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HOLOCENE FIRE HISTORY OF A COASTAL TEMPERATE RAIN FOREST BASED ON SOIL CHARCOAL RADIOCARBON DATES

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Abstract. The long-term role of fire in coastal temperate rain forest is poorly understood. To determine the historical role of fire on western Vancouver Island (British Columbia, Canada), we constructed a long-term spatially explicit fire history and examined the spatial and temporal distribution of fire during the Holocene. Two fire-history parameters (time-since-fire [TSF] and fire extent) were related to three landscape parameters (landform [hill slope or terrace], aspect, and forest composition) at 83 sites in a 730-ha low-elevation (less than ~200 m) area of a mountainous watershed. We dated fires using tree rings (18 sites) and 120 soil-charcoal radiocarbon dates (65 sites). Comparisons among multiple radiocarbon dates indicated a high probability that the charcoal dated at each site represented the most recent fire, though we expect greater error in TSF estimates at sites where charcoal was very old (>6000 yr) and was restricted to mineral soil horizons. TSF estimates ranged from 64 to ~12 220 yr; 45% of the sites have burned in the last 1000 yr, whereas 20% of the sites have not burned for over 6000 yr. Differences in median TSF were more significant between landform types or across aspects than among forest types. Median TSF was significantly greater on terraces (4410 yr) than on hill slopes (740 yr). On hill slopes, all south-facing and southwest-facing sites have burned within the last 1000 yr compared to only 27% of north- and east-facing sites burning over the same period. Comparison of fire dates among neighboring sites indicated that fires rarely extended >250 m. During the late Holocene, landform controls have been strong, resulting in the bias of fires to south-facing hillslopes and thus allowing late-successional forest structure to persist for thousands of years in a large portion of the watershed. In contrast, the early Holocene regional climate and forest composition likely resulted in larger landscape fires that were not strongly controlled by landform factors. The millennial-scale TSF detected in this study supports the distinction of coastal temperate rain forest as being under a fundamentally different disturbance regime than other Pacific Northwest forests to the east and south.

Key words: British Columbia, Canada; climate–terrain–fire interaction; climate change; coastal temperate rain forest; disturbance, long-term role; fire history; Holocene fire history; Pacific Northwest forests; paleoecology; radiocarbon dating; soil charcoal.

INTRODUCTION

The coastal temperate rain forest from southern British Columbia, Canada, north through southeast Alaska, USA, is noted for the near-absence of recent fire and the dominance of late-successional forest communities that experience a disturbance regime of small-scale tree-fall gaps (Veblen and Alaback 1996, Lertzman et al. 1996, Wells et al. 1998). These forests are also noted for the rarity of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), a long-lived seral species that requires fire for establishment in much of the Pacific Northwest (Munger 1940, Franklin and Dyrness 1988, Agee 1993). In the windward portions of coastal mountain ranges in British Columbia, evidence of fire is limited to the scattered occurrence of Douglas-fir on specific topographic features such as south-facing hill slopes (Schmidt 1960, 1970, Veblen and Alaback 1996). This pattern contrasts with nearby regions, where the presettlement landscape was dominated by forests containing evidence of large fires in the form of even-aged stands of Douglas-fir (Hemstrom and Franklin 1982). Thus, the rarity of Douglas-fir and lack of stand-structural evidence of fire distinguishes coastal temperate rain forest in the regional context of Pacific Northwest forests. However, other than these types of observations about modern forest condition, there is virtually no documentation of fire history in forests in this region, and it is not known whether the modern fire regime is a long-term feature (e.g., >1000 yr) of the coastal temperate rain forest landscape.

Factors affecting fire regimes operate at different temporal and spatial scales. At broad spatial scales, fire regimes are influenced by long- and short-term climatic changes and at more local scales by topographic features and vegetation types (e.g., Romme and Knight

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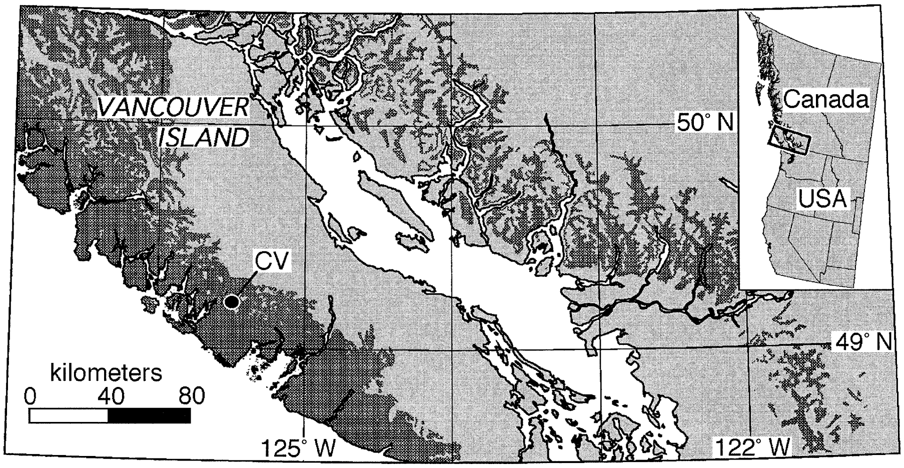

FIG. 1. Location of the Clayoquot Valley (CV) on Vancouver Island, British Columbia, Canada, showing the extent of the coastal temperate rain forest (darker areas), defined here as the wettest subzones of the Coastal Western Hemlock Biogeoclimatic Zone (Very Wet Hypermaritime, Very Wet Maritime–low elevation, and Very Wet Maritime–mid elevation; Meidinger and Pojar 1991).

1981, Lertzman and Fall 1998, Heyerdahl et al. 2001, 2002). The interaction of large- and small-scale controls causes both the locations and sizes of fires to vary over time by affecting the distribution of fire-susceptible forests (Turner and Romme 1994). For example, during generally cool and moist climatic periods, fires may be restricted to a small portion of the landscape (e.g., south-facing hill slopes), but during warm and dry intervals, fires may burn a large portion of the landscape. If climate undergoes major changes in the Pacific Northwest, larger areas of coastal temperate rain forest may become more susceptible to fire. This has been shown in other lowland regions of the Pacific Northwest, where several studies have found that large-scale climate change has greatly altered the fire regime through the Holocene (Cwynar 1987, Long et al. 1998, Brown and Hebda 2002). Our goal in this study is to examine the long-term roles of climate, topography, and vegetation in the fire regime of a coastal temperate rain forest that receives some of the highest annual precipitation in North America.

Fire-history studies must overcome significant challenges in areas with very long fire intervals. Traditional fire-history methods focus on particular spatial and temporal scales that might not be well suited to study the landscape pattern of past fires in coastal temperate rain forest (Lertzman and Fall 1998). For example, the use of tree-ring analysis to understand the pattern of fire at fine temporal and spatial scales has limited application in humid regions, where the time-since-the-last-fire (TSF) may exceed the ages of trees. Over longer time scales, fire occurrence may be addressed with charcoal records in lake sediments. However, this method is not spatially explicit, because lake-sediment records integrate fires within large source areas (Clark 1988). In this study we overcome the spatial and temporal constraints of traditional fire-history studies by using radiocarbon dates of soil charcoal to describe the spatial pattern of fire over long time scales (see also Niklasson and Granstrom 2000). Although charcoal is inert and should be preserved in stable soils, this method has rarely been used, and questions remain regarding the taphonomy of charcoal and the temporal resolution available from soil-charcoal records. Our overall objectives are to examine (1) the utility of radiocarbon-dated soil-charcoal records for fire history, (2) the length of time since the last fire in relation to topographic features and forest types, and (3) the temporal pattern of fire over the last ~11 000 years.

STUDY AREA

The research was conducted in the Clayoquot River watershed, on the western edge of the Vancouver Island Range and 20 km from the west coast of Vancouver Island, British Columbia, Canada (49°15′ N; 125°30′ W; Fig. 1 and Plate 1). The 7700-ha, 12-km-long watershed ranges in elevation from 15 to ~1200 m. High-elevation tundra and rock covers 16% of the watershed. Bedrock is of volcanic and sedimentary origin intruded by numerous granitic batholiths (Muller 1968). The watershed contains multiple terraces 5–40 m above the river that abut steep valley walls with slopes of 40% to >60%. The active floodplain is limited to the lower 4 km of river, and is constricted at several locations by colluvial fans from tributary valleys. Soils are shallow (<1 m) or absent on slopes above alluvial fans and terraces. Soils are mainly Spodosols (Humic Haplorthods) (Jungen 1985).

The study area was restricted to low-elevation areas (less than ~200 m) within the watershed. In the biogeoclimatic ecosystem classification, this area is in the submontane variant of the Very Wet Maritime subzone of the Coastal Western Hemlock zone (CWHvm1), described as having a wet, humid climate with cool sum-

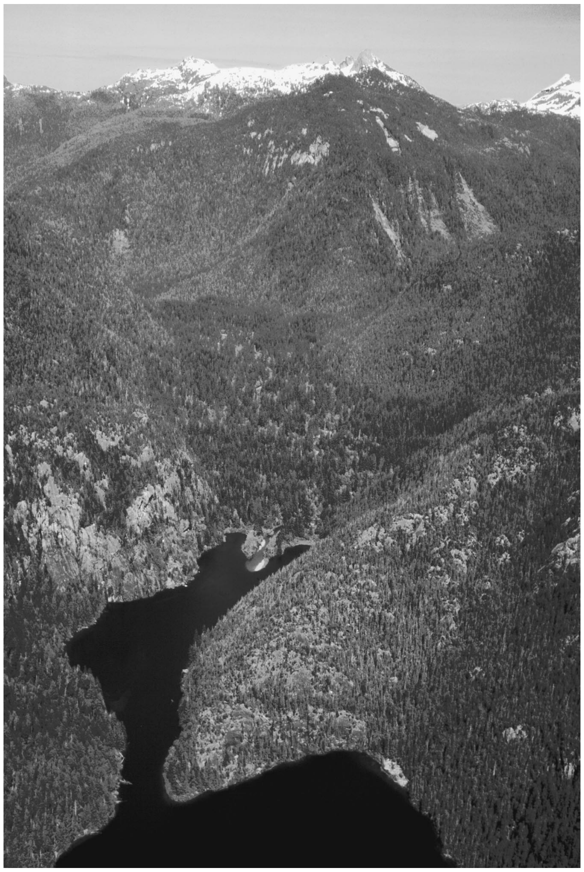

PLATE 1. Aerial photograph of the lower Clayoquot Valley. Photo by Adrian Dorst.

mers and mild winters with little snow (Meidinger and Pojar 1991). Because of its location on the western slope of the Vancouver Range, the study area receives significant orographic precipitation from moist air flows off the Pacific Ocean, though summer drought may nevertheless occur. A climate station in the study area managed by the Clayoquot Biosphere Project (currently defunct) measured a mean annual precipitation of 5400 mm between 1993 and 1998, of which less than 10% fell in June, July, and August. Mean temperatures in the study area were 14.5° and 4.9°C in July and December, respectively.

The Clayoquot River watershed has no history of logging or other industrial disturbance and the modern vegetation appears to be minimally affected by natural disturbances. Between 1950 and 1994 no forest fires occurred in the watershed, and only 19 lightning-ignited fires of limited extent burned in the surrounding 3500 km^2 Clayoquot Sound area (Ministry of Forests 1995). Avalanche and debris flows at high elevation currently affect 7.1% of the forested part of the watershed. No wind disturbances were detected in the Clayoquot Valley and adjacent watersheds over a 50-yr aerial photo record (Pearson 2000). This lack of recent disturbance differs from areas of coastal temperate rain forest exposed to strong winds that experience stand-replacing windthrow (Kramer et al. 2001). Old-growth forest structure is ubiquitous in the watershed, characterized by a wide range of tree sizes and canopy gaps created by small clusters of tree falls or by edaphic constraints (Scientific Panel 1995, Lertzman et al. 1996). The extent of canopy gaps in an adjacent watershed suggests that the canopy tree-replacement rate is 350–950 yr in the absence of large-scale disturbances (Lertzman et al. 1996).

Four broad forest types in the study area are closely associated with landforms and soils as described below (Jungen 1985, Green and Klinka 1994, Appendix A).

Sitka spruce forest is composed of Sitka spruce (*Picea sitchensis* (Bong.) Carr.), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and red alder (*Alnus rubra* Bong.). Most of this forest type is subject to frequent flooding, which contributes to an open canopy and a dense shrub layer of salmonberry (*Rubus spectabilis* Pursh). However, in places this forest type also extends onto low terraces directly above flooded areas. The soils in frequently flooded areas are developed in deep, sandy to gravelly fluvial deposits and have very shallow organic horizons. Soils on better-drained sites slightly above the floodplain have a mor humus over a highly weathered dark reddish brown illuvial horizon.

Cedar–hemlock forest is composed of large (1–1.5 m diameter) western redcedar (*Thuja plicata* Donn), western hemlock, and minor amounts of Pacific silver fir (*Abies amabilis* (Dougl.) Forbes) and Douglas-fir, and is typically found on terraces, hill slopes, and alluvial fans. Soils on terraces are developed in deep gravels, and generally have deeper clay-rich illuvial horizons than in the Sitka spruce forest. These terraces also show a pit-and-mound microtopography developed from tree tip-ups. Soils on hill slopes are developed on a shallow (50–100 cm) gravelly colluvium over bedrock. Alluvial fans are aggrading with gravel and cobbles.

Hemlock–fir forest is composed of Pacific silver fir with varying amounts of western hemlock and western redcedar. The canopy layer is relatively uniform, with no extremely large trees. This forest type occurs on terraces and hill slopes and has soils similar to the cedar–hemlock forest type.

Cedar–salal forest is composed of western redcedar (sometimes 100% of the tree layer) and minor amounts of western hemlock, shore pine (*Pinus contorta* var. *contorta* Dougl. ex Loud.), western white pine (*Pinus monticola* Dougl. ex D. Don in Lamb.), and Douglas-fir. This forest type is restricted to hill slopes, exhibits stunted growth forms, small tree crowns, and has a very dense shrub cover of salal (*Gaultheria shallon* Pursh), indicative of low soil nutrients (Mallik and Prescott 2001). Soils are developed on shallow colluvium (<50 cm) or directly over bedrock.

BACKGROUND: FIRE HISTORY FROM RADIOCARBON DATES OF SOIL CHARCOAL

Charcoal in forest soils has been recognized as a source of information about past fires at point locations (e.g., Sanford et al. 1985, Berli et al. 1994, Lavoie and Payette 1996, Carcaillet 1998). If soil-charcoal profiles are to provide estimates of fire dates to reconstruct a landscape-level fire history, the spatial and temporal precision of fire dates obtained by this method must be considered, especially uncertainties related to charcoal transport following fire, the taphonomic processes of charcoal burial and mixing within the soil profile, and the accuracy of radiocarbon-derived estimates of fire dates.

Large charcoal pieces in undisturbed soil are most likely formed by fire at that site. Charcoal particles >0.5 mm are generally not transported by air more than a few tens of meters during fire (Clark and Patterson 1997, Ohlson and Tryterud 2000). On steep mountain slopes surface runoff may transport charcoal, especially on smooth surfaces and following a fire (Swanson 1981, Meyer and Wells 1997). For example, post-fire debris flows may contain abundant coarse charcoal indicating a fire-induced origin, or may bury burned ground surfaces, primarily on alluvial fans, thus preserving both histories of fire and geomorphic disturbance (Meyer et al. 1992). However, the most intense erosional activity is usually concentrated in steep stream channels, and small flat areas or surface roughness from large unburned logs may significantly reduce colluvial transport (Reneau and Dietrich 1990, Lavee et al. 1995). Thus, proper site selection, such as small concavities and flats, is necessary to minimize erosional loss of charcoal from a site.

Occasionally, soils will preserve charcoal in stratigraphic layers that preserve relative temporal relationships of accumulation (e.g., cumulic mor humus soils; Hallett et al., *in press*), however in many other cases various processes disrupt the stratigraphic sequence and distort the charcoal record. For example, the decomposition of organic material may mix charcoal from different fires, and fires may consume humus, obliterating evidence of previous fires (McNabb and Cromack 1990, Ohlson and Tryterud 2000). The presence of charcoal at different depths in mineral soil horizons is usually the result of bioturbation (e.g., tree tip-up disturbances or animal burrowing), roots burning in situ, or burial by material derived from higher elevations, which may reduce the reliability of the charcoal stratigraphy for inferring the history of sequential fires (Carcaillet and Talon 1996, Birkeland 1999, Carcaillet 2001). Therefore, verification that the charcoal sampled truly represents its apparent position in the stratigraphic sequence is essential. For instance, estimating time elapsed since the last fire (time-since-fire, TSF) requires confirmation that the uppermost charcoal does in fact reliably represent that fire (see *Methods: Interpretation of time-since-fire,* below).

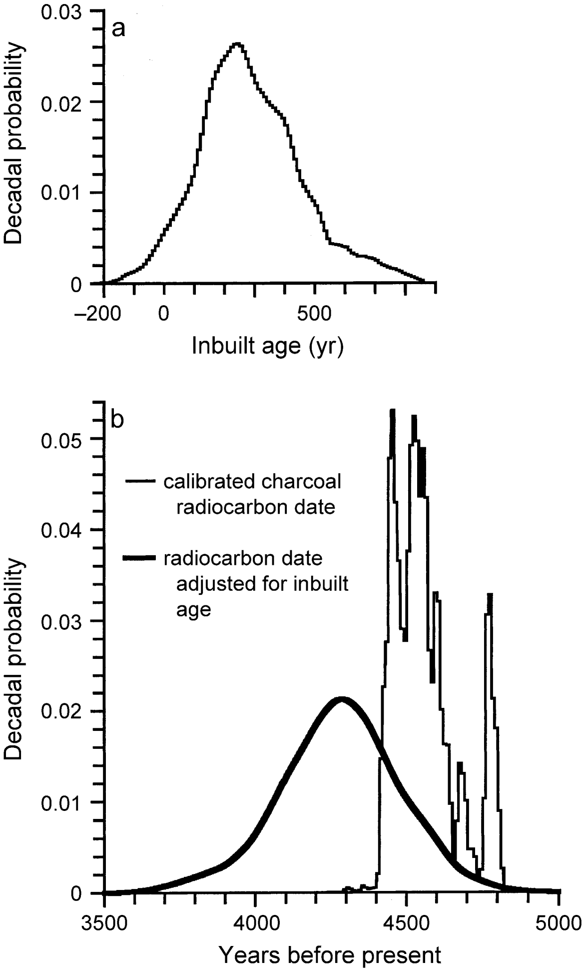

FIG. 2. The error of soil-charcoal radiocarbon dates due to the age of the wood at the time of the fire (inbuilt age) in the Clayoquot Valley. (a) The distribution of potential inbuilt age constructed by comparing 26 calibrated radiocarbon dates of surficial soil charcoal with the actual time of the fire determined by tree-ring counts. The known age of the fire was subtracted from each calibrated date, and the probability distributions from each date were averaged (Gavin 2001). Negative inbuilt age values on the above distribution result from calibrated radiocarbon ages that spanned the actual age of the fire. (b) An example of the adjustment of a calibrated radiocarbon date (4060 ± 50 ^{14}C years BP) to reflect inbuilt age. Calibration of radiocarbon dates typically results in an irregular probability distribution. This probability distribution was smoothed using the range of potential inbuilt age from panel (a) as the weights of a moving average filter (Gavin 2001).

The accuracy of radiocarbon dates on charcoal for estimating fire dates also deserves special attention. In addition to the inherent error of a calibrated radiocarbon date (Stuiver and Reimer 1993), radiocarbon dates also may overestimate the age of a fire because the wood may have been old at the time of the fire. This is a particular problem in temperate coastal rain forests, where the residence times of woody debris may be several centuries, but may be a significantly smaller problem in other ecosystems (Harmon et al. 1986). This error (termed ''inbuilt age'') describes the uncertainty of a fire-date estimate that is based on a radiocarbon-age estimate of a piece of charcoal produced by that fire. The inbuilt-age error of charcoal dates in the Clayoquot Valley has been estimated by comparing charcoal radiocarbon dates with the known age of fires based on tree-ring dates of fire (Gavin 2001). The inbuilt-age error ranged from 0 to 670 yr (5th and 95th percentiles, respectively) with a median of 270 yr (Fig. 2a). This error limits the ability to correlate dates among sites or with other events (Gavin 2001).

Despite the complexity of charcoal taphonomy in soils, wood charcoal is an ideal material for radiocarbon dating because it is mainly composed of chemically inert carbon and thus very resistant to decay and easily cleaned of contaminants, and easily distinguished from other soil material (Aitken 1990). Soil-charcoal radiocarbon dates have aided research on long-term disturbance regimes in a wide range of forest types. For example, in tropical rain forest soils, charcoal dates indicated a TSF of <1000 yr in Brazil (Saldarriaga and West 1986) and in Zaire (Hart et al. 1996). Other studies from Brazil (Sanford et al. 1985) and Costa Rica (Horn and Sanford 1992) have shown TSF may be much longer in these forests. In Australian tropical rain forests, soil-charcoal dates often indicated TSF >8000 yr (Hopkins et al. 1996). Millennial-scale TSF has also been found in temperate forests of New Zealand (Burrows 1996), France (Carcaillet 1998), and Québec (Bussières et al. 1996).

METHODS

Preliminary site selection

Sampling was primarily confined to a 730-ha area below 200-m elevation of the Clayoquot Valley (with the exception of six sites extending to 550 m), and excluded obviously disturbed areas (i.e., the floodplain, alluvial fans, and footslopes with thick cumulic soils derived from higher elevations). Ninety-one ''target sites'' for tree-core and soil-charcoal sampling were plotted on a map using a uniform 200-m grid in the 730-ha area. If tree cores could not be used to date past fires at a target site, that or the nearest suitable microsite was sampled for soil charcoal. Suitable microsites are characterized by a small concavity or level topography 2–20 m in diameter where charcoal is likely to accumulate following fire (Bassini and Becker 1990). Limiting charcoal sampling to these sites should not introduce bias because fire behavior is not affected by such small topographic features (Chandler et al. 1983). We classified each site by forest type (see *Study area*) and landform type (hill slope or terrace). Hill slopes were defined as areas with a slope $>25\%$ at least one tree height (35 m) above the nearest terrace or floodplain.

Tree-ring dates

We assessed each target site for stand-level evidence of fire, such as the presence of Douglas-fir trees or an even-aged group of western hemlock. At sites with such evidence, we collected increment cores as close to the ground as possible from the nearest 7–19 dominant canopy Douglas-fir or western hemlock (average = 11 trees). Of the 24 sites sampled, fire dates could not be obtained from tree-ring records at some sites because too few Douglas-fir (<7 trees) were present to core (3 sites), or the wide age range and slow initial growth of western hemlock indicated that the trees were not a post-fire cohort (3 sites). At sites with evidence of two cohorts consisting of large Douglas-fir surrounded by a uniformly smaller cohort of mostly western hemlock, we cored both size classes. At some of these sites there were too few trees in the larger size class (<7 trees) to estimate the age of the older fire.

Tree cores were air-dried, glued to small boards, and sanded to a smooth surface. We assigned calendar dates to tree rings by standard procedures (Stokes and Smiley 1996), and assigned fire dates to the estimated age of the oldest tree in a cohort determined from the estimate of the number of years between germination and growth to core height (resulting in the addition of 7–25 yr to the age of the innermost tree ring of individual tree cores). At sites with two age classes, Douglas-fir trees showed nearly synchronous (± 1 yr) abrupt decreases in ring widths. These growth declines were used to provide exact-year fire dates, because they corresponded to the approximate age of a western hemlock cohort. Assuming a late-summer fire, the fire year was set to the year preceding the first change in growth rate. If a neighboring target site had a similar fire date (<10 yr difference) based on Douglas-fir ages, that date was rejected in favor of the exact-year date.

Isolation of soil charcoal and final site selection

At 75 sites we obtained multiple soil cores using a 5-cm-diameter metal tube driven into the soil. These sites either (1) lacked stand-level evidence of fire (67 sites), (2) were not successfully dated using tree-ring methods (6 sites), or (3) were successfully dated using tree-ring records but where buried charcoal layers suggested that earlier fires could also be dated (2 sites). We disaggregated the soil of the first 3–8 cores taken at a site (spaced 20 m apart) and looked for charcoal fragments, particularly in the organic horizon where the charcoal from the last fire is most likely located (Carcaillet and Talon 1996). Any charcoal found at this time was labeled separately. We then obtained a second set of 3–5 soil cores spaced 2–5 m apart for later analysis in the laboratory. If the soil was >10 cm in depth and contained distinct organic and mineral horizons, suggesting that a series of charcoal layers might be detectable, we subdivided the soil cores into 2–5 cm

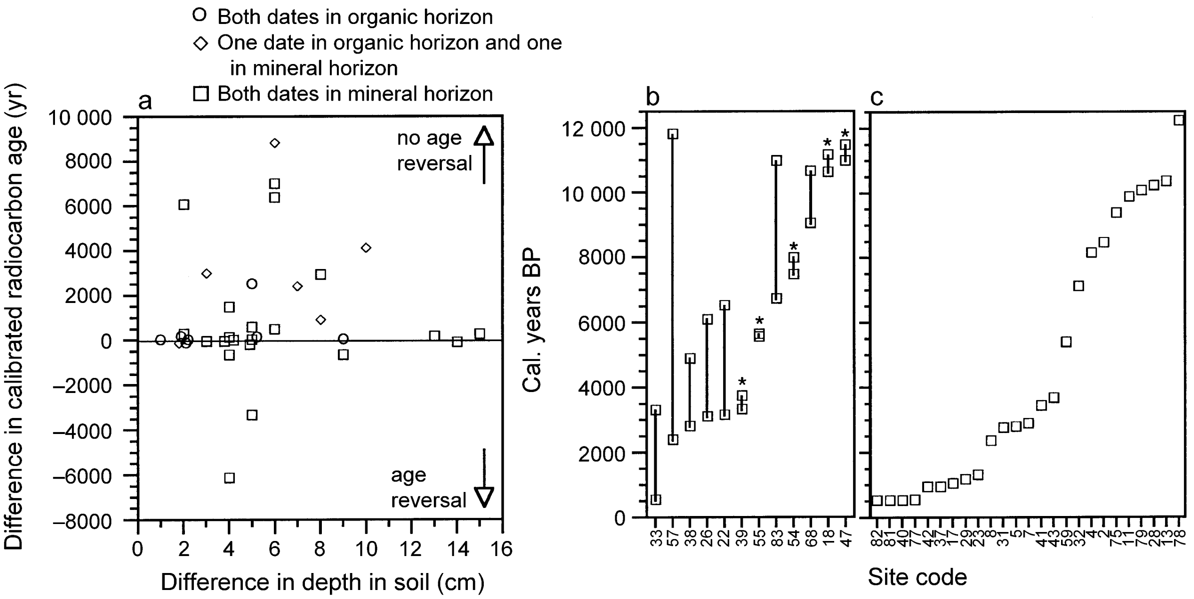

FIG. 3. Soil-charcoal radiocarbon dates. (a) Stratigraphic relationships among soil-charcoal radiocarbon dates from sites with multiple radiocarbon dates from the same soil core. All adjacent dates were compared (up to four dates or three comparisons per soil core), for a total of 35 comparisons from 21 cores. (b) Difference in dates from sites with dates from different cores. Only dates from the mineral horizon are shown. Sites with similar dates are indicated with a star. (c) Distribution of dates from sites with only one date from the mineral horizon. Sites codes in (b) and (c) refer to Fig. 4. (Note: ''Cal. years BP'' stands for calibrated years before AD 1950.)

increments (69% of the sites). Otherwise soil cores were not subdivided.

In the laboratory, soil-core sections ($n = 542$) were soaked for two hours in a warm 10% KOH solution to disperse organic clumps and then sieved through a 0.5-mm mesh screen. We dried the ≥0.5-mm fraction in a 70°C oven and identified charcoal under a binocular microscope. Charcoal pieces were weighed and the total mass for each site expressed relative to the volume of all sieved core sections. Eighteen sites yielded insufficient charcoal for a date (<1 mg); resampling within 50 m of these target sites during later field seasons yielded sufficient charcoal in 11 cases. In all, 8 of the original 91 target sites were excluded from the final data set: 7 sites with little or no charcoal and one with an anomalous radiocarbon date (see *Radiocarbon dates of soil charcoal,* below). These represent true ''holes'' in the spatial distribution of samples. Thus fire dates were available from 83 sites, consisting of 65 sites with radiocarbon dates, 16 sites with tree-ring records, and 2 sites with both radiocarbon dates and tree-ring records.

Because site selection was based on a number of criteria that could affect the spatial distribution of sample sites, we examined the spatial point pattern of the final data set to verify randomness with respect to the targeted spatial scale of the study (~200 m between sites). This was done by calculating all site-to-nearest-site distances (nearest-neighbor distances), expressed as a cumulative empirical distribution function, $\hat{G}$ (Diggle 1983). We compared $\hat{G}$ to simulated random point patterns generated by randomly choosing points from a list of 18 250 points on a 20-m grid in the irregularly shaped study area, and clumping or inhibition was identified at spatial scales where the $\hat{G}$ distribution fell outside the envelope generated from 99 simulations.

Radiocarbon dates of soil charcoal

The piece of charcoal closest to the surface of any soil core at a given site was selected for AMS (accelerator mass spectrometry) radiocarbon dating. All charcoal fragments were woody material (as opposed to bark or cones). Abundant charcoal near the surface of organic horizons was assumed to represent the most recent fire. We obtained more than one date at sites with sufficient charcoal and where there is less clear evidence of the most recent fire, e.g., where charcoal was present only in the mineral horizon and/or at low abundance, or where the first date was exceptionally old (>2000 yr BP). In all, 120 radiocarbon dates were obtained for 67 sites.

Each charcoal sample was cleaned using a warm 1 mol/L HCl rinse, several 1 mol/L KOH rinses, and a final 1 mol/L HCl rinse. If charcoal pieces were sufficiently large, radiocarbon dates were obtained from a single piece (80 dates). If all charcoal fragments were <1 mg following cleaning, it was necessary to combine two or more pieces from the same depth in the soil for a single radiocarbon date (40 dates). Such fragments were likely formed by the same fire event because in

TABLE 1. Number of sites with different numbers of dates per site in different soil horizons. Two rejected dates are not included.

	Number of dates per site				
	1	2	3	4	5
Soil horizon					
Organic only	7	1	0	2	0
Organic and mineral	···	2	3	1	1
Mineral only	25	22	2	1	0
Total number of sites	32	25	5	4	1

nearly all cases multiple dates from the same depth yielded identical radiocarbon ages (Fig. 3a). Charcoal was stored in 0.1 mol/L HCl before radiocarbon dating at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory (Livermore, California, USA). We calibrated radiocarbon dates to calendar years (Stuiver and Reimer 1993) using the INTCAL98 calibration curve (Stuiver et al. 1998). All dates are reported here in calibrated years before present (BP; note that ''present'' is defined as AD 1950). Two radiocarbon dates (CAMS-53488 and CAMS-53491 [CAMS-Center for Accelerator Mass Spectrometry, Lawrence Livermore]) were rejected because they were based on samples with low total carbon (∼0.2 mg) and were anomalous for the context of the surrounding forest, and thus appear to be contaminated with non-charcoal carbon.

Each calibrated radiocarbon date was adjusted to reflect the estimated error due to inbuilt age (Gavin 2001). This adjustment reduces the estimate of the overall age of the fire and increases the uncertainty of this estimate (Fig. 2b). Both adjusted and unadjusted calibrated radiocarbon dates are presented graphically. Because inbuilt-age adjustment affects each radiocarbon date similarly, statistical comparisons among sites are based only on unadjusted radiocarbon dates.

Interpretation of time-since-fire

Time-since-fire (TSF) for each site was estimated by a tree-ring date or the youngest calibrated radiocarbon date on charcoal. Comparisons among multiple radiocarbon dates at the same sites indicated that utilizing one radiocarbon date per site had a high likelihood of correctly identifying the time since the most recent fire. For example, where ≥2 dates were obtained from the same core (35 comparisons from 21 sites; Table 1), dates were similar (<300 yr difference) for 17 comparisons, dates increased with depth for another 14 comparisons, and age reversals occurred for only 4 comparisons (Fig. 3a). Charcoal in the organic horizon was always younger or the same age as charcoal at lower depths of the same core. Overall, charcoal in the organic horizon (i.e., high probability of dating the most recent fire) or tree-ring dates were available at 44% of the sites. Although the remainder of the sites were dated by charcoal in the mineral horizon and thus represent a potentially less accurate estimate of TSF, the increased number of dates we combined for inference at these sites (either by obtaining additional dates from the same core or from different cores) yielded similar fire dates 75% of the time (Fig. 3a and b). In all, only 25 sites were dated by a single date from the mineral horizon (Fig. 3c). We are confident that additional sampling would have corroborated these single dates ∼75% of the time.

Given that steep mountainous terrain as in the Clayoquot Valley causes a nonrandom spatial pattern of fire (Heyerdahl et al. 2001), the typical analysis of TSF frequency distributions using the negative exponential model (e.g., Johnson and Gutsell 1994) to estimate past fire frequency is inappropriate (Lertzman et al. 1998). Instead of using TSF to estimate a specific past fire frequency (the ''fire cycle''), we used the TSF frequency distribution to identify broad temporal patterns in past fire regimes. This interpretation is based on the assumption that climate change can override topographic controls over fire extent, resulting in charcoal age classes that are related to topographic features. For example, the presence of areas with longer-than-typical TSF may indicate that subsequent climate change was not sufficient to overcome topographic controls on fire extent. Thus clusters of sites with similar TSFs that deviate from the negative exponential distribution may indicate climatic periods when fires burned a larger portion of the landscape than during any subsequent period (Gavin 2000). This interpretation acknowledges that fire frequency may or may not change in concert with fire extent on the landscape.

Time-since-fire in different forest types and landforms

We compared TSF to forest vegetation and terrain characteristics in two ways. First, significant differences of median TSF among forest and landform categories were tested using randomization tests. Sites were grouped into three categories: forest plus landform type, forest type, and landform type. Each test consisted of comparing the difference in median TSF between two categories to a distribution generated from 3999 randomizations that allocated TSF dates to the two categories, adding the observed result as a value in the randomization distribution (Manly 1997). Significance was assessed as the proportion of randomizations in which differences in median TSF was as large or larger than that observed. Second, the relationship of TSF to the aspect of hill slopes was tested for each vegetation type with exponential regression. We transformed aspect to a continuous variable that is more closely related to the heating potential of solar radiation. Direct solar radiation during the warmest time of day is most effective at producing elevated surface temperatures. In the study area, maximum daily temperature in August occurs at ∼1430 hours, when

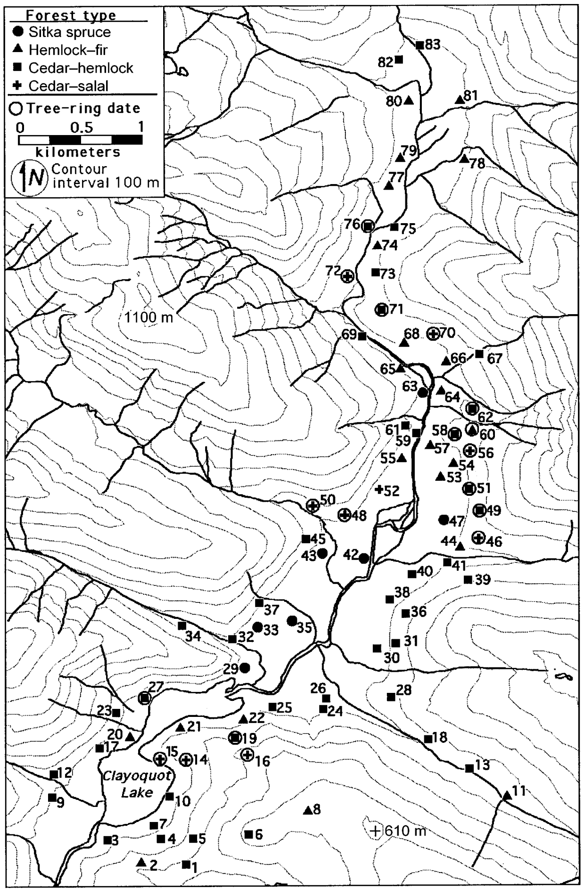

FIG. 4. Location of the 83 sample sites in the Clayoquot Valley, Vancouver Island, British Columbia, Canada (49°15′ N, 125°30′ W; see Fig. 1).

the solar azimuth is 15° west of south. The transformed aspect was then computed as cos(15 − aspect) + 1 (Beers et al. 1966), yielding values ranging between 0 and 2 for the warmest and coolest aspects, respectively.

Fire extent

We analyzed the spatial pattern of TSF to assess the scale at which fires burned. TSF cannot show the sizes of all fires because recent fires partially burn over and obscure the extent of older fires. However, the sizes of the most recent fires should be detectable as adjacent sites with similar TSF up to the scale of these fires. Thus, as a means of assessing fire extent, we compared TSF at adjacent sites to see if sites with similar dates were spatially aggregated. For all possible pairs of sites in nonoverlapping 250 m (the approximate median inter-site distance) distance classes, we computed the proportion of site pairs with TSF <300 yr apart (i.e., sites with effectively the same date). We assessed significant clumping of similar TSF using a randomization test (Manly 1997). This test consisted of comparing the proportion statistic for each distance class to a distribution of 3999 proportion statistics generated from randomly allocating the observed TSF dates to sites. Significance was assessed by constructing 95% confidence intervals from the randomization distribution, including the observed proportion statistic in the distribution. This analysis was run for all sites and by landform type (i.e., hill slope and terrace sites).

RESULTS

Site characteristics

The 83 sites were dispersed over the 730-ha study area. Approximately half of the sites (53%) were in the cedar–hemlock forest type, occurring mostly on east or west aspects (Fig. 4). Hemlock–fir forests were also well represented (27%), roughly equally common on terraces 10–60 m above the river and on hill slopes with north aspects. The remaining sites were in the cedar–salal forest type (12%), all of which were on south aspects, or the Sitka spruce forest type (8%) on terraces. Nearest-neighbor distances among sites ranged from 85 to 500 m, and were significantly evenly distributed relative to a random point pattern at scales <210 m. Sites were randomly distributed at scales of 210–500 m.

Tree-ring and soil-charcoal radiocarbon dates of fire

Twenty-three tree-ring estimates of fire dates ranged from ca. AD 1550 to AD 1886 (Table 2). Taken to-

TABLE 2. Tree-ring dates of fire events in the Clayoquot Valley on Vancouver Island (British Columbia, Canada) obtained by coring at least seven trees per cohort. All sites occurred on hill slopes.

Site code†	Vegetation type‡	Dating method	Fire date (year AD)§
14	CS	growth response	1805
		stand age	1620
15	CS	stand age	1805
16	CS	stand age	1805
19	CH	growth response	1805
27	CH	growth response	1886
46	CS	stand age	1655
48	CS	stand age	1550
49	CH	growth response	1872
50	CS	stand age	1550
51	CH	growth response	1872
		stand age	1683
56	CS	stand age	1683
58	CH	growth response	1872
		stand age	1610
60	HF	growth response	1683
62	CH	growth response	1872
70	CS	growth response	1830
		stand age	1620
71	CH	growth response	1805
		stand age	1620
72	CS	stand age	1620
76	CH	growth response	1805

† Site code refers to numbered locations in Fig. 4.

‡ CH = cedar–hemlock, CS = cedar–salal, HF = hemlock–fir.

§ Dates were determined from stand ages or from abrupt growth responses to fire injury in surviving trees.

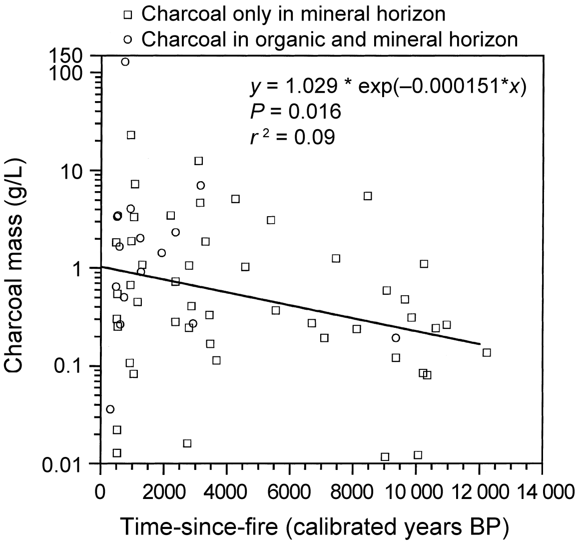

FIG. 5. Charcoal mass in soil related to time-since-fire at 65 sites in the Clayoquot Valley. Charcoal mass was determined from pieces >0.5 mm in 3–7 cores (5-cm diameter). Note logarithmic scale on the *y*-axis.

gether, these dates indicated 15 fire events. In five instances, similar tree-ring dates at adjacent sites suggest that fires spread between sites, though never more than 1 km. In two instances (AD 1895 and ca. AD 1620) the pattern of fire dates suggested near-synchronous fires from multiple ignitions, because sites were widely spaced and intervening sites did not show evidence of fire. The 120 calibrated radiocarbon dates on soil charcoal (67 sites) ranged from 310 to 12 220 yr BP (see Appendix B for a complete list of dates). Charcoal mass varied greatly among sites, and was only weakly related to the time since the most recent fire (TSF) ($r^2 = 0.09$) (Fig. 5).

Time-since-fire (TSF)

The estimates of TSF ranged from 64 to ~12 220 yr (Fig. 6). Though the number of sites in 200-yr TSF age classes generally decreased from 0 to 1400 yr, sites were present in most age classes over our record. Approximately 45% of the sites have burned in the last 1000 yr, whereas 20% of the sites have not burned for over 6000 yr (Fig. 6). Two clusters of sites indicate increased fire activity (spatial extent and possibly frequency of fire) during ca. 3200–2200 yr BP (11 sites) and 11 000–9000 yr BP (12 sites). Adjusting radiocarbon dates for inbuilt-age shifts the TSF distribution forward in time, but does not affect the overall form of the distribution.

The distribution of TSF differed greatly between hill slope and terrace sites (Fig. 7). On hill slopes the majority of sites (56%) burned within the last 1000 yr, and only a few (11%) exhibit a date >6000 yr ago. In contrast, terraces have a nearly even distribution over TSF age classes, with relatively few sites (21%) burning within the last 1000 yr compared to those (43%) with the most recent fire >6000 yr BP. Overall, the median TSF on terraces (4410 yr) was 6 times greater than on hill slopes (740 yr) ($P < 0.001$).

TSF showed a weaker relationship with forest type than landform (Fig. 7). In the cedar–hemlock, hemlock–fir and Sitka spruce forest types, the range of TSF spanned roughly the entire Holocene (0–11 200 yr BP). The range and median value of TSF was smaller in the cedar–salal forest type than in other forest types, though the difference was significant only with Sitka spruce forest ($P < 0.001$), and weakly significant with

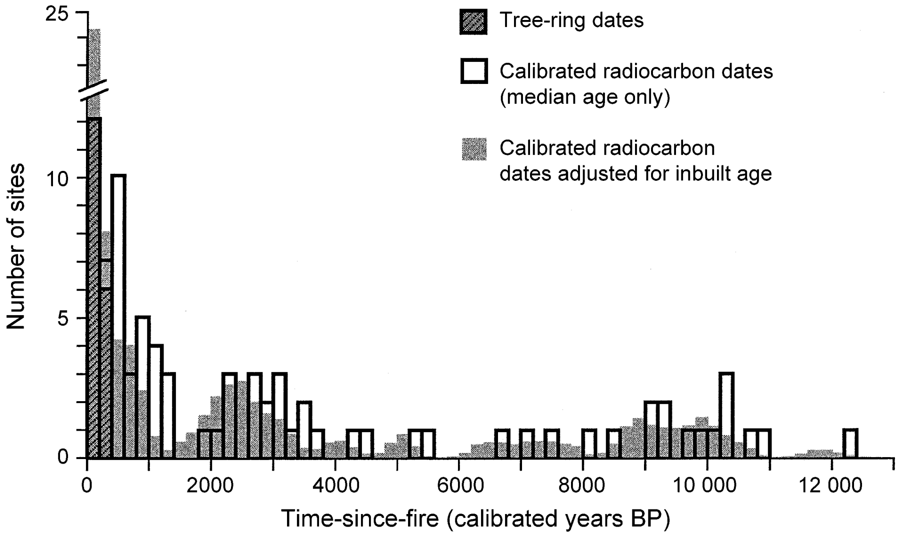

FIG. 6. Time-since-fire distribution at 83 sites in the Clayoquot Valley. Shaded bars represent the range of uncertainty in radiocarbon dates from radiocarbon calibration and from inbuilt age (age of wood at time of fire).

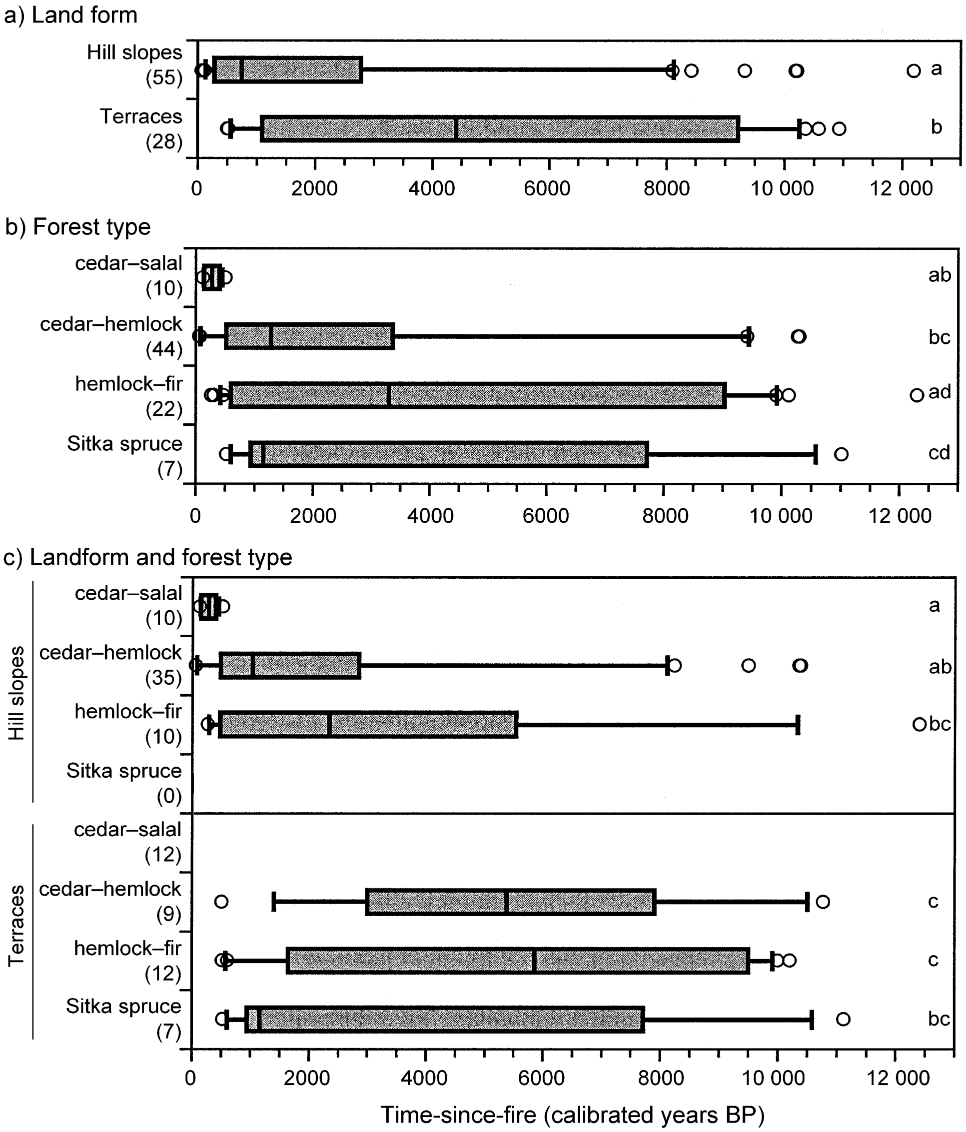

FIG. 7. Box-and-whisker plots of time-since-fire (TSF) for 83 sites in the Clayoquot Valley. Ranges of TSF are contrasted by landform, by forest type, or by both landform and forest type. Boxes represent the second and third quartiles (the center line represents the median), whiskers represent the 10th–25th and the 75th–90th percentiles, and circles represent outliers ($<$10th or $>$90th percentiles). The number of sites in each class is indicated in parentheses. Landforms and/or forest types in the same panel with the same lowercase letter are not significantly different in median TSF at $P < 0.05$ (as determined by randomization test). Note that the effect of inbuilt age on the interpretation of radiocarbon dates (see *Methods: Radiocarbon dates of soil charcoal*) would decrease each quantile in the above distributions by ~400 yr.

hemlock–fir forest ($P = 0.095$). However, when separated by landform, median TSF in cedar–salal forest was significantly shorter than all other forest type/landform combinations ($P < 0.001$, except for cedar–hemlock hill-slope forest, $P = 0.111$). Median TSF differed between the forest types that occur on both landforms (cedar–hemlock and hemlock–fir) ($P = 0.043$). This difference is attributable to large differences between these forest types on contrasting landforms. Specifically, cedar–hemlock *hill slopes* had a significantly shorter median TSF than cedar–hemlock *terraces* ($P = 0.004$) and hemlock–fir *terraces* ($P = 0.002$). In contrast, median TSF was similar between these forest types on the same landform ($P = 0.158$ and 0.873 for hill slopes and terraces, respectively).

All south- and west-facing hill slopes (transformed aspect $<$0.9) have burned within the last 1000 yr, compared to only 27% of north- and east-facing hillslopes (transformed aspect $>$0.9; Fig. 8). The slope parameter for the exponential regression between TSF and transformed aspect was significant for all 55 hill-slope sites ($\beta = 1.01$, $F = 13.8$, $P = 0.001$).

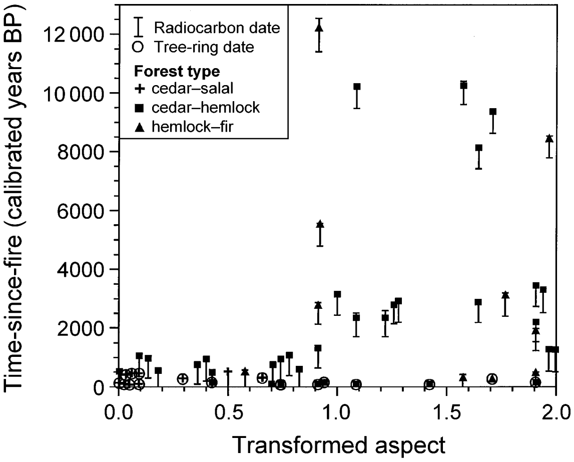

FIG. 8. Time-since-fire estimates relative to transformed aspect for the 55 sites on hill slopes. Error bars represent the 95% confidence interval of charcoal radiocarbon dates after adjusting for potential inbuilt age (see *Methods: Radiocarbon dates of soil charcoal*). In some cases points were slightly offset for clarity.

This relationship was significant for the cedar–hemlock forest sites ($\beta = 0.94$, $F = 5.33$, $P = 0.027$). Slope parameters were not significantly different from zero for cedar–salal and hemlock–fir forest ($P = 0.17$ and 0.64, respectively).

Fire extent

Sites with similar TSF were significantly more common than expected for randomly distributed fire dates at scales <250 m (Fig. 9). On hill slopes, fires frequently spread up to 250 m but not beyond, as the proportion of site pairs with similar TSF declined sharply at scales >250 m. At scales of 1250–2000 m, similar TSF among sites suggests an underlying regular pattern of fire in the study area, possibly due to the regular spacing of south aspects that burned at similar times. In contrast, there were no significant spatial relationships of TSF on terraces, suggesting fire extent was rarely larger than the smallest distances between sites (100–250 m). However, sampling on terraces may have been too sparse to detect a strong spatial pattern at this scale.

DISCUSSION

Obtaining fire-history data from soil charcoal

The soil charcoal record provides an ability to make inferences about fire history that would not otherwise be possible in forests such as the Clayoquot Valley, where fire scars and other sources of evidence are limited. Charcoal is ubiquitous and well-preserved in the Clayoquot Valley, and was found at nearly all of the targeted sites, sometimes as large pieces embedded in highly weathered clay-enriched mineral horizons of Spodosols. However, charcoal abundance was highly variable, suggesting the importance of processes that operate at small spatial scales, such as original charcoal production and the effects of microtopography on local charcoal deposition. Charcoal abundance may be affected to a lesser degree over time by fragmentation (from action of rootlets or freeze–thaw cycles; Carcaillet and Talon 1996). These factors result in a weak but significant relationship between charcoal mass and time-since-fire (TSF) (Fig. 5).

Although charcoal is common in soils, it was restricted to mineral soil horizons at most sites, especially in the older part of the record (>4000 yr BP). The charcoal stratigraphy in the mineral horizons may be complex because these horizons do not accumulate

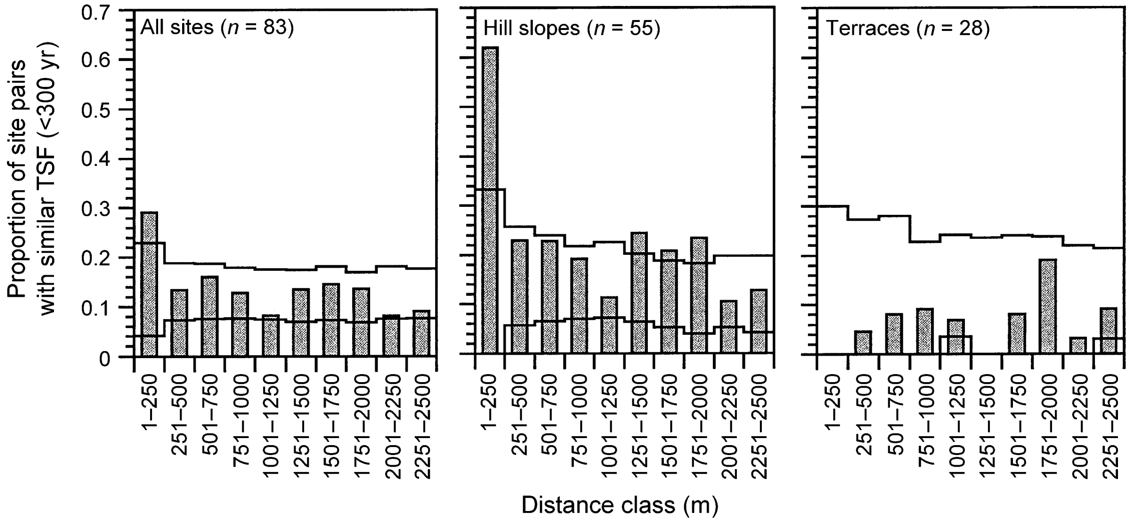

FIG. 9. The proportion of all possible site pairs that have differences in time-since-fire (TSF) < 300 yr in nonoverlapping distance classes. Horizontal lines indicate 95% confidence intervals based on 3999 randomizations of TSF among sites.

continuously, and the disturbances required to bury charcoal in the mineral horizon could also alter different parts of the record. For example, down-slope soil movement may rework soil, selectively removing surficial soil layers, and tree tip-ups may lift root plates to a vertical position and greatly mix soil horizons. Soil mixing may explain the several instances of age reversals found in this horizon (Fig. 3).

Despite these concerns regarding the soil record, our sampling methods appear to have maximized detection of charcoal from the most recent fire at each site and minimized the effects of processes that modify the soil charcoal record. First, we sampled small concavities and searched a broad area at each site for charcoal in organic horizons rather than a small area that may have been affected by a single soil disturbance. We demonstrated that the uppermost piece of charcoal in organic horizons was consistently the youngest piece of charcoal at each site, and multiple dates from mineral horizons were also consistent with each other 75% of the time (Fig. 3). Second, in another study we found abundant charcoal that dated to the most recent fire at sites where tree-ring fire dates were possible (Gavin 2001). Last, all the cases of very long TSF were consistent within the context of landscape variation in the susceptibility to fire (Figs. 7 and 8). In addition, the probability of detecting charcoal from the most recent fire rather than from older fires is increased because a fire itself consumes soils and erases the record of older fires. Thus, although there will always be an unresolvable level of uncertainty associated with millennial-scale TSF estimates based on soil charcoal, these multiple lines of evidence increase our confidence in the estimated TSF distribution.

Late Holocene fire pattern

Landform controls.—The clearest indication of the influence of terrain on the fire regime is the frequent occurrence of fires in the last 600 yr on south-facing hill slopes, especially cedar–salal stands where Douglas-fir trees are most common (Figs. 7 and 8). This finding supports the conclusion that recent fires on western Vancouver Island were largely limited to well-drained and exposed south-facing hill slopes based solely on the distribution of Douglas-fir (Schmidt 1960, 1970). Furthermore, the existence of isolated patches of Douglas-fir in the Clayoquot Valley suggests a long-term history of fire at such locations, because Douglas-fir requires a local seed source of live trees to reestablish following disturbance (Beach and Halpern 2001). For Douglas-fir to persist for multiple generations at a site, fires must reoccur locally at intervals within the typical life span of the oldest trees, ~700–800 yr (Franklin and Hemstrom 1981, Huff 1995). Thus the persistence of Douglas-fir in ecosystems such as the Clayoquot Valley likely depends on the long-term existence of isolated fire-susceptible patches in the landscape. In a parallel study of a sediment record from Clayoquot Lake (Fig. 4), we found strong support for the recurrence of fire on south-facing slopes (Gavin 2000). In that study, we detected 23 fires that occurred within 500 m of the lake during the last 1800 yr, and that, based on the spatial map of TSF, the locations of these fires were limited to south-facing slopes near the lake (Gavin 2000). This is consistent with the strong spatial heterogeneity of susceptibility to fire found in this study.

Some fires in the Clayoquot Valley could have been larger than those documented by this study (i.e., >250 m in extent) if they were ignited at dry sites on hill sides above the study area and spread down slope. This possibility is supported by the spatial distribution of forest types within the watershed. Specifically, cedar–salal forests, which are restricted to the highest hill slopes in the study area, consistently burned within the last 600 yr (Fig. 7). These stands are especially susceptible to fire because of their location on south-facing slopes and their open forest canopy that promotes drying of fuels. Since this forest type occurs extensively at middle elevations in Clayoquot Valley, many fires may have originated above our study area, where lightning and fire ignitions are more common (Pickford et al. 1980, Romme and Knight 1981). Extending sampling to higher elevations would be necessary to explore this possibility.

Climatic controls.—In the 15 fire events dated by tree rings, two instances of synchronous fires at widely disjunct sites were identified (AD 1805 and ca. AD 1620). Annual synchrony in fire is evidence that specific weather events influence fire occurrence (Swetnam 1993, Veblen et al. 1999). Synchrony on annual and decadal time scales is evidence that climatic events or short-term variations may also control fire extent (Swetnam and Betancourt 1990, Heyerdahl et al. 2002). The Clayoquot Valley fires may have been associated with atmospheric circulation patterns similar to those causing fires on the Olympic Peninsula (~150 km to the south), where the climatology of several large lightning fires has been studied (Huff and Agee 1980, Pickford et al. 1980). The Olympic Peninsula fires were ignited after more than three weeks without rain in years with below-average rainfall, and grew rapidly during dry foehn winds from east of the Cascade Range. These east winds usually occur when a high-pressure ridge over the northeast Pacific moves inland to southern British Columbia, producing strong easterly or northeasterly winds that become warmer and drier when they descend the west slope of the Cascade (Washington) or Coast (British Columbia) Range (Agee 1993). These ridges may persist and block moisture-bearing onshore winds for weeks (Skinner et al. 1999).

Weather patterns that cause synchronous fires within a single watershed may also influence fire occurrence at a regional scale. There is some evidence that the AD 1805 and ca. AD 1620 fires may have been coincident with fires in other areas of the Pacific Northwest. For example, Schmidt (1970) identified eight major fire events on Vancouver Island, one of which (AD 1610) is identical to a fire in the Clayoquot Valley (Table 2). Although old-growth Douglas-fir stands are thought to have originated from episodic, widespread fire events associated with specific climatic periods (e.g., Sprugel 1991, Agee 1993), little is known about synchronous fire events on a regional scale.

A period of high fire activity ca. 3200–2200 yr BP preceded a minimum in fire activity between 2200 and 1400 yr BP (Fig. 6). This pattern of high and low fire activity also matches climatic interpretations from a sediment record from eastern Vancouver Island that shows decreased precipitation during 3250–2100 yr BP followed by greatly increased precipitation during 2100–1750 yr BP (Nederbragt and Thurow 2001), the latter of which corresponds to the Roman Warm Period recognized in Europe (Lamb 1995). Correlation of fire activity with more recent climatic periods (Medieval Warm Period and Little Ice Age; Lamb 1995) are likely obscured by the error inherent in charcoal radiocarbon dates and the increasing trend in TSF frequency over the last 1000 yr.

Early Holocene fire pattern

Landform controls.—TSF estimates >6000 yr were restricted to terraces and a few north- and east-facing hillslopes (Figs. 7 and 8). These landforms have low susceptibility to fire because fire spreads more slowly on flat surfaces, and limited solar radiation in the understory (due to aspect and dense multitiered canopies) limits the drying of fuels. A regional climate that causes these landforms to be susceptible to fire would also cause the remainder of the landscape to be susceptible, perhaps resulting in large fire events. Instances of late Holocene fires on terraces and north-facing hill slopes likely resulted from fires that penetrated short distances into low-susceptibility terrain via spotting and intense radiant heat (e.g., Agee and Huff 1980). This pattern of fire on terraces and north-facing hill slopes resulted in the observed small fire size and uniform distribution of TSF encompassing the entire Holocene (Figs. 7 and 9).

Climatic controls.—Paleoclimate models and empirical evidence support the interpretation that the landscape was overall more susceptible to fire during the early Holocene. Orbital geometry at 10 000 yr BP caused an 8% increase in summer insolation at 50°N latitude (Thompson et al. 1993). A general-circulation model for this period suggests that increased seasonality of solar insolation and the intensification of the subtropical Pacific high-pressure system led to higher summer temperatures and lower precipitation in this region (Thompson et al. 1993). Charcoal and pollen in early Holocene lake sediments from Vancouver Island and the Olympic Peninsula document increased fire activity and increases in Douglas-fir and red alder, both of which require disturbance for regeneration in areas west of the Cascade Range (McLachlan and Brubaker 1995, Brown and Hebda 2002). The early Holocene forests also lacked western redcedar and contained little western hemlock, the two species that dominate the modern landscape (Hebda and Mathewes 1984). Thus, it is likely that different forest composition, canopy density, and fuel types during the early Holocene also contributed to a different fire regime (Cwynar 1987). The interpretation of variation in fire activity at finer temporal scales during the early Holocene is hampered by the paucity of high-resolution climate records from the Pacific Northwest.

Role of fire in the landscape dynamics of coastal temperate rain forest

Recent studies (Lertzman and Fall 1998, Heyerdahl et al. 2001) have emphasized that fire regimes can be controlled by small-scale terrain features and fuel dynamics (bottom-up controls) operating within the context of the large-scale (regional) variation in climate (top-down controls). The present study demonstrates that top-down controls have a temporal component, fluctuating with millennial-scale climate change. During the early Holocene, bottom-up controls of topography on fuel moisture and stand structure, which are strong under the present climate, were overcome by substantially different top-down controls (i.e., the climate regime), causing fires to be more common on terraces and north-facing hill slopes than in the late Holocene. In contrast, during the late Holocene, bottom-up controls of topography effectively limited the extent of fire, so that these types of sites were less often burned. Bottom-up controls also appear to be responsible for the modern mosaic of sites with forest stand structures such as Douglas-fir trees, even age classes, and/or stunted cedar–salal forest types, as were found at the majority of sites that burned in the last 600 yr (Figs. 7 and 8).

We confirm earlier reviews that suggest recent fires in the coastal temperate rainforest have been mostly restricted to steep south-facing hill slopes (Schmidt 1970, Veblen and Alaback 1996). The results also provide strong evidence that a significant proportion of low-elevation forest has not burned for the last 6000 yr. Such remarkably long fire-free intervals have rarely been documented in any forest type worldwide (e.g., Kershaw et al. 1997), and have important implications for long-term forest dynamics and regional forest patterns. First, in the absence of other large-scale disturbances, forest composition probably tracked Holocene climate change primarily through processes of gap replacement (Lertzman et al. 2002). Species turnover would have occurred through the differential success of shade-tolerant species recruiting into canopy gaps under a given set of climatic conditions. Due to the longevity of Pacific Northwest conifer species, compositional changes through gap replacement might often have lagged Holocene climate change by several centuries (Lertzman 1995). Second, the absence of recent fire at many sites suggests that old-growth forest structures also predominated on landscapes throughout the late Holocene (Lertzman et al. 2002). This landscape pattern contrasts sharply with forests east of the Vancouver Island Range as well as the majority of forests in the United States Pacific Northwest, which were dominated by Douglas-fir, indicative of larger fires in recent centuries (Franklin and Dyrness 1988). Our present study, therefore, supports the distinction of the wetter coastal temperate rain forest as affected by a fundamentally different disturbance history than the remainder of Pacific Northwest forests to the east and south.

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APPENDIX A

An aerial photograph of the Clayoquot Valley (Vancouver Island, British Columbia, Canada) showing the southern half of the study area is available in ESA's Electronic Data Archive: *Ecological Archives* E084-004-A1.

APPENDIX B

A complete list of the 120 radiocarbon dates of soil charcoal obtained from 67 sites in the Clayoquot Valley (Vancouver Island, British Columbia, Canada) is available in ESA's Electronic Data Archive: *Ecological Archives* E084-004-A2.