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13,000 years of fire history derived from soil charcoal in a British Columbia coastal temperate rain forest

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Abstract. Little is known regarding the fire history of high-latitude coastal temperate rain forests in the Pacific Northwest (PNW) of North America. While reconstructing historical fire regimes typically requires dendrochronological records from fire-scarred trees or stratigraphically preserved lake sediment data, this type of information is virtually non-existent in this region. To describe the long-term fire history of a site on the central coast of British Columbia, Canada, we radiocarbon-dated 52 pieces of charcoal. Charcoal ages ranged from 12,670 to 70 yr BP. Fires occurred regularly since 12,670 yr BP, with the exception of a distinct fire-free period at 7500–5500 yr BP. Time since fire (TSF) estimates from soil charcoal and fire-scarred trees ranged from 12,670 to 100 yr BP (median = 327 yr), and 70% of the sites examined had burned within the past 1000 yr. An increase in fire frequency in the late Holocene is consistent with the widely held hypothesis that anthropogenic fires were common across the PNW. We evaluate TSF distributions and discuss the difficulties in assigning actual fire dates from charcoal fragments with large inbuilt ages in a coastal temperate rain forest setting. We determine that a comprehensive approach using soil charcoal and fire scar analyses is necessary to reconstruct general trends in fire activity throughout the Holocene in this region.

Key words: British Columbia; coastal temperate rain forest; Holocene fire history; human–climate–fire interactions; Pacific Northwest; radiocarbon dating; soil charcoal.

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Introduction

Coastal temperate rain forests in the Pacific Northwest (PNW) of North America are believed to have a very low frequency of forest fires, reflecting their location in one of the wettest biomes on Earth (Veblen and Alaback 1996). This low forest fire activity is typically attributed to the high amounts of precipitation and to the rarity of lightning in these settings (McWethy et al. 2013). Taken together, these attributes decrease the probability of ignition in coastal forests characterized by large-diameter, moisture-laden fuels (Lertzman et al. 2002, Daniels and Gray 2006). Although the role of lightning relative to human ignitions in coastal temperate rain forest settings remains unclear, sustained periods of warm and dry conditions are likely required to promote fuel conditions conducive to fire initiation and spread (Bowman et al. 2011). Moreover, despite mounting ethnographic evidence for the human use of fire by Indigenous peoples in the PNW over millennia (Walsh et al. 2015), little is known of the influence of these practices on the magnitude and frequency of fires in coastal temperate rain forests. Nor is there a long-term perspective on how these fire regimes may have been altered as a result of cultural changes related to European contact and 20th-century policies of fire suppression (Lepofsky et al. 2005).

With the exception of the boreal forests, most contemporary forest types in Canada experience lightning- and human-caused fires in near equal proportions (Stocks 1991). Human-caused fires are predominantly associated with the locations of industry, roads, and cities (Pew and Larsen 2001). Lightning is rare in coastal temperate rain forests in British Columbia (average area burned as a result of lightning ignitions from 1959 to 1997 is < 0.01%) (Stocks et al. 2002). Prior to the 20th century, as they were in other parts of North America (Ryan et al. 2013), Indigenous peoples could have been an important ignition source, by synchronizing ignitions with the most fire-conducive period of the year (Marlon et al. 2012, McWethy et al. 2013).

The purpose of this research was to reconstruct the Holocene fire history of a coastal temperate rain forest on the central coast of British Columbia, Canada. Reconstructing historical fire regimes often involves high-resolution networks of georeferenced fire-scarred trees (Falk et al. 2011). Although fire-scarred trees can provide annually resolved records of fire activity, fire-scarred trees are rare in coastal temperate rain forests and do not fully reveal fire recurrence on time scales relevant to the slow dynamics of these forests (Daniels and Gray 2006). Over longer time periods and at regional scales, fire occurrence may be explored by examination of charcoal deposited in wetland or lake sediments (Hallett et al. 2003, Whitlock et al. 2010). Unfortunately, this method is not spatially explicit and sometimes includes charcoal fragments from distant fires (Gavin et al. 2003*a*). Using wood charcoal deposited in soils, however, can provide a complementary approach to these other methods for reconstructing long-term fire histories in coastal temperate rain forests (e.g., Lertzman et al. 2002, Gavin et al. 2003*b*).

Wood charcoal is an inert form of carbon that can persist in soil for millennia (Carcaillet 2001, Lertzman et al. 2002). However, various processes can disrupt the layering of temporal sequences of charcoal in soils. These include the decomposition or accumulation of organic material, bioturbation by roots or animals, tip up mounds, or more recent fires that consume humus and erase previous records of soil charcoal (Gavin et al. 2003*b*). Although microscopic charcoal may be transported significant distances by wind and water, macroscopic charcoal (> 5 mm) found in depositional hollows within standing forests likely originated within a few tens of meters (Clark and Patterson 1997). Thus, radiocarbon ages assigned to the latter can be used to date a fire that occurred at, or very near, the site of deposition (Higuera et al. 2007, Payette et al. 2012). As the radiocarbon ages assigned to the charcoal reflect the date of carbon dioxide fixation rather than fire, radiocarbon dates may predate the actual fire event. Addressing the source of this "inbuilt age" is critical in temperate rain forests where fires may burn old woody debris that may exceed ages of 1000 yr (Gavin 2001).

Methods

Study area

The research was completed within the Hakai Lúxvbálís Conservancy on Calvert and Hecate islands (51°38′ N, 128°05′ W), a 160-km^2 island group located on the central coast of British Columbia, Canada (Fig. 1). The study area is situated in the very wet hypermaritime subvariant of the Coastal Western Hemlock zone of British Columbia's biogeoclimatic classification system (Meidinger and Pojar 1991). This region receives some of the highest annual rainfall in North America (~4000 mm) and is characterized by subdued and rugged topography, moderate year-round temperatures (~7°C), and low rates of evapotranspiration (Banner et al. 1993). There is no history of industrial logging in the study area.

Ancient human land use and settlement patterns have varied spatially and temporally throughout the study area, and archeological evidence suggests human presence in the region for at least 13,000 yr (McLaren et al. 2014, 2015). The study area contains three formerly occupied habitation sites with extensive shell middens (> 3 m depth) and an abundance of near shore features including fish traps, clam gardens, and root

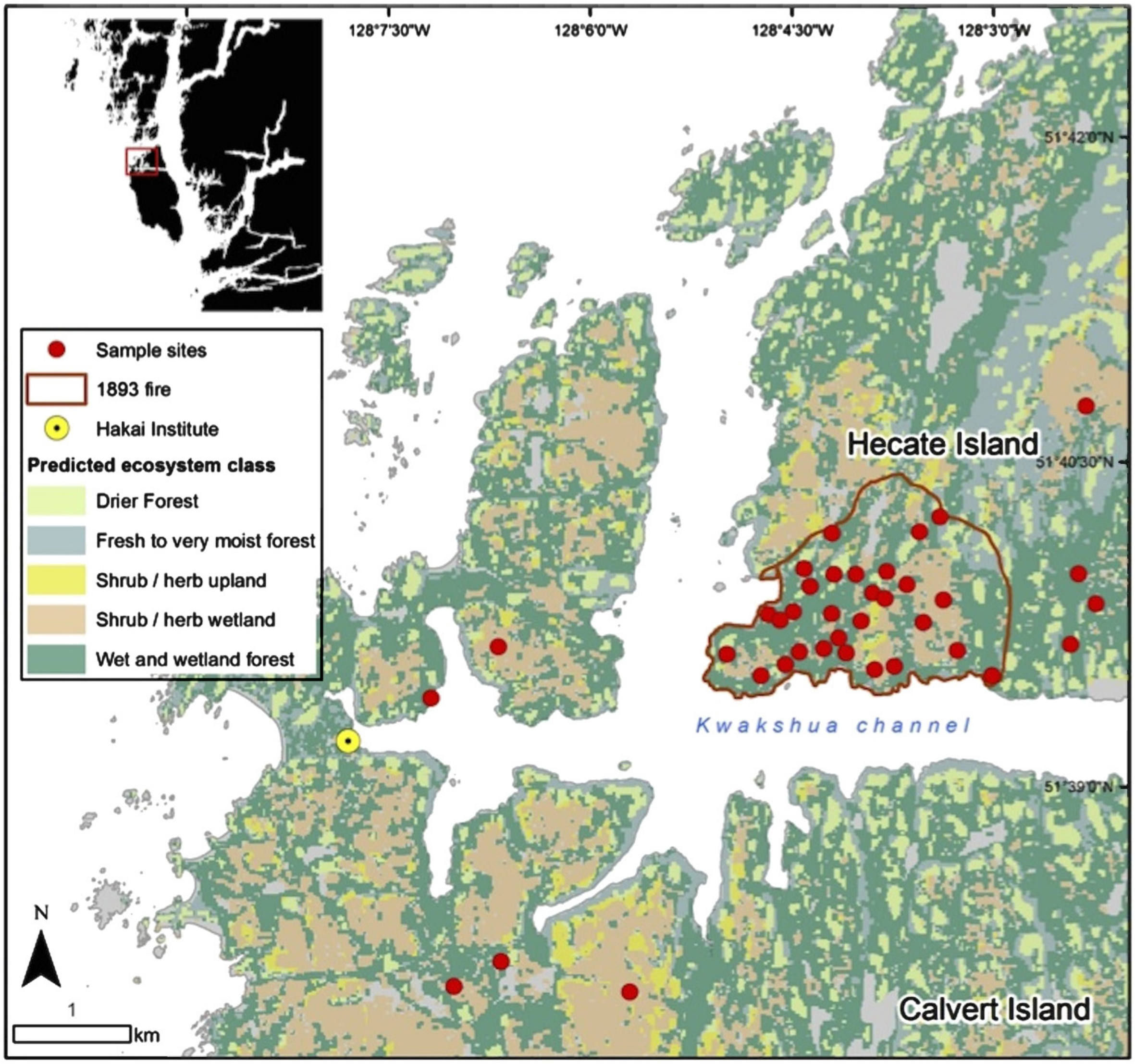

Fig. 1. The location of sample sites (red circles) on Calvert and Hecate islands. The inset provides the location of the study site on the central coast of British Columbia, Canada.

gardens that were continuously utilized throughout the Holocene (Stafford et al. 2009, McLaren et al. 2014). There are no records or evidence of fire in the study area in the 20th century and few oral histories of pre-contact anthropogenic fire. However, controlled burning by Indigenous peoples, referring to the purposeful burning of vegetation for plant and animal management, was used in nearby and analogous ecosystems (Turner 1999, Trusler and Johnson 2008).

The bedrock geology of Calvert and Hecate islands is almost entirely of igneous origin, comprised of a mix of quartz diorite and granodiorite (Roddick 1996). Compared to the adjacent mainland, there are very few glacial features or glaciogenic deposits. Upland mineral soils are generally nutrient-poor Ferro-Humic Podzols that are strongly influenced by the underlying bedrock geology (Banner et al. 1993). Shallow, imperfectly drained organic soils accumulate folic material (forest material, branches, roots) and are classified as Folisols. Poorly drained soils with high rates of peat accumulation are Typic or Fibric Mesisols (Valentine et al. 1978). Because of the subdued and low-lying terrain, there is little evidence of down slope movement of soils.

Four main vegetation types defined by dominant species and closely associated with terrain attributes and soils are found in the study area: zonal forests, bog forests, bog woodlands, and blanket bogs (Banner et al. 2005). Productive zonal forests are associated with hill slopes and riparian areas and are comprised of moderately drained Folisols where thin organic horizons developed on gravelly colluvium over bedrock (Banner et al. 1993). These forests are dominated by large-diameter western redcedar (*Thuja plicata* Donn ex D. Don.) and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) with lesser amounts of yellow-cedar (*Cupressus nootkatensis* [D. Don] Farjon and Harder) and Sitka spruce (*Picea sitchensis* [Bong.] Carr.) (Meidinger and Pojar 1991).

Bog forests have similar soils to zonal forests and are found almost exclusively on hillslopes. They exhibit stunted growth forms and are dominated by western redcedar, yellow-cedar, western hemlock, and shore pine (*Pinus contorta* var. *contorta* Douglas ex Louden) (Klinka et al. 1996). Bog woodlands are found in patchy mosaics of forested and unforested sites in subdued or rolling terrain and are dominated by western redcedar, yellow-cedar, and shore pine with lesser amounts of mountain hemlock (*Tsuga mertensiana* Bong.) (Klinka et al. 1996). Blanket bogs with both minerotrophic and ombrotrophic characteristics occur in sparsely forested wetland areas (Banner et al. 2005). Minerotrophic bogs are comprised of vascular plants and sedges with shallow, nutrient-poor Ferro-Humic Podzols forming over bedrock while ombrotrophic bogs are dominated by sphagnum species and contain organically enriched, nutrient-poor soils (MacKenzie and Banner 2001).

Forested sites in the study area are characterized by living and dead fuels in various stages of decay (Feller 2003). The majority of surface fuels are comprised of moisture-rich, large-diameter coarse woody debris, which is often covered by a dense canopy and moss on the forest floor (Daniels and Gray 2006). Surface fuels have low flammability compared to dead, standing fuels that can be significantly drier and may be an important fuel source in hypermaritime forests (Daniels 2003, Dorner and Wong 2003). Fire events are thought to be most common in the late summer when high-pressure ridges form on the coast of British Columbia, promoting sustained warm and dry weather conditions (Lertzman et al. 2002, Macias Fauria and Johnson 2006).

Thirty-nine sites stratified by the proportional representation of four vegetation types: zonal forest (15%), bog forest (26%), bog woodland (31%), and blanket bog (28%) were sampled in the 300-ha study area (Fig. 1). One soil pit was dug at each site, and multiple pieces of soil charcoal were sampled from each soil profile. The most intact fire-scarred trees were sampled at each site where they were present. The study area was selected to overlap (75% of sites) a 287-ha fire dated with fire-scarred trees to AD 1893. To compare the effects of time since the most recent fire event (time since fire [TSF]) on different fuel and vegetation characteristics apparent in the four vegetation types, we sampled the remaining 25% of sites with the same methods in forests with no recent aboveground fire evidence on Hecate and Calvert islands.

Charcoal sampling and analysis

Charcoal layered in discrete stratigraphy was apparent in soils throughout the study area, suggesting a long history of fire activity. Thirty-nine soil pits (one per sampling site) 20–150 cm in depth and 100–500 m apart were selectively sampled in concavities (1–2 m^2) found on locally level terrain. To minimize erosional loss of charcoal, sites were chosen in locations not affected by downslope movement (Carcaillet 2001, Lertzman et al. 2002). Macroscopic charcoal was sampled in the field, and microscopic charcoal was collected in stratigraphy (bulk soil) and sampled under a dissecting microscope in the laboratory. Detailed descriptions of soil charcoal stratigraphy and soil classifications are presented in Appendix S1: Table S1.

Samples were washed with deionized water in the laboratory, and charcoal fragments were sieved carefully through a 0.5-mm mesh. For charcoal pieces >5 mm, we used taphonomic keys developed by Mustaphi and Pisaric (2014) to obtain information about the species, morphology, and wood type. For these samples, radiocarbon dates were obtained from a single piece of charcoal. If charcoal fragments were <2 mm or did not contain enough mass for radiocarbon dating, two or three pieces of charred wood were combined from the same depth in the soil for radiocarbon dating (35% of samples). Multiple charcoal fragments deposited in the same stratigraphy likely formed from the same fire event (Lertzman et al. 2002). Gavin et al. (2003*b*) tested this hypothesis and found that 40 radiocarbon dates obtained from two to three microscopic charcoal fragments in the same stratigraphic layer yielded nearly identical radiocarbon dates. Although the total number of samples submitted for radiocarbon dating was constrained by the funds available, charcoal fragments were selected based on the quality, depth, and location of the sample in continuous stratigraphy and to best represent all vegetation and soil types.

Samples were radiocarbon-dated (^{14}C) using accelerator mass spectrometry (AMS) at Keck Carbon (University of California-Irvine, Irvine, California, USA). Radiocarbon dates were calibrated to calendar years with the INTCAL13 calibration curve (Rev 7.0.4 program) (Reimer et al. 2013). All dates are reported as calibrated years before present (yr BP [1950]) using the median of the probability distribution of each radiocarbon date. We submitted 10–20 charcoal samples at a time for dating, and the depth and age results obtained were used to adapt the strategy for further submissions.

We used Gavin's (2001) methodology and inbuilt age equation to create an inbuilt age model specific to our study area. When possible, we selectively sampled charred fragments of bark, needles, branches, or outer wood to decrease inbuilt age and to provide a more accurate age for radiocarbon dating. Fourteen fire scars dating the most recent fire event were used to calculate the inbuilt age distribution and the adjusted error (Table 1). We assigned radiocarbon dates to fire scars when a series of two or more fire scars could be matched to a stratigraphic pattern of soil charcoal. The adjusted error was calculated as a weighted moving average of the probability distribution of the calibrated radiocarbon age using the inbuilt age distribution as a set of weights (Gavin 2001). Inbuilt age adjustments were added to the two-sigma radiometric error of each radiocarbon date.

Fire scar sampling and analysis

Sampling fire scars in the study area was necessary to create estimates of inbuilt age, record recent fire activity for TSF estimates, and to validate selections of soil charcoal for radiocarbon dating. We removed wedges with a chainsaw from the bases of living, fire-scarred trees within the one-hectare area surrounding each study site (Arno and Sneck 1977). In areas with a high density of intact fire scars, the most sound or the oldest of the trees (determined after coring and measuring) were collected (Arno and Sneck 1977). To validate dating of fire scars, we obtained two 5-mm increment cores ~1.3 m from the

Table 1. Fourteen radiocarbon dates from the uppermost soil layers were corrected with known fire dates from fire-scarred trees in the study area.

Site	Method	Year of fire (AD)	^{14}C age BP	Median age cal AD (two-sigma error)	Inbuilt age
Hecate Island	Fire scar	1893	290 ± 20	1558 (1520–1653)	335
Hecate Island	Fire scar	1893	120 ± 15	1842 (1684–1953)	51
Hecate Island	Fire scar	1893	115 ± 20	1840 (1683–1953)	53
Hecate Island	Fire scar	1719	375 ± 15	1488 (1451–1618)	231
Hecate Island	Fire scar	1893	245 ± 15	1656 (1644–1795)	357
Hecate Island	Fire scar	1893	595 ± 15	1344 (1306–1404)	549
Hecate Island	Fire scar	1744	290 ± 15	1554 (1522–1651)	339
Hecate Island	Fire scar	1893	205 ± 15	1784 (1653–1950)	109
Hecate Island	Fire scar	1656	375 ± 40	1495 (1449–1585)	161
Hecate Island	Fire scar	1778	200 ± 15	1779 (1654–1951)	0
Hecate Island	Fire scar	1893	510 ± 15	1422 (1409–1436)	471
Hecate Island	Fire scar	1778	570 ± 20	1346 (1313–1416)	432
Hecate Island	Fire scar	1893	250 ± 20	1654 (1643–1793)	239
Hecate Island	Fire scar	1893	280 ± 15	1591 (1521–1662)	302

Note: Inbuilt age was calculated as the difference between the fire year and the median age calibrated AD intercept.

ground from 90 trees (three species-specific chronologies) in forest stands outside of the 1893 fire perimeter with no aboveground fire evidence (Johnson and Gutsell 1994).

In the laboratory, fire scar wedges and increment cores were processed using standard dendrochronological techniques (Stokes and Smiley 1968). Samples were visually cross-dated and then statistically verified using the computer program COFECHA (Grissino-Mayer 2001). We combined fire scar dates from the study area into a composite record and identified fire years as those in which at least two trees had fire scars. We determined the exact calendar year of fire occurrence by cross-dating fire scars to species-specific tree-ring chronologies (Johnson and Gutsell 1994).

Interpretation of TSF

Time since fire dates were acquired from fire scars or from the youngest calibrated radiocarbon date sampled at each site (Gavin et al. 2003*b*). Estimates for TSF were calculated and the lower and upper quantiles were compared between vegetation types and between the two study areas (sites located within and outside of the 1893 fire perimeter) with randomization tests in the WRS2 package in R statistical software (R Development Core Team 2016). The rationale for comparing TSF within the 1893 fire perimeter to outside of the 1893 fire perimeter was due to the close proximity of three former Indigenous habitation sites within the 1893 fire perimeter which may include targeted resource sites that were repeatedly burned over millennia. Because we do not know the historic composition and distribution of vegetation in the study area throughout the Holocene, we also assessed the relationship between terrain attributes derived from a digital elevation model (DEM) with TSF distributions.

Results

Radiocarbon dating and soil charcoal stratigraphy

In total, 97 soil charcoal samples were obtained. Thirty-five samples were deemed replicates with regard to soil type and stratigraphy. Ten samples that did not fit our ecological criteria (see *Methods*) were deprioritized due to budget allocation. Fifty-two samples from 39 sites were submitted for radiocarbon dating.

The radiocarbon ages assigned to the charcoal samples ranged from 12,670 to 70 yr BP. Radiocarbon age, calibrated dates, and median calibrated probabilities with associated errors are presented in Appendix S1: Table S2. One radiocarbon date was rejected because it was based on a sample with low carbon (< 1 mg). All radiocarbon dates were physically stratified by depth, with no age reversals, and charcoal fragments in organic soil types were consistently younger than charcoal in mineral soil types (Gavin 2003) (Appendix S1: Table S1). This finding confirmed that the uppermost charcoal layer accurately represented TSF distributions (Fig. 2a) (Gavin et al. 2003*b*).

Fire scars and soil charcoal

Cross-dating of 99 fire scars from 45 wedges revealed 15 distinct fire events during the period AD 1376–1893. The majority of wedges were from western redcedar (73%) and yellow-cedar (20%), but we also sampled a small portion of shore pine (7%). Fourteen sampling sites contained multiple fire events recorded on fire-scarred trees, and we were able to link the five most recent fires in the study area with soil charcoal buried in stratigraphy. The association between fire scars and soil charcoal was based on the expectation, supported by our investigations (Appendix S1: Table S1), that surficial charcoal deposited near the soil surface (< 5 cm) originated from the most recent fire event (Lertzman et al. 2002, Gavin et al. 2003*b*). Our criteria for linking fire scars to soil charcoal to build our inbuilt age model included selecting depressions or hollows where charcoal was likely to accumulate, avoiding sampling when there was evidence of past soil disturbances (e.g., tip up mounds, mass wasting), and prioritizing charred bark, twigs, and macroscopic charcoal deposited in stratigraphy. This sampling procedure was critical to building accurate inbuilt age adjustments for the broader study area (Table 1).

Time since fire

Time since fire was acquired from fire scars (54% of sites) or from the youngest calibrated radiocarbon date sampled at each site (46% of sites) (Appendix S1: Table S3). Several sites had shallow soils (median = 15 cm depth) with one charcoal date (67% of sites). Sites with > 2

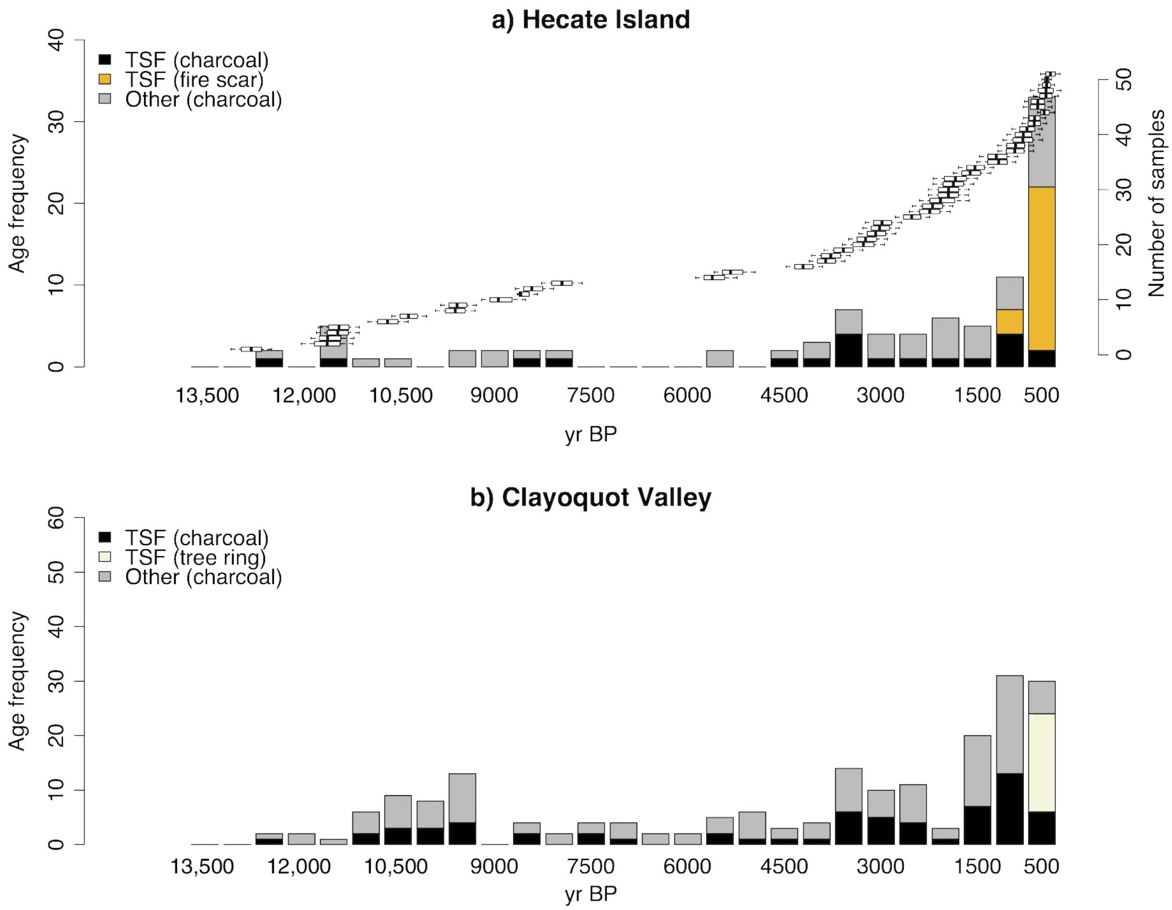

Fig. 2. (a) Age frequency of the calibrated median probability of 51 soil charcoal dates on Hecate Island from 13,500 yr to present. Time since fire (TSF) estimates were derived from the youngest calibrated radiocarbon dates at 19 sites. The remaining TSF dates were dated with fire scars at 20 sites. "Other (charcoal)" is the remaining soil charcoal radiocarbon dates obtained at sites where TSF was estimated by younger radiocarbon or tree-ring dates. The small box and whisker plots are radiocarbon dates with adjustments of inbuilt age (additional to the two-sigma radiometric and calibrated error) for each sample, and the *y*-axis (right side) shows the number of samples distributed through time. (b) For the purpose of regional comparison, TSF and age frequency of the calibrated median probability of 113 soil charcoal dates including radiocarbon samples used in inbuilt age adjustments from Clayoquot Valley over 13,000 yr. TSF estimates were derived from the youngest calibrated radiocarbon date from 65 sites. The remaining TSF estimates were dated from forest stands (tree rings) at sites that established after fire events (Gavin et al. 2003*b*). Note the different *y*-axes.

charcoal dates consistently demonstrated increased age with depth (Appendix S1: Table S1). Therefore, we are confident that using one radiocarbon date to estimate TSF had a high likelihood of correctly identifying the most recent fire (Gavin et al. 2003*b*).

Excluding dates from the AD 1893 fire, TSF estimates ranged from 12,670 to 100 yr BP (median = 327 yr) and the median of the charcoal-based TSF was 2030 yr BP (Fig. 3; Appendix S1: Table S3). There was no significant difference ($P = 0.54$) in TSF between the four vegetation types in the study area (Fig. 3a) nor between TSF and terrain attributes derived from the DEM (Appendix S2: Fig. S1). Because there were no fire scars present outside of the 1893 fire perimeter, we compared TSF with the youngest calibrated radiocarbon dates acquired from each

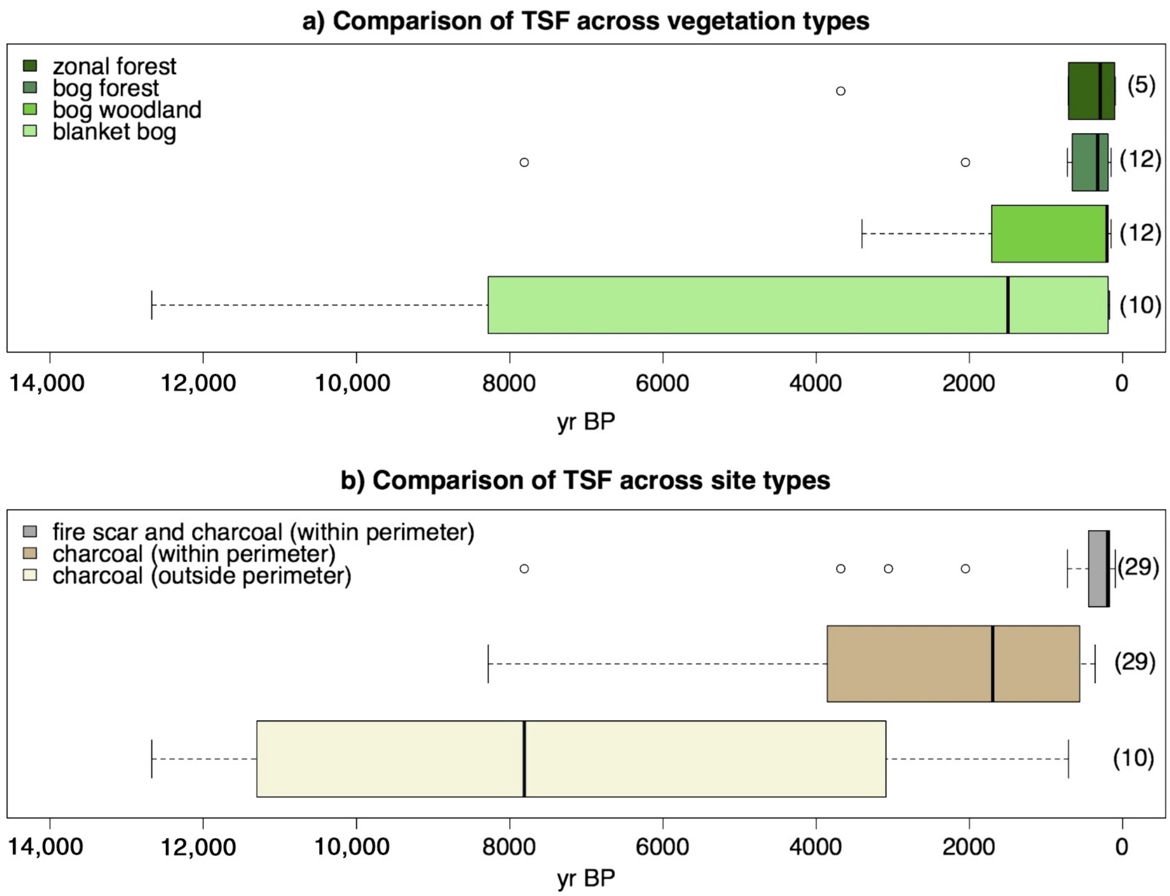

Fig. 3. (a) Box and whisker plots of time since fire (TSF) for 39 sites in the study area. Sample sizes are in brackets to the right of box and whisker plots. Boxes represent the second and third quartile ranges, and the center line is the median. Circles represent outliers. TSF was not statistically different when comparing vegetation types ($P = 0.54$). (b) Box and whisker plots of TSF distributions within and outside of the 1893 fire perimeter (fire scars and soil charcoal dating the 1893 fire were removed from this analysis). Sites outside of the 1893 perimeter had significantly longer TSF when compared to sites within the 1893 fire perimeter ($P = 0.003$). Sites that included fire scars in TSF distributions had significantly shorter TSF when compared to sites within the 1893 fire perimeter that had been dated with soil charcoal only ($P = 0.001$).

site (not including fire scars or soil charcoal from the 1893 fire). The removal of charcoal and fire scar dates derived from the 1893 fire revealed that sites sampled within the 1893 fire perimeter experienced more fire events and had significantly shorter TSF than elsewhere in the study area ($P = 0.003$) (Fig. 3b). Examinations of landform controls including aspect, slope, elevation, and derived terrain attributes did not explain the spatial pattern of TSF estimates within or outside of the 1893 fire perimeter. The summed probabilities of fire occurrence and TSF for each vegetation type are displayed in Appendix S2: Fig. S2 and a photograph of the four vegetation types in the study area are presented in Appendix S2: Fig. S3.

Inbuilt age

Inbuilt age adjustments ranged from 0 to 549 yr and one sample required no adjustment (Table 1; Appendix S2: Fig. S4). Most radiocarbon dates had errors >160 yr (25th percentile), >360 yr (75th percentile), and <471 yr (95th percentile). The greatest observed inbuilt age was 549 yr. Our inbuilt age model determined that in this vegetation type and with soil charcoal data, fires separated by < 549 yr cannot be considered separate events. We added the 549-yr maximum inbuilt age to the two-sigma radiometric error of each radiocarbon date to determine whether fire events were distinct or overlapping. Using the maximum inbuilt age, we recorded 15 distinct fire events with soil charcoal. Fire scar and soil charcoal-derived TSF estimates are presented in Fig. 2a along with the adjusted inbuilt age distribution of every radiocarbon date sampled in the study area.

Discussion

Our analyses of soil charcoal and fire scars from four vegetation types confirm that fire has been a feature of this landscape for millennia. The cumulative probability distributions of the 51 radiocarbon dates demonstrate lengthy periods with a higher frequency of recurring fires from 12,700 to 7500 and from 5500 to 70 yr BP, with a distinct fire-free interval between ~7500 and 5500 yr BP (Fig. 4a). Because 23% of our samples recorded fires in the 12,700–7500 yr BP period, we can be confident that our interpretation of temporal trends in fire activity is not limited by a decrease in the number of samples through time (Gavin 2003). There is an abrupt increase in fire evidence after ~3200 yr BP across all sites (Fig. 4b). This increase could represent ignitions by Indigenous peoples and cultural shifts associated with increasing populations and a growing demand for plant resources surrounding village sites (Deur 2002, Lepofsky et al. 2005).

Although forest fires are often linked to large-scale climate variability (Macias Fauria and Johnson 2006), an increase in the summed probability distribution of radiocarbon dates from ~3200 yr BP to AD 1893 is apparent in our data despite a transition to a cooler and wetter climate in the late Holocene (Brown and Hebda 2002, McLaren et al. 2015). When we compare these findings to those of a related study of soil charcoal in the Clayoquot Valley, ~300 km to the south on Vancouver Island, synchronous increases in fire activity appear in both records at 11,000–9000 and 3200 yr BP, as well as decreases between ~7500 and 5500 yr BP (Gavin et al. 2003*b*, Fig. 2b). Declines in fire activity in the mid-Holocene likely correspond to a complex mix of cultural and environmental shifts occurring in the region (Brown and Hebda 2002). These include rising sea levels (McLaren et al. 2015), decreased summer insolation and an increase in the strength of the Aleutian low (Bartlein et al. 1998), and the arrival of western hemlock and culturally significant western redcedar (Hebda and Mathews 1984).

The composition of the forests that burned over the past 13,000 yr in the study area remains largely unknown. While the species of 54% of the radiocarbon samples was determined, we were unable to determine species assemblages in the early Holocene (Appendix S1: Table S2). Western redcedar, a rot-resistant and long-lived species that has been present in the study area for at least 6000 yr dominated the remains of charcoal in the mid- and late Holocene (Pojar and MacKinnon 1994, Brown and Hebda 2002). Increased dating and identification of charcoal deposited in lower soil stratigraphy could reveal more accurate estimates of when western redcedar arrived in the region. We attempted to select short-lived species such as shore pine to decrease the inbuilt age of radiocarbon dates, but found that shore pine comprised only 13% of samples (Appendix S1: Table S2). This confirms that attempting to decrease inbuilt age estimates through selective sampling in this vegetation type may not be feasible.

Estimates of TSF varied from just over 100 yr to several millennia across all vegetation types in the study area (Fig. 3). An abrupt increase in the summed probability of fire occurrence is clear in the late Holocene, with 70% of sites recording TSF of < 1000 yr (Appendix S1: Table S3). Broadly similar findings were reported by Lertzman et al. (2002) and Gavin et al. (2003*a*) in the Clayoquot Valley, where, despite 20% of the landscape not having burned for > 6000 yr, the TSF at 45% of sites examined was < 1000 yr BP (Fig. 2b). Notably, in our study, 10% of sites examined had not burned in over 7000 yr and one blanket bog appears not to have burned since 12,672 yr BP. For both the Clayoquot Valley case and our own, although there has been fire present on the landscape over time, it is patchily distributed in space and time and the TSF distributions have an exceedingly long tail.

While TSF is often related to landscape features such as slope position, aspect, and elevation and also often varies with regard to vegetation type (Lertzman et al. 2002, Gavin et al. 2003*b*, Berg and Anderson 2006), there was no obvious such spatial pattern of fire occurrence in the study area.

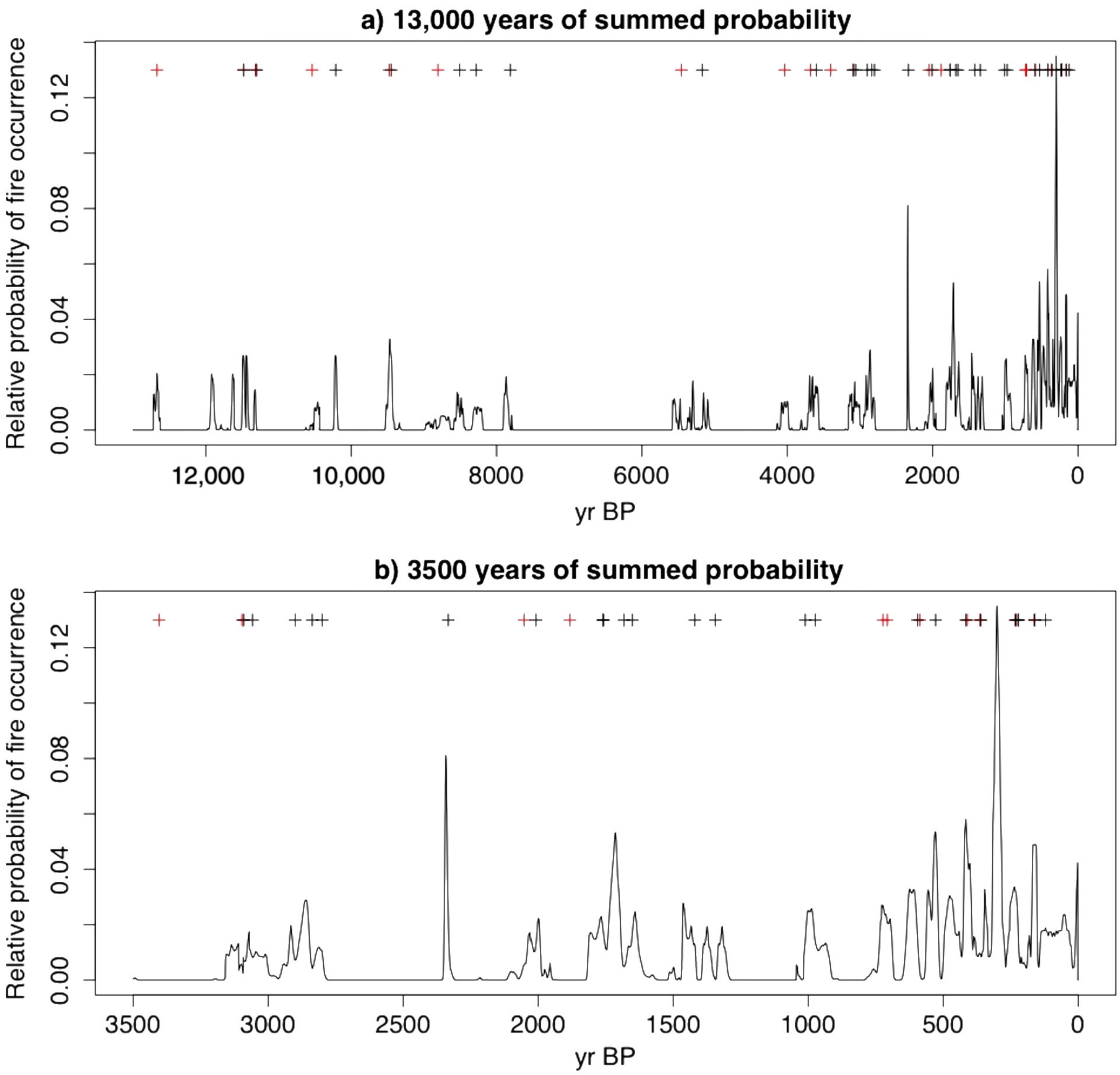

Fig. 4. (a) The entire record of soil charcoal-based fire dates. Crosses (+) display the median age of each radiocarbon date. Red crosses indicate distinct fire events and black crosses indicate unconfirmed fire events due to overlapping probability distributions after inbuilt age adjustments. The relative probability of fire occurrence is demonstrated by totaling the summed probability distributions of 51 radiocarbon dates across the study area from 13,000 yr BP to 0 (representing the AD 1893 fire). (b) A subset of 34 dates, showing the most recent 3500 yr at higher resolution. An increase in the probability of fire occurrence is recorded from ~3200 yr BP to 0 (representing the AD 1893 fire). There is no fire evidence in the study area after AD 1893.

Our results show no difference in TSF between vegetation types despite large differences in fuel availability and fuel moisture (Fig. 3a; Appendix S1: Table S3), nor were there any significant differences across terrain types (Appendix S2: Fig. S1). There were significant differences in TSF within and outside of the 1893 fire perimeter, suggesting the 1893 fire was located in a portion of the landscape more frequently experiencing fire (Fig. 3b). We suggest this pattern may reflect differences in available ignition sources due to the proximity of three continuously inhabited sites within the 1893 fire perimeter compared to one seasonally inhabited site outside of the 1893 fire perimeter (McLaren et al. 2015). If this is true, the fire regime is more influenced by human activities than site-by-site inherent ecological or topographic characteristics.

To avoid misidentifying fire events, we only considered soil charcoal radiocarbon dates as a proxy for fire events when they were separated by at least the greatest observed inbuilt age (549 yr) (Gavin 2001) (Appendix S2: Fig. S4). This approach provided a minimum estimate of the number of fire events in the study area throughout the Holocene. Although inbuilt age errors are likely significantly smaller in drier, fire-prone ecosystems, not adjusting for inbuilt age and solely identifying fire events using the assigned radiometric error would have, probably falsely, incurred a 93% increase in fire occurrence in the study area (29 compared to 15 fire events recorded with soil charcoal). We opted for a cautious approach, utilizing an inbuilt age model, to identify fire events and assess fire regimes in forests with long-lived conifer species.

The marked increase in the summed relative probability of charcoal ages after ~3200 yr BP ends abruptly with the 287-ha fire in AD 1893. Although Indigenous people continue to use the area for seasonal resource gathering, habitation sites have not been occupied since the late 19th century (McLaren et al. 2015). The 13,000-yr pattern of coexistence of fire and people in the study area contrasts with the relative absence of both fire and people from the study area in the 20th century. This conjunction of a long history of human habitation with the presence of fire in a very wet, hypermaritime landscape is an important area for future study.

This is the first reconstruction of fire activity on the central coast of British Columbia and within hypermaritime forests in British Columbia and Alaska. When soil charcoal was matched to fire scars in living trees, we found that the uppermost layer of charcoal dated the most recent fire event in both organic and mineral soils and that the most abundant charcoal was found at the interface of organic and mineral horizons (Appendix S2: Figs. S5 and S6). We did not find any examples where soil charcoal was present and had an age < 500 yr BP with no aboveground evidence of fire activity. Because fire scars form on trees under specific physical and biological conditions, we can infer that portions of recent fire events were low and mixed in severity (Falk et al. 2011). Like in other systems (Heyerdahl et al. 2012), in this region, it is important to combine different types of evidence to reconstruct patterns of long-term fire activity. In our case, combining soil charcoal and fire scar analyses allowed us to describe millennia of fire activity, which we could not from either source alone.

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Literature Cited

Arno, S. F., and K. M. Sneck. 1977. A method for determining fire history in coniferous forests of the mountain west. USDA Forest Service General Technical Report INT-42. Intermountain Forest and Range Experiment Station, Ogden, Utah, USA.

Banner, A., W. MacKenzie, S. Haeussler, S. Thomson, J. Pojar, and R. Trowbridge. 1993. A field guide to site identification and interpretation for the Prince Rupert Forest Region. Land Management Handbook 26. Ministry of Forests, Victoria, British Columbia, Canada.

Banner, A., P. LePage, J. Moran, and A. de Groot. 2005. The HyP3 Project: pattern, process and productivity in hypermaritime forests of coastal British Columbia-a synthesis of 7-year results. Special Report 10:142. Ministry of Forests, Victoria, British Columbia, Canada.

Bartlein, P., K. Anderson, P. Anderson, M. Edwards, C. Mock, R. Thompson, R. Webb, and C. Whitlock. 1998. Paleoclimate simulations for North America over the past 21,000 years: features of the simulated climate and comparisons with paleoenvironmental data. Quaternary Science Reviews 17:549–585.

Berg, E. E., and R. S. Anderson. 2006. Fire history of white and Lutz spruce forests on the Kenai

Peninsula, Alaska, over the last two millennia as determined from soil charcoal. Forest Ecology and Management 227:275–283.

Bowman, D. M. J. S., et al. 2011. The human dimension of fire regimes on Earth. Journal of Biogeography 38:2223–2236.

Brown, K., and R. J. Hebda. 2002. Origin, development, and dynamics of coastal temperate conifer rainforests of southern Vancouver Island, Canada. Canadian Journal of Forest Research 32:353–372.

Carcaillet, C. 2001. Are Holocene wood-charcoal fragments stratified in alpine and subalpine soils? Evidence from the Alps based on AMS ^{14}C dates. Holocene 11:231–242.

Clark, J. S., and W. A. Patterson III. 1997. Background and local charcoal in sediments: scales of fire evidence in the paleorecord. Springer-Verlag, Berlin, Germany.

Daniels, L. D. 2003. Western redcedar population dynamics in old-growth forests: contrasting ecological paradigms using tree rings. Forestry Chronicle 79:517–530.

Daniels, L. D., and R. W. Gray. 2006. Disturbance regimes in coastal British Columbia. Journal of Ecosystems and Management 7:44–56.

Deur, D. 2002. Rethinking precolonial plant cultivation on the Northwest Coast of North America. Professional Geographer 54:140–157.

Dorner, B., and C. Wong. 2003. Natural disturbance dynamics on the North Coast. Report to the Land Resource Management Plan. Province of British Columbia, Victoria, British Columbia, Canada.

Falk, D. A., E. K. Heyerdahl, P. M. Brown, C. Farris, P. Z. Fulé, D. McKenzie, T. W. Swetnam, A. H. Taylor, and M. L. Van Horne. 2011. Multi-scale controls of historical forest-fire regimes: new insights from fire-scar networks. Frontiers in Ecology and the Environment 9:446–454.

Feller, M. C. 2003. Coarse woody debris in the old-growth forests of British Columbia. Environmental Reviews 11:135–157.

Gavin, D. G. 2001. Estimation of inbuilt age in radiocarbon ages of soil charcoal for fire history studies. Radiocarbon 43:27–44.

Gavin, D. G. 2003. Forest soil disturbance intervals inferred from soil charcoal radiocarbon dates. Canadian Journal of Forest Research 33:2514–2518.

Gavin, D. G., L. B. Brubaker, and K. P. Lertzman. 2003*a*. An 1800-year record of the spatial and temporal distribution of fire from the west coast of Vancouver Island, Canada. Canadian Journal of Forest Research 33:573–586.

Gavin, D. G., L. B. Brubaker, and K. P. Lertzman. 2003*b*. Holocene fire history of a coastal temperate rain forest based on soil charcoal radiocarbon dates. Ecology 84:186–201.

Grissino-Mayer, H. D. 2001. Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. Tree-Ring Research 57: 205–221.

Hallett, D. J., D. S. Lepofsky, R. W. Mathewes, and K. P. Lertzman. 2003. 11,000 years of fire history and climate in the mountain hemlock rain forests of southwestern British Columbia based on sedimentary charcoal. Canadian Journal of Forest Research 33:292–312.

Hebda, R. J., and R. W. Mathews. 1984. Holocene history of cedar and native Indian cultures of the North American Pacific Coast. Science 225:711–713.

Heyerdahl, E. K., K. Lertzman, and C. M. Wong. 2012. Mixed-severity fire regimes in dry forests of southern interior British Columbia, Canada. Canadian Journal of Forest Research 42:88–98.

Higuera, P. E., M. E. Peters, L. B. Brubaker, and D. G. Gavin. 2007. Understanding the origin and analysis of sediment-charcoal records with a simulation model. Quaternary Science Reviews 26:1790–1809.

Johnson, E. A., and S. L. Gutsell. 1994. Fire frequency models, methods and interpretations. Advances in Ecological Research 25:153–166.

Klinka, K., H. Qian, J. Pojar, and V. Del Meidinger. 1996. Classification of natural forest communities of coastal British Columbia, Canada. Vegetatio 125:149–168.

Lepofsky, D., D. Hallett, K. Washbrook, A. McHalsie, K. Lertzman, and R. Mathewes. 2005. Documenting precontact plant management on the Northwest Coast: an example of prescribed burning in the central and upper Fraser Valley, British Columbia. Pages 218–239 *in* D. E. Deur and N. J. Turner, editors. Keeping it living: traditions of plant use and cultivation on the Northwest coast. University of Washington Press, Seattle, Washington, USA.

Lertzman, K., D. Gavin, D. Hallett, L. Brubaker, D. Lepofsky, and R. Mathewes. 2002. Long term fire regime estimated from soil charcoal in coastal temperate rainforests. Conservation Ecology 6:2–5.

Macias Fauria, M., and E. A. Johnson. 2006. Large-scale climatic patterns control large lightning fire occurrence in Canada and Alaska forest regions. Journal of Geophysical Research: Biogeosciences 111:2005–2012.

MacKenzie, W. H., and A. Banner. 2001. A classification framework for wetlands and related ecosystems in British Columbia: third approximation. Research Branch, British Columbia Ministry of Forests, Victoria, British Columbia, Canada.

Marlon, J. R., P. J. Bartlein, D. G. Gavin, C. J. Long, R. S. Anderson, C. E. Briles, K. J. Brown, D. Colombaroli, D. J. Hallett, and M. J. Power. 2012. Long-term perspective on wildfires in the western USA. Proceedings of the National Academy of Sciences USA 109:535–543.

McLaren, D., D. Fedje, M. B. Hay, Q. Mackie, I. J. Walker, D. H. Shugar, J. B. Eamer, O. B. Lian, and C. Neudorf. 2014. A post-glacial sea level hinge on the central Pacific coast of Canada. Quaternary Science Reviews 97:148–169.

McLaren, D., F. Rahemtulla, Gitla (E. White), and D. Fedje. 2015. Prerogatives, sea level and the strength of persistent places: archaeological evidence for long-term occupation of the central coast of British Columbia. BC Studies: British Columbian Quarterly 187:155–191.

McWethy, D. B., P. E. Higuera, C. Whitlock, T. T. Veblen, D. M. J. S. Bowman, G. L. Cary, and G. L. W. Perry. 2013. A conceptual framework for predicting temperate ecosystem sensitivity to human impacts on fire regimes. Global Ecology and Biogeography 22:900–912.

Meidinger, D., and J. Pojar. 1991. Ecosystems of British Columbia. Special Report Series 6. Ministry of Forests Research Branch, Victoria, British Columbia, Canada.

Mustaphi, C. J. C., and M. F. Pisaric. 2014. A classification for macroscopic charcoal morphologies found in Holocene lacustrine sediments. Progress in Physical Geography 38:734–754.

Payette, S., A. Delwaide, A. Schaffhauser, and G. Magnan. 2012. Calculating long-term fire frequency at the stand scale from charcoal data. Ecosphere 3:59.

Pew, K. L., and C. P. S. Larsen. 2001. GIS analysis of spatial and temporal patterns of human-caused wildfires in the temperate rain forest of Vancouver Island, Canada. Forest Ecology and Management 140:1–18.

Pojar, J., and A. MacKinnon. 1994. Plants of the Pacific Northwest coast. Lone Pine, Vancouver, British Columbia, Canada.

R Development Core Team. 2016. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://cran.r-project.org/web/packages/WRS2/

Reimer, P. J., et al. 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0-50,000 years cal BP. Radiocarbon 55:1869–1887.

Roddick, J. A. 1996. Queens Sound (102P) British Columbia: Geological Survey of Canada, open file 3278, scale 1:250,000. Natural Resources Canada, Ottawa, Ontario, Canada.

Ryan, K. C., E. E. Knapp, and J. Morgan Varner. 2013. Prescribed fire in North American forests and woodlands: history, current practice and challenges. Frontiers in Ecology and the Environment 11:15–24.

Stafford, J., J. Maxell, and T. Christensen. 2009. Hakai Luxvbalis and outer coast islands conservancies, archaeological impact assessment of 11 selected recreation sites. HCA Permit 2008-372. Archaeology Branch, Victoria, British Columbia, Canada.

Stocks, B. J. 1991. The extent and impact of forest fires in northern circumpolar countries. Massachusetts Institute of Technology Press, Cambridge, Massachusetts, USA.

Stocks, B. J., et al. 2002. Large forest fires in Canada, 1959-1997. Journal of Geophysical Research 108:FFR5–1.

Stokes, M. A., and T. L. Smiley. 1968. An introduction to tree-ring dating. University of Chicago Press, Chicago, Illinois, USA.

Trusler, S., and L. M. Johnson. 2008. “Berry patch” as a kind of place—the ethnoecology of black huckleberry in Northwestern Canada. Human Ecology 36:553–568.

Turner, N. J. 1999. Time to burn: traditional use of fire to enhance resource production by Aboriginal Peoples in British Columbia. Pages 185–218 *in* R. Boyd, editor. Indians, fire and the land in the Pacific Northwest. Oregon State University Press, Corvallis, Oregon, USA.

Valentine, K. W. G., P. N. Sprout, T. E. Baker, and L. M. Lawkulich. 1978. The soil landscapes of British Columbia. Ministry of Environment, British Columbia Resource Analysis Branch, Victoria, British Columbia, Canada.

Veblen, T. T., and P. B. Alaback. 1996. A comparative review of forest dynamics and disturbance in the temperate rainforests of North and South America. Pages 173–213 *in* R. Lawford, P. Alaback, and E. Fuentes, editors. High-latitude rainforests and associated ecosystems of the west coast of the Americas. Springer, New York, New York, USA.

Walsh, M. K., J. R. Marlon, S. J. Goring, K. J. Brown, and D. G. Gavin. 2015. Regional perspective on Holocene fire–climate–human interactions in the Pacific Northwest of North America. Annals of the Association of American Geographers 105:1135–1157.

Whitlock, C., P. E. Higuera, D. B. McWethy, and C. E. Briles. 2010. Paleoecological perspectives on fire ecology: revisiting the fire-regime concept. Open Ecology Journal 3:6–23.

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