the Morkill-Fraser River confluence and the village of McBride (53°18′N, 120°10′W; Figure 1).

Few suitable exposures were available in the lower Morkill River valley, so sampling relied primarily on manually excavated pits. At 0.5–1.0 km intervals, we initially augered (1 m depth) to identify potential sampling sites at the base of the glaciolacustrine terrace scarps. We used the presence of visible charcoal-containing layers or buried soils with charred forest floor organic horizons to determine whether a full excavation was warranted. We excavated and augered until we encountered (1) glaciolacustrine or fluvial deposits that did not appear to have been reworked by slope processes, (2) a water-table, or (3) at least a 1 m thickness of sediment lacking visible charcoal concentrations. Local site characteristics (slope, aspect, landform) were described, and soil profiles and the stratigraphy of surficial deposits were measured and photographed. We used colour aerial photographs, a helicopter flight and ground observations to examine two areas of active post-fire erosion on glaciolacustrine sediments in the Morkill River watershed.

We did not use physical separation methods (eg, sieving or flotation) to extract charcoal from bulk soil or sediment, but relied on field recognition of obvious charcoal-bearing horizons or sedimentary layers. Charcoal was sampled from (1) forest floor organic horizons, usually at the contact with mineral soil, (2) recognizable buried soil horizons, and (3) discrete black layers (~ 1–10 cm thick) with visible concentrations of charcoal within the mineral soil. Charcoal obtained from (2) and (3) could be either *in situ* or sedimentary, and may include material reworked from older deposits. Soil horizons were usually weakly expressed on the depositional landforms where we sampled, so there was often no reliable basis for distinguishing (2) and (3). Multiple charcoal particles, usually less than 0.5 mm diameter, were hand-picked from each sample and oven-dried (30°C), with root detritus removed prior to radiocarbon dating by accelerator mass spectrometry (AMS). We used the conventional acid-alkali-acid cleaning procedure, which usually caused disintegration of the charcoal particles, resulting in each sample being a blended mixture of finer particles. After pretreatment, charcoal fragments were combusted in the presence of CuO to CO_2, which was reduced to graphite for AMS dating. We performed the AMS measurements and calculated the results as described by Donahue *et al.* (1990) and Jull *et al.* (2003).

Radiocarbon dates were converted to calendar years BP (cal. yr BP) with Calib 4.4 (Stuiver *et al.*, 1998) and the probability density function plotted separately for the forest floor and mineral soil samples. Where a central-point estimate of a calibrated age was needed, median values were used in preference to the intercept method (Telford *et al.*, 2004). At each site, fire return intervals (FRI) were estimated from the calendar year intervals between successive calibrated ages in order of increasing depth (cf. Lertzman *et al.*, 2002). Where an age versus depth inversion was encountered, the resulting negative interval was not included. All interval data for the Morkill study area were pooled and the median fire return interval was estimated. Time since fire (TSF) was estimated from the uppermost dated sample at each site.

Results

Modern post-fire slope processes

Except for slope failures related to active gullying or stream channel migration, almost all unvegetated landslides were associated with major disruptions of vegetation cover by logging, road construction or fires. At two sites examined in detail, slope instability and erosion occurred within a decade of partial or complete destruction of forest stands by fire.

At the M 12.1 site, a 1989 escape of a post-logging prescribed fire killed standing trees on the adjacent glaciolacustrine terrace scarp. The 1995 aerial photographs indicated the dead standing trees on the scarp, but an unvegetated failure surface was not visible. By 2001, an expanding shallow (< 2 m) earth slide had formed, with active displacement of trees and surface soil from the retreating headwall at the top of the steep (40°) failure surface (Figure 2a). Rill erosion had created small gullies up to 1 m deep, contributing to sediment transport from the exposed failure surface. Blocks of surface soil 1–2 m in diameter and up to 1 m thick, held together by the surface root mat, were accumulating at the base of the slide (Figure 2b), coming to rest in all possible orientations including completely inverted. Approximately 50 m laterally and downslope from this accumulation, there was a transition from colluvial deposits to a zone of recent alluvial deposition on a more gently sloping (5–10°) fan, with 25–50 cm of sandy sediments accumulated on the apparent pre-1989 forest floor (Figure 2c). Revegetation occurs rapidly in this moist climate, and by early summer 2004 all but the steepest portions of the failure scar were colonized by seedlings of wind-dispersed broadleaf shrubs and trees, especially willow (*Salix* spp.) and black cottonwood.

The 1992 Cush Fire burned ICH and higher-elevation subalpine forests on and above the glaciolacustrine terraces immediately east of the confluence of Forgetmenot Creek and the Morkill River. Part of the burned area was salvage-logged, but a June 2002 helicopter flight revealed shallow, unvegetated earth slides (Cruden and Varnes, 1996) on steep glaciolacustrine terrace scarps throughout the burned area (Figure 3). These failures were not evident in 1995 1:10 000 scale colour aerial photographs, and their locations appeared unrelated to roads and logging trails.

Site characteristics

Approximately 75% of the 147 dated charcoal samples were obtained from colluvial deposits at the base of terrace scarps. Nineteen of the 29 sampling sites were at the base of 15–40° scarps with no associated gully system upslope, and contained multiple buried soil horizons and laterally discontinuous (< 1 m long, 1–5 cm thick) layers enriched in charcoal and soil organic matter (Figure 4). Although Podzolic soils (Soil Classification Working Group, 1998) predominate on loamy and sandy parent materials in the Morkill River valley, and have strongly contrasting light grey eluvial horizons overlying reddish brown illuvial horizons, buried soils in colluvium may have this horizon sequence inverted, (eg, site M28.0). Three sites were located at the toes of lobe-shaped deposits below a bowl-shaped failure scar, and charcoal was usually found in 1–3 cm thick laterally discontinuous bands throughout the slump deposit rather than in obvious buried soil horizons.

Seven sites were on alluvial fans, identified by slopes usually ranging from 5 to 15° and the presence of active or abandoned channels connected to a gully in the glaciolacustrine terrace. Charcoal-bearing horizons tended to be more laterally continuous than in colluvium, at least over the 1–2 m wide excavated exposures (Figure 5). Charcoal was found in apparently *in situ* burned forest floors of buried soil profiles

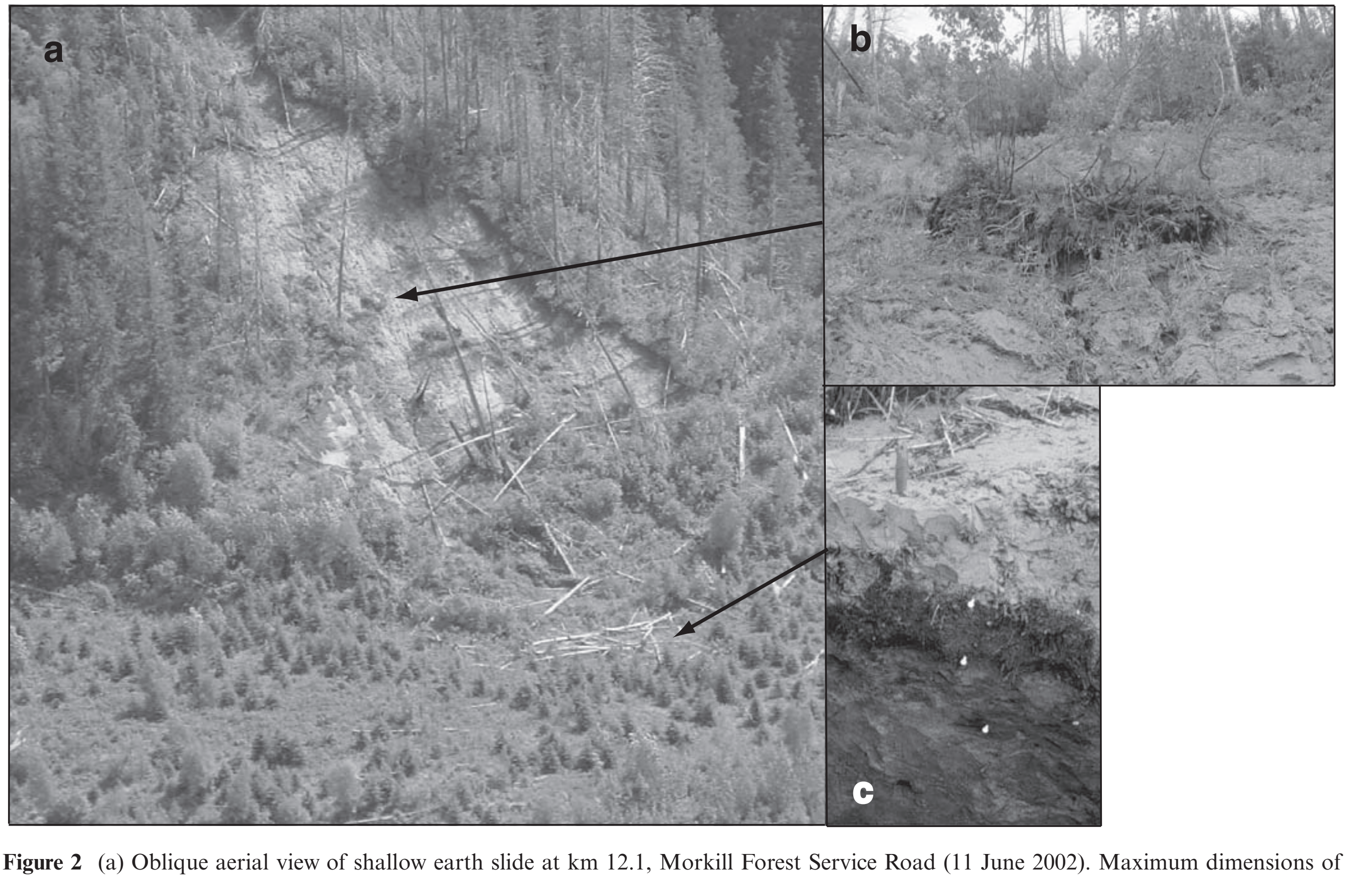

Figure 2 (a) Oblique aerial view of shallow earth slide at km 12.1, Morkill Forest Service Road (11 June 2002). Maximum dimensions of unvegetated slide scar are 75 m × 48 m. (b) Detail of root mat and surface soil block (50 cm thick). (c) Detail of water-transported sand on buried soil profile (knife handle is 10 cm long)

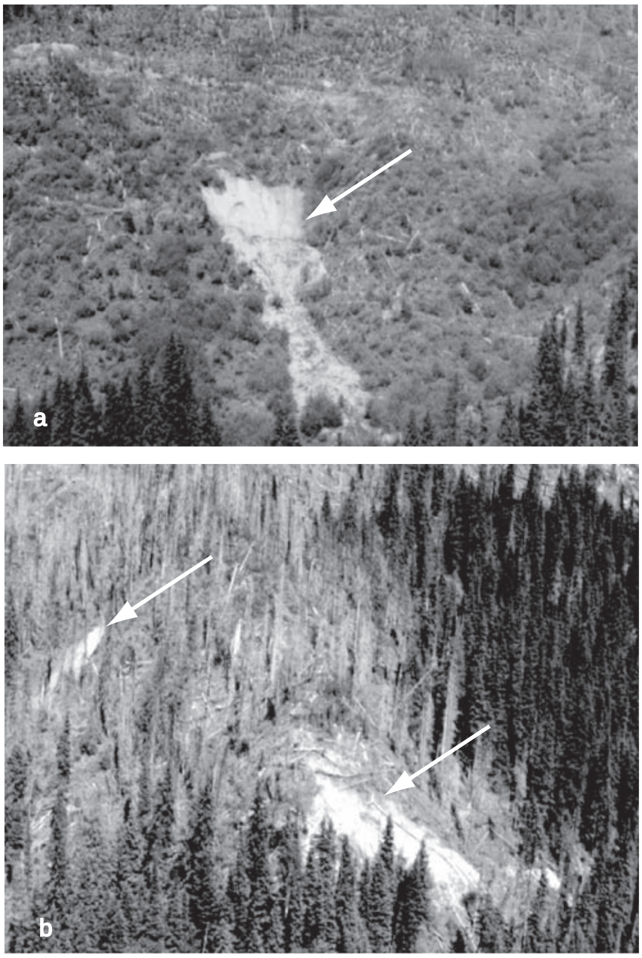

Figure 3 Shallow earth slides (arrowed) in (a) salvaged and (b) unsalvaged portions of 1992 Cush fire (11 June 2002) (scale is provided by 20–25 m mature trees)

and disseminated through poorly sorted silty diamictons. We made multiple auger probes of virtually every accessible alluvial fan in the lower Morkill River valley and found much more buried charcoal than in the colluvial deposits.

The fan and colluvial deposits consisted predominantly of silts and fine sands, with little gravel. The uppermost portions of the soil profiles usually displayed only limited morphological development of eluvial and illuvial horizons. Surface or buried profiles with well-expressed Podzolic morphologies (Soil Classification Working Group, 1998) were usually associated with sandier textures. Where morphologically distinct B horizons were present, typical Munsell colour hues were 10YR and 7.5YR. At two sites (M 1.8 and M 2.6), more reddish hues (5YR) in surface or buried soil horizons (*c*. 2–10 cm thick) occurred immediately below pronounced accumulations of charcoal. Such features have been interpreted as fire-reddening (Dormaar and Lutwick, 1975), but appear to be produced only under heavy fuel accumulations and are uncommon even after severe forest fires (Meyer *et al.* 1995).

The abundant buried charcoal in the lower Morkill River valley contrasts strongly with its much sparser occurrence in the five other ICH watersheds that we examined. The highly erodible glaciolacustrine deposits typical of the Morkill River valley were largely absent from these watersheds, and the colluvium and alluvial fan deposits on their lower valley slopes were derived from coarser-textured morainal deposits. Despite careful inspection and excavation of roadcuts along almost 30 km of access roads, we obtained only 11 samples of charcoal from buried soils and associated sediments.

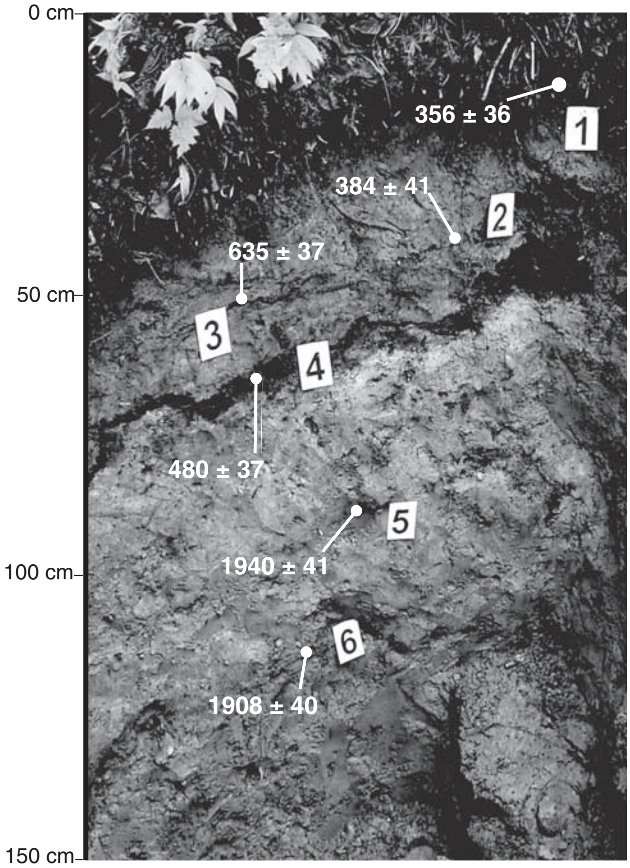

Figure 4 Colluvial deposit at the base of 32° terrace scarp, km 8.4, Morkill Forest Service Road, with radiocarbon ages of charcoal samples (^{14}C yr BP). Tags indicate sample numbers

Distribution of radiocarbon dates

In five other ICH watersheds, the 11 soil charcoal radiocarbon dates ranged from almost modern to 8283 cal. yr BP (Table 1). This range almost equals that of the much larger data set from the Morkill River valley, where the 147 dates (up to 15 per site) ranged from 182 to 9558 cal. yr BP, from depths ranging from the forest floor to 495 cm (Table 2; Figure 6). Only 20 dates were older than 6000 cal. yr BP, likely reflecting a lower probability of preservation and discovery of older charcoal.

Samples from adjacent sites on the same landform revealed the spatial variability of the soil charcoal record. For example, at site F 0.5, three conspicuous 2240–2775 cal. yr BP charcoal-bearing layers were absent from a second excavation 50 m away downslope where the two buried charcoal layers dated at 383 and 9558 cal. yr BP. Adjacent sites may also have clusters of dates that are broadly similar, but with considerable differences in the number of obvious charcoal-bearing layers. For example, sites M 4.5 and M 5.0 are located 200 m apart on the same colluvial toeslope, but M 5.0 had more than twice as many datable charcoal layers in the 2000–7000 cal. yr BP interval. Inversions in age-depth relationships were also common in both alluvial fan and colluvial deposits. For example, at M 1.8 most charcoal ages increased with depth to a maximum of 9099 cal. yr BP, but the remaining dates below 4 m depth were younger and in a much narrower range (Table 2; Figure 5).

Adjacent sites on different landforms also displayed differing age versus depth patterns. At site M 12.1, a 3 m deep excavation at the base of the failing glaciolacustrine terrace scarp revealed a complex sequence of 2 to 10 cm thick bands of charcoal-rich organic material dipping downslope at 15–20°. Apart from young charcoal in the recently buried forest floor at 102–106 cm (467 cal. yr BP), the five deeper charcoal samples

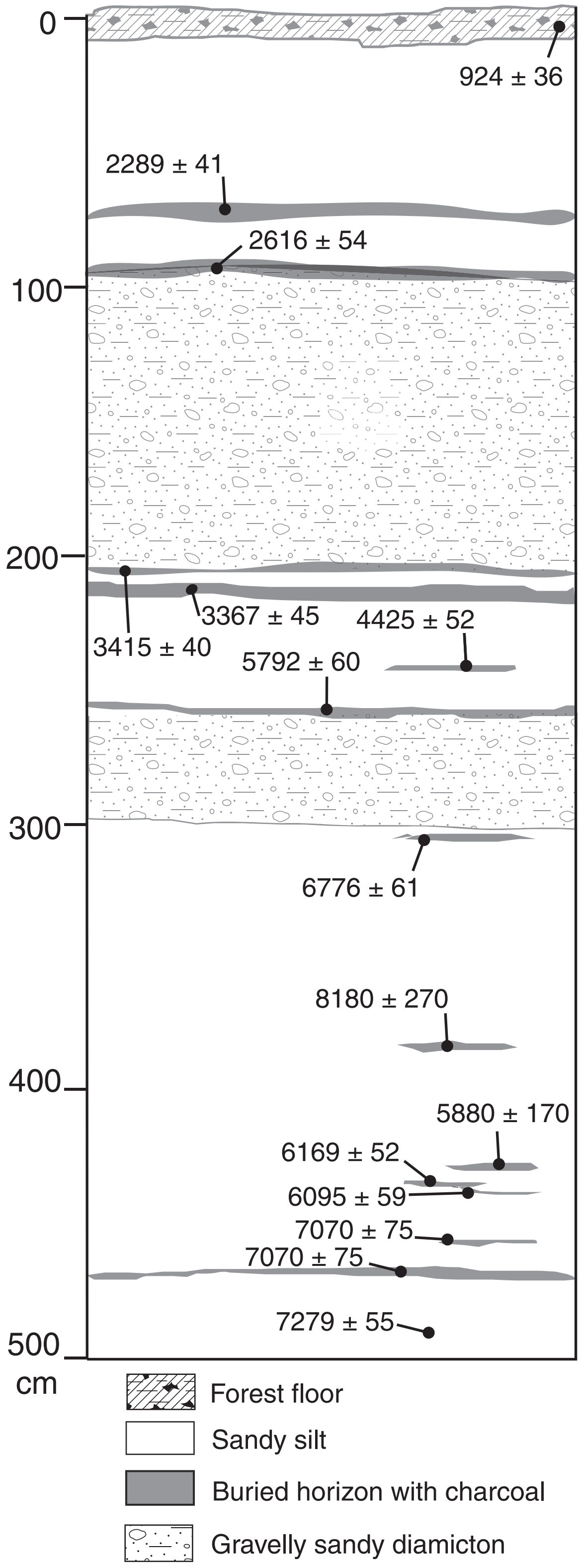

Figure 5 Charcoal radiocarbon dates (^{14}C yr BP) for alluvial fan section at km 1.8, Morkill Forest Service Road

clustered between 3400 and 4700 cal. yr BP, with no clear age–depth relationship. In contrast, in the alluvial fan approximately 100 m to the west (M12.0), the dates of the four charcoal-containing layers increased progressively with depth, and the three deepest samples were in an age range (673–2315 cal. yr BP) unrepresented at M 12.1.

The distribution of mineral soil calibrated dates ($n = 130$) displays a general trend to lower probability earlier in the Holocene (Figure 6a), reflecting a preservation bias common in such records (Meyer *et al*., 1995; Pierce *et al*., 2004). Several prominent peaks occur in the cumulative probability distribution at *c*. 7100, 3900, 2300, 1600 and 250–1000 cal. yr BP. Conspicuous minima occurred at *c*. 7400, 5500, 4800, 2100 and 1300 cal. yr BP. The forest floor charcoal dates ($n = 17$) also show predominant peaks *c*. 250–1000 cal. yr BP, with a lesser peak at *c*. 1800 cal yr BP (Figure 6b).

Time since fire and fire return intervals

The median TSF determined from the uppermost charcoal dates at all 29 sites was 467 cal. yr (range: 182–2834 cal. yr), and the probability distribution indicates that most of our study area had likely experienced forest fire in the past 1000 cal. yr (Figure 6c). A median FRI of 824 cal. yr was obtained for 91 non-inverted intervals. Without dendrochronological evidence for stand age, we did not attempt locally derived adjustments for the inbuilt age error (Gavin, 2001). Based on estimates of the inbuilt age error from coastal rainforests on Vancouver Island, BC, Lertzman *et al*. (2002) used a minimum separation of 300 years to exclude stratigraphically sequential charcoal samples that were likely to have been created by the same fire. For old-growth inland rainforests with similarly large trees and abundant coarse woody debris, this 300-yr restriction provides a reasonable starting point, resulting in 66 intervals with a median FRI value of 1188 cal. yr.

The orientation of the Morkill River and limited access to sites on the north side of the valley did not allow fully representative sampling of all slope aspects, particularly the S and SE aspects in the lower and middle reach of the main valley below Forgetmenot Creek. The FRI and TSF estimates were compared for sites in our data set with the most strongly contrasting aspects: NW–NE vs. SW–SE (Table 3). FRI and TSF values did not differ significantly by aspect ($p = 0.500$ and 0.080, respectively, Kolmogorov-Smirnov two-sample test).

Discussion

Evidence for fire-related erosion and sedimentation

Dates as old as 9558 cal. yr BP from alluvial fans and toeslope colluvium suggest that early Holocene erosion of the thick glaciolacustrine sediments was rapid, but subsequently the terrace remnants would have experienced much slower erosion under intact forest cover. Removal of the surface root mat is critical to initiation of shallow earth slides in these materials (Froese, 1998; Froese and Cruden, 2001), but before the advent of industrial logging, such disruptions would have resulted primarily from stand-destroying forest fires. The juxtaposition of the steep scarps of the highly erodible glaciolacustrine terrace remnants, with the relatively flat Holocene fluvial terraces downslope, created conditions suitable for generating and trapping sediments produced by post-fire erosion and slope instability. This combination of conditions differs considerably from that found in adjacent watersheds where the morainal and colluvial deposits mantling lower valley sides are thinner, less deeply gullied and exhibit gentler slopes. These geomorphic contrasts likely account for the formation and preservation of a soil and sedimentary charcoal record in the lower Morkill River watershed that is much richer than in valleys lacking thick and highly erodible glaciolacustrine deposits.

The abundant buried charcoal in alluvial fans and colluvium suggests a relationship between fire and sedimentation, but does not prove a causal connection. Inferring a fire-induced origin for these charcoal-rich sediments therefore depends heavily on observations of modern processes. At the Cush Fire and M 12.1 sites, shallow landslides occurred within a

Table 1 Accelerator radiocarbon dates for soil charcoal from sites in the Interior Cedar-Hemlock zone, upper Fraser River valley. Calibrated ages expressed as median and 2 σ interval

Site	Latitude/longitude	Lab no.	Sample no.	Depth (cm)	$\delta^{13}C$ (‰)	^{14}C yr BP	Calibrated years BP
Minnow Creek	53°28′N/120°21′W	AA35368	M10-79	12 (forest floor)	−25.2	395±53	417 [315–518]
		AA35369	M10-86	98–100	−22	4735±50	5455 [5324–5586]
East Twin Creek	53°28′N/120°22′W	AA35370	E7-1	15 (forest floor)	−20.7	445±45	435 [325–545]
		AA35371	E7-4	24–25	−25.8	2350±60	2430 [2159–2700]
		AA35372	E7-6	44–53	−25.5	4045±50	4612 [4417–4806]
Goat Station Road	53°30′N/120°37′W	AA39409	Goat Stn -1-FF	(forest floor)	−23.2	580±48	590 [525–655]
		AA39410	Goat Stn -1-2	130	−23.8	7378±60	8190 [8040–8339]
McKale River Road	53°25′N/120°17′W	AA39411	McKale 1.6-1-1	20–22	−25.5	30±39	129 [0–257]
		AA39412	McKale 1.6-1-3	93	−24.2	580±54	590 [522–657]
		AA39413	McKale 1.6-1-4	101–102	−24.5	1224±37	1163 [1063–1262]
West Twin Creek	53°26′N/120°32′W	AA39421	W Twin 3-1-1	75–77	−24.7	7467±57	8283 [8182–8382]

decade after fires, presumably after loss of root strength in the fire-killed stand (Schmidt *et al.*, 2001). Accumulation of root mats and soil blocks at the base of the active failure at M 12.1 provides a plausible mechanism for the formation of multiple buried layers of organic matter-rich soil in the deeper colluvium at this site, likely created by a similar disturbance pre-3500 cal. yr BP. These may represent a single fire-triggered episode of slope instability, with the age–depth inversions between 3426 and 4648 cal. yr BP resulting from colluvial accumulation of charcoal-containing blocks of surface soil.

The contrasting age–depth patterns for the charcoal dates from the adjacent M12.0 and M 12.1 sites may indicate that alluvial fans and toeslope colluvium capture different parts of the post-fire sedimentation record, or reflect the inherent spatial variability in fire impacts on slope stability. These contrasts demonstrate the need for large numbers of dates in reconstructing the history of fire-related erosion and sedimentation, even in study areas that appear ecologically and geomorphically homogeneous.

Elsewhere in western North America, the severity of fire events has been inferred from characteristics of charcoal-containing alluvial fan deposits (Meyer *et al.*, 1995; Pierce *et al.*, 2004). In central Idaho, thick coarse-textured debris-flow units overlying burned soil surfaces were interpreted as the product of more severe fires (Pierce *et al.*, 2004). In our study area, post-fire sedimentation resulted predominantly from shallow earth slides that followed loss of root strength, rather than by debris flows resulting from enhanced runoff, as in the watersheds studied by Meyer *et al.* (1995), Meyer and Wells (1997), and Pierce *et al.* (2004). These differences have important implications for the fire records captured by soil and sedimentary charcoal. The western USA studies sampled charcoal-rich fan deposits and burned forest floors buried by debris flow and flood deposits, but our charcoal samples were obtained primarily from colluvium that incorporated pieces of charred forest floor and associated mineral soil. A single section or soil profile could contain multiple stacked charcoal-containing bands, contributing to a greater abundance of age versus depth reversals than was observed in the western US fan deposits. It is also more difficult to infer fire severity from the colluvial deposits in our study area, since the triggering of post-fire slope failures by loss of root strength could follow stand-destroying fires that differed considerably in their severity.

We did not examine the lateral variability in radiocarbon dates within a single charcoal-bearing horizon. Narrow radiocarbon age ranges were reported for multiple charcoal dates within individual deposits in alluvial fans in Yellowstone (Meyer *et al.*, 1995) and Idaho (Pierce *et al.*, 2004). However, these drier western USA ecosystems lack the abundant coarse woody debris of BC coastal and inland rainforests, making inbuilt ages much less of a limitation for soil and sedimentary charcoal studies. Inbuilt ages can be minimized if charcoal derived from annually produced tissues (eg, leaves, conifer cones) can be dated, but we were unable to identify non-woody detrital components in our charcoal samples. Our dated materials consisted of charred woody fragments or finer charcoal particles concentrated in mineral sediments or in humified remnants of buried forest floors.

Much of the charcoal that we recovered would have originated from charred woody detritus on or in the forest floor. Forest floors in ICH old-growth stands are quite thick (10–15 cm +) and, even in dry summers such as 1998, the humified (H) lower organic horizons remain moist. Even a severe stand-destroying fire is unlikely to remove the forest floor completely, but would consume the uppermost L and F horizons in which recognizable fine detritus, such as conifer needles and cones, is concentrated.

Not all fires would have been sufficiently severe to create a buried charcoal record. At almost 60% of our sites, the uppermost charcoal sample was obtained from surface forest floor organic horizons. In such cases, the absence of overlying sediment suggests that the most recent fire was very localized and did not affect potential sediment sources upslope, or else it did not sufficiently weaken the root mat to trigger failures. The fire history represented by the buried charcoal record consists of events that had a geomorphic influence, by modifying slopes and delivering sediment to gullies and alluvial fans, but likely did not include all events that would have influenced forest age and stand structures.

Time since fire and fire return intervals

Our TSF estimates are consistent with data from the 18 old-growth ICHwk3 stands within 50 km of the Morkill valley (A. Hoggett, University of British Columbia, personal communication, 2003). Single charcoal samples from each of these additional sites had a similar median age (393 cal. yr BP), but a narrower range (64 to 603 cal. yr BP). Although drier and warmer southerly aspects should be more fire-prone, the sedimentation events that preserved this soil charcoal record may have been triggered by fires that were sufficiently severe that aspect had no strong influence on their spatial patterns.

These long fire return intervals are consistent with other evidence for infrequent stand-destroying fires in the northern ICH zone. Elsewhere in the ICHwk3 variant, old-growth stands are over 300 years old, although these ages were estimated from extrapolated ring sequences in the outer shell of sound wood in redcedars (DeLong *et al.*, 2004). Despite these old stand ages, lightning activity is much higher in these inland rainforests than in their coastal counterparts. Light-

Table 2 Accelerator radiocarbon dates for soil charcoal from sites in the Interior Cedar Hemlock zone of the Morkill River valley

Site	Landform/slope/aspect	Lab no.	Sample no.	Depth (cm)	δ^{13}C (‰)	^{14}C years BP	Calibrated years BP
M 1.2	F/7°/SW	AA51075	M 1.2-1	70–72	−23.0	2747±41	2834 [2764–2945]
		AA51076	M 1.2-2	98–99	−22.9	6038±52	6872 [6732–7006]
M 1.8	F/15°/SW	AA46049	M 1.8-FF	0 (forest floor)	−24.2	924±36	848 [743–926]
		AA46050	M 1.8-1	74–76	−25.1	2289±41	2289 [2155–2353]
		AA46051	M 1.8-2	94–96	−24.4	2616±54	2746 [2491–2851]
		AA46052	M 1.8-3	212–215	−25.7	3415±40	3664 [3558–3826]
		AA46053	M 1.8-4	219–225	−24.4	3367±45	3600 [3473–3693]
		AA46054	M 1.8-5	250–252	−24.7	4425±52	5022 [4865–5282]
		AA46055	M 1.8-6	260–262	−27.2	5792±60	6589 [6414–6729]
		AA46056	M 1.8-7	315–317	−25.1	6776±61	7625 [7508–7731]
		AA46057	M 1.8-8	394–396	−25.1	8180±270	9099 [8410–9688]
		AA46058	M 1.8-9	439–440	−25.1	5880±170	6701 [6309–7158]
		AA46059	M 1.8-10	442–443	−24.2	6169±52	7069 [6904–7230]
		AA46060	M 1.8-11	447–448	−25.0	6095±59	6950 [6757–7177]
		AA46061	M 1.8-12	466–467	−26.7	6646±70	7521 [7425–7655]
		AA46062	M 1.8-13	477–479	−26.6	7070±75	7877 [7700–8021]
		AA46063	M 1.8-14	495	−23.9	7279±55	8085 [7973–8177]
M 2.6	CT/23°/W	AA51077	M 2.6-1	15 (forest floor)	−25.6	1855±47	1786 [1632–1917]
		AA51078	M 2.6-2	24–25	−25.3	2519±43	2581 [2362–2747]
		AA51079	M 2.6-3	30–31	−24.2	3767±46	4132 [3981–4344]
		AA51080	M 2.6-4	34–38	−24.4	3781±45	4155 [3987–4346]
		AA51081	M 2.6-5	95–97	−25.6	3811±91	4204 [3926–4496]
M 2.7	CT/15°/N	AA46382	M 2.7-1	25–27	−22.7	1619±39	1504 [1410–1608]
M 3.3	CT/23°/W	AA51082	M 3.3-1	10 (forest floor)	−22.6	655±55	607 [543–675]
		AA51083	M 3.3-2	21–23	−23.7	1799±57	1725 [1568–1867]
		AA51084	M 3.3-3	35–36	−23.8	2279±58	2251 [2120–2429]
		AA51085	M 3.3-4	55–60	−25.2	3222±60	3442 [3272–3628]
		AA51086	M 3.3-5	87–89	−23.4	3230±61	3450 [3273–3630]
M 4.5	CT/35°/NW	AA51087	M 4.5-1	8 (forest floor)	−23.0	386±54	433 [313–514]
		AA51088	M 4.5-2	35–37	−24.4	2481±49	2561 [2361–2728]
		AA51089	M 4.5-3	50–51	−22.1	2972±58	3143 [2961–3327]
		AA51090	M 4.5-4	72–78	−24.4	3880±48	4307 [4152–4418]
		AA51091	M 4.5-5	98–102	−24.5	4999±62	5737 [5611–5891]
		AA51092	M 4.5-6	126–130	−24.4	4828±55	5545 [5331–5658]
		AA51093	M 4.5-7	191–198	−27.2	6191±58	7089 [6911–7248]
M 5.0	CT/35°/W	AA39423	M 5.0-3	43	−24.7	1581±39	1467 [1353–1547]
		AA46377	M 5.0-6	83	−25	2297±41	2312 [2155–2356]
		AA46378	M 5.0-7	88	−23.0	2966±57	3134 [2957–3323]
		AA46379	M 5.0-8	95	−23.0	3863±59	4281 [4091–4420]
		AA46380	M 5.0-9	101	−25.3	3622±51	3930 [3732–4088]
		AA39424	M 5.0-10	115	−24.5	3734±41	4083 [3930–4233]
		AA39425	M 5.0-14	136	−25.9	3767±52	4133 [3933–4346]
		AA39426	M 5.0-15	160	−25.8	5201±48	5961 [5767–6170]
		AA46381	M 5.0-19	176	−25.0	4083±44	4585 [4423–4812]
		AA39427	M 5.0-21	205	−23.4	6101±54	6957 [6761–7176]
		AA39428	M 5.0-22	240	−23.8	6062±50	6903 [6751–7153]
M 6.1	CT/25°/W	AA51094	M 6.1-1	23–27	−23.4	310±45	386 [291–476]
		AA51095	M 6.1-2	63–65	−22.6	3191±45	3414 [3270–3548]
		AA51096	M 6.1-3	87–91	−25.6	3642±48	3957 [3832–4089]
M 6.9	CT/23°/W	AA46383	M 6.9-1	7 (forest floor)	−25.1	277±37	367 [154–459]
		AA46384	M 6.9-2	26–29	−26.9	995±39	915 [791–969]
		AA46385	M 6.9-3	58–60	−25.1	2220±41	2232 [2127–2335]
		AA46386	M 6.9-4	67–69	−22.6	2297±44	2308 [2151–2359]
		AA46387	M 6.9-5	111–113	−23.5	2479±42	2562 [2361–2714]
		AA46388	M 6.9-6	157–160	−24.5	2708±34	2809 [2753–2863]
M 8.4	CT/32°/N	AA51495	M 8.4-1	10 (forest floor)	−28.4	356±36	398 [314–497]
		AA51496	M 8.4-2	28–29	−25.3	384±41	440 [316–511]
		AA51497	M 8.4-3	33–34	−25.0	635±37	600 [550–659]
		AA51498	M 8.4-4	46–50	−25.2	480±37	520 [473–616]
		AA51499	M 8.4-5	85–87	−24.4	1940±41	1887 [1742–1991]
		AA51500	M 8.4-6	115–118	−25.8	1908±40	1850 [1729–1946]
M 9.6	CT/33°/W	AA51097	M 9.6-1	25 (forest floor)	−23.7	411±42	472 [320–526]
		AA51098	M 9.6-2	45–47	−24.7	2437±46	2497 [2352–2710]
		AA51099	M 9.6-3	52–54	−25.1	2247±44	2236 [2151–2344]
		AA51100	M 9.6-4	70–85	−26.4	2882±46	3010 [2870–3203]

Table 2 (*continued*)

Site	Landform/slope/aspect	Lab no.	Sample no.	Depth (cm)	$\delta^{13}C$ (‰)	^{14}C years BP	Calibrated years BP
M 10.1	SL/23°/SW	AA51101	M 10.1-1	16 (forest floor)	−23.5	323±46	389 [296–483]
		AA51102	M 10.1-2	65–68	−26.9	1677±49	1584 [1421–1707]
		AA51103	M 10.1-3	92–94	−23.5	1152±42	1060 [970–1171]
		AA51104	M 10.1-4	113–115	−24.8	1748±43	1655 [1542–1814]
		AA51105	M 10.1-5	144–145	−29.1	3141±47	3364 [3214–3467]
M 11.0	CT/19°/S	AA46064	M 11.0-1	10–12 (forest floor)	−22.8	533±38	544 [508–642]
		AA46065	M 11.0-2	38–39	−25.1	2920±43	3062 [2928–3235]
		AA46066	M 11.0-3	51–52	−23.0	4898±48	5634 [5491–5732]
		AA46067	M 11.0-4	116–118	−25.3	4455±54	5103 [4873–5291]
		AA46068	M 11.0-5	142–143	−26.6	5492±56	6287 [6123–6405]
M 12.0	F/10°/NW	AA51106	M 12.0-1	25–27	−24.8	315±47	387 [292–482]
		AA51107	M 12.0-2	46–48	−22.8	729±52	673 [572–756]
		AA51108	M 12.0-3	53–55	−25.9	1180±47	1101 [971–1255]
		AA51109	M 12.0-4	92–93	−24.4	2303±44	2315 [2152–2430]
M 12.1	CT/40°/NW	AA46036	M 12.1-1	102–106	−24.4	402±38	467 [320–518]
		AA46037	M 12.1-2	188–190	−28.1	3346±42	3577 [3471–3686]
		AA46038	M 12.1-3	208–211	−29.7	3211±41	3426 [3355–3550]
		AA46039	M 12.1-4	243–255	−24.0	3831±51	4235 [4091–4408]
		AA46040	M 12.1-5	263–274	−25.4	4124±81	4648 [4424–4832]
		AA46041	M 12.1-6	283–288	−24.1	3617±42	3922 [3778–4084]
M 14.6	CT/23°/SW	AA51491	M 14.6-1	20 (forest floor)	−25.4	867±37	777 [691–911]
		AA51492	M 14.6-2	42–45	−26.0	1713±39	1618 [1536–1707]
		AA51493	M 14.6-3	62–64	−26.5	2505±49	2574 [2362–2743]
		AA51494	M 14.6-4	126–128	−25.2	3304±44	3534 [3409–3637]
M 16.0	F/5°/NW	AA39414	M 16.0-1	30	−26.5	264±105	302 [232–505]
		AA39415	M 16.0-2	60	−24.7	1010±38	932 [793–1047]
M 19.9	CT/15°/NE	AA51110	M 19.9-1	15 (forest floor)	−25.6	201±42	182 [0–311]
		AA51111	M 19.9-2	40–41	−24.3	325±41	389 [301–476]
		AA51112	M 19.9-3	52–53	−26.4	889±43	816 [711–920]
M 20.3	SL/10–15°/NE	AA46406	M 20.3-1	45–47	−24.5	333±32	388 [309–470]
		AA46407	M 20.3-2	85–88	−24.1	439±32	500 [340 –536]
		AA46408	M 20.3-3	105–107	−24.6	956±33	856 [788–945]
		AA46409	M 20.3-4	124–126	−23.3	507±32	530 [505–619]
		AA46410	M 20.3-5	166–167	−27.1	346±46	396 [309–496]
		AA46411	M 20.3-6	222–224	−25.8	664±32	600 [557–668]
		AA46412	M 20.3-7	270–274	−26.9	393±32	464 [322–512]
		AA46413	M 20.3-8	430	−26.4	2123±99	2107 [1894–2337]
M 21.3	CT/30°/N	AA46398	M 21.3-1	12 (forest floor)	−23.3	903±31	832 [739–913]
		AA46399	M 21.3-2	17–19	−24.5	3641±45	3954 [3835–4086]
		AA46400	M 21.3-3	57–59	−25.0	3549±36	3833 [3702–3959]
		AA46401	M 21.3-4	66–68	−24.0	3589±37	3886 [3728–4057]
		AA46402	M 21.3-5	80–82	−26.5	3619±39	3924 [3781–4080]
		AA46404	M 21.3-7	139–141	−28.3	6140±150	7014 [6666–7411]
		AA46405	M 21.3-8	236–237	−26.4	7850±150	8701 [8368–9085]
M 25.6	F/6°/W	AA51502	M 25.6-2	48–49	−25.9	260±52	313 [3–467]
		AA51503	M 25.6-3	67–68	−29.2	207±40	184 [1–313]
		AA51504	M 25.6-4	101–105	−25.6	360±41	404 [314–501]
M 26.9	CT/15°/SW	AA51481	M 26.9-1	39–41	−23.1	979±39	876 [790–956]
		AA51482	M 26.9-2	60–61	−23.9	924±43	845 [741–927]
		AA51483	M 26.9-3	110–111	−24.3	334±39	390 [306–480]
		AA51484	M 26.9-4	116–117	−25.1	375±39	432 [315–508]
		AA51485	M 26.9-5	140–141	−26.5	666±50	612 [548–677]
M 27.3	CT/34° /E	AA43093	M 27.3-2	45–47	−24.5	374±38	431 [316–507]
		AA43094	M 27.3-4	120–122	−25.9	3010±41	3208 [3076–3339]
M 27.7	CT/7°/SW	AA46042	M 27.7-1	0 (forest floor)	−25.9	409±46	466 [318–526]
		AA46043	M 27.7-2	13–14	−25.3	378±43	432 [315–509]
		AA46044	M 27.7-3	77–79	−27.9	4605±45	5327 [5052–5467]
		AA46045	M 27.7-4	90–92	−24.5	4573±44	5231 [5049–5449]
		AA46046	M 27.7-5	130–131	−24.6	4424±52	5020 [4865–5282]
		AA46047	M 27.7-6	138–140	−24.8	5315±45	6080 [5946–6266]
		AA46048	M 27.7-7	160–161	−24.9	5785±55	6583 [6501–6657]
M 28.0	CT/30°/N	AA39417	M 28.0-1	26–29	−26.4	270±38	333 [5–459]
		AA39418	M 28.0-2	66–67	−25.1	1641±62	1539 [1392–1698]
		AA39419	M 28.0-3	85–86	−26.7	1716±51	1624 [1519–1808]
		AA39420	M 28.0-4	99–101, 102–103	−27.6	2380±63	2448 [2211–2711]

Table 2 (*continued*)

Site	Landform/slope/aspect	Lab no.	Sample no.	Depth (cm)	δ^{13}C (‰)	^{14}C years BP	Calibrated years BP
M 29.0	SL/15–20°/SE	AA46392	M 29.0-1	0 (forest floor)	−24.7	402±32	474 [323–516]
		AA46393	M 29.0-2	30	−24.4	546±31	550 [513–637]
		AA46394	M 29.0-3	50–70	−26.2	337±31	388 [311–471]
		AA46395	M 29.0-4	110–111	−25.6	473±31	518 [480–544]
		AA46396	M 29.0-5	120–122	−29.4	325±30	387 [309–463]
		AA46397	M 29.0-6	175	−23.5	2900±35	3032 [2894–3204]
M 29.9	CT/30°/SW	AA46389	M 29.9-1	0 (forest floor)	−23.1	644±32	598 [553–661]
		AA46390	M 29.9-2	25–30	−25.4	1583±32	1469 [1392–1539]
		AA46391	M 29.9-3	85–90	−26.4	5597±40	6365 [6297–6447]
F 0.5L	F/17°/SE	AA43090	F 0.5L-1	0–6 (forest floor)	−25.2	480±33	520 [481–547]
		AA43091	F 0.5L-2	40–43	−24.5	297±38	383 [291–463]
		AA43092	F 0.5L-3	90–92	−27.7	8572±81	9558 [9332–9885]
F 0.5U	F/17°/SE	AA51486	F 0.5U-1	0 (forest floor)	−22.7	370±41	422 [314–506]
		AA51487	F 0.5U-2	30–32	−24.4	452±46	502 [326–616]
		AA51488	F 0.5U-3	55–56	−24.1	2261±48	2240 [2151–2348]
		AA51489	F 0.5U-4	68–69	−25.1	2475±46	2557 [2359–2714]
		AA51490	F 0.5U-5	147–148	−24.9	2658±50	2775 [2724–2865]

Site codes: M, Morkill; F, Forgetmenot. Landforms: F, fan; CT, colluvial toeslope; SL, slide, earthflow, debris flow lobe. Bracketed δ^{13}C value (−25) was assumed and not measured. Calibrated ages expressed as median and 2 σ interval.

ning-caused fires tend to be small, and can be confined to a single dead redcedar because the weather conditions needed for high intensity crown fires occur rarely. Lightning fire frequency and lightning strike frequency ranged from 3 to 10 and from 240 to 360 per 100 km^2, respectively, during the 1989–1998 period in the Morkill River valley (Hawkes *et al*., 2002). Compared with the rainforests of coastal BC, this area has three to ten times the frequency of lightning-caused fires (Larson, 1998). Aboriginal burning is well-documented elsewhere in BC (Johnson, 1999), but the apparently sparse pre-contact aboriginal populations in the wetter northern ICH and the predominance of old forest age-classes, suggest that this was not a major influence on the disturbance regime.

Inter-regional comparisons and climatic change

The median estimated TSF in the lower Morkill River valley of *c*. 500 cal. yr BP contrasts with similarly derived values from coastal BC forests. Lertzman *et al.* (2002) estimated median TSF in Clayoquot Sound rainforests and Fraser Valley subalpine forests at 1300 and 1550 cal. yr BP, respectively.

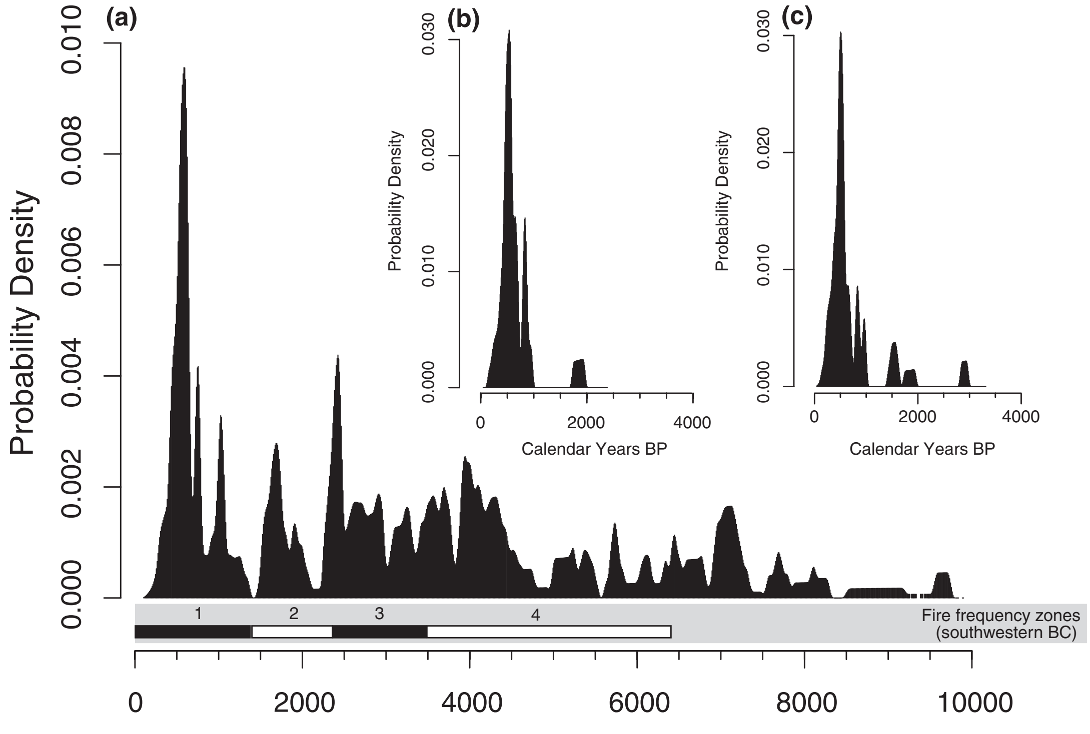

Figure 6 Cumulative probability distributions of calibrated radiocarbon dates for charcoal from 29 sites in the Interior Cedar Hemlock zone of the Morkill River valley: (a) charcoal from mineral soils ($n = 130$), (b) charcoal from forest floors ($n = 17$) and (c) uppermost charcoal from each site ($n = 29$). Fire frequency zones for southwestern BC, with climatic or environmental history indicated after Hallett *et al.* (2003): 1, 'Little Ice Age', 'Mediaeval Warm Period'; 2, 'Fraser Valley Fire Period'; 3, glaciers advance; 4, variable mid-Holocene fire frequencies

Table 3 Estimated fire return interval (FRI) and time since fire (TSF) (calendar years) based on calibrated radiocarbon dates for soil charcoal from contrasting slope aspects, Morkill River valley

	Slope aspect	Median (cal. yr)
FRI	NW–NE ($n = 29$)	630
	SW–SE ($n = 36$)	958
TSF	NW–NE ($n = 10$)	393
	SW–SE ($n = 11$)	544

FRI estimates derived from the relatively small number of sites with multiple soil charcoal dates in these study areas also exceeded 1000 cal. yr, leading Lertzman *et al.* (2002) to conclude that fire has been a minor ecological influence. When intervals of less than 300 years were excluded to allow for in-built ages, their Fraser Valley subalpine study area had a median FRI of 1200 cal. yr, which is almost identical to our estimate for the Morkill River valley.

In comparing our results with these coastal data, the apparent contradiction presented by these similarly long FRI estimates but greatly differing TSF values may reflect inherent biases in the soil charcoal record. For the Fraser Valley subalpine forests, Hallett *et al.* (2003) derived much shorter FRI estimates from lake sediment charcoal accumulation rates, and highlighted factors leading to systematic overestimation of FRI from soil charcoal dating alone, such as incomplete preservation of older charcoal. Their detailed analysis of both lines of evidence points out the need for complementary studies of associated lake sediments. The twentieth-century historical record of fires and lightning activity in the ICH relative to coastal rainforests makes it reasonable that soil charcoal dating also overestimates FRI in the inland rainforests.

We did not attempt to correct for inbuilt charcoal ages because of the inherent limitations of dendrochronology in redcedar-dominated inland rainforests, so it is unclear how much this potential error affected the accuracy of our fire history reconstructions. Because of these and other limitations of FRI estimates derived solely from soil charcoal, and the limited pre-6000 cal. yr BP record in our study area, we did not attempt to detect changes in FRI over the Holocene.

Patterns in the Morkill valley calibrated dates suggest similarities to fire activity trends elsewhere in western North America, as well as parallels with broader Holocene climatic changes. Some inter-regional similarities over the past 4000 cal. yr can be found between the records of fire-related sedimentation in the Morkill River valley and in Yellowstone (Meyer and Pierce, 2003), notably the peaks in the probability distributions at *c.* 500–1000 and 1600–1800 cal. yr BP, and the minimum at *c.* 1400 BP. The conspicuous peaks in the Morkill probability distribution between *c.* 1600 and 2400 cal. yr BP partially overlap with the clustering of TSF ages between 2200 and 3200 cal. yr BP at Clayoquot Sound. This episode of fire activity in our study area may correspond to the 'Fraser Valley Fire Period' (1300–2400 cal. yr BP) identified in high-elevation charcoal records in southwestern BC (Hallett *et al.*, 2003). Soil and lake sediment charcoal evidence for increased fire frequencies *c.* 3500–4500 cal. yr BP and during the 'Mediaeval Warm Period' (*c.* 600–1000 cal. yr BP) (Hallett *et al.*, 2003), broadly match the probability distribution of soil charcoal dates from the Morkill ICH study area.

The correspondence between reduced fire frequency *c.* 2400–3500 cal. yr BP reported by Hallett *et al.* (2003) and our own record for that period is less clear, although this interval is bracketed by peaks in the Morkill probability distribution at 2300 and 3900 cal. yr BP (Figure 6). This period of reduced fire activity in coastal BC coincides with reduced charcoal influx to Crowfoot Lake in the Alberta Rocky Mountains (Reasoner and Huber, 1999), and low fire frequencies in Kootenay National Park in southeastern BC (Hallett and Walker, 2000). Glacier expansions throughout the northern hemisphere during this interval (Denton and Karlen, 1973) are represented by the Peyto Advance in the Rocky Mountains south of our study area at the Robson (Luckman, 1995) and Stutfield Glaciers (Osborn *et al.*, 2001).

The conspicuous peaks between 250 and 1000 cal. yr BP in the Morkill probability distributions pose difficulties in interpretation since cooler climates during this period should have been accompanied by reduced fire activity. This interval overlaps the 'Little Ice Age', represented in the Canadian Rockies by the Cavell Advance, which began in the twelfth to thirteenth centuries, culminating in maximum regional ice cover in the mid-nineteenth century (Luckman, 2000; Osborn *et al.*, 2001). The strong representation of post-1000 cal. yr BP dates in our record may just indicate a preservation bias favouring younger charcoal. In addition, tree-ring records indicate that the past millennium did include multidecade intervals with positive temperature and/or negative precipitation anomalies (Luckman, 2000), and these could have created conditions suitable for fires that would be represented in our record.

Other studies have reported apparent correspondences between Holocene fire activity in western North America and North Atlantic climate cycles. In Yellowstone, Meyer and Pierce (2003) found a consistent matching of periods of reduced fire-related sedimentation with North Atlantic cold episodes (Bond *et al.*, 1997). The Morkill valley data show some similarities to the Yellowstone record, but with less clearly defined periods of apparently reduced fire activity.

Complementary lake sediment studies would greatly strengthen this reconstruction of fire history in the inland rainforest of east-central BC. The more continuous record provided by charcoal influx data would have a better representation of mid- and early Holocene events that are poorly recorded by soil charcoal, even in the unusually rich deposits of our study area. Vegetation changes interpreted from lake sediment pollen records would also facilitate inferences regarding fire severity (Whitlock and Bartlein, 2004), and help to identify non-climatic controls of fire regimes, such as changes in forest productivity that influence fuel accumulation. For example, despite the generally cooler and moister climates that prevailed in south-central BC after *c.* 4000 BP (Hebda, 1995), the persistence of high lake sediment charcoal influx rates in lakes could have resulted from higher biomass that accompanied denser subalpine forests (Heinrichs *et al.*, 2002). Long-term floristic changes in east-central BC forests are poorly documented, but these may have contributed to changes in fire regimes. In particular, the western hemlock and redcedar communities that currently dominate the inland rainforest may be recent arrivals in our study area, given evidence for the late Holocene increase in western hemlock in southeastern BC pollen records (Rosenberg *et al.*, 2003).

Conclusions

(1) A rich Holocene record of soil and sedimentary charcoal indicates that fire has been an important geomorphic factor in the inland temperate rainforest of east-central BC. Abundant charcoal in colluvial and alluvial fan deposits created by erosion of glaciolacustrine terrace scarps, combined with

observations of post-fire geomorphic processes, suggest that most sedimentation events have followed forest fires.
(2) Estimated fire return intervals of approximately 800–1200 years, and clustering of charcoal radiocarbon dates *c.* 3900, 2300 and 1600 cal. yr BP, and in multiple peaks between *c.* 250 and 1000 cal. yr BP, suggest similarities to Holocene fire activity in subalpine forests in coastal BC. Correpondences to Holocene fire history at more distant sites in western North America are less clear.
(3) Future fire history studies in BC inland temperate rainforests will need locally derived estimates of inbuilt age errors in soil charcoal dates from sites where Douglas-fir tree-ring chronologies are available. With evidence from coastal BC subalpine forests suggesting that soil charcoal dating systematically underestimates fire frequencies, complementary studies of lake sediment charcoal accumulation rates are also needed.
(4) Although the charcoal record created and preserved by post-fire slope instability and sedimentation may record only more severe fires, these events can have important consequences for ecosystems in mountain environments. Future studies should use soil and sedimentary charcoal evidence to provide historical perspective to studies of landscape ecology and watershed processes in the inland rainforest region.
(5) Soil and sedimentary charcoal can provide both a site-specific and watershed-scale record of fire history where other evidence (tree-rings, lake sediments) is lacking. Several other valleys in east-central BC contain similar landforms created by deep gullying of thick glaciolacustrine deposits, so there is potential to refine the approach used in this study, and extend it to other areas.

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