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Evidence of a historical frequent, low-severity fire regime in western Washington, USA

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Abstract

Fire is a common disturbance in many forests. We conducted a fire history study on 40 Douglas-fir (*Pseudotsuga menziesii*) trees from two sites, Kellett Bluff and Turn Point, in the San Juan Islands of Washington state, USA. In total, 146 fire scars were identified and dated, representing 34-35 fires per site. Fires occurred between 1565 and 1964. Individual trees recorded up to 10 fires. The composite mean fire interval (MFI) was 11-13 years over the entire study period and 6 years in the historical period (1780-1895). These sites were structured by frequent, low-severity fires, yet supported a tree component for centuries - the oldest tree in this study was more than 500 years old. A program of frequent, low-severity fire may be critical for their long-term persistence. Comparisons of fire history data among these and five other local sites indicate frequent fires but little synchronicity; the MFI was 4 years but most fires were only recorded at single sites. Although forests west of the Cascade Mountains are often described as subject to infrequent, high-severity fires, these results highlight the need for a more refined understanding of historical fire regimes in this region.

Keywords: fire history, Douglas-fir, *Pseudotsuga menziesii*, island, fire scars, dendrochronology

Introduction

The structure and function of ecosystems can be shaped by individual disturbances and by the disturbance regimes that reflect differences in the type and spatial and temporal patterning of disturbances (Johnson and Miyanishi 2007). Detailed studies of individual sites are necessary to understand the effects of disturbances and/or disturbance regimes at small scales, but can also
contribute to large-scale assessments that require synthesizing multiple studies under diverse
abiotic conditions (Falk et al. 2011).

Fire is a common disturbance in many forests, and understanding historical fire regimes
provides a valuable context for understanding current and future fire regimes. In northwestern
North America, historical fire regimes are often assumed to have been strongly spatially
separated: forests west of the Cascade Mountains were subject to infrequent, high-severity fires,
while those east of the Cascades were subject to frequent, low-severity fires (Agee 1993).
However, the region west of the Cascades historically included widespread prairies (Dunwiddie
and Bakker 2011), the management of which is fire-dependent (Hamman et al. 2011).
Furthermore, the climate in this region is spatially complex. For example, even though the towns
of Sequim and Forks are less than 100 km apart, their long-term mean annual precipitation
ranges from 430 to 2900 mm (PRISM 2018). A more nuanced understanding of the historical fire
regime in this region, and its drivers, is obviously required.

Fire regimes are influenced by landscape position, including the permeability of the
landscape to fire. For example, increasing prevalence of water reduces permeability to fire
(Nielsen et al. 2016). Studies in Canada (Bergeron 1991) and Sweden (Hellberg et al. 2004)
have shown that areas with reduced permeability to fire, such as islands in a lake or a forest with
many scattered wetlands, have more but smaller fires, and a longer fire interval, than areas that
are more permeable to fire, such as a contiguous forest without wetlands. However, these
patterns can change over time, likely due to changes in human-related sources of ignitions
(Niklasson et al. 2010).

We conducted a fire history study at two forested sites in the San Juan Islands of western
Washington state, USA. At each site, we documented the frequency and temporal variability of
fires, evaluated the extent and spatial patterns of fires, and examined the seasonality of fires. To
explore larger-scale patterns in fire history, we compared the fire histories of these sites with
those of other sites in the San Juan Islands.

Materials and methods

Study sites

Field work occurred at two sites, Kellett Bluff and Turn Point, in the San Juan Islands. The San Juan Islands are an archipelago between the mainland of North America and Vancouver Island, in the rain shadow of the Olympic Mountains to their southwest. Average annual precipitation at these sites is ~ 790 mm, with a pronounced summer drought: less than 25% of precipitation occurs from April to September (PRISM 2018). The sites are about 11 km apart on separate islands, and are managed by the Bureau of Land Management.

Kellett Bluff is a south-facing rocky headland at the southwest tip of Henry Island (N48 58’ 86”, W123 20’ 6”). It is 25 ha (63 acres) in size. The site was reserved in the 1890s as a potential lighthouse location, though one was never established – a navigation light was established in the late 1800s and a fog warning bell installed after 1907 (McDonald 1990). Old marine charts of the area show a Coast Salish settlement in Open Bay, just east of Kellett Bluff, and the area was a popular reef netting site until the 1950s. The earliest settler land patents on Henry Island date to 1886, but permanent Euro-American settlement did not occur until the early 1900s, when settlers began commercial fishing, sheep farming, and mining limestone.

Turn Point is mostly forested with exposed rocky headlands, and is at the northwest tip of Stuart Island (N 48 68’ 88”, W 123 23’ 73”). It is 28 ha (70 acres) in size. A light station was built at the site in 1893 (BLM 2018). When the island was surveyed in 1874, a Native American
settlement was noted in Reid Harbor. Sandstone cliffs along the west shore were also noted; these were quarried around 1904. The first land patent application was in 1876, but most settlement occurred in the 1890s, when twelve families received land patents and moved to the island. Cattle-raising, limestone quarrying and fishing provided income for the early settlers of Stuart Island (McDonald 1990).

Currently, most of the area at each site is forested, though there are also substantial grassland areas. Douglas-fir (Pseudotsuga menziesii) is the dominant tree, with western red cedar (Thuja plicata), pacific madrone (Arbutus menziesii), grand fir (Abies grandis), and Garry oak (Quercus garryana) in areas.

Sample collection and preparation

Reconnaissance work began in Autumn 2010. Each site was thoroughly examined to identify fire-scarred live trees, snags, down logs, and intact stumps. Each of these structures was inspected for number of visible scars, soundness of wood, and distance to roads and paths. Selected structures were not clearly visible from roads or paths, and at least one tree length from them. Locations of structures suitable for sampling were recorded using a portable GPS device.

A partial cross-section was removed from the boles of live trees and snags. Cross-section width was minimized to ensure the tree’s structural integrity but was deep enough to include the pith. Full cross-sections were taken from downed logs and stumps to provide a more complete inventory of fire scars and a higher potential for intact wood for crossdating. Useable samples could not be obtained from all assessed structures.

In total, we secured 40 samples, 19 at Kellett Bluff and 21 at Turn Point (Figure 1; Table S1; Table S2). All samples were Douglas-fir. Samples from Kellett Bluff were obtained during Summer and Autumn 2011, and were primarily from dead trees (n = 10 of 19). Samples from
Turn Point were obtained during Winter and Spring 2011, and were primarily from live trees (n = 13 of 21). All samples were allowed to dry at room temperature until Spring 2012. Samples were glued onto plywood to prevent breakage and loss, and were then planed and sanded with progressively finer grits (50 to 400) to obtain a smooth, polished surface. Samples were sanded to the point where cell walls were clearly visible under 10x magnification so that false or missing growth rings could be distinguished during crossdating and details of fire scars were evident (Stokes and Smiley 1968; Speer 2010).

During sample collection, increment cores were also taken from 16 live Douglas-fir trees at Kellett Bluff that were free from apparent injury and defect. Selected trees were located away from localized ground water sources and depressions and thus were more likely to be climatically sensitive. Increment cores were mounted and sanded using standard dendrochronological procedures (Stokes and Smiley 1968; Fritts and Swetnam 1989). Given the proximity of the sites and their similar climates, we assumed that a chronology built at Kellett Bluff would also be applicable at Turn Point.

**Dendrochronological analysis**

A master ring-width chronology was built from the increment cores taken from live trees. Cores were scanned with a high-resolution digital scanner and the images imported into WinDENDRO 2012a software (http://www.regent.qc.ca/products/dendro/DENDRO.html), where ring widths were measured to the nearest 0.01 mm. The ring widths were analyzed using the Dendrochronology Program Library in R (dplR) (Bunn et al. 2015) package in R (R Core Team 2015). The mean interseries correlation was 0.62. Standardized ring width indices were calculated for each tree and averaged to compile a master chronology (Stokes and Smiley 1968; Fritts and Swetnam 1989) covering the period from 1650 to 2011 (Figure S2). In total, we
identified 84 narrow rings and 36 wide rings during this period (Table S2). We used this pattern of marker years to crossdate fire scar samples to ensure accurate tree ages and dates for past fires (Brown and Swetnam 1994).

Cross-section samples were analyzed using a boom-mounted dissecting scope. Fire scar samples from live trees were visually crossdated following the methods outlined in Yamaguchi (1991) and by comparing ring width patterns to those in the master chronology. Samples from dead trees were crossdated by numbering the rings from the outer to the inner ring, noting which rings were narrower or wider than expected relative to surrounding rings, and then evaluating the fit between this set of narrow and wide rings and the master list of marker years (Table S2).

Each potential outer ring date from 2011 to 1650 was tested. For each outer ring date, the putative date of each narrow and wide ring was determined. The correspondence between these dates and the master list of marker years was then calculated to determine which outer ring date had the strongest support. We identified the pith and death dates where possible, or the dates of the innermost and outermost extant rings.

Fire scars were identified by the characteristic band of previously killed cambium tissue and the subsequent pattern of radial growth healing (McBride 1983; Speer 2010). Scars were carefully examined to distinguish them from other forms of tree injury (Smith et al. 2016). Other types of damage were noted as they may have made the tree susceptible to scarring, but are not reported here.

The position of the dead cambium in the growth ring was recorded using six categories: early earlywood, middle earlywood, late earlywood, latewood, dormant, and undetermined (Sutherland et al. 2015). The number of fires associated with each category was tallied and
linked with the phenology of radial growth in Douglas-fir (Gould et al. 2012; Beedlow et al. 2013) to infer the seasonality of fire.

A tree was considered to be a recorder from the year of a fire until the year the scar healed over. Dormant season scars were assigned to the earlier (inner) year based on our experience that fires in this region generally occur in the autumn. Fire history data were analyzed in FHAES (v.2.0.2; Brewer et al. 2016). Each site was analyzed separately. Data were summarized across the entire period of record and for each of two time periods, historical and post-settlement. To simplify comparisons among sites, we used the same date, 1895, as the start of the post-settlement period. Our sampling began 115 years later, in 2010, so the post-settlement period extended from 1896-2010 for Turn Point (at Kellett Bluff, samples were obtained after the next growing season, so the post-settlement period ran from 1896-2011). We set the historical period to also be 115 years long (1780-1895).

Fire intervals were analyzed using individual-tree and composite methods to characterize fire history at different scales and to provide results comparable to similar studies (Romme 1980). Individual-tree fire intervals were based on the fires recorded by each individual sample. Composite intervals or “site intervals” were calculated based on the combined fire dates across the entire site. Summary statistics for the entire period of record and for each time period included the mean fire interval (MFI), Weibull median probability interval (WMPI), and range of intervals detected. These statistics were selected for comparability with previous studies. The interval after the last fire event was included as an interval in these analyses.

Fire synchronicity at these two sites were not compared statistically as the data did not meet the necessary assumption for a chi-square test of independence (Swetnam 1993). In particular, too few fires occurred at both sites in the same year.
Comparisons with other local fire history studies

A search of the published and unpublished literature uncovered fire history information about five other sites in the San Juan Islands (Table 1). Cross-sections through fire scars were obtained from three sites: Iceberg Point and Point Colville on Lopez Island (Spurbeck and Keenum 2003), and Point Disney on Waldron Island (Sprenger and Dunwiddie 2011). Smaller amounts of information are available from Orcas Island, where increment cores were obtained from 14 relict trees (Peterson and Hammer 2001) and from Patos Island, where limited samples could be crossdated (Gray and Daniels 2006). These latter studies likely underestimate the prevalence of fire historically. We compiled composite plots for our two sites and these five published sites into a single fire history chart for inter-site comparisons. Statistical analyses of synchronicity were not conducted because of large differences in sample depth among sites.

Results

Considerable evidence of past fire was found at both sites. Many of the mature Douglas-fir trees had charred bark and visible fire scars on the lower bole of the tree. In some areas, large, mature Douglas-fir trees with substantial lower limb branches were present, indicating that they grew in open conditions in the past.

Kellett Bluff

At Kellett Bluff, samples recorded between one and 10 fires, with a mean of 3.6 scars per sample. A total of 69 fire scars were identified across the 19 samples, representing 35 distinct fire years between 1565 and 1926 (Figure 1; Table 2). Particularly widespread fires occurred in 1895 (recorded by 10 trees), 1844 (6 trees), 1868 (4 trees), and 1883 (4 trees). The vast majority of fires occurred when cambial growth was dormant (Table 3).
Individual trees were scarred by fire on average every 40-50 years, but this ranged from 1 to 270 years (Table 2). Many fire scars healed over before the next fire was recorded (Figure 3). The fire return interval was more than three times longer in the post-settlement period than in the historical period. Considering the site as a whole, the mean fire return interval was 13 years, but ranged from 1 to 85 years. The composite fire return interval was 4.5 times longer in the post-settlement period than the historical period (27 vs. 6 years).

**Turn Point**

At Turn Point, samples recorded between one and six fires, with a mean of 3.9 scars per sample. A total of 77 fire scars were identified across 20 samples (Figure 4; Table 4), representing 34 distinct fire years between 1624 and 1964. Particularly widespread fires occurred in 1850 (recorded by 13 trees), 1822 (10 trees), 1868 (7 trees), and 1804 (5 trees). The vast majority of fires occurred when cambial growth was dormant (Table 3).

Individual trees were scarred by fire on average every 35-48 years, though this ranged from 2 to 180 years (Table 4). The fire return interval was 25 years in the historical period but 64 years in the post-settlement period. Considering the site as a whole, the mean fire return interval was 7-11 years, but ranged from 1 to 88 years. The mean fire interval rose from 6 years in the historical period to 14 years in the post-settlement period.

**Comparisons among local fire history studies**

The seven fire history studies recorded evidence of fires in 111 years between 1530 and 1964 (Figure 5). The mean fire interval was 4 years and the Weibull median probability interval was 3 years; fire occurred in at least one site in about a quarter of years.

There was little correspondence or synchronicity between sites in terms of when fires occurred: in most years (81 of 111), fire was only recorded at one site. Fires were recorded at
two sites in 24 years, at three sites in only four years (1712, 1850, 1868, 1870) and at four sites in only two years (1765, 1839).

Discussion

Abundant fire historically

Trees are imperfect recorders of fire: not every fire scars every tree, and even when scarring occurs, a stem cross-section may not include the area that was scarred. Furthermore, fires can consume the evidence of previous fires. In spite of these limitations, fire scars are one of the best sources of information about this historical disturbance regime. This study clearly demonstrates that fire was a dominant structuring force at both Kellett Bluff and Turn Point: during the historical period, fires occurred on average every 6 years at each site. The patterns we observed are more consistent with low severity fires than with high severity, stand replacing fire. For example, many trees recorded multiple fires, and we encountered large Douglas-fir trees with substantial lower limbs that would have been killed by fires with large flame lengths. This growth form often appears when trees are open-grown. We also did not see other dendroecological evidence of high severity fires, such as high correspondence in tree death dates or changes in tree-ring growth (Guiterman et al. 2015).

Fires usually did not occur in the same year at both Kellett Bluff and Turn Point – this only happened in 7 years. Even in years where fires occurred at both sites, it is highly probable that they reflect separate ignitions given that the sites are 11 km apart on different islands. A fire that was hot enough to produce embers that could be carried across the water would be unlikely to also be of sufficiently low severity to scar trees without killing them. Lightning from the same
storm could conceivably strike both sites though, as explained below, this region has among the
lowest lightning strike densities in the continental United States.

Widespread fires – those scarring multiple trees within a site – occurred infrequently: in
only four years (1868, 1870, 1895, 1902) were fires recorded by two or more trees at a site.
Interestingly, these years are in a narrow period of time around the time of Euro-American
settlement; the later dates may indicate fires that spread onto these sites from nearby land
clearing efforts of settlers (McDadi and Hebda 2008).

Although the local fire history studies differ in sampling intensity and temporal depth,
when all seven sites are considered together, the longest historical fire-free interval was 29 years
(1663 to 1692). Intriguingly, an assessment of the Pacific Northwest region also noted that the
period from 1650-1800 experienced reduced area burned (Weisberg and Swanson 2003)
suggesting that this might have been a widespread phenomenon. Weisberg and Swanson (2003)
also suggested that there was regional synchronicity in the fire regimes of western Oregon and
Washington, but our results do not support this conclusion, perhaps because these sites are on
islands and/or because of the finer temporal resolution of our study (annual vs. 25-year intervals
in Weisberg and Swanson (2003)).

Two fire history studies have been conducted in the Olympic Mountains, ~ 60 km
southwest of the San Juan Islands, and they both document the frequent presence of fire on the
landscape. In the Morse Creek drainage (2500 ha), Wetzel and Fonda (2000) compiled a 600-
year fire history and reported that few decades had < 5 fires. They calculated mean fire intervals
at multiple spatial scales. At the 200 ha scale (considerably larger than the scale of our sites), the
mean fire interval was 21 years, while across the entire drainage (2500 ha) it was 3 years. In the
lower Elwha River watershed (1873 ha), Wendel and Zabowski (2010) compiled a 440-year fire
history. Low elevation south-facing slopes, the edaphic combination most similar to conditions at our study sites, had a mean fire interval was 85 years.

Although these mainland studies concur with our island studies in documenting an abundance of fire on the landscape, methodological differences make it difficult to assess the consistency of these studies with prior research showing that islands have more but smaller fires than on the mainland (Bergeron 1991; Hellberg et al. 2004). Wetzel and Fonda (2000) did not crossdate their samples and used increment cores rather than stem cross-sections. Furthermore, they identified germination dates and fire release markers from increment cores, so their approach is more likely to detect fires that are of high enough severity to cause a release in tree growth (but not so high as to have killed the sampled trees). Wendel and Zabowski (2010) required at least 3 fire scars to indicate a fire, so their estimate is an underestimate of the actual fire frequency.

Another difference is that the mainland studies were conducted over much larger areas. At these scales, the authors were able to conduct landscape-scale analyses such as looking at aerial photographs for evidence of even-aged stands that suggest the occurrence of high-severity stand-replacing fires. Given the relatively small areas of our sites, we were not able to conduct these types of analyses. We did observe areas that appeared to be even-aged but, as described below, we feel these are more likely a result of ingrowth in formerly open stands than the replacement of one forest stand with another.

Fire histories can be studied indirectly by analyses of charcoal and pollen (Sugimura et al. 2008; Walsh et al. 2015). In this region, studies that used these approaches have estimated fire return intervals that are broadly similar to the mainland studies described above. For example, Pellatt et al. (2015) reported mean fire return intervals of 26–41 years for Pender Island
and Vancouver Island, British Columbia (< 20 km from our sites), and Lucas and Lacourse
(2013) reported 15 fires over 1300 years on Pender Island, for a mean fire return interval of 88
years. However, charcoal and pollen are proxies for actual fires that are sampled over longer
timeframes, and thus are recommended for identifying historical trends rather than individual
fires (Remy et al. 2018). There are several reasons for the difference between our results and
those of these types of studies, including differences in sampling intensity (multiple trees vs. a
single sediment core) and temporal resolution (Lucas and Lacourse report, for example, a
standard deviation of 42 years around an estimated sediment date of 1851 (see their Table 1)).
Nonetheless, our overall conclusion about the prevalence of fire historically is also supported by
these studies.

**Anthropogenic fire**

While fires do not leave any evidence of their ignition source, it is sometimes possible to
identify patterns that are consistent with different ignition sources (Bowman et al. 2011). We
find it highly likely that the fire regime identified here is the result of Native American practices,
as has been argued elsewhere in the region (Weiser and Lepofsky 2009; McCune et al. 2013;
Pellatt and Gedalof 2014).

Anthropogenic fire obviously requires the presence of people with the means and motives
to start fires (Bowman et al. 2011). The San Juan Islands have been occupied by humans for
thousands of years (Taylor et al. 2011), and oral histories and written accounts of early travelers
to the area provide evidence that certain vegetation communities were maintained by indigenous
burning (Turner 1999). Early surveyor and explorer records of the Pacific Northwest describe
frequent burning by Native Americans and an open vegetation structure in many areas of the
Puget Trough lowlands including prairies, savannas and woodlands (Storm and Shebitz 2006).
Another line of evidence supporting anthropogenic fire is a low ability to predict their occurrence from simple climate-fuels-fire relationships (Bowman et al. 2011). We see evidence of this in the lack of natural ignition sources, fire seasonality, and low correspondence among sites. Lightning is a common natural ignition source, but western Washington has one of the lowest lightning strike densities in the continental United States (Koshak et al. 2015), and thunderstorms that do occur are typically accompanied by precipitation which makes fires unlikely. In Olympic National Park, southwest of the San Juan Islands, lightning started fires in less than one-third of years from 1916 to 1975 (Pickford et al. 1980). Studies in other regions have shown that islands are drier and warmer than the mainland and have higher lightning densities (e.g., Drobyshev et al. 2010), but we are not aware of comparable studies in our study area. We also have no reason to expect that lightning density has changed over time.

Fire seasonality is also consistent with a human origin. Most fires occurred during the dormant season, when trees’ diameter growth was ceased. Though the exact timing varies among sites and years, Douglas-fir produces latewood in the late summer or early autumn. For example, mature Douglas-fir at a coastal Oregon site produced latewood from August to October (Beedlow et al. 2013), while seedlings in western Washington produced 90% of their annual basal area increment by late September (Gould et al. 2012). Thus, fires noted in the latewood may have occurred in August or September while those noted in the dormant season occurred later. However, weather conditions in late autumn and winter are generally too moist to support fires, suggesting that dormant-season fires occurred in September or October, before the autumn rains.

Finally, the sheer number of fires across the region and the low correspondence between sites (Figure 5) are also consistent with anthropogenic ignitions. If fires were weather-driven, we
would expect synchronicity among sites because conditions would be suitable simultaneously at multiple sites. Furthermore, we would expect that synchronicity to be linked to climate. For example, a dry year with a rare lightning storm might serve as the ignition source for fires on separate islands. This does not appear to be the case, however, as Palmer Drought Severity Index (PDSI) during years when fires burned at 2 or more sites did not differ significantly from PDSI during other years (Table S4).

Although a few fires occurred soon after Euro-American settlement, fires have not occurred at these sites in several decades. For example, considering all 7 sites together, the last recorded fire was in 1964. This is consistent with patterns in recent decades throughout western North America, and with the notion that historical fires were largely of anthropogenic rather than natural origin.

**Stand structural changes**

In many studies, the cessation of a frequent burning regime is accompanied by a rapid rise in tree density. Depending in part on the scale of analysis, this rise in tree density may be described as the in-filling of open forests or expansion across open meadows. Both of these changes have been demonstrated in this region. For example, in-filling occurred at Point Disney on Waldron Island, where stem density increased from 99 stems/ha in 1881 to 927 stems/ha in 2007 (Dunwiddie et al. 2011). Expansion across open meadows was described at a small (0.9 ha) site at Rocky Point on Vancouver Island (Gedalof et al. 2006). This site was largely prairie in 1850, but numerous Garry oak established in the 1850s and Douglas-fir and grand fir have encroached on the site since the 1950s. On south-facing slopes of Mount Constitution (Orcas Island), both of these processes occurred: in the 19th century, these areas were open-grown
Douglas-fir mixed with prairie (7 stems/ha) but in ca. 2000 they were primarily closed canopy forest (426 stems/ha; Peterson and Hammer 2001).

The presence of live, old Douglas-fir trees at both Kellett Bluff and Turn Point indicates that these sites have supported trees for numerous centuries. Many of the fire-scarred trees were rapidly growing, suggesting that they were in relatively open stands with low densities, and recovered rapidly after fire, with scars healing over in less than a decade. Aerial images (Figure S1) also suggest that in-filling and expansion have occurred at both sites. However, additional research would be required to assess the spatial patterning of stands historically, and the size and extent of grasslands that have experienced in-filling in recent decades.

Tree establishment may have occurred in pulses, as has been described elsewhere in the region (Agee and Dunwiddie 1984; Agee 1987; Schroeder 2007; Dunwiddie et al. 2011). For example, many of the sampled trees at Turn Point have pith dates of ca. 1800, and these trees are in relatively close proximity, suggesting the establishment of an even-aged cohort. In dense forests, an even-aged cohort is an indication of a prior severe fire. However, if the stand was open and of low density in the 1700s, a longer than usual fire interval could have increased the survival of Douglas-fir seedlings. We believe this latter explanation to be more consistent with the fire history of these sites and with environmental histories of other sites in the region, such as the establishment of pulses of trees on a prairie site on Vancouver Island (Gedalof et al. 2006).

Unfortunately, the trees sampled in this study were not a random sample of the stand and thus do not provide a statistically rigorous assessment of current stand structure. Stand structural analyses would provide valuable insights into stand development and environmental history at these sites.
**Forest development patterns**

Frequent, low-severity fires are understood to shape dry forests east of the Cascade Mountains, but the conventional understanding of forest development gives relatively little consideration to this type of fire west of the Cascades. This study suggests that a reinterpretation of forest development patterns may be required in the drier areas of the Puget Lowlands to include anthropogenic burning. A growing body of research is leading to similar conclusions for Vancouver Island (McDadi and Hebda 2008; Bjorkman and Vellend 2010; McCune et al. 2013). Interestingly, Bjorkman and Vellend (2010) also note that open habitats were often associated with Douglas-fir before Euro-American settlement, which is consistent with the apparent openness of our sites historically.

The fire intervals reported here are among the shortest known for forests in western Washington. The fires that occurred at Kellett Bluff and Turn Point were of low enough intensity that trees were able to survive multiple fires; on average, the trees sampled for this study recorded evidence of having survived 4 fires. Limited research suggests that some sites outside of the San Juan Islands experienced similar fire regimes. For example, the northeastern portion of the Olympic Mountains, where the rainshadow is pronounced, has a record of abundant fire (Wetzel and Fonda 2000). Further south in Puget Sound, it has been suggested that bear grass (*Xerophyllum tenax*) savannas in the southeastern Olympic Peninsula were maintained by frequent fire (Peter and Shebitz 2006), though a detailed fire history analysis was not conducted.

Non-forest ecosystems also occurred west of the Cascades and may have had even shorter fire intervals. For example, Boyd (1986) reported that the Kalapuyan Indians annually burned large tracts of vegetation in the Willamette Valley. Large areas in southern Puget Sound
were dominated by prairies historically (Dunwiddie and Bakker 2011) and it is assumed that these grasslands were also fire-maintained. To our knowledge, no formal fire histories have been conducted in these areas, though soil charcoal evidence suggests that the prairie-forest ecotone was historically stable (Hegarty et al. 2011). Further research to determine the prevalence of frequent, low-severity fires in the Puget Lowlands would be beneficial, as would research into stand structural development patterns.

**Future options**

This study did not assess current stand conditions or stand development. Nonetheless, the absence of fires from Kellett Bluff and Turn Point for much of the last century has likely increased the risk that future fires will be more intense due to the accumulation of fuel on the ground, the presence of smaller trees and shrubs that can act as ladder fuels, and the continuity of the canopy. If exposed to fire in their current condition, these stands may experience significant mortality. Wildfire is also a concern on these remote islands because of the logistical difficulties associated with mobilizing a suppression response.

Increasing the resilience of these stands would require active management, creating conditions that support low-severity fires and then permitting these fires to occur. Stand conditions can be modified through forest thinning operations, as has been done elsewhere in the San Juan Islands where Garry oaks are released by cutting the Douglas-fir that have overtopped them (Dunwiddie et al. 2011). Given the isolated nature of these stands and how unlikely natural ignitions are, as noted above, prescribed fires would likely be necessary. Recurring fires would alter the composition of the overstory by favoring those species that are more fire-resistant. Such fires would also affect the shrub and understory strata, such as by increasing plant diversity (Rossman et al. 2018).
Finally, we reiterate that even though both of these sites experienced frequent fires, they supported a tree component for centuries - the oldest tree in this study was more than 500 years old. A program of frequent, low-severity fire may be critical for the long-term persistence of these old-growth trees.

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Table 1. Characteristics of seven fire history studies from the San Juan Islands. Species codes are PSME (*Pseudotsuga menziesii*; Douglas-fir) or THPL (*Thuja plicata*; western red cedar). NR = Not reported.

| Site               | Abbrev. | Island | Study | Number of Area (ha) | Number of samples | Species Sampled | Number of fire scars | Number of fire years | Source                                      |
|--------------------|---------|--------|-------|---------------------|------------------|-----------------|----------------------|---------------------|---------------------------------------------|
| Iceberg Point      | ICE     | Lopez  | 30    | 6                   | PSME             | 42              | 20                   |                     | Spurbeck & Keenum 2003                      |
| Kellett Bluff      | WKB     | Henry  | 25    | 19                  | PSME             | 69              | 35                   |                     | This study                                   |
| Mount Constitution | WMC     | Orcas  | 50    | 14                  | PSME             | NR              | 7                    |                     | Peterson & Hammer 2001                      |
| Patos Island       | PAT     | Patos  | 84    | 1                   | THPL             | 2               | 2                    |                     | Gray & Daniels 2006                          |
| Point Colville     | COL     | Lopez  | 162   | 17                  | PSME, THPL       | 50              | 20                   |                     | Spurbeck & Keenum 2003                      |
| Point Disney       | WDE     | Waldron| 155   | 15                  | PSME             | 62              | 31                   |                     | Sprenger & Dunwiddie 2011                   |
| Turn Point         | WTP     | Stuart | 28    | 21                  | PSME             | 77              | 34                   |                     | This study                                   |


Table 2. Individual tree and composite fire interval statistics for Kellett Bluff. Abbreviations: MFI = mean fire interval; WMPI = Weibull median probability interval. The fire history chart for Kellett Bluff is shown in Figure 3.

| Type      | Time period   | # of Intervals | MFI | WMPI | Range  |
|-----------|---------------|----------------|-----|------|--------|
| Individual| Total (1502-2011) | 69             | 53  | 40   | 1-270  |
| tree      | Historical (1780-1895) | 35             | 26  | 21   | 1-108  |
|           | Post-settlement (1896-2011) | 7              | 89  | 91   | 70-109 |
| Composite | Total (1502-2011) | 35             | 13  | 9    | 1-85   |
|           | Historical (1780-1895) | 17             | 6   | 6    | 1-17   |
|           | Post-settlement (1896-2011) | 4              | 27  | 16   | 3-85   |
Table 3. Fire seasonality at Kellett Bluff and Turn Point, as expressed by the number of fire scars in each category and the percentage of fire scars for which the season was determined.

| Season         | Kellett Bluff | Turn Point |
|----------------|--------------|------------|
|                | Number | %     | Number | %     |
| Early earlywood| 0      | 0     | 0      | 0     |
| Middle earlywood| 0     | 0     | 3      | 5     |
| Late earlywood | 5      | 10    | 3      | 5     |
| Latewood       | 11     | 21    | 16     | 24    |
| Dormant        | 36     | 69    | 44     | 66    |
| Undetermined   | 17     | -     | 11     | -     |
| Total          | 69     | 100   | 77     | 100   |
Table 4. Individual tree and composite fire interval statistics for Turn Point. Abbreviations: MFI = mean fire interval; WMPI = Weibull median probability interval. The fire history chart for Turn Point is shown in Figure 4.

| Type       | Time period               | # of Intervals | MFI | WMPI | Range |
|------------|---------------------------|----------------|-----|------|-------|
| Individual | Total (1616-2010)          | 77             | 48  | 35   | 2-180 |
| tree       | Historical (1780-1895)     | 56             | 25  | 22   | 4-91  |
|            | Post-settlement (1896-2010)| 11             | 64  | 45   | 2-114 |
| Composite  | Total (1616-2010)          | 34             | 11  | 7    | 1-88  |
|            | Historical (1780-1895)     | 18             | 6   | 5    | 1-13  |
|            | Post-settlement (1896-2010)| 8              | 14  | 10   | 2-46  |
Figure 1. Aerial photographs of Kellett Bluff (top) and Turn Point (bottom) showing fire scar sample locations.

Figure 2. Site map showing locations of Kellett Bluff (WKB), Turn Point (WTP), and five other fire history sites in the San Juan Islands. Site abbreviations are explained and other details are provided in Table 1.

Figure 3. Fire history chart of Kellett Bluff (1502-2011). The horizontal axis shows the date, in years. There are three components to this chart, an index plot (top), chronology plot (middle), and composite plot (bottom). The index plot shows the recorder depth – the number of trees that were scarred and not healed over (blue line) – and the percentage of those trees that were scarred in each year. The chronology plot shows the fire history of individual trees. Each horizontal line is the lifespan of a tree; the line is solid during years when the tree is a recorder, and dashed when it is not. The end points of each line are vertical if the sample begins with the pith (left) and/or ends with bark (right), and diagonal otherwise. Fire scars are denoted by vertical bars. The composite plot shows the overall fire history of the site. Any fire recorded on any tree is recorded as a tall vertical line here, and the year is listed at the bottom of the plot. The blue vertical lines spanning all components of this chart denote the start and end of the historical time period (1780-1895).

Figure 4. Fire history chart of Turn Point (1616-2010). The horizontal axis shows the date, in years. Components of a fire history chart are explained in the caption for Figure 3.
Figure 5. Fire history chart of seven sites in the San Juan Islands (1498-2011). The horizontal axis shows the date, in years. Components of a fire history chart are explained in the caption for Figure 3, except that in this chart each horizontal line is the composite plot from a site rather than the fire history of an individual tree. Site abbreviations are explained in Table 1.
Figure 1
Figure 2
Figure 3
Figure 4
Comparison among Sites in the San Juan Islands

Figure 5