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Long-term vegetation and wildfire dynamics in the high Cascade Mountains, Pacific Northwest, USA

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Abstract

Current wildfire activity in the United States is often described as ‘unprecedented’. To evaluate whether present-day vegetation and wildfire dynamics fall outside of their historical range of variability, palaeoecological records provide a baseline of natural disturbance regimes and forest dynamics. In the Pacific Northwest, concerns have grown over changes in fire regimes, yet high-elevation forests in the Cascade Mountains remain relatively understudied. In the high Cascade Mountains, pollen and charcoal preserved in sediment from Little Monon Lake (~2,500 cal yr BP) and Pyramid Lake (~6,400 cal yr BP) were analysed to reconstruct vegetation and fire histories. Both records reveal persistent dominance of Pinaceae forests, with only modest compositional shifts linked to disturbance-associated taxa. Statistically significant differences in pollen assemblages identify two periods of distinct vegetation at Little Monon Lake and three at Pyramid Lake, with the most recent periods at both sites beginning around 700 cal yr BP. Mann-Whitney U tests confirm significant differences in fire activity between these pollen zones at both sites, indicating a close link between vegetation composition and burning. This transition coincides with a marked decline in fire activity, suggesting a regional shift in disturbance dynamics. This downturn is more plausibly explained by climatic change, likely linked to the onset of the Little Ice Age, than by anthropogenic suppression. Site differences reflect contrasting ecological contexts: Little Monon Lake shows fewer but potentially more severe fires, influenced by lodgepole pine-dominated forests, while Pyramid Lake exhibits frequent fire events, consistent with its diverse conifer assemblage and mid-elevation setting. These records demonstrate that high Cascade forests have been resilient to long-term shifts in fire regimes, with vegetation and wildfire interactions dynamic but not driving major ecological change. However, projected increases in fire frequency, severity, and extent under climate change may test this resilience beyond the range of variability observed.

Lay Summary

Current wildfire activity in the United States is often described as "unprecedented" because recent fires are believed to have been unusually large, frequent and destructive. However, to know whether today's fire activity truly falls outside the natural range of variation, it is possible to turn to the past: thousands of years of vegetation and fire history preserved in lake sediment. In this study, sediment records from two high-elevation lakes in Oregon's Cascade Mountains were examined: Little Monon Lake, with a record stretching back about 2,500 years, and Pyramid Lake, with a record reaching 6,400 years. Over time, layers of mud have accumulated on the bottom of each lake, with each layer capturing tiny pieces of the surrounding environment at the moment it was deposited. The sediment contains two particularly valuable pieces of information: pollen grains, which show what kinds of plants were growing nearby, and microscopic charcoal fragments, which record past wildfires. By taking sediment cores from the bottom of the lakes and then analysing the pollen and charcoal found layer by layer it was possible to reconstruct how vegetation and wildfire have changed through time. The results show that high Cascade forests have been dominated by conifer trees, such as pine, fir, and hemlock, for thousands of years, suggesting long-term stability. Still, there were some important shifts in vegetation. Around 700 years ago, both lakes recorded subtle changes in forest composition alongside a marked decline in fire activity. This decline occurred before Euro-American settlement, and because both remote sites show the same pattern, it is best explained by regional climate change rather than human influence. Specifically, this timing coincides with the onset of the Little Ice Age, a time of cooler and wetter climate which would have reduced fire frequency and intensity. Overall, these findings suggest that while wildfire activity has fluctuated, the vegetation of the high Cascade Mountains has been fairly stable and resilient for thousands of years. However, the current pace and scale of climate change is likely to push wildfire and vegetation dynamics beyond what has been previously observed in the past record, which may lead to more frequent fires and changing forests.

Little Monon Lake, high Cascade Mountains, Oregon, USA. Burned trees from recent fire are visible near the shoreline. This is where one of the sediment samples was taken in 2016.

Universities Declarations and Statements

Declaration

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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Statement 1

This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

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I hereby give consent for my thesis, if accepted, to be available for electronic sharing.

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Statement 3

The University's ethical procedures have been followed and, where appropriate, that ethical approval has been granted.

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Chapter 1: Introduction

1. Research context

Records of wildfire in the fossil record start with identification of charcoal in the Late Silurian (~420 million years ago), this record coincides with the evolution of terrestrial plants and O_2 concentrations above 13% (Scott & Glasspool, 2006). Since then vegetation fires have been a persistent disturbance within the Earth system (Scott, 2014). These fires are currently viewed as being particularly prevalent and pervasive and are associated with high economic costs, with the US alone spending hundreds of billions of dollars annually on wildfire intervention, mitigation and losses (Bowman et al., 2009; Thomas et al., 2017).

In recent years there has been growing concern that contemporary fire regimes and vegetation dynamics in the western United States may represent a departure from historical baselines (Burke et al., 2021; Dennison et al., 2014; Iglesias et al., 2022). The increase in fire has been linked to the accumulation of fuel from long-term fire suppression, together with climate driven reductions in fuel moisture and longer fire seasons (Holden et al., 2018; Marlon et al., 2008, 2012). These concerns highlight the need to compare present-day dynamics with long-term records to determine whether current conditions exceed the range of historical variability.

To understand whether the combination of present-day wildfires and vegetation dynamics is unusual we must assess whether they deviate from a ‘normal’ trajectory (Guyette et al., 2002; Littell et al., 2009; Rowney et al., 2023). In order to determine this, typical baseline palaeoecological proxies can be used to provide evidence about vegetation shifts, ecological functioning and environmental drivers (Cole et al., 2015; Gorham et al., 2001; Willis et al., 2007). While determining this baseline it is critical to remember there will be natural fluctuations, such as those caused by disturbance regimes, as only with this understanding of variability can we determine if present ecosystems dynamics are genuinely ‘unprecedented’ within the historical record and therefore if they require intervention to prevent biodiversity loss and safeguard ecosystem functioning (Froyd & Willis, 2008).

To establish a baseline of wildfire and vegetation dynamics it is necessary to establish a ‘fire-regime’. The term ‘fire-regime’ is used to describe parameters of fire according to frequency, seasonality, intensity/severity and type within specified spatial and temporal context (Bond & Keeley, 2005; Krebs et al., 2010). This can then be further extended to include ‘pre-requisites for fire’ or ‘conditions of fire’ which include factors such as fuel characteristics, causes of fire, anthropogenic conditions and weather, as they in turn control fire regimes over time (Bond & Wilgen, 2012; Krebs et al., 2010). Vegetation and wildfire dynamics are particularly intertwined at a fire regime scale through the combination of fuel characteristics and climate conditions which can either promote or reduce the potential of fire (Moritz et al., 2005; Whitlock et al., 2010). The historical fire regime can be reconstructed through either palaeoecological analysis of charcoal preserved in lake or bog sediments, or through dendrochronology, although the latter typically provides shorter temporal records (Harley et al., 2018; Scott, 2010). Meanwhile vegetation dynamics and species composition can be explored through the identification of subfossil pollen grains as well as spores from bryophytes and ferns (Birks, 1996).

Understanding what the natural fire regime and vegetation dynamics of a region is can enable understanding of whether an ecosystem is functioning within its range of natural fluctuations (Gorham et al., 2001). This is particularly significant for regions, such as the Pacific Northwest, which are increasingly affected by climate change (Halofsky et al., 2020). Global warming is predicted to increase fire frequency, severity and extent by decreasing precipitation levels, reducing fuel moisture and lengthening both the fire and growing seasons (Holden et al., 2018; Iglesias et al., 2022; Littell et al., 2010).

2. The Pacific Northwest and high Cascade Mountains

The Pacific Northwest of North America encompasses the Canadian province of British Columbia and the states of Washington, Oregon, Idaho in the USA and small sections of adjacent states such as Alaska and California. It is a highly varied region with coastal, mountainous and desert zones each with variable geology, vegetation, precipitation, and temperature. The Pacific Northwest encompasses diverse physiographic provinces, including the Olympic Peninsula, Coast Range, Cascade Range, Blue Mountains, and Klamath Mountains, as well as lowland regions such as the Willamette Valley and the Puget Trough (Franklin & Dyrness, 1973).

A defining feature of the region is the Cascade Range (Figure 1), which is dominated by dense, moist, high-elevation conifer forests (Halofsky et al., 2020; Waring & Franklin, 1979). These mixed conifer forests are moderately productive due to the long, warm and dry summers and cold, wet winters which favour the growth of conifers (Agee & Huff, 1987; Falk et al., 2022; Waring & Franklin, 1979). However, the topographical complexity of the Cascades gives rise to numerous microclimates, which in turn influence local vegetation patterns. For example, the western side of the range receives significantly more rain and snowfall than the eastern side, which supports the cool, moist conditions characteristic of temperate rainforests (Franklin & Dyrness, 1973). This spatial heterogeneity contributes to a mosaic of vegetation zones and fire regimes across the range.

Recent studies indicate substantial declines in spring snowpack across the Cascade Mountains, with reductions of 15–35% during the latter half of the 20th century, primarily driven by rising temperatures rather than precipitation decreases (Mote et al., 2008). Globally, snow droughts, periods of below-average snow accumulation, are becoming more frequent and severe (Huning & AghaKouchak, 2020). In the Pacific Northwest, below-average snowpack is increasingly associated with snow droughts, as higher temperatures shift precipitation from snow to rain (Sproles et al., 2013, 2017). Furthermore, analyses have suggested that snow drought occurrences have increased by approximately 10–15% over the last 30 years (Roberts-Pierel et al., 2024). These trends are particularly important for high-elevation ecosystems, where snowpack acts as a control on groundwater storage, water quality, growing season length, and disturbance regimes such as wildfire.

Within this region, the high Cascade Mountains remain underrepresented in long-term vegetation studies. The majority of palaeoecological research has focused on lower elevation western regions of the Pacific Northwest (Blinnikov et al., 2002; Minckley & Long, 2016; Sea & Whitlock, 1995; Walsh, Pearl, et al., 2010; Walsh, Whitlock, et al., 2010; Whitlock, 1992; Whitlock & Bartlein, 1997), which has left a gap in the understanding of long-term vegetation and fire dynamics at higher elevations.

Figure 1: The Cascade Range of the Pacific Northwest, spanning northern California, Oregon, and Washington. Major volcanic peaks are labelled, along with key geographic features such as the Western Cascades and high Cascades subregions. The map highlights the position of the Cascade Range relative to surrounding cities and states, with the yellow line showing the general extent of the range (Sherrod, 2023).

The vegetation of the forested regions of the western Cascade Mountain region, have been broadly classified into three zones by Franklin and Dyrness (1973) (Table 1). These vegetation zones are named after their dominant climax old-growth species and consist of greater levels of variation within their understory species.

The highest and coldest forest zone in the high Cascade Mountains is the *Tsuga mertensiana* (mountain hemlock) zone, which occurs at altitude above 1,500 m (Chatters, 1998; Franklin & Dyrness, 1973). This zone is dominated by *Tsuga mertensiana* and associated conifer species (Table 1). Much of the precipitation here falls as snow, which creates a subalpine environment with prolonged snowpack (Franklin, 1966). Below this, the *Abies amabilis* (Pacific silver fir) zone occupies mid elevations (1000-1500 m), while the *Tsuga heterophylla* (western hemlock) zone is found at altitudes below 1000 m on the western flank of the Cascades. These vegetation zones correspond with clear gradients in temperature and precipitation, which range from 8–9 °C and 1,500–3,000 mm at lower elevations to 3–5 °C and similar or higher precipitation, mostly as snow, at higher elevations (Franklin & Dyrness, 1973).

Table 1: Key species and environmental features of broad vegetation zones of the Cascade Mountains. Adapted from Franklin and Dryness (1973) and Chatters (1998).

Zone	***Tsuga heterophylla***	***Abies amabilis***	***Tsuga mertensiana***
Altitude (a.s.l)	<1000 m	1000-1500 m	>1500 m
Average temperature	8 to 9 ºC	~5.5 ºC	3 to 5 ºC
Main species	*Pseudotsuga menziesii* *Tsuga heterophylla* *Thuja plicata* *Abies grandis* *Picea monticola*	*Abies amabilis* *Tsuga heterophylla* *Abies procera* *Pseudotsuga menziesii* *Thuja plicata* *Pinus monticola*	*Tsuga mertensiana* *Abies amabilis* *Pinus contorta* *Abies lasiocarpa* *Chamaecyparis nootkatenis*

On the eastern slopes of the Cascades, the climate is considerably drier due to the rain-shadow effect, with lower levels of precipitation and snow compared to the west (Franklin & Dyrness, 1973; Siler et al., 2013). At the crest, *Tsuga mertensiana* and, in some areas, *Abies amabilis* are still present, but these quickly transition downslope to forests dominated by *Abies grandis* (grand fir). The *Abies grandis* zone is the most extensive forest type in eastern Oregon and is often intermixed with *Pseudotsuga menziesii* (Douglas-fir), *Pinus ponderosa* (ponderosa pine) and *Larix occidentalis* (western larch) (Agee, 1993; Franklin & Dyrness, 1973; Wright & Agee, 2004). Scattered stands of *Pinus contorta* (lodgepole pine) are also present, as on the western Cascades. At lower elevations, *Pseudotsuga menziesii* and *Larix occidentalis* forests shift into more open *Pinus ponderosa* stands, which dominate the driest forested sites along the eastern Cascades (Franklin & Dyrness, 1973). At their lower limits, ponderosa pine forests grade into *Juniperus occidentalis* (western juniper) woodlands, a community more typical of the arid interior basins (Franklin & Dyrness, 1973; Minckley & Whitlock, 2000). While these vegetation patterns largely reflect climatic and topographic gradients, they have also been shaped by human activity.

Anthropogenic influence is highly perversive and is increasingly causing global change (Steffen et al., 2005). In the Cascade Mountains, industrial-scale timber harvest has occurred for over a century, driven by the high productivity of the region's temperate forests (Grant & Wolff, 1991). Land-use change from logging and associated road construction has major impacts on ecosystems across the Cascade Mountains (Haugo et al., 2010; Scott & Wohl, 2018). Due to the remoteness of the high Cascade Mountains the region is less impacted by these activities. Hence, these higher elevation sites were used for the study to help minimise the influence of recent human activity.

3. Palaeoecological proxies

The high density of lakes and bogs in the High Cascade Mountains provides ideal settings for palaeoecological research (Whitlock, 1992). Sediment cores extracted from these sites can be analysed for different palaeoecological proxies that can offer insight into site influences, ecosystem functioning and vegetation composition.

The most valuable proxies used to examine vegetation and wildfire dynamics are charcoal which can be used to reconstruct fire histories and pollen which can provide evidence of vegetation shifts (Iglesias et al., 2015). Micro- and macro-charcoal particles preserved in lake sediments can provide a record of fire activity, which can be used to reconstruct fire history (further discussed in Section 3.2) (Franzén & Malmgren, 2012; Whitlock et al., 2010; Whitlock & Larsen, 2001). Meanwhile, pollen analysis provides information on local and regional vegetation shifts (further discussed in Section 3.1) (Mander & Punyasena, 2018; Prentice, 1988). The combined analysis of these proxies can enhance the ability to interpret disturbance regimes. Multiproxy approaches are especially useful for disentangling complex signals, for example, distinguishing between wildfires and prescribed burns becomes more feasible when charcoal data are interpreted alongside pollen records (Peng et al., 2011; Vannière et al., 2008).

3.1. Palynology

Palynology, the study of pollen, enables the reconstruction of vegetation at sites from which sediment cores have been taken (Whitlock, 1992). It can then in turn inform on local and regional vegetation, climate and anthropogenic influences (Prentice, 1988). To study changing vegetation at these sites, shifts over time can be reconstructed using pollen data extracted from multiple intervals within sediment cores.

To make any conclusions on vegetation shifts it is critical to consider limitations of proxy interpretation. Considering how pollen is transported can help with interpretations of how vegetation reconstructions can be distorted (Ackerman, 2000). Anemophilous pollen is transported in wind, which can result in changes in depositions that reflect regional rather than local vegetation dominance (Haseldonckx, 1977). The morphological characteristics of anemophilous pollen, such as their size, shape and presence/absence of air sacks can greatly alter the ability of pollen to disperse, with some types (e.g. *Pinus* and *Picea*) having potential to be transported thousands of km (Lu et al., 2022; Xu et al., 2016; Zhang & Li, 2017). Meanwhile, zoophilous (entomophilous) pollen, transported by insects, which usually has a thicker exine and increased levels of surface ornamentation, typically gives a more local signal (Cole et al., 2015; Lu et al., 2022).

The deposition of pollen also affects how it appears in the fossil record. Typically lake sediments contain uninterrupted and unaltered stratigraphies (Xu et al., 2016). However, water circulation within lakes can cause secondary transportation and re-sedimentation, a process known as ‘sediment focusing’, which impacts different pollen species in various ways (Davis et al., 1984). The deposition process may also damage pollen, for example if the lake ever dries up and the water table drops below the sediment level it can result in crumpled grains, although this is more typically observed in a peatland environment (Bunting & Tipping, 2000; Campbell, 1991, 1999; Cushing, 1967; Davies et al., 2015).

When pollen samples are processed using the typical acid-base-acid process (Bennett & Willis, 2001), the pollen can be altered through the extraction and as such their size and shape may have been changed, the harmomegathic effect (Halbritter et al., 2018). This alongside the fact that several pollen taxa contain species that are largely indistinguishable can make it difficult to distinguish pollen to the desired taxonomic level (Birks & Birks, 2000; Weir & Thurston, 1977). This limitation is particularly relevant for *Pinus* species, which are abundant in the high Cascade Mountains. Rather than being identified to species level, *Pinus* pollen is typically grouped into two broad types, diploxylon-type and haploxylon-type, as this represents the highest taxonomic resolution achievable through light microscopy, and allows for meaningful ecological interpretation, given that diploxylon pines are generally more fire-adapted (Singh et al., 2023). This distinction is particularly useful when interpreting past fire regimes and vegetation dynamics in conifer-dominated systems such as those found in the high Cascades.

Once pollen has been identified to a desired level care must also be taken in interpretation of a sample. It is wrong to assume that pollen percentages have a linear relationship with plant abundance although there is value in using pollen percentage threshold values as indicators for regional presence of vegetation (Bennett & Willis, 2001; Lisitsyna et al., 2011). It is also important to consider the pollen production of various plant species. For instance, anemophilous species generate large amounts of pollen to offset their low pollination efficiency (Damialis et al., 2011). Additionally abiotic and biotic factors can influence pollen production and viability (Moore, 1991; Razzaq et al., 2019).

Therefore, it is important to consider the source of pollen (local vs. regional signal) and to observe pollen at a sufficiently high sampling resolution to detect meaningful changes in vegetation over time.

Despite these challenges, palynological records remain one of the most robust proxies for reconstructing past vegetation, tracking shifts in forest composition, and inferring broader environmental conditions such as climate and disturbance regimes (Prentice, 1988; Willis et al., 2007). Additionally, their value extends beyond palaeoecology, as such records are highly applicable to informing modern conservation and ecological management (Froyd & Willis, 2008; Schoonmaker & Foster, 1991). Moreover, changes in pollen assemblages following charcoal peaks often provide clear evidence of post-fire succession and disturbance dynamics (Conedera et al., 2009; Whitlock & Larsen, 2001).

3.2. Charcoal analysis

Charcoal analysis serves as a valuable proxy in palaeoecological studies, particularly in understanding fire dynamics and disturbance regimes in past ecosystems. The size of charcoal fragments plays a significant role in interpreting fire history, as smaller micro-charcoal particles, often transported by wind, may represent a more regional signal, while larger macro-charcoal fragments (≥2 mm) typically offer a localized fire record as they often settle closer to the fire source (Conedera et al., 2009; Ohlson & Tryterud, 2000; Whitlock & Larsen, 2001). However, the transportation of charcoal is influenced by both the size and temperature of its formation, and as such the presence of significant macro-charcoal does not always indicate a local fire (Nichols et al., 2000). Additionally, different fire types affect the size of charcoal fragments produced with higher severity crown fires often producing small fragments while surface fires may produce larger (>1mm) charcoal fragments (Scott, 2014). Hence, understanding the potential origin of charcoal in the sediment record can help inform on fire histories.

Charcoal records can be influenced by anthropogenic activity, pest outbreaks, and preservation biases, all of which may distort fire and vegetation signals (Vachula et al., 2021). Thus, understanding the dispersal and deposition processes of charcoal fragments is critical to accurately reconstructing past fire regimes, as these factors critically affect the reliability of palaeoecological interpretations (Sjögren et al., 2010).

4. Vegetation and fire interactions of the region

The high Cascade Mountains provide a unique setting for exploring past fire and vegetation dynamics due to their diverse topography, climate and vegetation, which create a complex disturbance regime. In particular much of the key vegetation is interestingly affected by fire and some species have key life history events linked to specific fire regimes (Bowman et al., 2009). *Tsuga mertensiana*, *Pinus contorta* (lodgepole pine), *Tsuga heterophylla*, and *Abies amabilis*, are all impacted significantly by fire dynamics (Agee, 1993). Each species exhibits different adaptations and responses to wildfire, influencing their regeneration and the forest structure.

Tsuga mertensiana experience slower tree regeneration following fire due to the species' life history traits, with *Pinus contorta* instead often dominating post-fire regeneration, as pioneer species, which are then succeeded by the more shade tolerant *Tsuga mertensiansa* (Acker et al., 2017; Lotan & Critchfield, 1990). Although *Tsuga mertensiana* produces light seeds and can have heavy cone crops at intervals, it requires partial shade to establish as a seedling (El-Kassaby & Edwards, 2001; Minore, 1979; Woodward et al., 1994). Consequently, it tends to lag in regeneration for decades after high-severity fires, often giving way to shrubs and other resilient plants, which have seed banks and high resprouting ability (Acker et al., 2017). *Tsuga mertensiana* regenerates best during wet periods, highlighting its vulnerability in drought conditions (Agee & Smith, 1984). The colder climate in which high elevation *Tsuga mertensiana* forests dominate is also a likely contributor to the prolonged persistence of snags and coarse woody debris found on these sites after fire, due to the temperatures being too cold for decay organisms to work optimally (Acker et al., 2013). Hence, the persistence of snags likely increases fire severity in localized areas due to their high flammability (Acker et al., 2013). Yet this same severity can result in canopy gaps which may ultimately acting as a barrier to the lateral spread of crown fires (Acker et al., 2013). As such the spread of fire in these areas is likely not as severe, which is beneficial for its growth. However, it is not as well adapted to fire as some of its more fire-prone counterparts such as *Pinus contorta* which can be the dominant vegetation in some *Tsuga mertensiana* vegetation zones (Franklin & Dyrness, 1973).

Pinus contorta is highly adapted to fire-prone environments (Arno, 1980; Lotan et al., 1985; Schoennagel et al., 2003). It thrives in post-fire conditions, largely due to its serotinous cones, which open to release seeds in response to fire (Schoennagel et al., 2003). Alongside its serotinous cone, *Pinus contorta* has high levels of seed viability, seed production, juvenile growth and an ability to persist on low nutrient soil, all of which contribute to its aggressive post-fire establishment (Lotan et al., 1985). Lodgepole pine forests typically consist of even-aged stands, with the species rapidly germinating after stand-replacing crown fire (Axelson et al., 2009). Although fire can be intense in some lodgepole pine forests because of the tree’s thin, fire-prone bark, frequent low-intensity fires and the pines open, self-pruning crowns help prevent fuel buildup and maintain their presence (Lotan et al., 1985). These pines are thought of as a seral species which are typically succeeded by more shade-tolerant species such as *Tsuga mertensiana*, *Pseudotsuga menziesii*, *Picea engelmannii* (Englemann spruce) and *Abies lasiocarpa* (subalpine fir) (Lotan et al., 1985). However, they can also exist in persistent stands where a fire-regime of frequent fires eliminates seed sources of other species (Lotan et al., 1983, 1985).

Abies amabilis is another fire-sensitive species, due to its combination of thin bark and shallow rooting system (Agee, 1993; Crawford & Oliver, 1990). Following fire, *Abies amabilis* regeneration is slow, and its ability to establish is often influenced by climatic factors such as precipitation levels, as moist, cool conditions are ideal for their germination (Crawford & Oliver, 1990). Like other conifers in these forests, the species is affected by both direct fire impacts and the availability of suitable microsites for seedling establishment. Once germinated they require full sunlight for maximum growth, hence fire disturbance could help open the canopy for them (Crawford & Oliver, 1990).

Tsuga heterophylla is a fire-sensitive, late-successional species (Wimberly & Spies, 2002). It grows in dense stands, but its thin bark, highly flammable foliage and shallow roots make it vulnerable to fire (Arno & Davis, 1980). *Tsuga heterophylla* requires gaps in the canopy created by disturbances like fire to establish and grow, typically dispersing its lightweight seeds into these openings (Wimberly & Spies, 2002). Though characteristic of its zone, *Tsuga heterophylla* typically occupies the understory, with canopy dominance by long-lived *Pseudotsuga menziesii*.

Other disturbances, such as *Dendroctonus* bark beetle outbreaks, also influence vegetation and fire dynamics in the region. While understanding their interactions with habitat and climate is valuable, it lies beyond the scope of this study.

5. Aims

This study will explore the long-term interaction between fire and vegetation in high-elevation mixed conifer forests in the high Central Cascades. The palaeoecological analysis of fossil material preserved in sediments from two lakes in Oregon should help determine if there have been recent ‘unprecedented’ threats of fire to forest health or if the vegetation and fire dynamics currently observed are typical of this particularly understudied region.

Using previously collected sediment cores the study has two main aims:

1. To reconstruct past vegetation dynamics in the high Cascade Mountains using palynology and assess whether the present-day vegetation observed during 2016 fieldwork reflects long-term community composition. This includes evaluating the unusual Pinus contorta–dominated stands at Little Monon Lake, located within the high-elevation Tsuga mertensiana zone, to determine whether this forest type represents a persistent community or a more recent development potentially influenced by changing fire regimes. This aim is considered in comparison with the more compositionally diverse forest communities at Pyramid Lake, where lodgepole pine occurs alongside other tree species.
2. To reconstruct past fire regimes using macroscopic charcoal data, to evaluate how fire disturbances have influenced vegetation change over time, including potential shifts in community composition.

This study should help to provide a baseline for natural disturbance in the area so that current observed fluctuations in fire regimes or vegetation are understood. This understanding can then be utilised to inform on forest successional processes and in turn help guide conservation and management strategies.

Chapter 2: Methods

1. Site selection

This study focused on two high-elevation lake sites located in the Cascade Range of Oregon, expanding beyond the traditional focus on lower-elevation sites in the Coast Range, Willamette Valley, and the high-productivity temperate rainforests of the western hemlock zone on the western flank of the Cascades.

Little Monon Lake (44°47'50"N, 121°47'17"W) lies at an elevation of 1,511 meters (Figure 2). It is a shallow, 5-acre lake approximately 150 meters in width. It is located in Jefferson County, Mt Hood National Forest, Oregon. The lake lies within the *Tsuga mertensiana* zone of the western Cascade Range, the coolest and wettest forested zone in western Oregon and Washington, where much of the annual 1,600–2,800 mm of precipitation falls as snow (Franklin & Dyrness, 1973). The catchment surrounding Little Monon Lake is dominated by a coniferous forest composed of *Pinus contorta*, *Tsuga mertensiana*, and *Callitropsis nootkatensis* (Alaska yellow cedar). The presence of local single species *Pinus contorta* stands nearby is notable, as it is relatively uncommon in the region and may influence the site's ecological response to disturbance. Little Monon Lake is flanked by two larger water bodies: Monon Lake (65 acres) to the south and Olallie Lake (240 acres) to the north.

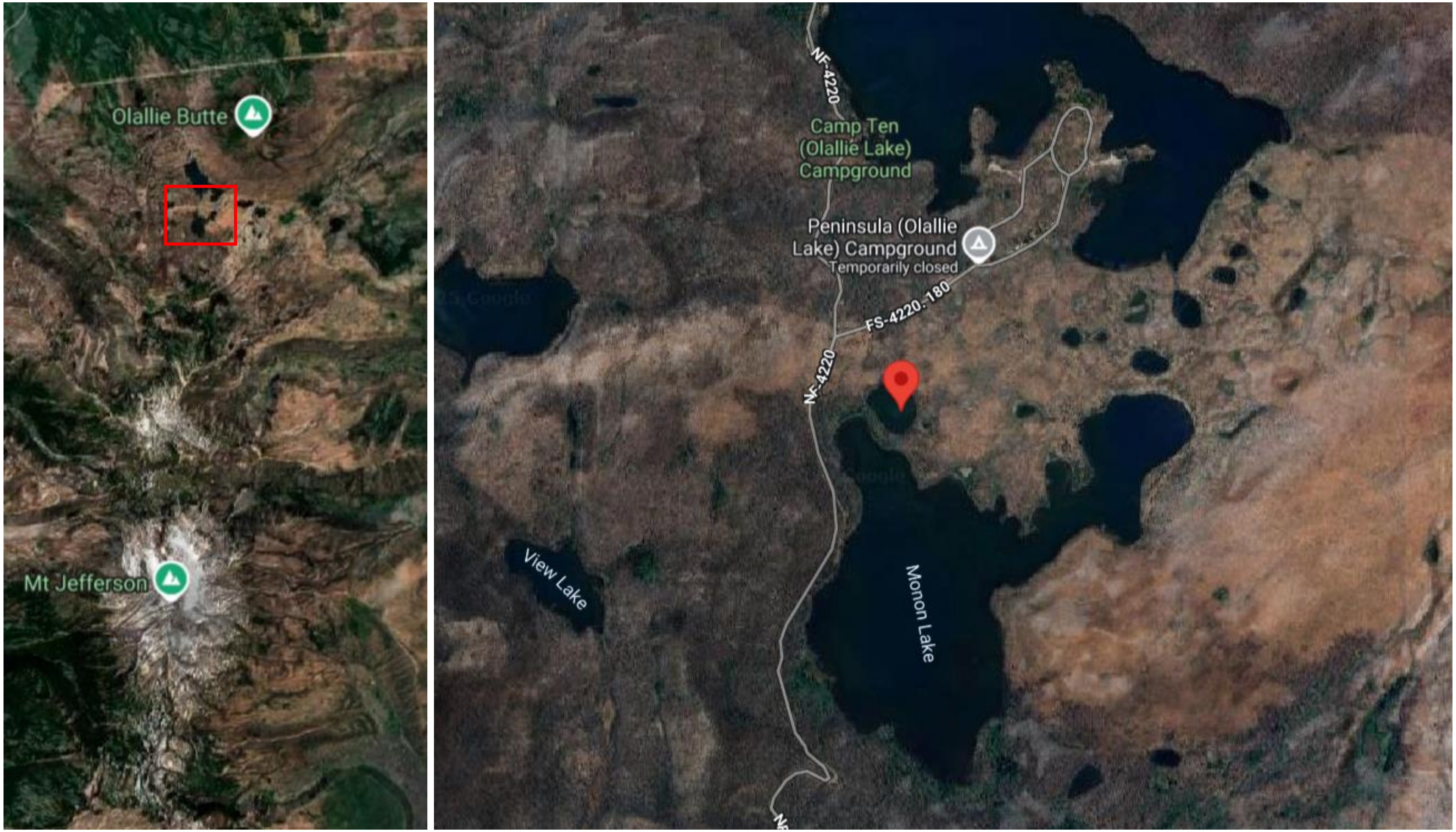


Figure 2: Little Monon Lake is marked by a red pin within the Olallie Lakes area, in Jefferson County, Mt Hood National Forest, Oregon (right). The red box (left) indicates the broader region in which Little Monon Lake is located. Images are sourced from Google Maps (Google Maps, 2025a).

Pyramid Lake (45°08'48"N, 121°55'35"W) is located at 1,213 meters elevation and spans approximately 5 acres, with a diameter of about 283 meters (Figure 3). It is within the Roaring River Wilderness Area, Mt Hood National Forest, Oregon. It lies within the *Abies amabilis* zone, where the elevation ranges from 1000-1500 m (Franklin & Dyrness, 1973). The dominant vegetation of the surrounding watershed includes *Abies amabilis, Tsuga mertensiana*, *Tsuga heterophylla*, *Abies procera* (noble fir), *Pseudotsuga menziesii*, *Thuja plicata* (western redcedar) , *Pinus monticola* (western white pine) and *Pinus contorta*. The understory is composed of *Alnus rubra* (red alder), *Salix* spp. (willow), *Pteridium aquilinum* (bracken fern) *Rhododendron macrophyllum* (Pacific rhododendron), *Vaccinium membranaceum* (big huckleberry*), Xerophyllum tenax* (beargrass), *Achlys triphylla* (vanilla leaf) and prince’s pine (*Chimaphila umbellata*) contributing to a diverse forest structure.

Both sites were deliberately selected within areas of minimal timber harvesting activities to minimize the influence of direct human impacts such as logging, in order to better isolate and understand the natural vegetation composition and disturbance regime, particularly the role of fire. In addition to the limited anthropogenic input the lakes were also selected due to topographic position and a number of physical criteria of the lakes. Both lakes are small and approximately circular in shape, lacking major inflowing streams, meaning the primary pollen influx comes from the local watershed (Jacobson & Bradshaw, 1981; Pennington, 1979). The absence of large inflows reduces the contribution of upstream vegetation to the pollen and charcoal record, meaning the sediment cores primarily reflect local vegetation and fire history rather than broader regional inputs. This helps to ensure continuous undisturbed sediment with minimal depositional disturbances, with a preference for moderately deep lakes (2 - 4 m). Additionally, the lakes have well-defined shorelines which is advantageous as their size is more likely to have remained stable throughout the Holocene. However, it is important to note that both sites may have been affected by more recent historical fire suppression practices, from 19thC Euro-American settlers as well as from earlier Native American populations (Walsh, Whitlock, et al., 2010).

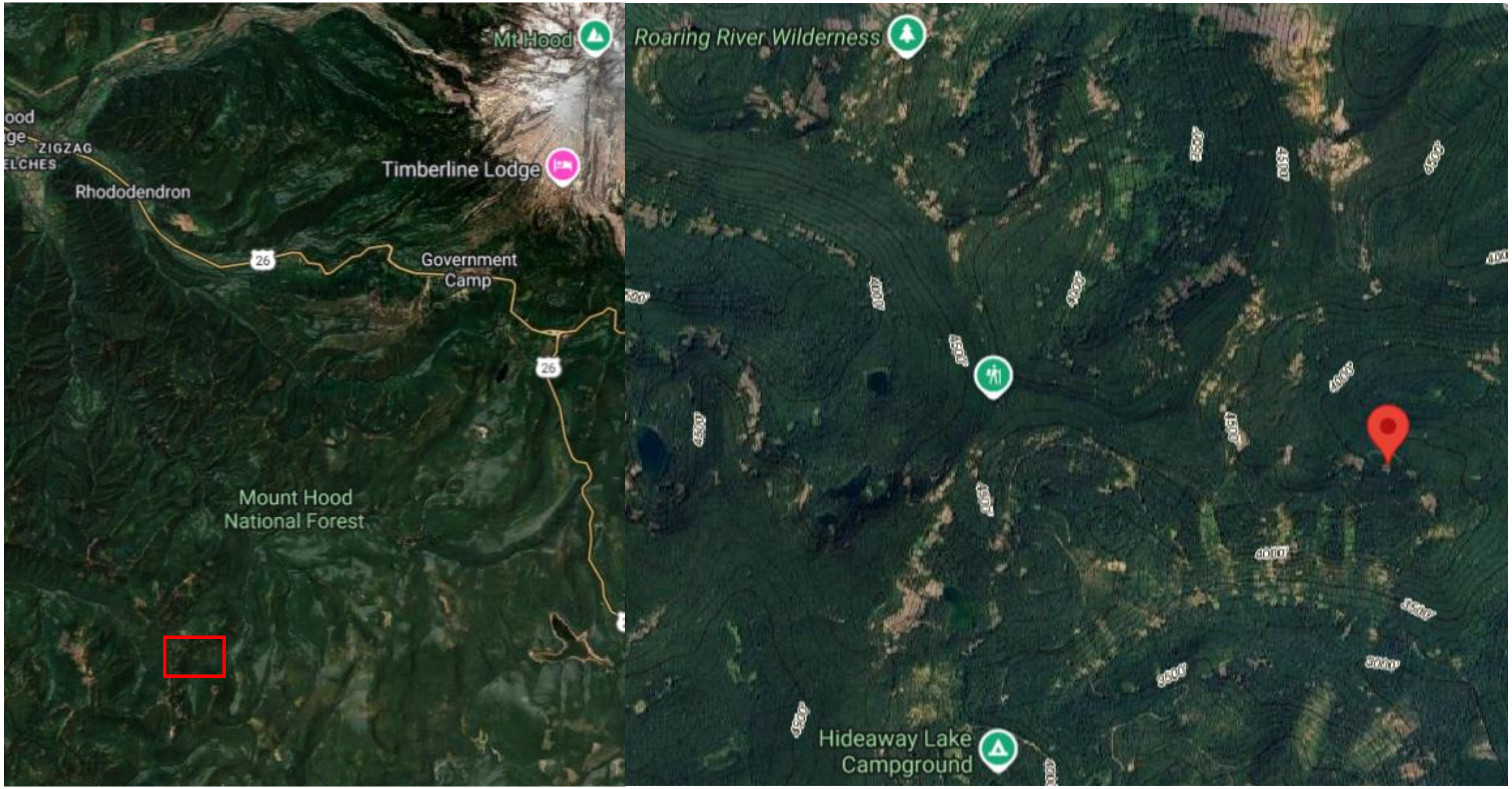


Figure 3: Pyramid Lake is marked by a red pin within the Roaring River Wilderness Area, Mt Hood National Forest, Oregon (right). The red box (left) indicates the broader region in which Pyramid Lake is located. Images are sourced from Google Maps (Google Maps, 2025b).

2. Sediment collection and sub-sampling

Sediment core collection was undertaken by Dr. Matthew Watkins in July 2016 and further details are available within Watkins (2022) methodology.

Single cores were obtained from both Little Monon Lake and Pyramid Lake within the Mt. Hood National Forest in Oregon for analysis of charcoal and pollen. Cores were retrieved from the deepest part of each lake, with a stabilised inflatable dingy. The cores were from the deepest part of the basin as this area would typically have greatest sediment accumulation from sediment focussing (Hilton et al., 1986), which means there is a higher likelihood of continuous accumulation and therefore stratigraphic integrity. The cores were taken until shallow bedrock and/or the presence of thick tephra layers at each site, made coring beyond not possible. Cores were obtained from the lake using a Bolivia corer, which is a modified Livingstone-type rod piston corer, with the barrel consisting of a decontaminated PVC pipe. The cores obtained were 230 mm and 670 mm in length, respectively.

After retrieval, the sediments were capped with floral foam and sealed with plastic caps and duct tape to maintain the integrity of the sediment-water interface and prevent mixing. Cores were then frozen at -20 °C upon finishing of fieldwork. For sub-sampling, the cores were cut into 10 cm sections and allowed to thaw horizontally to prevent sediment mixing. A high-resolution 2 mm contiguous sampling strategy was employed to provide a detailed reconstruction of disturbance regimes, including macroscopic charcoal and exploratory bark beetle DNA analysis (Watkins, 2022; DNA data not used in this dissertation). Non-contiguous sub-samples, also at 2 mm resolution, were subsequently taken for fossil pollen analysis and radiocarbon dating.

3. Radiocarbon dating

A total of 20 bulk-sediment samples, each taken at a 2 mm sampling depth resolution, were taken to iThemba LABS at the University of the Witwatersrand, Johannesburg, South Africa, where they were dated using the 6MV Tandem AMS (Accelerator Mass Spectrometry) system by Watkins (2022). Cores were sampled at the top, middle, and bottom, with additional high-resolution radiocarbon dates concentrated in the upper 58 mm of the Little Monon Lake core and the upper 40 mm of the Pyramid Lake core. This finer resolution was intended to support Watkins' aim of enabling more detailed interpretation and understanding of recent disturbance dynamics.

A further two radiocarbon dates, also at the 2 mm depth resolution, were submitted in 2025 to the ^{14}CHRONO Centre at Queen's University Belfast for analysis. These dates were selected from undated sections of the Pyramid Lake site core, specifically between the upper high-resolution section and the middle of the core, as well as between the middle and basal sections. The purpose of these samples is to improve chronological coverage and improve the age depth model (Table 2). Results are pending.

Table 2: Summary table of raw radiocarbon dates. Dates are reported in years Before Present (BP), where "Present" is defined as 1950 AD. Age error represents the 2-sigma (±2σ) uncertainty, corresponding to a 95% confidence interval. All samples were taken at a high-resolution 2 mm depth interval.

Site	Depth (mm)	^{14}C Age (yr BP)	Age error
Little Monon Lake	2	120	30
	8	70	30
	14	150	31
	20	360	40
	26	670	38
	32	900	45
	38	910	33
	44	1030	33
	50	1170	34
	58	1220	48
	115*	1610	46
	230	2350	42
Pyramid Lake	2	-500	31
	8	40	31
	16	90	32
	24	460	34
	36	590	36
	40	590	42
	162	2242	22
	340*	2160	35
	506	4605	27
	670	5330	35

Note. Each site includes a surface, middle (*) and basal date, along with high-resolution dating of the upper sequence and two intermediate dates at Pyramid Lake. Radiocarbon dates were primarily obtained from iThemba LABS, except for those at 162 mm and 506 mm depth at Pyramid Lake, which were submitted to the ^{14}CHRONO Centre for analysis.

The raw radiocarbon dates were calibrated into calendar years (cal. yr BP), with "before present" (BP) referring to 1950 AD. These were calibrated using an age-depth model from the "rBacon" R package (Blaauw & Christen, 2011). This package is typically used for Bayesian data, although in this case it was used for its flexibility and visualization abilities. Most of the radiocarbon dates were calibrated using IntCal13, due to the sites being located in the northern hemisphere, while the few post-bomb dates (before 1950) were calibrated using NH Zone 2 (Hua et al., 2022), as the samples are bounded in the north by ~40°N latitude and in the south by the mean summer intertropical convergence zone (Riemer et al., 2004). These age-depth models were selected due to their goodness of fit to the radiocarbon data and plausible sedimentation rates, as shown in Figures 4.1 and 4.2. Sediment cores from Little Monon Lake and Pyramid Lake had mean basal calibrated ages of 2,487 cal yr BP and 6,397 cal yr BP, corresponding to depths of 230 mm and 670 mm, respectively. At Little Monon Lake, the mean sediment accumulation rate is ~11 yr/mm, so each 2 mm sample represents ~22 years. At Pyramid Lake, accumulation rates are slower, ~9 yr/mm, meaning each 2 mm sample represents ~18 years.

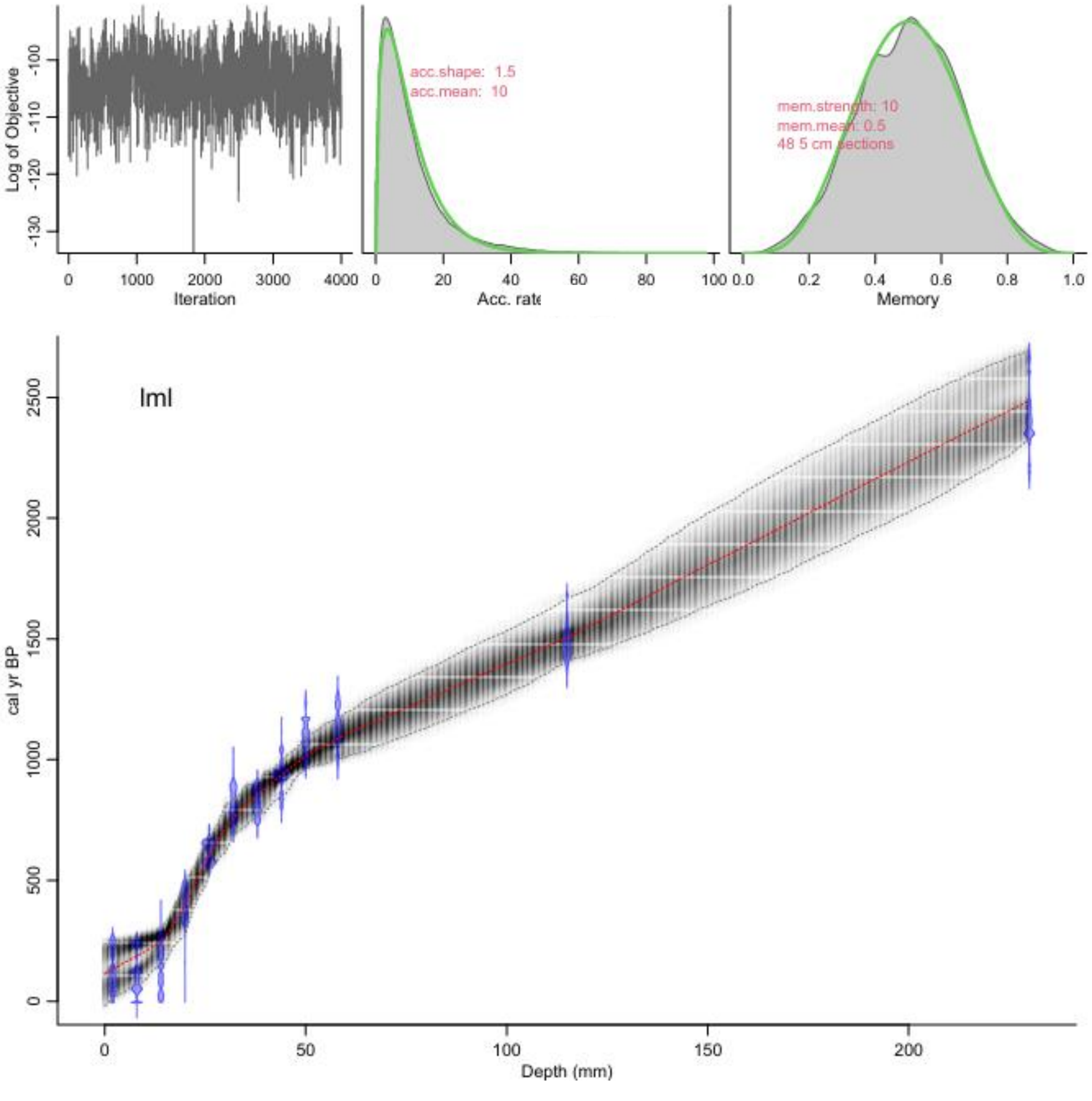


Figure 4.1. Age-depth model for Little Monon Lake, constructed using the IntCal13 calibration curve and NH2 settings in the R package "rBacon" (Blaauw & Christen, 2011). The main panel displays radiocarbon dates in blue, the modelled age–depth relationship in grey, the mean modelled age as a red line, and 95% confidence intervals as dashed grey lines. The top left plot shows the Markov Chain Monte Carlo (MCMC) simulation. The top middle plot shows the accumulation rate distribution (yr/mm), and the top right plot shows memory distribution. In both distributions, the green lines represent the prior distribution whilst the shaded grey areas indicate the posterior distributions estimates derived from the data.

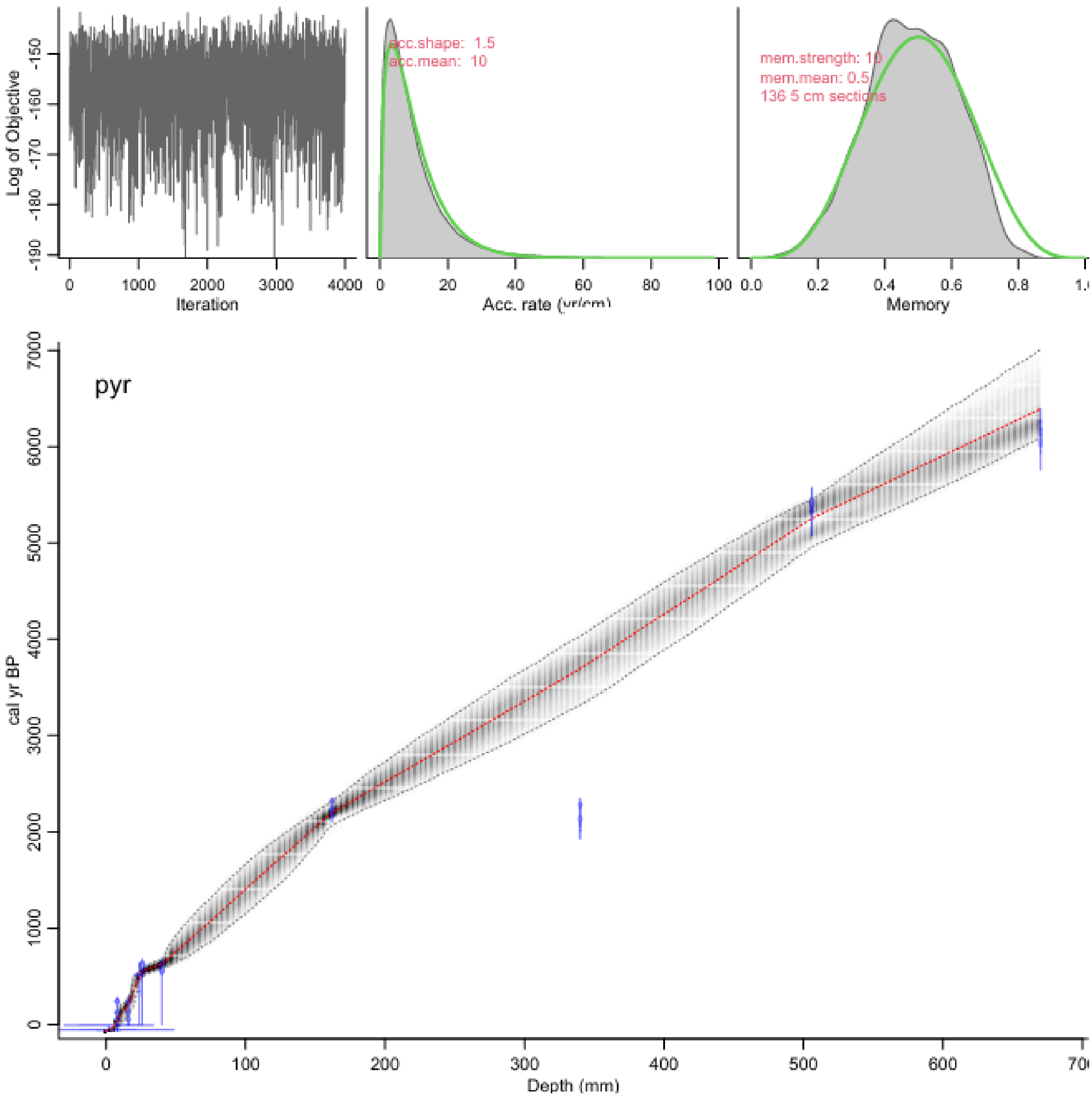


Figure 4.2. Age-depth model from Pyramid Lake, constructed using the IntCal13 calibration curve and NH2 settings in the R package "rBacon" (Blaauw & Christen, 2011). The main panel displays radiocarbon dates in blue, the modelled age–depth relationship in grey, the mean modelled age as a red line, and 95% confidence intervals as dashed grey lines. The top left plot shows the Markov Chain Monte Carlo (MCMC) simulation. The top middle plot shows the accumulation rate distribution (yr/mm), and the top right plot shows memory distribution. In both distributions, the green lines represent the prior distribution whilst the shaded grey areas indicate the posterior distributions estimates derived from the data.

4. Pollen

4.1 Pollen extraction

Vegetation reconstructions were based on 23 samples from Little Monon Lake and 18 samples from Pyramid Lake. Samples from the Pyramid Lake core between 162 mm and 330 mm were unfortunately discovered to be missing from the storage facility; two samples had originally been planned for this interval.

Pollen preparation followed a standard acid–base–acid protocol (Bennett & Willis, 2001). Sediment subsamples of 5 ml were transferred into 50 ml centrifuge tubes using distilled water and ethanol to deflocculate floating particles. Known quantities of dissolved lycopodium spp. tablets (two per sample) were added to the samples to enable pollen concentration to be calculated.

To remove carbonates, 7% hydrochloric acid (HCl) was added, and samples were heated in a 90 °C water bath for 30 minutes. After centrifugation and decanting, residues were whirlimixed and rinsed repeatedly with distilled water until the supernatant cleared.

To remove humic acids and disaggregate the samples 10% sodium hydroxide (NaOH) was added and heated in a 90°C water bath for 3 minutes. Samples were then washed with distilled water and sieved through a 180 µm mesh, so that large particles were removed. After additional rinsing, residual carbonates were removed with a second treatment of 7% HCl.

Colloidal silica and silicofluorides were removed by treating samples with 40% hydrofluoric acid (HF) and heating at 90 °C for 60 minutes. After centrifugation and decanting, samples were rinsed again with 7% HCl, heated for 60 minutes, and washed thoroughly with distilled water.

Acetolysis followed, to digest cellulose, involving dehydration with glacial acetic acid and digestion with a 9:1 acetic anhydride to concentrated sulfuric acid mixture in a 90 °C water bath for 3 minutes. Samples were then washed multiple times with glacial acetic acid and distilled water.

For staining, 2–4 drops of 0.2% aqueous safranin were added. After mixing and rinsing, tertiary butyl alcohol (TBA) was added, centrifuged and decanted till approximately 1.5 cm volume of TBA was left in the tubes. Finally, silicone oil was added in a volume roughly equal to the remaining residue, and samples were stirred gently using a toothpick. Tubes were left open for at least 24 hours to allow the TBA to evaporate, after which samples were ready for pollen identification and counting.

4.2 Pollen identification

Prior to analysis potential species lists for the sites were created using various literature, pollen diagrams and vegetation reconstructions from nearby areas (Chatters, 1998; Franklin & Dyrness, 1973; Minckley & Long, 2016). These species lists were then combined with laboratory reference slides, the online Global Pollen Project (Martin & Harvey, 2017) and pollen guides (Faegri et al., 2000; Kapp, 1969; McAndrews et al., 1973; Moore, 1991; Reille, 1999). The majority of pollen was identified to genus or family level, with the exception of greater differentiation within the Pinaceae family. This increased level of distinction was essential due to the varying fire-related life history traits of different pine species and their differing abilities to withstand fire. Additionally, although the pollen type Cupressaceae is typically recorded as a single group due to the difficulty of distinguishing species-level differences, the species *Callitropsis nootkatensis* was identified to species level based on distinctive morphological characteristics, as described by Kapp (1969) (Appendices, Supplementary Information 5). *Populus* was commonly found as clumped grains on the microscope slides. Although, it is sometimes typical to count clumped pollen as just one grain of their type (Krüger et al., 2020), as the *Populus* grains were still distinguishable they were counted as individual grains. The *Pseudotsuga*/*Larix*-type pollen was grouped due to morphological similarity between the two taxa, which prevents reliable separation under light microscopy.

To prepare the samples they were stirred for five minutes with a toothpick to reduce pollen clumping and allow the pollen and silicone oil to be fully combined. The samples were then mounted on a glass microscope with more silicone oil to reduce clumping. A cover slip was then placed on top with clear nail polish used to seal around the edges. Pollen grains were identified under a Leica DM2000 light microscope at 400× magnification, with a minimum of 300 grains counted per sample.

4.3. Pollen analysis

Terrestrial pollen and spore percentages were derived from raw pollen and spore counts using the total sum of terrestrial pollen and spores (TLPS). Percentages for aquatic vegetation pollen were calculated using the combined sum of TLPS and aquatic pollen. The programme Psimpoll 4.27 (Bennett, 1992) was used for analysis of palaeoecological data of pollen by calendar ages. TLPS and aquatics percentages were combined with the calibrated age-depth model from the "rBacon" R package to create pollen diagrams (Blaauw & Christen, 2011). These diagrams were analysed through numerical zonation in order to identify what pollen changes could be considered significant and useful in aiding their interpretation (Bennett, 1996). Different numerical zonation methods, binary and optimal splitting by sum-of-squares and information content, were applied to the datasets, with the aim of achieving the greatest reductions in variance of the datasets through statistically significant splits. Although optimal splitting is considered more satisfactory than binary splitting, because it identifies the best placement of $n-1$ boundaries for dividing a sequence into n zones, rather than placing splits successively within existing zones, all methods were applied (Bennett, 1996). This is because using multiple zonation methods can help reveal inconsistencies and improve the robustness of the interpretation (Birks, 1974; Gordon & Birks, 1972). All methods yielded similar results and as such optimal splitting by information content was selected as it found the best combination of zones, which had the greatest variance reduction, across both sites. Rarefaction analysis was performed on the TLPS dataset in Psimpoll, with a count size of 200 used for standardisation, to provide a quantitative basis for comparing community richness and composition across sites and zones (Birks & Line, 1992).

5. Macrofossil charcoal

5.1. Charcoal sampling

Macrofossil charcoal sample preparation and raw counts were undertaken by Watkins (2022), Samples of $0.5 cm^3$ every contiguous 2mm interval were taken using a calibrated syringe, providing exceptionally high stratigraphic resolution sampling. Sediment was limited in the top 30 mm at Little Monon Lake, so a reduced volume of $0.25 cm^3$ was used. The samples were then soaked in 10% sodium hexametaphosphate for 7 days to deflocculate the sediment. After soaking, the samples were washed through a series of sedimentology sieves (500, 250, and 125 µm). The material retained on each sieve was collected and analysed under a 40x stereomicroscope, and charcoal fragments were identified and counted in three size classes: 125-250 µm, 250-500 µm, and >500 µm. The counts from all categories were summed to yield a total count of charcoal fragments exceeding 125 µm. Although the fire history analyses were conducted on the combined >125 µm charcoal fraction, the dataset was also analysed separately for the 125–250 µm, 250–500 µm, and >500 µm size categories to assess correlations among the different particle sizes.

The charcoal counts span the entire depth of the Little Monon Lake core whilst the charcoal counts span just over half of the Pyramid Lake core as they extend to 336 mm (3662 cal yr BP), rather than its full depth of 670 mm (6393 cal yr BP).

5.2. Charcoal accumulation rates (CHAR)

To account for variation in raw charcoal counts caused by differing sedimentation rates, charcoal accumulation rates (CHAR) were calculated. Charcoal counts were first integrated with age–depth models using the R package 'rBacon' (Blaauw & Christen, 2011). CHAR was then derived in the tapas R package (Finsinger & Bonnici, 2022) by dividing the charcoal counts in each sample by the corresponding time interval, and is expressed in particles $mm^{-2} yr^{-1}$. For the upper 30 mm of the Little Monon Lake core, a smaller sediment volume ($0.25 cm^3$) was extracted compared to the standard $0.5 cm^3$ volume used for the rest of the core. To account for this reduced volume and make charcoal counts comparable across all depths, the counts from the top 30 mm were multiplied by a factor of two. This scaling ensures that the CHAR values reflect comparable charcoal concentrations across samples and that the smaller extracted volume does not artificially lower the apparent charcoal concentration.

The analysis of the sediment-charcoal record was based on the conceptual framework of the CharAnalysis software developed by Higuera (2009) which has been implemented in the R package tapas (Finsinger & Bonnici, 2022). The CHAR record was proportionally binned to an evenly spaced time series using linear interpolation. The resampling interval was based on the median temporal resolution of the record (approximately 17 years at both sites). This interpolation stops threshold statistics being biased to sections of the record with different sampling intervals resulting from variable sediment accumulation.

5.3. Peak-detection analysis of fire events

The resampled CHAR series was decomposed into a slowly varying background component ($\mathrm{CHAR}_{\mathrm{background}}$) and a residual peak component ($\mathrm{CHAR}_{\mathrm{peak}}$). Background charcoal accumulation was estimated using a robust locally weighted regression (robust LOESS) smoother with a 500-year window. This window width was selected based on sensitivity analyses that optimised signal-to-noise index (SNI) values and Kolmogorov–Smirnov (KS) goodness-of-fit statistics (see below). The peak component was obtained by subtracting the background estimate from the resampled CHAR series, producing detrended residuals that represent deviations from long-term trends.

This $\mathrm{CHAR}_{\mathrm{peak}}$ component, consisting of the detrended residuals, was then screened to distinguish signal from noise using a local Gaussian mixture model. The use of a local, rather than global, threshold avoids systematic bias associated with heteroscedasticity in $\mathrm{CHAR}_{\mathrm{peak}}$, which can otherwise lead to preferential detection of either small or large peaks depending on which dominates the record. Local Gaussian mixture models were applied within a 500-year moving window centred on each time step, which allows for variance of the noise component through time. This window size also aligns with recommendations that local thresholds be based on a minimum of ~30 samples (Higuera et al., 2010)

Within each window, detrended residuals were modelled as a two-component Gaussian mixture consisting of a noise distribution centred on zero and a signal distribution representing fire events. Fire peaks were identified using a threshold defined as the 95th percentile of the noise distribution. Where consecutive samples exceeded the threshold, only the oldest sample was retained to prevent artificial inflation of fire events (Higuera et al., 2010). A 'minimum count test' was also applied to ensure that identified peaks did not arise from statistically insignificant differences in charcoal abundance, by assessing the probability that two resampled counts originated from the same Poisson counting process (Higuera et al., 2010).

The suitability of the CHAR record for peak detection was evaluated using the signal-to-noise index (SNI) (Kelly et al., 2011). Smoothed SNI values were calculated from the positive residuals, with median SNI used to assess overall record quality. Median SNI values near or exceeding 3 indicate reliable separation of fire-related charcoal input from background variability (Kelly et al., 2011).

Peak-detection quality was further assessed using a two-sample Kolmogorov–Smirnov (KS) test, comparing the distribution of CHAR noise residuals with the distribution of identified fire peaks

(Clark, 1990; Higuera et al., 2010). A significant KS test can indicate effective separation between noise and fire-related charcoal inputs, while the KS D statistic provides a measure of the contrast between the two components.

6. Statistical analysis of pollen and charcoal

The CHAR dataset was analysed using the R package changepoint to assess time periods of significant change in the fire record (Killick & Eckley, 2014). CHAR was used in preference to raw charcoal counts to account for variations in sedimentation rate and temporal sample resolution. The breakpoint analysis examined shifts in both the mean and variance of the CHAR series. Multiple changepoints were detected using the pruned exact linear time (PELT) (Killick et al., 2012) method which can detect changepoints while controlling for overfitting. The modified Bayesian information criterion (MBIC) was used as the penalty function and a minimum segment length equal to the mean fire return interval at each site was imposed to ensure detected changepoints represented sustained shifts in fire regime rather than variability associated with individual fire events. Secondly, an at-most-one-change (AMOC) method was applied to identify the single most prominent changepoints in the CHAR record, with the MBIC penalty. The AMOC analysis is particularly valuable in highlighting the most dominant shift in CHAR through time.

To test whether CHAR values varied significantly across pollen zones, as defined by numerical zonation, non-parametric Mann-Whitney U tests were applied to each charcoal particle size class. This method was selected due to the non-normal distribution of the CHAR data.

Chapter 3: Results

1. Pollen

1.1. Vegetation reconstructions

There was a total of 32 pollen/spore types identified at Little Monon Lake and Pyramid Lake (including *Callitropsis nootkatensis* as separate type). Most of these vegetation types overlapped between the sites, although their distributions differed significantly. Rarefaction analysis estimated that palynological richness values ranged between approximately 15 and 20 pollen types, with broadly comparable richness between Little Monon Lake and Pyramid Lake. The terrestrial pollen percentage changes were visualized (Figure 5) in the Psimpoll programme (Bennett, 1992) for Little Monon Lake.

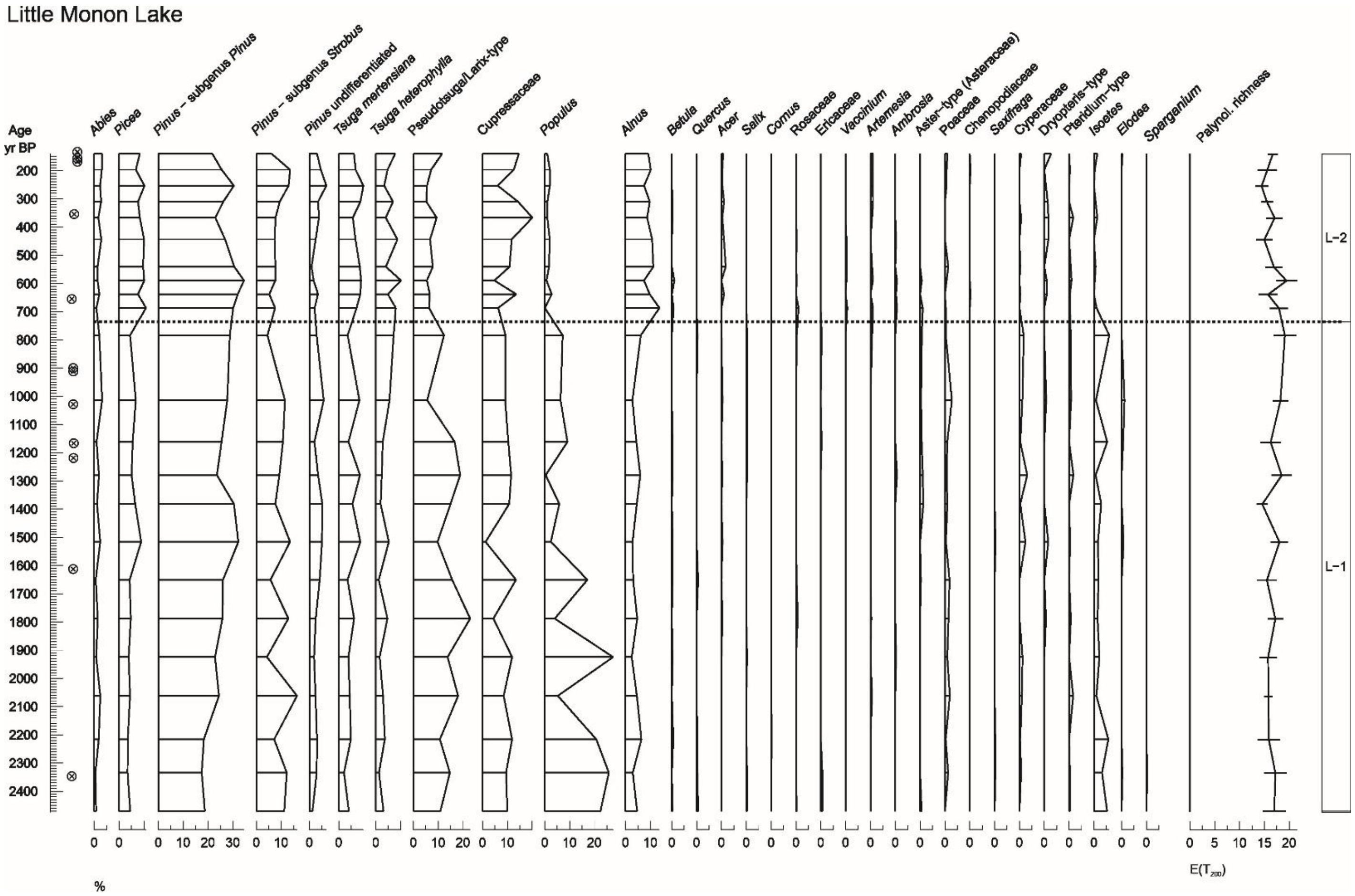


Figure 5. Pollen percentage diagram for Little Monon Lake plotted against calibrated sediment age. The ⊗ symbol represents the subsampling location raw ^{14}C radiocarbon dates. The Age (yr BP) timescale was calibrated from raw ^{14}C radiocarbon dates using an age-depth model from "rBacon" with calibrations based on IntCal13 and NH2 for post-bomb dates (Blaauw & Christen, 2011). The dotted line, at 735 cal yr BP, shows the zones (L-1 and L-2) which were identified through optimal splitting by information content. On the right side of the diagram is palynological richness was estimated using rarefaction analysis, standardised to a count size of 200 grains per sample. The depth of the samples ranges from 2 to 228mm.

In addition to the main terrestrial pollen diagram, the Cupressaceae pollen type was further subdivided into *Callitropsis nootkatensis* (Alaska yellow cedar) and the remaining Cupressaceae taxa (Figure 6). However, this distinction was not included in the main pollen percentage diagram or in any quantitative analyses, as it is not standard practice to separate this species within Cupressaceae. Moreover, the separation carries a degree of uncertainty, given that previous studies have not consistently distinguished *C. nootkatensis* at the species level.

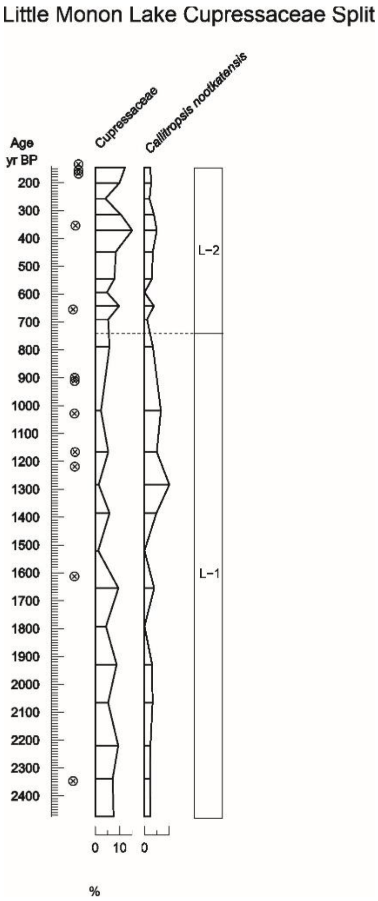


Figure 6. Pollen percentage diagram with visual split of Cupressaceae pollen type into Callitropsis nootkatenisis and other Cupressaceae for Little Monon Lake plotted against calibrated sediment age. The ⊗ symbol represents the subsampling location raw ^{14}C radiocarbon dates. The Age (yr BP) timescale was calibrated from raw ^{14}C radiocarbon dates using an age-depth model from "rBacon" with calibrations based on IntCal13 and NH2 for post-bomb dates (Blaauw & Christen, 2011). The dotted line, at 735 cal yr BP, shows the zones (L-1 and L-2) which were identified through optimal splitting by information content.

Changes in terrestrial pollen percentages at Pyramid Lake were visualized using Psimpoll (Bennett, 1992) (Figure 7). Despite the absence of two samples in the Pyramid Lake core between 162 mm and 330 mm, pollen assemblages immediately above and below this interval show no substantial shifts in composition.

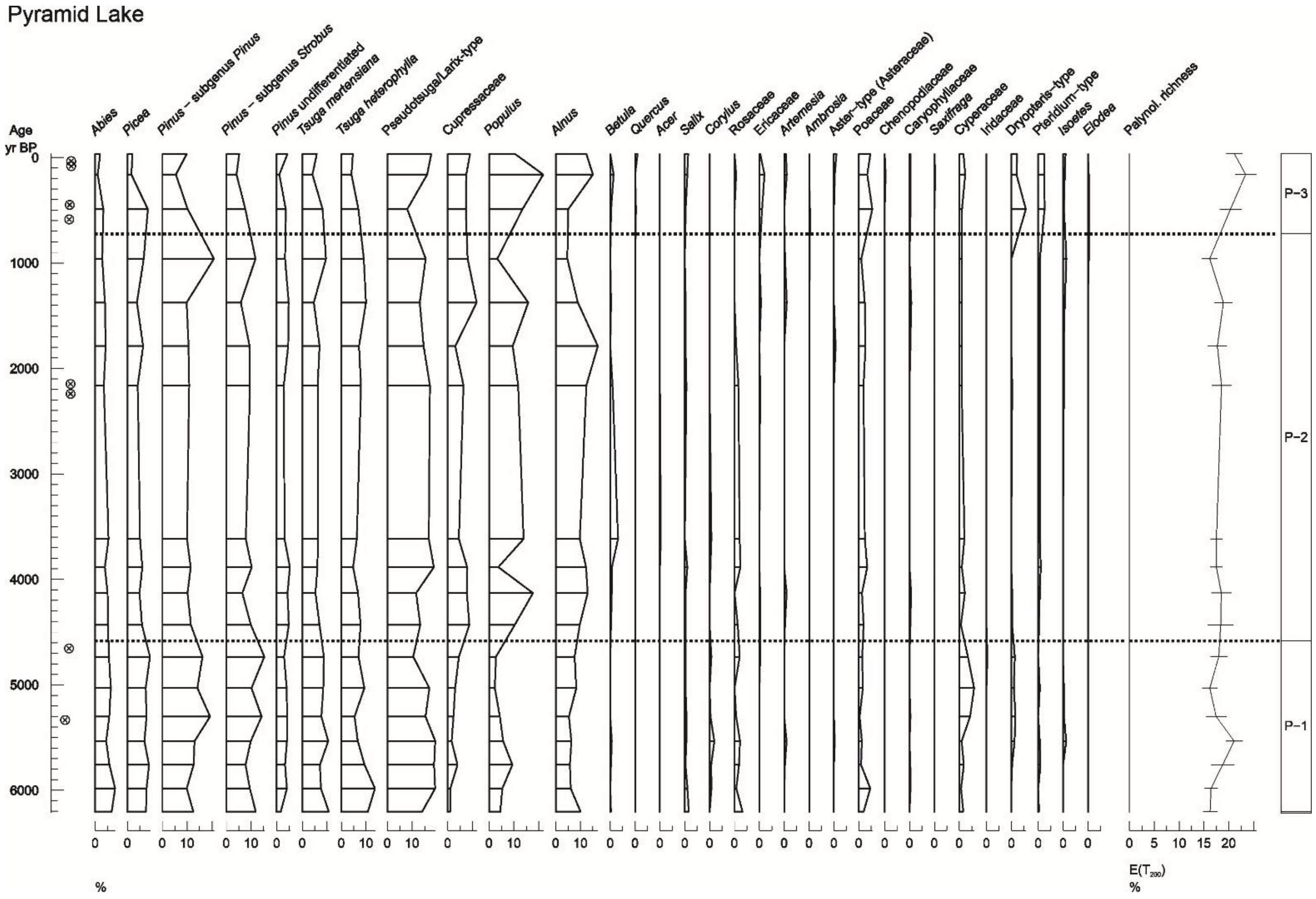


Figure 7. Pollen percentage diagram for Pyramid Lake plotted against calibrated sediment age. The ⊗ symbol represents the subsampling location raw ^{14}C radiocarbon dates. The Age (yr BP) timescale was calibrated from raw ^{14}C radiocarbon dates using an age-depth model from "rBacon" with calibrations based on IntCal13 and NH2 for post-bomb dates (Blaauw & Christen, 2011). The dotted lines, at 725 cal yr BP and 4582 cal yr BP, shows the zones (P-1, P-2 & P-3) which were identified through optimal splitting by information content. On the right side of the diagram is palynological richness was estimated using rarefaction analysis, standardised to a count size of 200 grains per sample. The depth of the samples ranges from 2 to 642mm.

In addition to the main terrestrial pollen diagram, the Cupressaceae pollen type was further subdivided into *Callitropsis nootkatensis* (Alaska yellow cedar) and the remaining Cupressaceae taxa (Figure 8). Both vegetation types appear to exhibit similar trends, indicating that the subdivision does not alter the overall pollen signal.

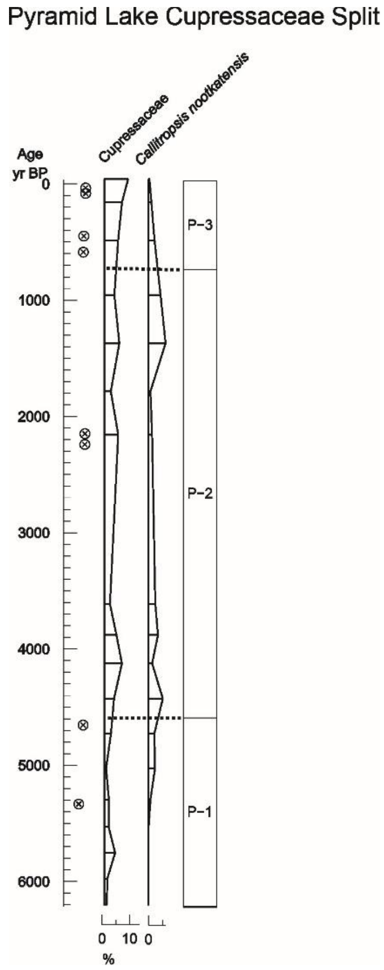


Figure 8: Pollen percentage diagram with visual split of Cupressaceae pollen type into Callitropsis nootkatenisis and other Cupressaceae for Pyramid Lake plotted against calibrated sediment age. The ⊗ symbol represents the subsampling location raw ^{14}C radiocarbon dates. The Age (yr BP) timescale was calibrated from raw ^{14}C radiocarbon dates using an age-depth model from "rBacon" with calibrations based on IntCal13 and NH2 for post-bomb dates (Blaauw & Christen, 2011). The dotted lines, at 725 cal yr BP and 4582 cal yr BP, shows the zones (P-1, P-2 & P-3) which were identified through optimal splitting by information content.

1.2. Zonation

Optimal splitting by information content was used as the method of numerical zonation, due to it having the greatest variance reduction across both sites, compared to other methods. This resulted in a single split at Little Monon Lake at 735 cal yr BP and 34 mm depth (Table 3) and two splits at Pyramid Lake at 725 and 4,582 cal yr BP, corresponding to depths of 50 mm and 434 mm, respectively (Table 4). These splits produced statistically significant zones which respectively accounted for 41.76% and 45.67% of variance within the data. To avoid over splitting only statistically significant zones were included.

Table 3: Statistical results of zonation by optimal splitting by information content into two zones of Little Monon Lake site from Psimpoll (Bennett, 1992).

n	Residual variance	Variance with n zones as % of total	Variance reduction (% of total) from n-1 zones to n zones	Variance reduction (% of n – 1 zones) from n-1 zones to n zones	Age marker (cal yr BP)	Depth marker (mm)
1	3.7724	1.0000	-	-	-	-
2	2.1969	0.5824	0.4176*	0.5824	735	34.000

Table 4: Statistical results of zonation by optimal splitting by information content into three zones of Pyramid Lake site from Psimpoll (Bennett, 1992).

n	Residual variance	Variance with n zones as % of total	Variance reduction (% of total) from n-1 zones to n zones	Variance reduction (% of n – 1 zones) from n-1 zones to n zones	Age marker (cal yr BP)	Depth marker (mm)
1	2.0902	1.0000	-	-	-	-
2	1.4475	0.6925	0.3075*	0.6925	4582	434.000
3	1.1360	0.5435	0.1490*	0.7848	725 4582	50.000 434.000

Both pollen assemblage zones at Little Monon Lake are dominated by *Pinus* pollen, particularly from the subgenus *Pinus*. The lower zone (L-1) is characterised by high proportions of pollen from the Pinaceae family, with percentages averaging 67.2%, this increases in the upper zone (L-2) to an average of 72.1%. There are also slightly higher proportions of *Pinus* subgenus *Pinus* averaging 24.7% in L-1 compared to 28.1% in L-2. *Pinus* subgenus *Strobus* remains relatively stable across both zones, with minimal variation, 9.8% in L-1 and 8.6% in L-2. The percentage of *Picea* increases by slightly less than half from 5.0% in L-1 to 9.0% in L-2. *Tsuga heterophylla* increases from 3.4% to 6.3%, and *Tsuga mertensiana* increases from 5.2% to 7.7%. Percentages of *Populus* decrease markedly, from around 11.8% to 1.4% from L-1 to L-2. From zone L-1 to L-2, Pseudotsuga/Larix declines substantially, from 14.2% to 7%, while *Alnus* increases from 4.3% to 9.8%. Other pollen types, including *Abies*, *Acer*, *Saxifraga*, *Aster*-type, Poaceae, and *Pteridium*-type, show little variation between the zones.

Although there are three pollen assemblage zones at Pyramid Lake, all are dominated by Pinaceae pollen, similar to Little Monon Lake. The proportions of Pinaceae pollen decrease by over 10% between each zone, from 76.2% in the lower zone (P-1), to 63.4% in the middle zone (P-2), and reaching 48.3% in the upper zone (P-3). All species within the Pinaceae family follow this trend of increasing from P-1 to P-3. The pollen taxa within the Pinaceae family that has the largest percentage is *Pinus* subgenus *Pinus* which range from 13.9% to 11.8% to 8.5%, whilst *Pinus* subgenus *Strobus* ranges from 11.2% to 8.8% to 5.6%. *Abies* increases from 6.1% to 4.3% to 2.1%, *Picea* from 7.8% to 5.3% to 3.9%, *Tsuga mertensiana* from 8.7% to 6.5% to 6.0%, and *Tsuga heterophylla* from 8.8% to 7.5% to 5.2%. A similar increasing trend is observed in Cupressaceae, which increases from 2.5% in P-1 to 7.2% in P-2 and 7.9% in P-3, and in Alnus, which increases from 7.1% in P-1 before increasing and remaining constant at10.9% in P-2 and P-3. Other pollen types such as *Equisetum*, Cyperaceae, Pseudotsuga/Larix type, Rosaceae, *Aster*-type and *Isoetes* have very little variation in percentage levels between zones.

2. Charcoal

Raw charcoal count data were taken from Watkins (2022). CHAR and fire events were analysed here using standard peak-detection methods following Higuera et al. (2011) using R package tapas (Finsinger & Bonnici, 2022). Raw charcoal counts of the three size fractions (>500 µm, to 250-500 µm to 125-250 µm) were compared to assess the likelihood that fractions > 125 represented local burning.

One-tailed spearman rank correlations show a significant positive relationship between the 250–500 µm and 125–250 µm fractions at Little Monon Lake ($\rho = 0.63$, $p < 3.61e-13$) and Pyramid Lake ($\rho = 0.78$, $p < 2.2e-16$), supporting the interpretation that these fractions capture a consistent local charcoal signal. Correlations involving the >500 µm fraction were weaker at Little Monon Lake (500 µm and 250–500 µm: $\rho = 0.21$, $p = 0.013$; 500 µm and 125–250 µm: $\rho = 0.29$, $p = 0.0012$), and Pyramid Lake (500 µm and 250–500 µm: $\rho = 0.17$, $p = 0.034$; 500 µm and 125–250 µm: $\rho = 0.12$, $p = 0.15$), which is acceptable given the relatively low number of particles in this largest size class. Despite the weaker correlations for the >500 µm fraction, pooling all size classes >125 µm is appropriate, as it increases total charcoal counts, improves statistical robustness and reduces uncertainty in fire history reconstructions, particularly when individual fractions yield few particles (Higuera et al., 2010). Additionally, the size class of >125 µm has been found to provide a good record of local fires and is common practice for charcoal sedimentary analysis (Clark, 1990; Gardner & Whitlock, 2001; Higuera et al., 2010; Whitlock & Millspaugh, 1996)

2.1. Raw charcoal counts

The maximum number of charcoal particles found at Little Monon Lake and Pyramid Lake increased from the size class of >500 µm, to 250-500 µm to 125-250 µm (Table 5). With Pyramid Lake containing the lowest mean number of particles across all size classes.

Table 5: Summary statistics of raw charcoal count data.

		Total (>125 µm)	>500 µm	250-500 µm	125-250 µm
Little Monon Lake					
	Min	10	0	0	10
	Max	212	5	35	181
	Mean	88.96	0.3429	9.419	79.2
Pyramid Lake					
	Min	9	0	0	9
	Max	146	2	17	113
	Mean	49.17	0.1203	3.981	45.07

To visualise the distribution of charcoal counts, violin plots were produced using the R package ‘vioplot’ (Adler et al., 2025). These plots combine box plots with kernel density estimates to display both the spread and frequency of charcoal particle counts across samples (Figure 9.1 & 9.2). At both sites, the >500 µm charcoal particles show a similar distribution, with the majority of sampling depths containing no particles in this size class. In contrast, all samples in the 125–250 µm class contain charcoal, with differing distribution patterns between the sites: Little Monon Lake exhibits a roughly normal distribution, while Pyramid Lake shows a unimodal distribution skewed toward lower particle counts. This same skew toward lower charcoal counts is also observed in the 250–500 µm size class at both sites.

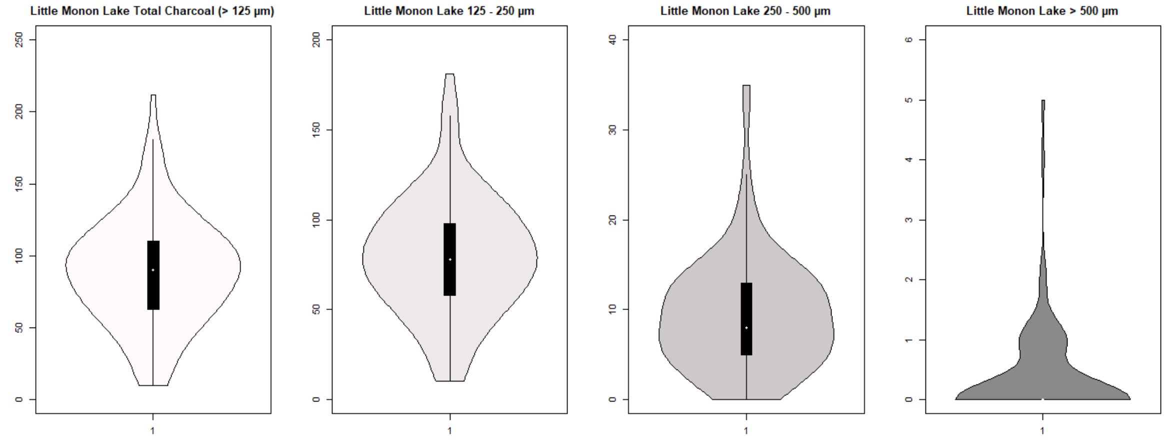


Figure 9.1 Violin plots of raw charcoal counts at Little Monon Lake. The width of each violin represents the frequency of samples with a given count. The left axis indicates the number of charcoal particles per sample for each size class: Total (> 125 µm), 125–250 µm, 250–500 µm, and >500 µm.

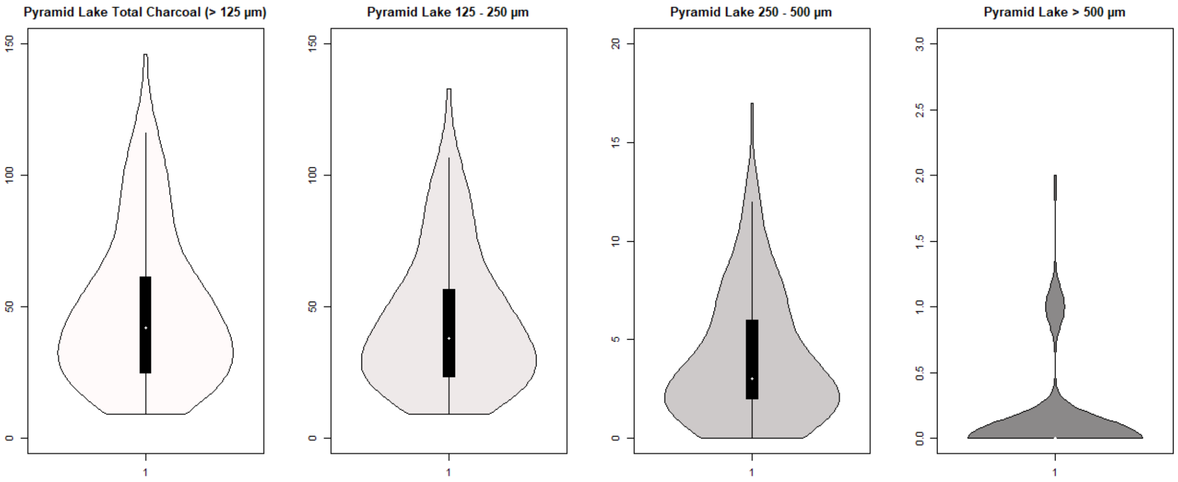


Figure 9.2 Violin plots of raw charcoal counts at Pyramid Lake. The width of each violin represents the frequency of samples with a given count. The left axis indicates the number of charcoal particles per sample for each size class: Total (> 125 µm), 125–250 µm, 250–500 µm, and >500 µm.

2.2. Charcoal accumulation rates (CHAR)

2.2.1 Little Monon Lake

The earliest portion of the Little Monon Lake record (before ~1500 cal yr BP) exhibits moderate CHAR values with periodic fluctuations, ranging from ~10 to ~30 particles mm^{-2} yr^{-1} (Figure 10). Around 1500 cal yr BP, a pronounced peak exceeds 45 particles mm^{-2} yr^{-1}, representing the highest accumulation rate in this size class. Following this peak, CHAR values fluctuate markedly at lower levels, sometimes reaching 0 particles mm^{-2} yr^{-1}, indicating reduced frequency and magnitude of fire activity between ~1400 and 1200 cal yr BP. A sustained decrease occurs from ~1000 to 250 cal yr BP, during which CHAR remains low and relatively stable, often below 5 particles mm^{-2} yr^{-1}. Finally, the record shows a slight increase in CHAR during the most recent 250 years.

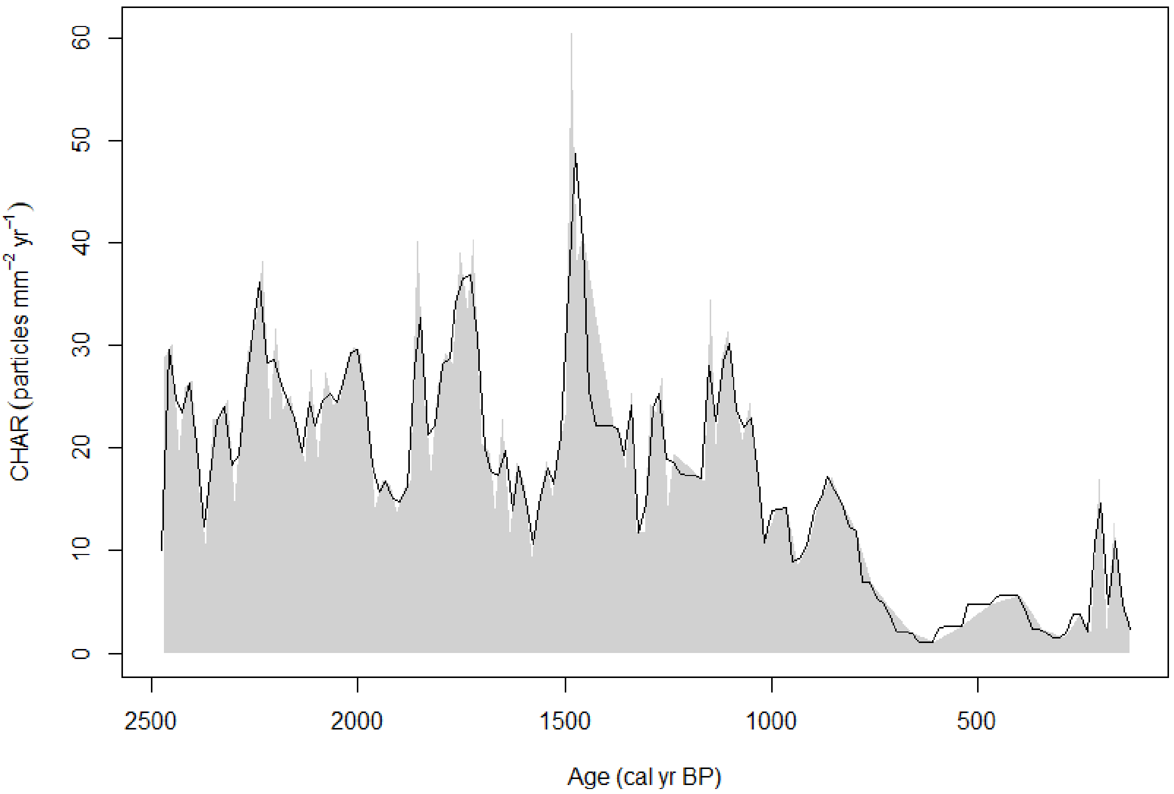


Figure 10: Charcoal accumulation rate (CHAR) for the >125 µm grouped charcoal at Little Monon Lake. CHAR represents the number of charcoal particles deposited per mm² per year. The black line shows re-sampled accumulation rates at equal sampling intervals, based on median sampling interval of raw record (17 years), while the grey shaded area represents the non-resampled accumulation rates.

2.2.2. Pyramid Lake

Charcoal accumulation (CHAR) for the grouped charcoal (>125 µm) at Pyramid Lake, which contains 7769 charcoal particles, shows much variability across most of the record (Figure 11). From ~3700 to 2100 cal yr BP, CHAR frequently fluctuates between ~7 and 25 particles mm^{-2} yr^{-1}, with a pronounced peak at ~2200 cal yr BP exceeding 30 particles mm^{-2} yr^{-1}, representing the highest accumulation rates observed. Between 2100 and 700 cal yr BP, fluctuations persist but at lower levels, generally ranging from ~5 to 10 particles mm^{-2} yr^{-1}. After ~700 cal yr BP, both the magnitude and frequency of peaks decline, with most values falling below 5 particles mm^{-2} yr^{-1}.

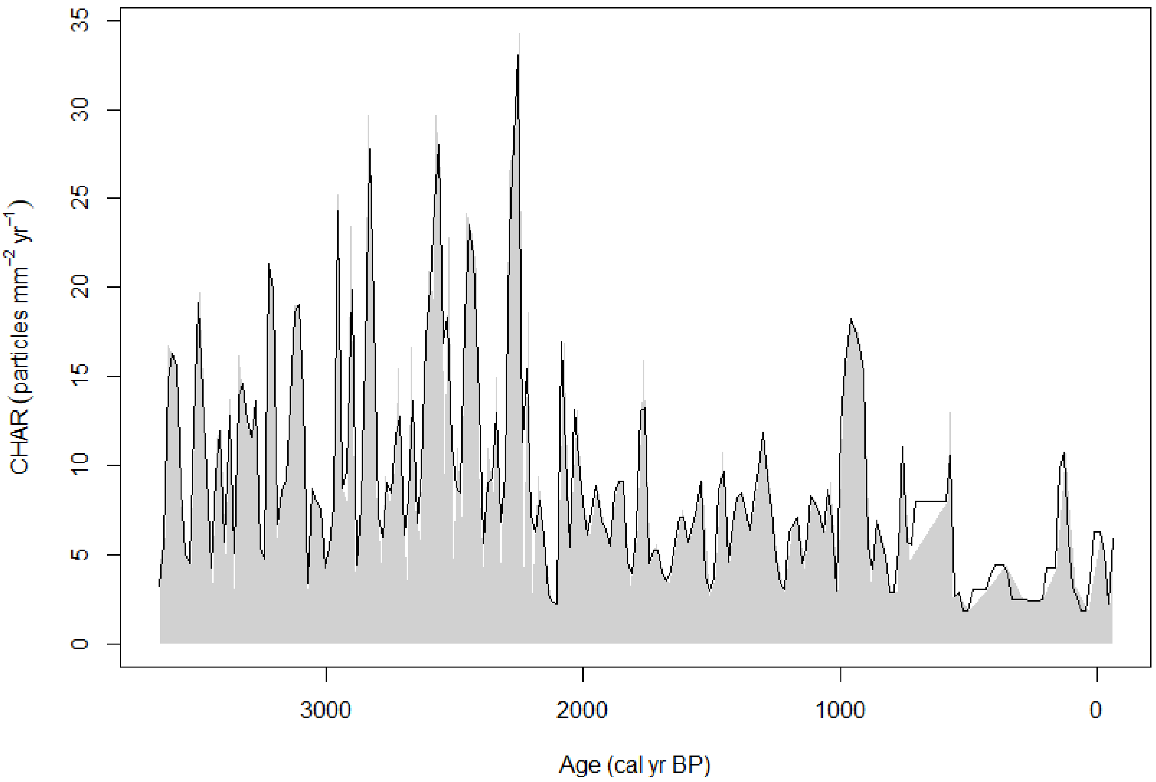


Figure 11: Charcoal accumulation rate (CHAR) for the >125 µm grouped charcoal at Pyramid Lake. CHAR represents the number of charcoal particles deposited per mm² per year. The black line shows re-sampled accumulation rates at equal sampling intervals, based on median sampling interval of raw record (17 years), while the grey shaded area represents the non-resampled accumulation rates.

2.3. Peak-detection analysis of fire events

To detect fire events, the CHAR series was decomposed into a slowly varying CHAR$_{background}$ and a residual CHAR$_{peak}$ component. Sensitivity analyses were conducted by repeatedly running SNI and KS statistics after all stages of the analysis to optimize both the LOESS smoothing window (100–1000 years) and the parameters of the local Gaussian mixture model. This iterative approach ensured that the local model accurately distinguished fire-related peaks from background noise while preserving long-term trends. A 500-year LOESS smoothing window was identified as optimal for both study sites.

The CHAR$_{peak}$ component was then screened using a local Gaussian mixture model with a 500-year moving window, in which fire peaks were defined as values exceeding the 95th percentile of the local noise distribution. Consecutive peaks were consolidated to retain only the oldest sample, preventing artificial inflation of events. A minimum count test was applied to remove peaks that could arise from statistically insignificant differences in charcoal abundance. A total of 11 fire events were identified at Little Monon Lake with a mean fire return interval (FRI) of 207.4 years (Figure 12).

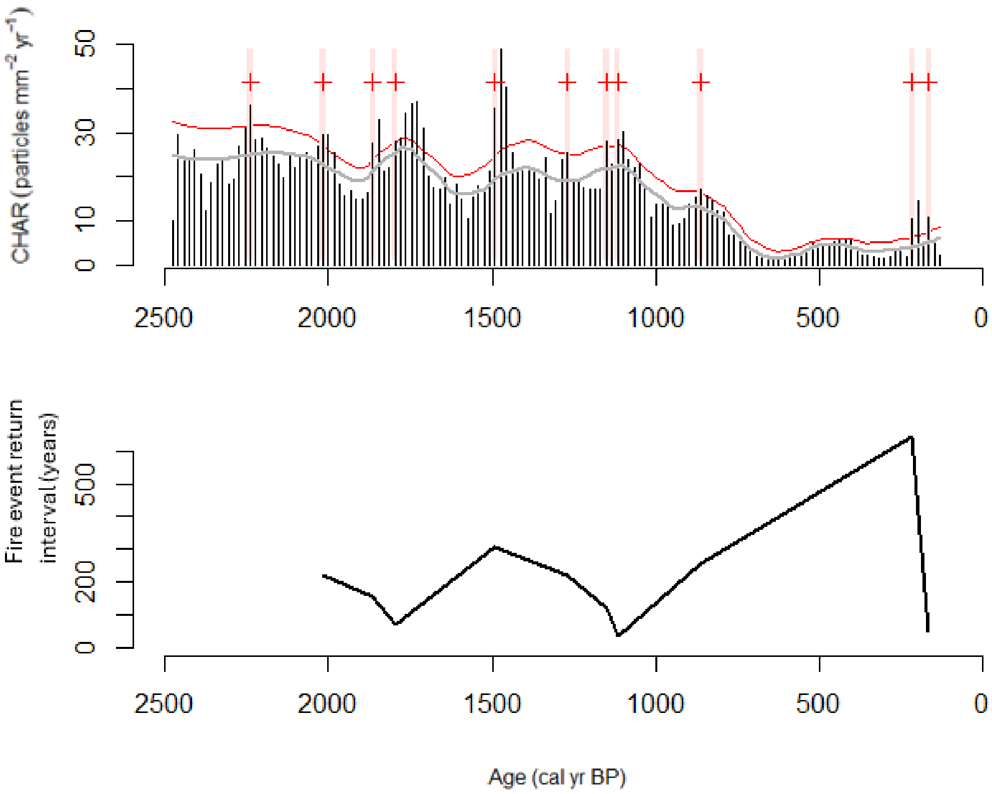


Figure 12: Little Monon Lake peak detection and fire return interval. Upper panel: Charcoal accumulation rate (CHAR) and identified fire episodes based on peak detection analysis. Black bars represent interpolated charcoal accumulation rate. The grey line shows the 500-year locally weighted regression (robust LOESS) smoothing used to estimate background charcoal. The red line indicates the locally defined 95th percentile threshold used to identify significant peaks above background variability. Red crosses mark statistically significant positive peaks interpreted as local fire events. Lower panel: Fire return intervals (FRI) calculated from the identified fire events.

A total of 24 fire events were identified at Pyramid Lake (Figure 13). These had a mean FRI of 150 years.

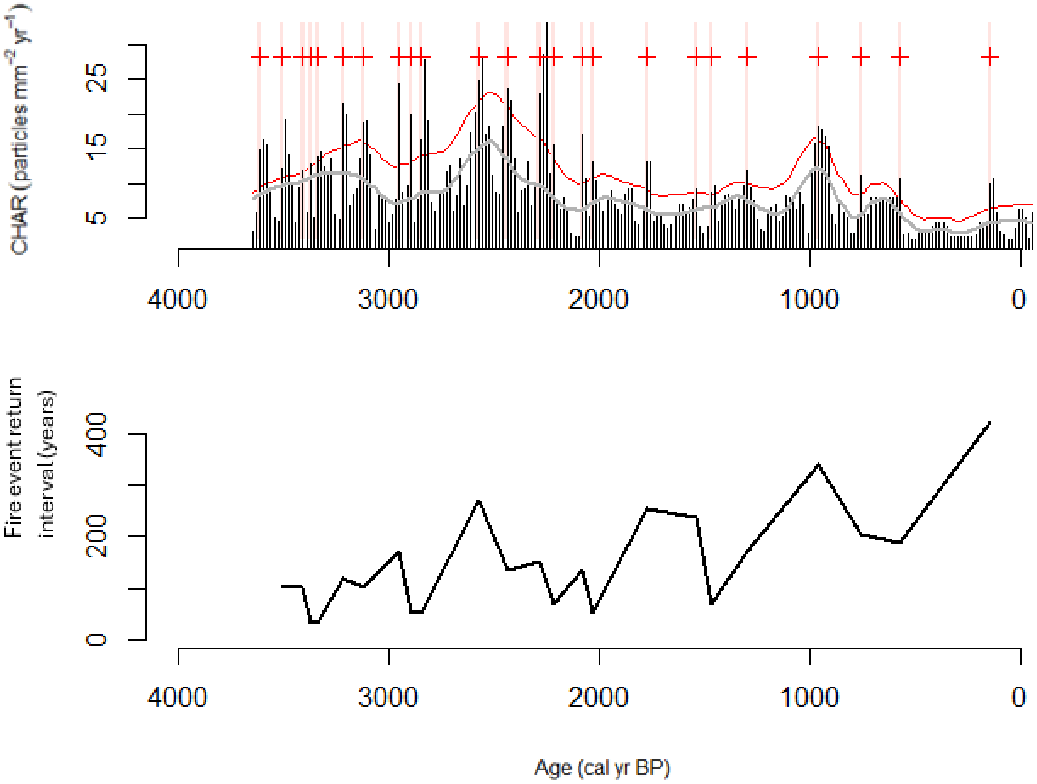


Figure 13: Pyramid Lake peak detection and fire return interval. Upper panel: Charcoal accumulation rate (CHAR) and identified fire episodes based on peak detection analysis. Black bars represent interpolated charcoal accumulation rate. The grey line shows the 500-year locally weighted regression (robust LOESS) smoothing used to estimate background charcoal. The red line indicates the locally defined 95th percentile threshold used to identify significant peaks above background variability. Red crosses mark statistically significant positive peaks interpreted as local fire events. Lower panel: Fire return intervals (FRI) calculated from the identified fire events.

The SNI values indicated reliable separation of fire-related peaks from background variability at both sites. At Little Monon Lake the mean SNI was 2.83 and the median 2.26, while at Pyramid Lake, the mean SNI was 3.0 and the median 2.84, indicating moderately strong separation. Whilst a SNI value ≥3 consistently identifies records appropriate for peak detection, Higuera (2009) suggested that levels >0.5 are generally sufficient to justify peak analysis. Peak detection quality was further evaluated using a two-sample KS test, which assesses peak detection quality. This goodness-of-fit metric confirmed that there was a significant degree of contrast between the noise and fire peaks as modelled by the Gaussian mixture model for Little Monon Lake (D = 0.8192, p-value = 2.399e-14) and Pyramid Lake (D = 0.86858, p-value < 2.2e-16).

2.4. Breakpoint analysis

Breakpoint analysis using the R package changepoint (Killick & Eckley, 2014), identified shifts in the mean and variance of the CHAR series, with a MBIC penalty function. A total of two changepoints

(777 and 1032 cal yr BP) were identified at Little Monon Lake with the pruned exact linear time (PELT) method (Killick et al., 2012). The at-most-one-change (AMOC) method was then applied to identify the most prominent changepoint was at 777 cal yr BP (Figure 14).

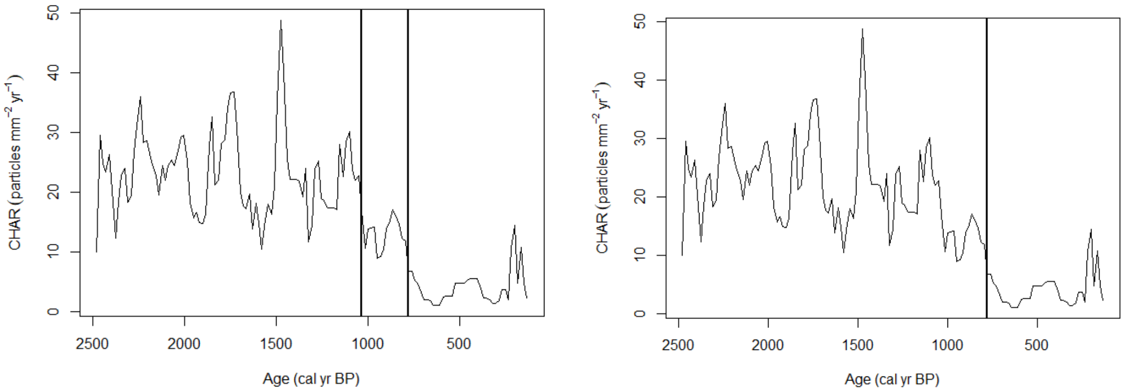


Figure 14: Changepoint analysis of Little Monon Lake's CHAR record using two methods with a modified Bayesian information criterion (MBIC) penalty. Left panel: The pruned exact linear time (PELT) method, detecting multiple changepoints across the record. Right panel: The at-most-one-change (AMOC) method, identifying a single dominant changepoint.

Three changepoints were identified at Pyramid Lake using the PELT method at 146, 554 and 2203 cal yr BP (Figure 15). The most dominant shift in CHAR is at 2203 cal yr BP and was identified with the AMOC method.

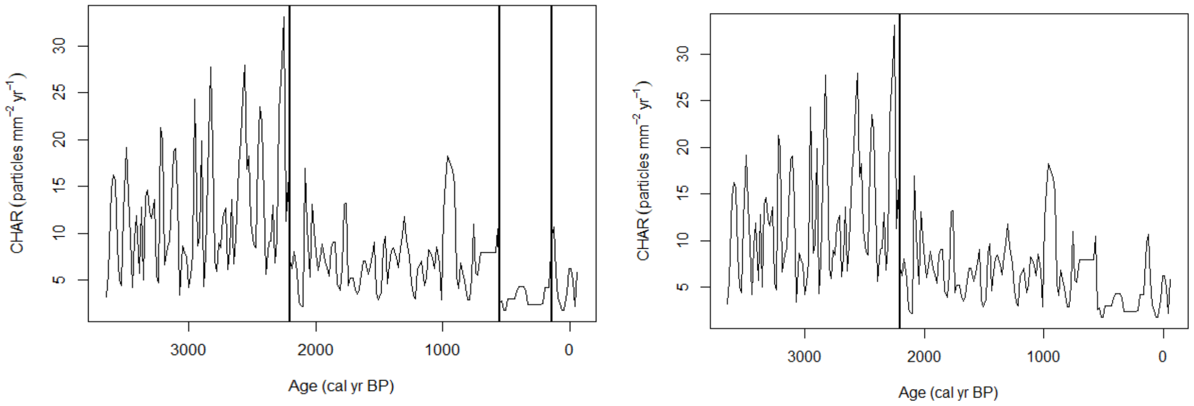


Figure 15. Changepoint analysis of Pyramid Lake's CHAR record using two methods with a modified Bayesian information criterion (MBIC) penalty. Left panel: The pruned exact linear time (PELT) method, detecting multiple changepoints across the record. Right panel: The at-most-one-change (AMOC) method, identifying a single dominant changepoint.

3. Charcoal and pollen analysis

Figure 16 & 17 show the variation in vegetation and wildfire activity at each site over time.

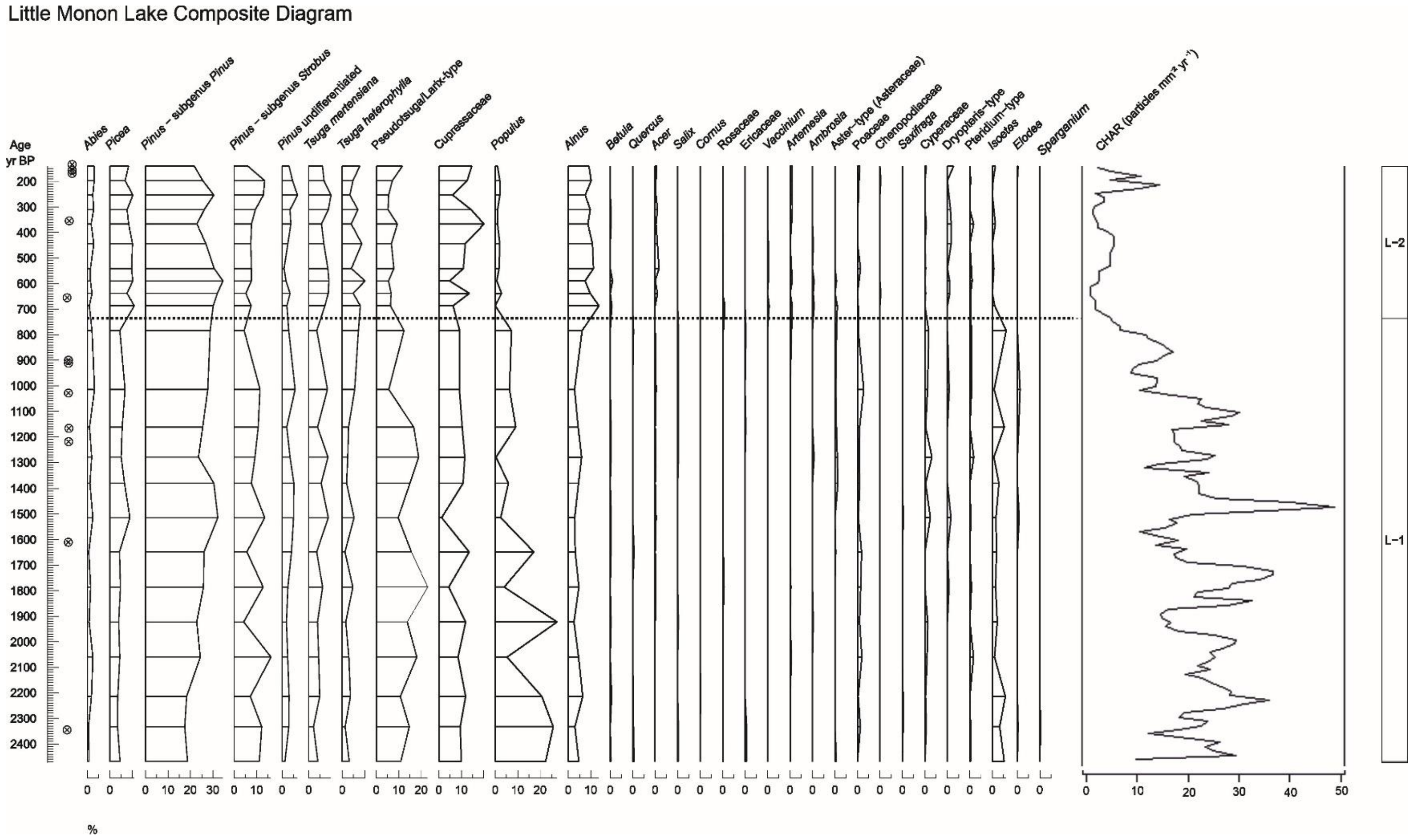


Figure 16: Composite vegetation–fire diagram for Little Monon Lake. Terrestrial pollen percentages (left panels) are plotted by calibrated age (Age yr BP), alongside charcoal accumulation rate (CHAR; right panel) for the combined charcoal category (particles mm^{-2} yr^{-1}). The black CHAR line shows re-sampled accumulation rates at equal sampling intervals, based on median sampling interval of raw record (17 years). The ⊗ symbol represents the subsampling location raw ^{14}C radiocarbon dates. The Age (yr BP) timescale was calibrated from raw ^{14}C radiocarbon dates using an age-depth model from "rBacon" with calibrations based on IntCal13 and NH2 for post-bomb dates (Blaauw & Christen, 2011). The dotted line, at 735 cal yr BP, shows the pollen assemblage zones (L-1 and L-2) which were identified through optimal splitting by information content.

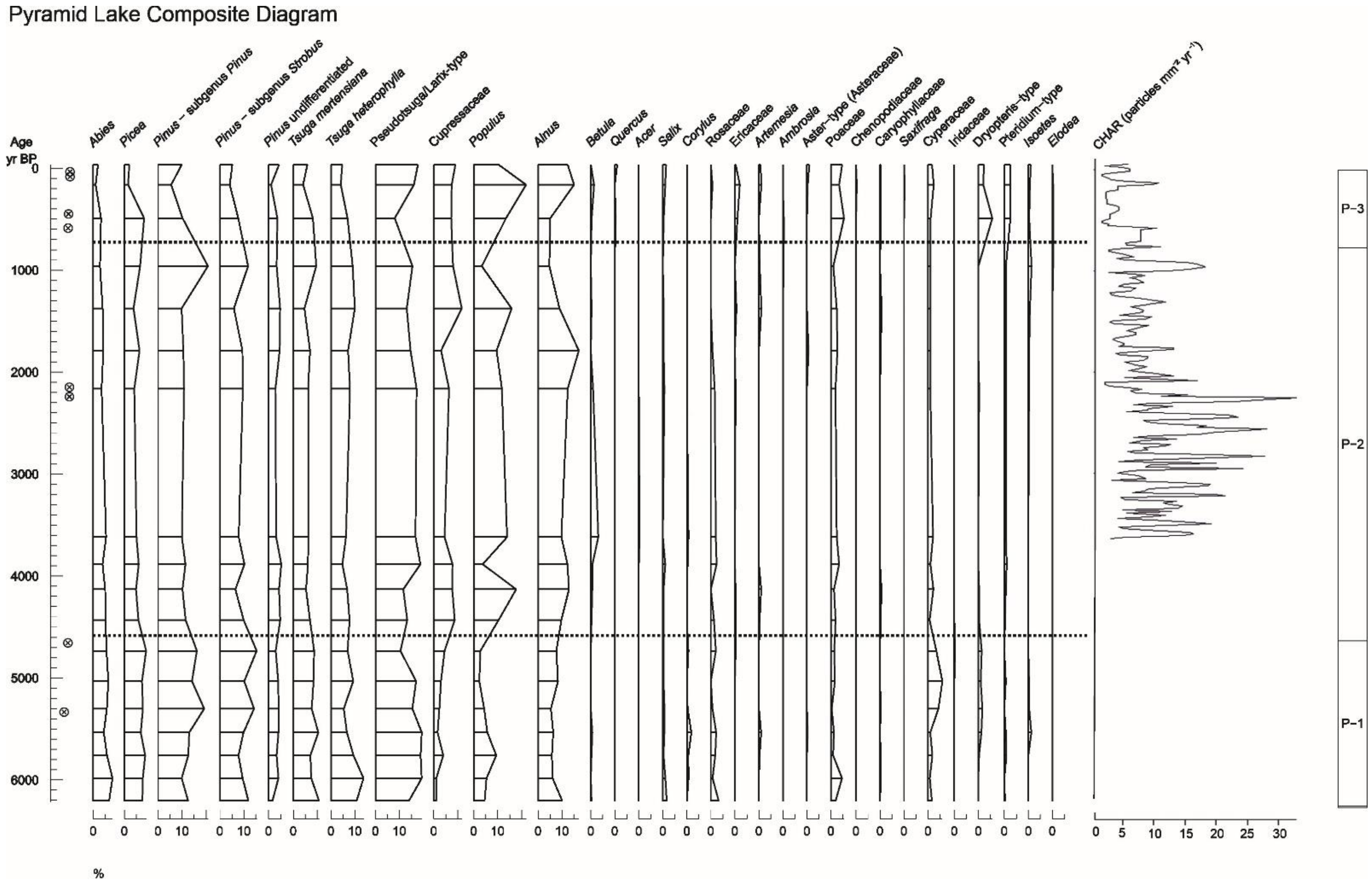


Figure 17: Composite vegetation–fire diagram for Pyramid Lake. Terrestrial pollen percentages (left panels) are plotted by calibrated age (Age yr BP), alongside charcoal accumulation rate (CHAR; right panel) for the combined charcoal category (particles mm^{-2} yr^{-1}). The black CHAR line shows re-sampled accumulation rates at equal sampling intervals, based on median sampling interval of raw record (17 years). The ⊗ symbol represents the subsampling location raw ^{14}C radiocarbon dates. The Age (yr BP) timescale was calibrated from raw ^{14}C radiocarbon dates using an age-depth model from "rBacon" with calibrations based on IntCal13 and NH2 for post-bomb dates (Blaauw & Christen, 2011). The dotted lines, at 725 cal yr BP and 4582 cal yr BP, shows the pollen assemblage zones (P-1, P-2 & P-3) which were identified through optimal splitting by information content. Note: The charcoal was only counted down to 336 mm, 3662 cal yr BP, which is why the CHAR data does not extend past this point.

To further explore the relationship between vegetation change and fire activity, the range and mean of CHAR within each pollen zone were calculated alongside the mean fire return interval (Tables 6 & 7).

Table 6: Mean CHAR identified in different pollen zones at Little Monon Lake.

Depth Zone (mm)	Age Range (cal yr BP)	Mean CHAR ($mm^{-2}yr^{-1}$)	CHAR Range ($mm^{-2}yr^{-1}$)	Mean Fire Return Interval (yrs)
0-34	131 to 735	3.99	13.4	348.5
34-230	735 to 2487	21.2	43.4	172.13

Table 7: Mean CHAR identified in different pollen zones at Pyramid Lake.

Depth Zone (mm)	Age Range (cal yr BP)	Mean CHAR ($mm^{-2}yr^{-1}$)	CHAR Range ($mm^{-2}yr^{-1}$)	Mean Fire Return Interval (yrs)
0-50	-58 to 725	4.65	8.93	306
50- 336	725 to 3662	9.90	30.8	136

Note. Although the pollen zones extend to a depth of 670 mm at Pyramid Lake, charcoal was only counted down to 336 mm. Therefore, only the first two zones are included in the fire event analysis, with the second zone not extending to its full depth of 434mm and 4582 cal yr BP.

Mann-Whitney U tests were conducted to determine whether charcoal accumulation rates (CHAR) differed significantly between pollen zones at each site. The test revealed a highly significant difference between zones at Little Monon Lake ($W = 40$, $p < 2.2e-16$) and at Pyramid Lake ($W = 1476$, $p = 2.66e-11$).

Chapter 4: Discussion

This study aimed to reconstruct late Holocene vegetation and fire dynamics in high-elevation mixed conifer forests of the high Cascade Mountains, and to evaluate whether recent fire and vegetation patterns represent unprecedented ecological change. The vegetation reconstructions indicate that conifer-dominated forests, particularly those within the Pinaceae, have persisted at both sites for the past ~2500 years (Little Monon Lake) and ~6100 years (Pyramid Lake). Although minor fluctuations in disturbance-associated taxa occurred, there is no evidence for major, long-term compositional reorganisation. These findings suggest that current forest composition broadly reflects late Holocene community structure rather than representing a novel ecological state. Fire regime reconstructions reveal spatial heterogeneity. Pyramid Lake experienced more frequent fire events and shorter mean fire return intervals, consistent with its mid-elevation position in the *Abies amabilis* zone. In contrast, Little Monon Lake, located in the higher-elevation *Tsuga mertensiana* zone, recorded longer fire return intervals but substantially higher background CHAR values. Elevated background CHAR at Little Monon Lake suggests either continuous low-intensity burning at the site or fewer but potentially larger area or more biomass-consuming fires (Leys et al., 2015; Scott, 2014), where charcoal transport to the lakes persists for several years following fires, contributing to prolonged elevated levels of CHAR (Whitlock & Millspaugh, 1996). Both sites exhibit a marked decline in fire activity after ~700 cal yr BP, broadly coincident with the onset of cooler and wetter conditions associated with the Little Ice Age. The coherence of this downturn across elevational gradients suggests a possible regional climatic driver rather than anthropogenic suppression. Importantly, this reduction in fire activity did not result in major vegetation reorganisation, reinforcing the resilience of these conifer-forest systems.

1. Vegetation reconstructions

To determine long-term vegetation dynamics at both Little Monon Lake and Pyramid Lake, vegetation reconstructions were used to characterise dominant taxa and ecological changes across the late Holocene. These reconstructions span approximately 2500 cal. yr BP at Little Monon Lake and 6100 cal. yr BP at Pyramid Lake, offering valuable insight into long-term vegetation dynamics, while acknowledging that pollen records integrate signals across varying spatial scales and may under-represent low pollen–producing taxa.

At both sites, the Pinaceae family dominates the record (Figures 5 & 7), a finding consistent with regional records of vegetation of the high Cascade Mountains, which is characterised by coniferous vegetation (Baig & Gavin, 2023; Minckley & Long, 2016; Minckley & Whitlock, 2000). This coniferous vegetation includes species from both the Pinaceae (*Abies, Picea, Pinus and Tsuga*) and Cupressaceae (*Callitropsis, Thuja, Juniperus and Cupressus*) families.

The most pronounced shift in palynological richness occurred in the uppermost pollen assemblage zone at Pyramid Lake (P-3), where palynological richness increased to ≥20 taxa compared to ~16 taxa in the previous zones. This rise suggests a modest expansion in diversity or increased representation of previously minor taxa during the most recent interval. In contrast, palynological richness at Little Monon Lake remained within the 15–20 pollen types range but exhibited greater variability through time, indicating fluctuations in community composition without a sustained directional increase in diversity. These patterns suggest broadly stable conifer-dominated systems at both sites during the late Holocene, punctuated by more recent compositional diversification at Pyramid Lake.

1.1 Little Monon Lake

At Little Monon Lake, *Pinus* subgenus *Pinus* is the dominant vegetation throughout the past ~2500 years, which suggests the persistence of *Pinus contorta* at the site. There were minor fluctuations in *Abies*, *Picea* (most likely *Picea engelmannii*), *Tsuga mertensiana* and *Tsuga heterophylla* but their consistent presence over the time highlights the mostly stable pollen assemblage. However, subtle or short-lived compositional changes may not be resolved at the temporal resolution of the pollen record.

This stability is similarly reflected in the zonation where only two statistically significant pollen assemblage zones (L-1 and L-2) were identified. It appears that the split at ~700 cal yr BP (34mm) was heavily influenced by notable decreases in *Populus* and increases in *Alnus*, both of which are often associated with increased levels of disturbance (Franklin & Dyrness, 1973; Gill et al., 2017; Marchais et al., 2022). There were also notable decreases in *Pseudotsuga/Larix*-type , which consists of two taxa , *Pseudotsuga menziesii* and *Larix occidentalis*, the former is more widely distributed across the Cascade Range whilst the latter is more commonly located on the eastern side of the mountains (Hermann & Lavender, 1990; McDonald, 1995). It is therefore, likely that much of this pollen is from *Pseudotsuga menziesii* which is a xerophytic (drought-tolerant) and disturbance tolerant species (Agee, 1993; Minore, 1979).

The separation of *Callitropsis nootkatensis* from the other Cupressaceae pollen taxa (Figure 6) was conducted for exploratory purposes. However, due to methodological uncertainty and this division being inconsistent within the literature for pollen groupings for other palaeoecological sequences, this split was not included in the main quantitative analyses. Still, *C. nootkatensis* shows a broadly similar trend to total Cupressaceae. It also highlights that approximately 30% of Cupressaceae pollen likely consists of *C. nootkatensis*, a species which is found at Little Monon Lake in the present-day (Watkins, 2022). *C. nootkatensis* is typically distributed along the crest of the Cascade Mountains (Harris, 1971), which is why it makes up a large proportion of the Cupressaceae pollen at the analysis sites, although the remainder of the Cupressaceae pollen may have come from *Thuja plicata* (western redcedar) as this is widely distributed on the lower elevation western side of the range (Minore, 1990), with smaller proportions of pollen, such as *Juniperus occidentalis,* possibly blowing up from the dry eastern side of the Cascades (Minckley & Whitlock, 2000).

1.2. Pyramid Lake

At Pyramid Lake, the vegetation reconstruction was divided into three statistically significant zones (P-1 to P-3). As with Little Monon Lake, Pinaceae pollen dominates the record, with proportions steadily decreasing over time. The proportions of *Pinus* subgenus *Pinus* and *Pinus* subgenus *Strobus* appear to be fairly stable across zones which may have meant that there were limited major stand-replacing disturbances throughout the record as there was long term persistence of stable conifer-dominated forest structure at Pyramid Lake (Minckley & Long, 2016). There are higher proportions of *Abies*, *Tsuga mertensiana* and *Tsuga heterophylla* pollen at Pyramid Lake compared to Little Monon Lake. This was mostly expected as it is located within a lower elevation vegetation zone, the *Abies amabilis* zone as opposed to the *Tsuga mertensiana* zone, which is more suitable for *Abies* species (*A. amablis*, *A. procera*, *A. grandis, A. lasiocarpa*) due to lower elevation, warmer conditions and slightly less precipitation (Minckley & Whitlock, 2000). *Tsuga heterophylla* is also more commonly found at these slightly lower elevations whilst although *Tsuga mertensiansa* is clearly a dominant species within the *Tsuga mertenisana* zone, it is also a dominant species in the *Abies amabilis* zone (Franklin & Dyrness, 1973; Minckley & Whitlock, 2000). This difference between the sites is also due to the Little Monon Lake site being dominated by *Pinus contorta* stands.

There are also higher proportions of *Pseudotsuga/Larix*-type pollen at Pyramid Lake. The higher proportion of Pseudotsuga/Larix pollen at Pyramid Lake is likely due to a greater presence of *P. menziesii*, which is more widely distributed across the Cascade Range and particularly abundant both in the low elevation western hemlock zone and in the mid-elevation *Abies amabilis* zone (Franklin & Dyrness, 1973). In northern Oregon, *P. menziesii* also commonly co-occurs with *C. nootkatensis*, *Tsuga heterophylla*, and *Abies procera* in this vegetation zone, which is observed in the vegetation reconstructions (Crawford & Oliver, 1990).

The opposite trend to that of Pinaceae is seen in both Cupressaceae and *Populus*, as they become more abundant towards the top of the core. This likely reflects a growing local abundance of *C. nootkatensis* and the increase in both Cupressaceae and *Populus* pollen may indicate a shift towards a more mixed conifer forest.

Alnus pollen is more abundant in the upper zones which may indicate a change in disturbance intensity over the last ~700 years. Both *Alnus alnobetula* subspecies *sinuata* (Sitka alder) and *Alnus rubra* (red alder), which occur in the Cascade Mountains, are early-successional, pioneering, disturbance-adapted species (Marques, 2024; Minckley & Long, 2016). *A. rubra*, in particular, is strongly associated with fire-related disturbance (Cwynar, 1987).

Although two samples were missing from the core between 162 mm and 330 mm, assemblages immediately above and below this interval show no substantial changes, suggesting that vegetation composition remained relatively stable during the time represented by the gap. As such, the continuity of the pollen record and the robustness of zonation are not significantly compromised. However, this interpretation assumes relatively consistent sediment accumulation and limited post-depositional disturbance. Indicators such as pronounced sediment mixing, substantial age reversals in the chronology, or abrupt, changes in pollen taxa across adjacent samples would challenge this interpretation and suggest that zonation robustness may be reduced, however, no such evidence is observed here.

Overall variation between zones is modest, and changes in pollen percentages are generally subtle. This suggests a relatively stable forest composition with limited major ecological transitions over the periods studied at each site. The relationship between vegetation and fire disturbance will be discussed later (Section 3.2).

2. Fire reconstructions

2.1. Raw charcoal counts

The charcoal records from Little Monon Lake and Pyramid Lake offer insight into the fire history of high-elevation forests in the high Cascade Mountains. The exceptionally fine continuous 2 mm sampling resolution of these data enhances temporal precision. Although sediment accumulation rates are relatively low (~10 yr/mm), the contiguous sampling strategy eliminates temporal gaps in the record, preserving stratigraphic continuity and supporting a fairly consistent reconstruction of fire activity through time, further reinforced by the relatively stable age–depth model.

At both sites, the highest charcoal particle counts were observed in the smallest size class (125–250 µm), with progressively lower counts in the 250–500 µm and >500 µm fractions. This is expected, as smaller particles are more easily transported, reflecting both local and regional fire activity (Conedera et al., 2009; Ohlson & Tryterud, 2000; Whitlock & Larsen, 2001). Charcoal counts were aggregated across all size classes for analysis, which is common practice in sedimentary charcoal research, as the size class of >125 µm has been found to provide a good record of local fires (Clark, 1990; Gardner & Whitlock, 2001; Higuera et al., 2010; Whitlock & Millspaugh, 1996). Combining size classes, which were correlated, can maximise the particle counts which helps improve statistically robust interpretation.

Charcoal counts at Pyramid Lake were consistently lower than those at Little Monon Lake across all size classes. This likely reflects a lower intensity of background fire at Pyramid Lake, although differences in charcoal creation, transportation and preservation may also play a role (Scott, 2000, 2010).

2.2. CHAR records and fire events

Comparing fire episodes across studies can be challenging due to differences in temporal resolution (Minckley & Long, 2016). By interpolating CHAR to a consistent ~17 year temporal interval, this study reduces biases associated with uneven sediment accumulation and variable temporal sampling resolution. This ensures that changes in peak frequency reflect ecological variability rather than changes in sampling density. Additionally, because proportional binning conserves charcoal mass by redistributing the charcoal without changing its overall quantity, trends in CHAR reflect genuine shifts in charcoal influx rather than artificial inflation of fire activity.

The decomposition of CHAR into $\mathrm{CHAR}_{\mathrm{background}}$ and $\mathrm{CHAR}_{\mathrm{peak}}$ components allows long-term trends in regional fire activity, arising from changes in fuel availability and sediment focussing, to be distinguished from discrete fire events (Giesecke & Fontana, 2008; Higuera et al., 2010). The selection of a 500-year background window was to optimise the SNI and KS sensitivity analyses, to ensure robust separation between background variability and fire-related peaks. The mean SNI values at Little Monon Lake (2.83) and Pyramid Lake (3.0) indicate that the records are at, or very near, the commonly cited threshold of 3 for consistently reliable peak detection (Kelly et al., 2011). Moreover, both values substantially exceed the minimum threshold of 0.5 considered sufficient to justify peak analysis (Higuera, 2009), supporting the robustness of the identified fire events. The high D statistics and small p values for the KS test further indicates there is a significant contrast between noise and fire peaks, indicating clear statistical separation of the two distributions as modelled by the Gaussian mixture framework.

The use of local 500-year Gaussian mixture model thresholds further strengthens confidence in event detection by accommodating temporal changes in variance, reducing the likelihood that shifts in noise are misinterpreted as changes in fire frequency. Importantly, the application of a minimum count test provides an additional safeguard against false positives by ensuring that identified peaks represent statistically significant increases in charcoal influx rather than stochastic variability inherent in low-count data. Together, these methodological choices increase confidence that identified peaks reflect real variations in fire activity.

The analysis identified a greater number of fire events at Pyramid Lake (24) compared to Little Monon Lake (11), despite Pyramid Lake exhibiting lower overall charcoal accumulation. It is important to note, however, that the Pyramid Lake record extends approximately 1,000 years longer than that of Little Monon Lake, which partly contributes to the disparity in total number of detected events. At Little Monon Lake, elevated CHAR values likely reflect a heightened background signal, potentially linked to continuous low-intensity burning or regional charcoal contributions. By contrast, a nearby charcoal sequence from Breitenbush Lake, where lodgepole pine is not dominant, shows markedly lower CHAR values (~0.5 particles $\mathrm{cm}^{-2}\ \mathrm{yr}^{-1}$), indicating that persistent low-intensity burning is the more plausible driver of the elevated background signal (Minckley & Long, 2016). In contrast, Pyramid Lake’s lower background, combined with a greater number of distinct peaks, indicates that fire events there were more discrete and readily detectable in the CHAR record.

Nonetheless, the frequency of detected fires at both sites implies relatively average fire intervals, with a mean of ~200 years at Little Monon Lake and ~150 years at Pyramid Lake (Agee, 1993; Minckley & Long, 2016). Furthermore, the greater abundance of larger charcoal particles at Little Monon Lake suggests a stronger local fire signal, as larger fragments are typically deposited closer to their source and are often associated with more intense or proximal burning (Conedera et al., 2009b; Ohlson & Tryterud, 2000; Patterson et al., 1987; Scott, 2010). Together, the records at Pyramid Lake and Little Monon Lake emphasize the spatial heterogeneity of fire regimes in high-elevation forests of the Cascade Mountains and the need to interpret charcoal records in the context of both local and regional ecological processes.

3. Vegetation and wildfire dynamics

3.1. CHAR and vegetation analysis

To investigate vegetation and wildfire dynamics in the high Cascade Mountains, composite diagrams and statistical analyses were used. The diagrams (Figure 16 & 17) indicated lower levels of CHAR in the most recent zones which was confirmed by the Mann-Whitney U tests which revealed statistically significant differences in CHAR across pollen assemblage zones at both study sites. Mean CHAR and fire return interval at Little Monon Lake (Table 6) further support this pattern: in the earlier zone, before ~700 cal yr BP, the mean fire return interval as 172.13 years compared with 348.5 years in the more recent interval. This suggests that fire activity, as inferred from charcoal, varied notably between stratigraphic periods marked by shifts in vegetation.

Similarly, at Pyramid Lake, significant differences in CHAR were detected across pollen assemblage zones indicating that fire activity also changed over time in relation to vegetation composition. Here too, the mean fire return interval (Table 7) was shorter earlier zone, with 136 years compared with 306 years in the more recent interval. It is important to note that due to the absence of charcoal data earlier than ~3700 cal yr BP (336 mm), the statistical analysis could not include the lowest pollen zone (P-1), limiting comparison with the earliest phase of the vegetation reconstruction.

Breakpoint analysis of the CHAR record was conducted to identify periods of significant change in fire activity. At Little Monon Lake, the most prominent shift (~777 cal yr BP) in CHAR mean and variance closely aligns with the pollen zonation boundary at ~700 cal yr BP, suggesting a strong connection between fire activity and broader ecological changes, such as forest composition. Pyramid Lake exhibited greater complexity in its fire record, with three changepoints. Although the dominant shift (~2200 cal yr BP) does not coincide with pollen zonation, it corresponds to a clear change in CHAR, with the period after ~2200 cal yr BP showing reduced mean CHAR and variability. The two more recent changepoints (~150 and 550 cal yr BP) occur near the P-2 to P-3 transition, on either side of a low CHAR level, suggesting a significant decline in fire activity around this low point.

3.2. Vegetation and wildfire interactions

3.2.1 Little Monon Lake

At Little Monon Lake, forests were consistently dominated by *Pinus* subgenus *Pinus*, interpreted as *Pinus contorta* (lodgepole pine), which accounted for roughly a quarter of the total pollen throughout the ~2500 year record. This dominance is significant given the species' well-established association with fire disturbance and its serotinous, fire-adapted life history traits (Arno, 1980; Lotan et al., 1985; Schoennagel et al., 2003). Local fire episodes at Little Monon Lake are consistent with the ecological role of *Pinus contorta* in promoting, and in turn being reinforced by, recurrent burning (Figure 16).

Although there were slightly higher levels of *Pinus contorta* in the lower zone (L-1), than in the more recent higher zone (L-2), there were lower levels of CHAR in the more recent years, and a less frequent fire return interval in the more recent pollen zone (Figure 12). This is an unexpected trend as *Pinus contorta* is strongly linked to a more intense fire regime, however as the decline in the pollen percentage was only minimal this may not be a particularly significant trend, especially since there is still much fluctuation in CHAR levels in the older zone (L-1).

Other Pinaceae taxa, including *Picea* and *Tsuga*, show little change across zones, suggesting long-term persistence of a stable conifer-dominated canopy. In contrast, disturbance-associated taxa fluctuate more strongly. The pollen zonation boundary at ~700 cal yr BP appears to have been strongly influenced by changes in *Alnus*, *Populus* and *Pseudotsuga/Larix*-type. This pattern aligns with the AMOC changepoint analysis, which identified ~777 cal yr BP as the most prominent shift in CHAR, highlighting a coherent link between changes in disturbance-sensitive taxa and shifts in fire regime at Little Monon Lake.

Populus is frequently an understory disturbance taxon that can expand in post-disturbance landscapes, being less sensitive to climatically driven disturbances such as fire (Gill et al., 2017; Marchais et al., 2022). *Pseudotsuga* which is a disturbance tolerant species is adapted to fire and is often found as a seral taxa after fire (Agee, 1993; Cwynar, 1987; Minore, 1979; Sea & Whitlock, 1995). The higher abundances of these taxa in the older zone (L-1), before ~700 cal yr BP, are consistent with the greater frequency of fire events and elevated CHAR levels. By contrast, the lower levels of *Alnus* in the older zone are unexpected, given its common association with disturbance, particularly drier conditions and higher fire frequency (Minckley & Long, 2016).

The fire record is characterised by a major peak around 1500 cal yr BP (Figure 10), followed by a prolonged decline. This pattern is consistent with post-fire negative feedbacks, in which fuel depletion, limited ignition potential and canopy gaps reduce the likelihood of subsequent burning (Donato et al., 2013; Halofsky et al., 2020). However, in productive west-side forests, such feedbacks would be short-lived due to rapid regrowth and abundant early-successional fuels (Agee & Huff, 1987), which may explain why fire activity did not remain suppressed for long. This peak was also evident in the >500 µm size class. Because large charcoal fragments are less easily transported by wind and usually settle close to the fire source, this supports the interpretation of a highly localized fire (Conedera et al., 2009; Gardner & Whitlock, 2001; Ohlson & Tryterud, 2000; Whitlock & Larsen, 2001). While high-severity crown fires can produce small fragments that disperse widely, surface fires tend to generate larger particles (>1 mm) that deposit locally (Scott, 2014). The presence of elevated CHAR across multiple size categories, therefore, indicates an intense, local fire event, although the fire type (crown versus ground) cannot be resolved.

Vegetation shifts following this fire event are not indicated in the pollen abundance data, likely reflecting the lower temporal resolution of the pollen record compared to charcoal. The absence of a zonation change suggests the event did not substantially alter forest composition, although a slight increase in lodgepole pine may indicate a modest disturbance response. This is consistent with the fire-adapted ecology of *Pinus contorta*, which thrives in post-fire conditions (Lotan & Critchfield, 1990). Such traits, combined with consistently higher CHAR across all charcoal size classes at Little Monon Lake relative to Pyramid Lake, likely contributed to the persistence of lodgepole pine stands that would otherwise be succeeded by more shade-tolerant species such as *Tsuga mertensiana*, *Pseudotsuga menziesii*, and *Abies lasiocarpa* (Lotan et al., 1985).

A more sustained decline in fire activity occurs ~700 cal yr BP, broadly coinciding with the zonation and changepoint boundaries. The timing of this decline predates Euro-American settlement and fire suppression, implying it was environmentally driven rather than anthropogenic (Littell et al., 2010). It is also important to note that although there was a reduction in this disturbance the continued persistence of lodgepole pine at the site may have been due to the previously frequent fire-regime removing the seed sources of other species (Lotan et al., 1983, 1985).

Overall, the Little Monon Lake record indicates a resilient lodgepole pine dominated forest, punctuated by episodic disturbance, with disturbance-associated taxa (*Alnus, Pseudotsuga/Larix, Populus*) tracking shifts in fire activity. The strong peak ~1500 cal yr BP and subsequent decrease in fire activity highlight the dynamic, but ultimately self-stabilising, nature of fire and vegetation interactions at the site.

3.2.2. Pyramid Lake

The pollen record at Pyramid Lake shows a persistent dominance of Pinaceae throughout the past ~6100 years, with both *Pinus* subgenera maintaining relatively stable proportions across zones (P-1 to P-3). Conifer stability is further supported by the consistent presence of *Abies* and *Tsuga* pollen, indicating long-term resilience of the canopy composition. Unlike *Pinus contorta* at Little Monon Lake, these taxa are generally not well adapted to fire, being sensitive to burning and slow to regenerate (Acker et al., 2013; Agee, 1993; Arno & Davis, 1980; Crawford & Oliver, 1990; El-Kassaby & Edwards, 2001; Minore, 1979; Wimberly & Spies, 2002). Their persistence alongside relatively stable *Pinus* proportions highlight that although there is a shorter fire return interval at Pyramid Lake they could be less intense and non-stand-replacing due to the maintenance of these populations of species and lower CHAR levels relative to Little Monon, despite higher fire frequency at Pyramid Lake.

In contrast to the relatively stable conifer signal, disturbance-associated taxa show clearer fluctuations. *Alnus* is more abundant in the lower zones (P-1 and P-2) but declines in the most recent zone (P-3), suggesting reduced disturbance intensity in the late Holocene, consistent with the decrease in fire activity ~700 cal yr BP. Both *Alnus alnobetula* subspecies *sinuata* and *Alnus rubra* occur in the Cascades and are early-successional, disturbance-adapted species (Marques, 2024; Minckley & Long, 2016). While *Alnus rubra* is strongly associated with fire-related disturbance, *Alnus alnobetula* subspecies *sinuata* is more common at higher elevations, making it difficult to determine if one of these species contributed to the Pyramid Lake record more significantly (Cwynar, 1987).

Populus another disturbance indicator (Gill et al., 2017; Marchais et al., 2022; Walsh, Pearl, et al., 2010), are present at fairly consistent levels throughout the record, a pattern broadly consistent with their ability to quickly colonise and expand into disturbed areas, although their stable abundance makes it difficult to link them to specific fire episodes and may instead indicate a relatively stable disturbance regime at Pyramid Lake, compared to that of Little Monon Lake.

The charcoal record is dominated by high variability in the middle zone (P-2), when CHAR values and fire-event frequencies are highest (Figure 11). After ~700 cal yr BP, fire activity declines markedly, a pattern that coincides with the P-2 to P-3 transition. While this decline is not directly captured as a distinct changepoint, the nearest breakpoint at ~554 cal yr BP is closely associated with this transition. This pattern parallels the reduction observed at Little Monon Lake, suggesting a potentially regional decrease in fire activity rather than a site-specific event.

Despite variability in fire history, the vegetation record at Pyramid Lake shows little evidence of major compositional change. The persistence of Pinaceae dominance into P-3 suggests that the reduction in fire disturbance over the past ~700 years has not been enough to cause a significant compositional change in the vegetation. This interpretation is supported by the relatively stable abundances of both canopy and understory taxa, indicating that fire has not been a major driver of ecosystem change (Minckley & Long, 2016). It may also reflect the nature of fires at Pyramid Lake, with less severe events failing to substantially alter conifer communities (Agee, 1993). Furthermore, the charcoal signal may represent more regional burning rather than local fires, as indicated by the relatively low CHAR levels in comparison to Little Monon Lake (Conedera et al., 2009; Gardner & Whitlock, 2001; Ohlson & Tryterud, 2000; Whitlock & Larsen, 2001).

Interpretation of the earliest pollen assemblage zone (P-1), and part of the middle zone (P-2) is constrained by the lack of charcoal data below 336 mm (3662 cal yr BP). While the pollen record suggests broadly similar conifer dominance during this period, fire activity cannot be directly evaluated. Nevertheless, the long-term trajectory at Pyramid Lake points to a conifer forest that persisted through variable fire regimes, with disturbance intensity diminishing in the last 700 years.

3.2.3. Regional trends and local variability

Across both high-elevation Cascades sites, pollen and charcoal records demonstrate that coniferous forests dominated by Pinaceae persisted through the late Holocene with only minor compositional shifts. Disturbance-associated taxa fluctuated alongside episodic fire activity, including a pronounced peak around 1500 cal yr BP at Little Monon, but overall vegetation structure remained stable. Both records show an abrupt decline in fire activity after ~700 cal yr BP, coinciding with a shift in the vegetation communities at both sites and pointing to a regionally coherent reduction in burning rather than a site-specific anomaly. This downturn predates Euro-American settlement and, given the remoteness of the sites, was unlikely to have been strongly influenced by Native American activity, suggesting it does not reflect anthropogenic fire suppression (Littell et al., 2010; Walsh, Whitlock, et al., 2010). Instead it may reflect broader climatic changes, with potential cooler and wetter conditions during the late Holocene reducing fire frequency and severity in the region (Prichard et al., 2009). Increased moisture would have limited both the likelihood of ignition and the spread of fire, this dynamic is in keeping with other palaeoecological records showing shifts in moisture and climate driving changing fire activity (Giuliano & Lacourse, 2023; Prichard et al., 2009). Notably, this reduction of fire activity coincides with the onset of the Little Ice Age (~700 to 100 cal yr BP), a period of cooler and more variable climate that may have further contributed to reduced burning in the Cascade Range, through a shortened fire season and suppression of fire ignition (Grove, 2019; Hotchkiss et al., 2007; Walsh et al., 2008). Tree-ring (Graumlich & Brubaker, 1986; Weisberg & Swanson, 2003) and lake-sediment records (Brunelle & Whitlock, 2003; Larocque & Smith, 2005; Walsh et al., 2008) from the Pacific Northwest also document cooler conditions and reduced fire activity during the Little Ice Age, with similar patterns reported more widely (Hotchkiss et al., 2007).

Fire histories differ between the two sites, with Pyramid Lake recording a more frequent fire return interval than Little Monon Lake, but with consistently lower CHAR levels. A greater number of fire events is expected at Pyramid Lake due to its mid-elevation setting, in the *Abies amabilis* zone, which is generally thought to support shorter fire return intervals due to warmer, drier conditions (Franklin & Dyrness, 1973). This is in contrast to Little Monon Lake which is in the cooler, wetter and less productive higher elevation *Tsuga mertensiana* zone (Franklin & Dyrness, 1973).

However, despite the lower number of fire events and less frequent fire return interval at Little Monon Lake, the substantially higher background CHAR values indicate greater overall charcoal accumulation and thus higher background fire activity. This distinction is important: fewer fire events do not necessarily imply lower local fire influence. Instead, the elevated CHAR at Little Monon Lake suggests there may be more intense fire events, with increased levels of fuel consumption. The presence of stands of fire-adapted lodgepole pine (Lotan et al., 1985) further supports the interpretation of a disturbance-prone environment. Additionally, although the *Tsuga mertensiana* zone is less fire-prone this can lead to a build-up of woody fuels and snags which promote infrequent but severe fires; conditions that favour the persistence of lodgepole pine (Acker et al., 2013, 2017; Lotan et al., 1985).

These interpretations are primarily limited by the shortened charcoal record at Pyramid Lake. Despite this, the similarities of the overarching fire trends and fairly consistent vegetation between sites supports the general interpretations. Overall, the results highlight resilient forests where long-term fire–vegetation interactions were dynamic but did not drive major ecological shifts (Falk et al., 2022; Minckley & Long, 2016)

4. Future research

Continued research is critical to ensure that the findings from this study can be fully contextualized, interpreted accurately, and applied to understanding long-term forest resilience and fire–vegetation interactions in high-elevation Cascade mountains. Targeted investigation of fire activity during the LIA using sedimentary charcoal records from surrounding high-elevation lakes would help refine our understanding of late-Holocene climate–fire relationships. Multi-site comparisons focused on the last several thousand years could test whether cooler climatic intervals consistently correspond to reduced fire frequency and magnitude or intensity. Additional sediment cores collected from other lakes in the high Cascade during the 2016 fieldwork collection period provide an important opportunity to expand this work, and ongoing analyses of these records will help determine whether the post ~700 cal yr BP decline observed here represents a widespread climatic signal.

Integrating CHAR-derived fire events with independent fire-scar chronologies from dendrochronological studies would further strengthen interpretation of detected peaks. Cross-validation between sedimentary charcoal and tree-ring fire records would help confirm the reliability of peak detection methods and improve separation of true fire events from background variability.

Finally, incorporating charcoal morphological analysis (e.g., distinguishing arboreal from non-arboreal fragments) could help better resolve fire severity and fire type (Mueller et al., 2014; Vachula et al., 2021). This is as charcoal morphometry provides a proxy for identifying fuel sources and combustion characteristics. Collectively, these approaches would maximize the impact of this research by improving temporal resolution and ecological understanding.

5. Conclusion

The vegetation and wildfire reconstructions from Little Monon Lake and Pyramid Lake demonstrate that Pinaceae-dominated forests have persisted over at least the last ~2,500 and ~6,400 cal yr BP respectively, with only minor compositional changes. These shifts are mainly linked to disturbance-associated taxa, which fluctuated in response to episodic fire activity rather than indicating major ecological transitions. At both sites, the most recent pollen zone, beginning around 700 cal yr BP, coincides with a marked decline in fire activity, a pattern unlikely to reflect anthropogenic suppression and more plausibly tied to climate dynamics, such as that from the 'Little Ice Age' (Grove, 2019; Littell et al., 2010; Walsh, Whitlock, et al., 2010). Differences in fire history between the sites underline the role of local setting: Pyramid Lake had more a more frequent fire return interval with consistently lower CHAR values and supports a more diverse conifer forest, while Little Monon is dominated by fire-adapted lodgepole pine and experiences more intense, less frequent, fire events, likely with continuous low-intensity burning in the area. These differences suggest that elevation, species composition, and disturbance sensitivity influenced fire regimes at each site, while broader climate patterns drove the overall long-term trends across the high Cascades.

The persistence of stable dominant vegetation despite statistically significant changes in fire activity suggests resilience in these high-elevation forests. Although recent centuries have seen a marked reduction in wildfire activity, the long-term record shows that forest composition has remained relatively resilient to shifts in fire frequency, severity and extent (Falk et al., 2022). This demonstrates that vegetation and wildfire interactions in the high Cascades have been dynamic but have not driven major ecological change (Minckley & Long, 2016). However, with climate change expected to increase fire activity through warmer and drier conditions and longer growing and fire seasons, there remains uncertainty over whether this past resilience will continue (Abatzoglou et al., 2025; Halofsky et al., 2020; Holden et al., 2018; Littell et al., 2009; Reilly et al., 2021). The scale and rate of current global warming and associated fire risk exceed those evident in the late Holocene, raising questions about how these forests will respond under future conditions (Burke et al., 2021; Dennison et al., 2014; Marlon, 2020; Westerling et al., 2006).

Appendices:

Appendix A: Supplementary Information

Statement of Expenditure

Student Name: Karenza Pearson. Student Number: 2402028

Project title: Long-term vegetation and wildfire dynamics in the high Cascade Mountains, Pacific Northwest, USA

Category	Item	Description	Cost
Operational Equipment Maintenance	HDPE Wide Neck Bottles.	12x HDPE Wide Neck Bottles, 500ml Capacity	37.79
Office equipment materials/ consumables	Storage Boxes	2x Large Sample Storage Boxes	31.61
Laboratory consumables	Centrifuge tubes	500x Fisher Brand Centrifuge conical tubes	79.42
Laboratory consumables	Gloves	Medium Nitrile Gloves	3.82
Laboratory consumables	Gloves	Large Nitrile Gloves	4.09
Laboratory consumables	Centrifuge tubes	Half box (shared code) 50ml centrifuge tubes	40.80
Other materials and consumables	Spatula	X5 Spatula, 150x4mm stainless steel	15.23
Chemicals	Hydrofluoric acid	1 Lt of Hydrofluoric acid.	83.41
Laboratory analysis	Radiocarbon dating	Submission of two sediment samples to ^{14}CHRONO Centre for AMS radiocarbon dating and calibration	680.40
Chemicals	Ethanol	2.5 Lt of Ethanol	10.50

Laboratory consumables	Blue roll	2 rolls of Blue roll	8.66

I hereby certify that the above information is true and correct to the best of my knowledge: Karenza Pearson

Statement of Contributions

This is according to the guidance given by PLOS journals.

Contributor Role	**Role Definition**
Conceptualization	Ideas; formulation or evolution of overarching research goals and aims. KP, CF
Data Curation	Management activities to annotate (produce metadata), scrub data and maintain research data (including software code, where it is necessary for interpreting the data itself) for initial use and later reuse. KP, MW
Formal Analysis	Application of statistical, mathematical, computational, or other formal techniques to analyze or synthesize study data. KP, MW
Funding Acquisition	Acquisition of the financial support for the project leading to this publication. N/A
Investigation	Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection. KP, CF, GW, BL, MW
Methodology	Development or design of methodology; creation of models. KP, CF, MW
Project Administration	Management and coordination responsibility for the research activity planning and execution. KP, CF
Resources	Provision of study materials, reagents, materials, patients, laboratory samples, animals, instrumentation, computing resources, or other analysis tools. CF
Software	Programming, software development; designing computer programs; implementation of the computer code and supporting algorithms; testing of existing code components. NA
Supervision	Oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team. CF

Contributor Role	**Role Definition**
Validation	Verification, whether as a part of the activity or separate, of the overall replication/reproducibility of results/experiments and other research outputs. N/A
Visualization	Preparation, creation and/or presentation of the published work, specifically visualization/data presentation. KP
Writing – Original Draft Preparation	Creation and/or presentation of the published work, specifically writing the initial draft (including substantive translation). KP
Writing – Review & Editing	Preparation, creation and/or presentation of the published work by those from the original research group, specifically critical review, commentary or revision – including pre- or post-publication stages. KP, CF

Acronyms: KP (Karenza Pearson), CF (Prof Cynthia Froyd), MW (Dr Mathew Watkins), GW (Grahame Walters), BL (Bethany Lee)

Copy of Ethics Approval

Swansea University
Prifysgol Abertawe

Approval Date: 30/01/2025

Research Ethics Approval Number: 1 2025 12574 11791

Thank you for completing a research ethics application for ethical approval and submitting the required documentation via the online platform.

Project Title	Long-term vegetation and wildfire dynamics in the high Cascade Mountains, Pacific Northwest, USA
Applicant name	KARENZA DIANA ARWEN PEARSON
Submitted by	KARENZA DIANA ARWEN PEARSON /
Full application form link	https://swansea.forms.ethicalreviewmanager.com/Project/Index/14850

The Science and Engineering ethics committee has approved the ethics application, subject to the conditions outlined below:

Approval conditions

1. The approval is based on the information given within the application and the work will be conducted in line with this. It is the responsibility of the applicant to ensure all relevant external and internal regulations, policies, and legislations are met.
2. This project may be subject to periodic review by the committee. The approval may be suspended or revoked at any time if there has been a breach of conditions.
3. Any substantial amendments to the approved proposal will be submitted to the ethics committee prior to implementing any such changes.

Specific conditions in respect of this application:

The application has been classified as Low Risk to the University.

No additional conditions.

Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics Committees. It complies with the guidelines of UKRI and the concordat to support Research Integrity.

Science and Engineering Research and Ethics Chair

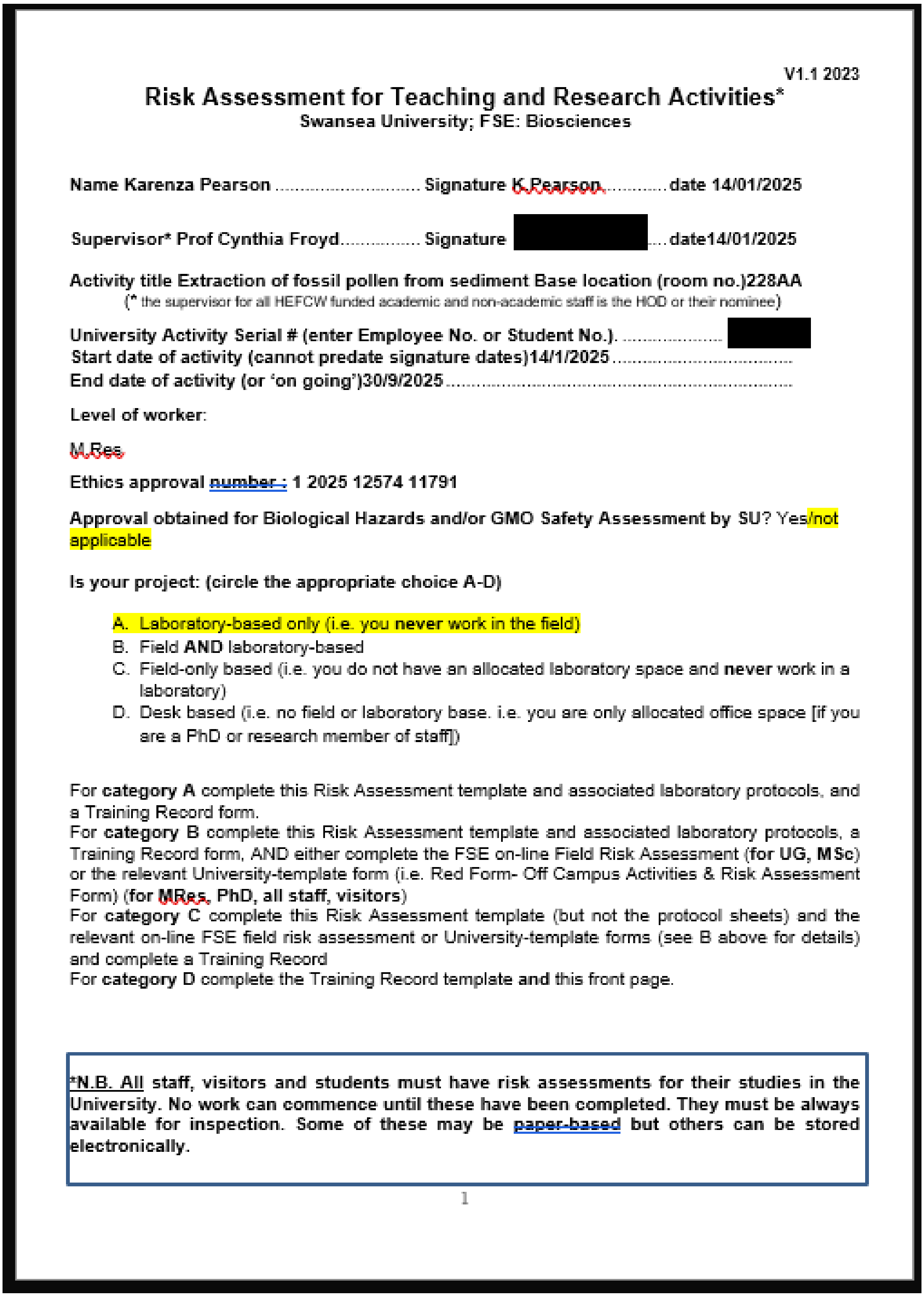
Swansea University.

If you have any queries regarding this notification, then please contact your research ethics administrator for the faculty.

- For Science and Engineering contact FSE-Ethics@swansea.ac.uk
- For Medicine, Health and Life Science contact FMHLS-Ethics@swansea.ac.uk
- For Humanities and Social Sciences contact FHSS-Ethics@swansea.ac.uk

Copy of H&S and Risk Assessments

Pollen Extraction Risk Assessment



V1.1 2023

Risk Assessment for Teaching and Research Activities*

Swansea University; FSE: Biosciences

Name Karenza Pearson .... Signature K Pearson............date 14/01/2025

Supervisor* Prof Cynthia Froyd............... Signature [redacted]....date14/01/2025

Activity title Extraction of fossil pollen from sediment Base location (room no.)228AA

(* the supervisor for all HEFCW funded academic and non-academic staff is the HOD or their nominee)

University Activity Serial # (enter Employee No. or Student No.). .... [redacted]

Start date of activity (cannot predate signature dates)14/1/2025 ....

End date of activity (or 'on going')30/9/2025 ....

Level of worker:

M.Res

Ethics approval number : 1 2025 12574 11791

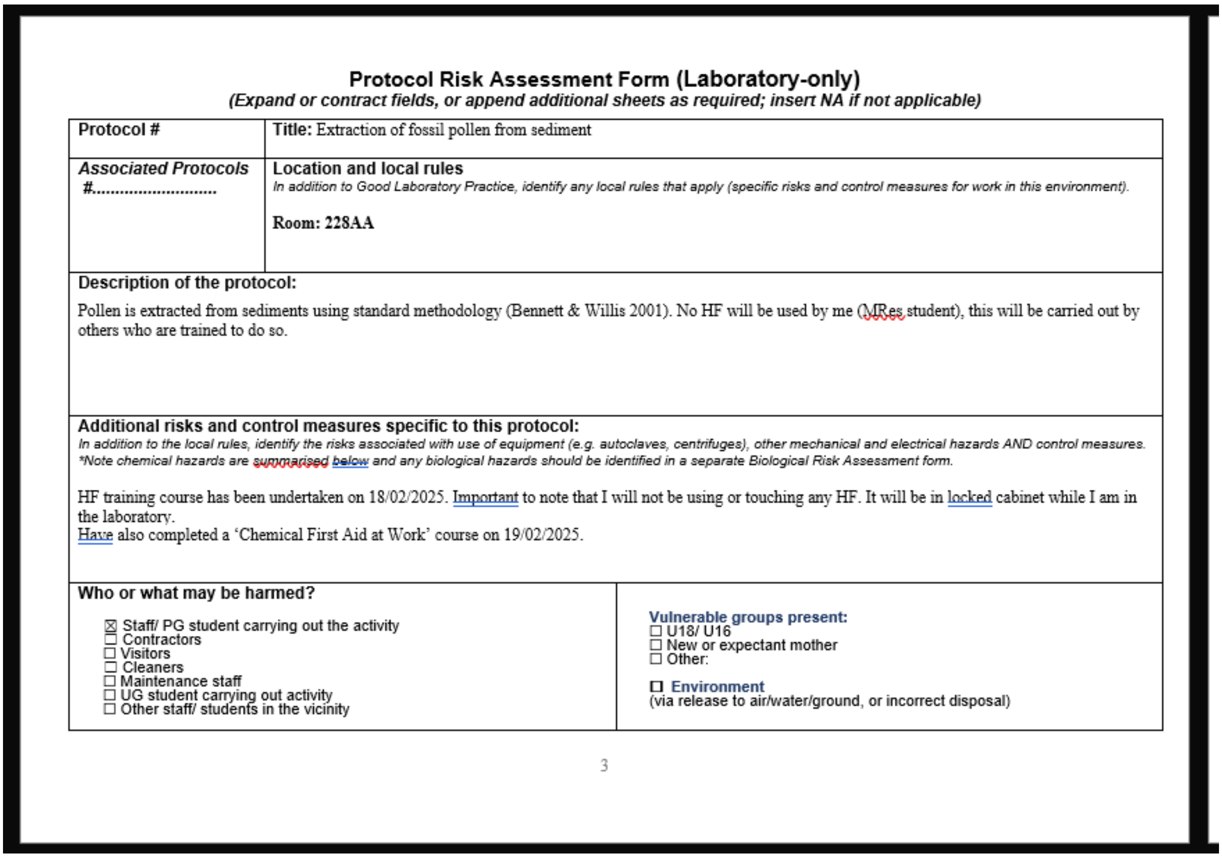
Approval obtained for Biological Hazards and/or GMO Safety Assessment by SU? Yes/[✓ not applicable]

Is your project: (circle the appropriate choice A-D)

- [✓ A. Laboratory-based only (i.e. you **never** work in the field)]
- B. Field **AND** laboratory-based
- C. Field-only based (i.e. you do not have an allocated laboratory space and **never** work in a laboratory)
- D. Desk based (i.e. no field or laboratory base. i.e. you are only allocated office space [if you are a PhD or research member of staff])

For **category A** complete this Risk Assessment template and associated laboratory protocols, and a Training Record form.
For **category B** complete this Risk Assessment template and associated laboratory protocols, a Training Record form, AND either complete the FSE on-line Field Risk Assessment (**for UG, MSc**) or the relevant University-template form (i.e. Red Form- Off Campus Activities & Risk Assessment Form) (**for MRes, PhD, all staff, visitors**)
For **category C** complete this Risk Assessment template (but not the protocol sheets) and the relevant on-line FSE field risk assessment or University-template forms (see B above for details) and complete a Training Record
For **category D** complete the Training Record template **and** this front page.

***N.B. All staff, visitors and students must have risk assessments for their studies in the University. No work can commence until these have been completed. They must be always available for inspection. Some of these may be paper-based but others can be stored electronically.**



Protocol Risk Assessment Form (Laboratory-only)

(Expand or contract fields, or append additional sheets as required; insert NA if not applicable)

Protocol #	**Title:** Extraction of fossil pollen from sediment
Associated Protocols **#………………………**	**Location and local rules** *In addition to Good Laboratory Practice, identify any local rules that apply (specific risks and control measures for work in this environment).* **Room: 228AA**

Description of the protocol:

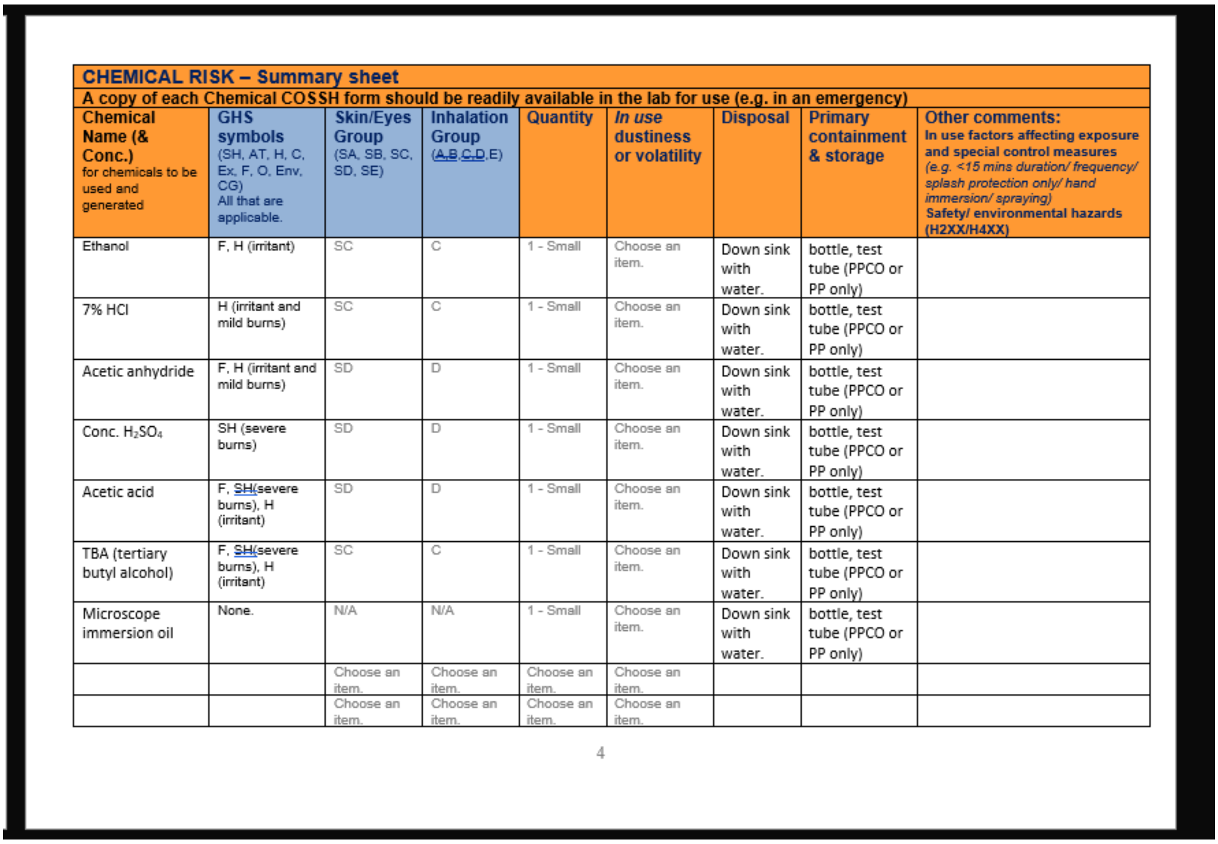
Pollen is extracted from sediments using standard methodology (Bennett & Willis 2001). No HF will be used by me (MRes student), this will be carried out by others who are trained to do so.

Additional risks and control measures specific to this protocol:

*In addition to the local rules, identify the risks associated with use of equipment (e.g. autoclaves, centrifuges), other mechanical and electrical hazards AND control measures. *Note chemical hazards are summarised below and any biological hazards should be identified in a separate Biological Risk Assessment form.*

HF training course has been undertaken on 18/02/2025. Important to note that I will not be using or touching any HF. It will be in locked cabinet while I am in the laboratory.
Have also completed a 'Chemical First Aid at Work' course on 19/02/2025.

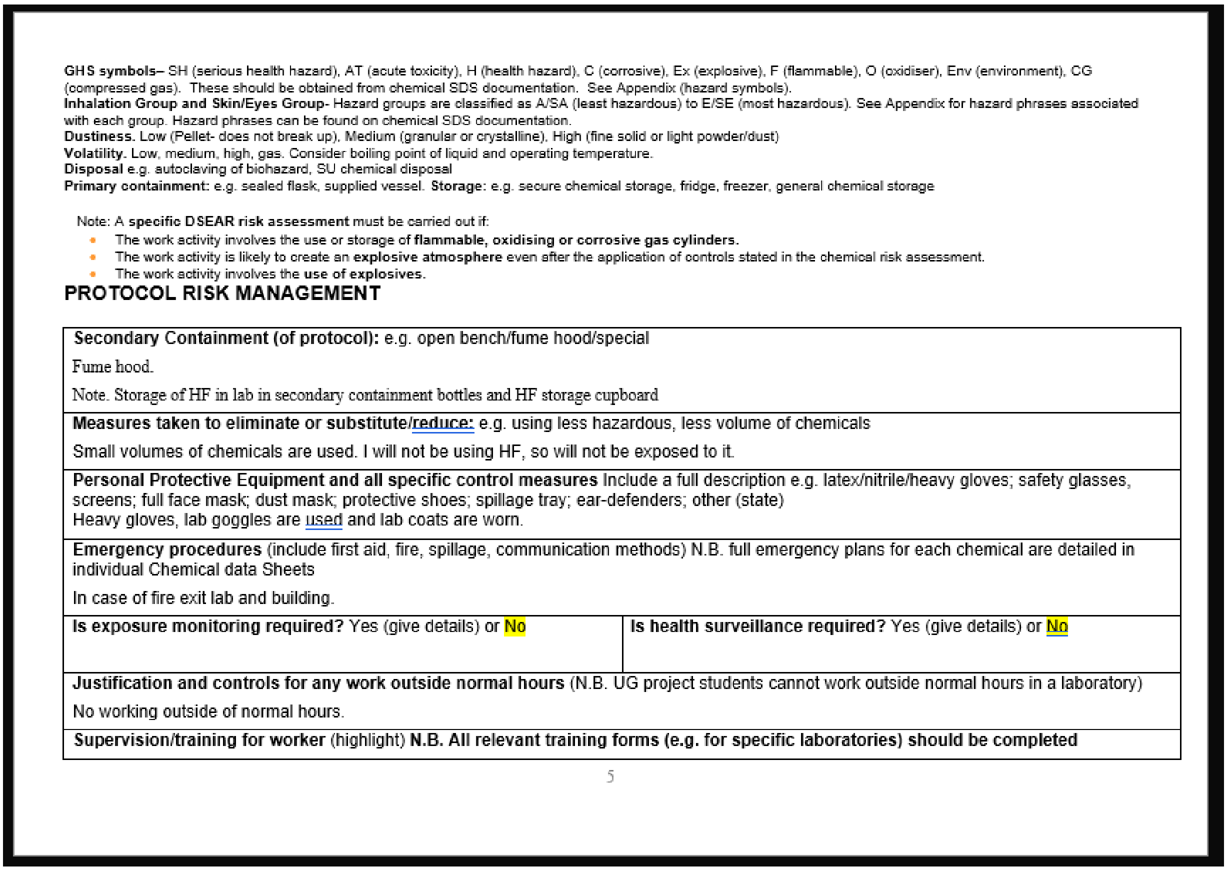
Who or what may be harmed?	
☒ Staff/ PG student carrying out the activity ☐ Contractors ☐ Visitors ☐ Cleaners ☐ Maintenance staff ☐ UG student carrying out activity ☐ Other staff/ students in the vicinity	**Vulnerable groups present:** ☐ U18/ U16 ☐ New or expectant mother ☐ Other: ☐ **Environment** (via release to air/water/ground, or incorrect disposal)



CHEMICAL RISK – Summary sheet

A copy of each Chemical COSSH form should be readily available in the lab for use (e.g. in an emergency)

Chemical Name (& Conc.) for chemicals to be used and generated	**GHS symbols** (SH, AT, H, C, Ex, F, O, Env, CG) All that are applicable.	**Skin/Eyes Group** (SA, SB, SC, SD, SE)	**Inhalation Group** (A,B,C,D,E)	**Quantity**	***In use* dustiness or volatility**	**Disposal**	**Primary containment & storage**	**Other comments:** **In use factors affecting exposure and special control measures** *(e.g. <15 mins duration/ frequency/ splash protection only/ hand immersion/ spraying)* **Safety/ environmental hazards (H2XX/H4XX)**
Ethanol	F, H (irritant)	SC	C	1 - Small	Choose an item.	Down sink with water.	bottle, test tube (PPCO or PP only)	
7% HCl	H (irritant and mild burns)	SC	C	1 - Small	Choose an item.	Down sink with water.	bottle, test tube (PPCO or PP only)	
Acetic anhydride	F, H (irritant and mild burns)	SD	D	1 - Small	Choose an item.	Down sink with water.	bottle, test tube (PPCO or PP only)	
Conc. H_2SO_4	SH (severe burns)	SD	D	1 - Small	Choose an item.	Down sink with water.	bottle, test tube (PPCO or PP only)	
Acetic acid	F, SH(severe burns), H (irritant)	SD	D	1 - Small	Choose an item.	Down sink with water.	bottle, test tube (PPCO or PP only)	
TBA (tertiary butyl alcohol)	F, SH(severe burns), H (irritant)	SC	C	1 - Small	Choose an item.	Down sink with water.	bottle, test tube (PPCO or PP only)	
Microscope immersion oil	None.	N/A	N/A	1 - Small	Choose an item.	Down sink with water.	bottle, test tube (PPCO or PP only)	
		Choose an item.	Choose an item.	Choose an item.	Choose an item.			
		Choose an item.	Choose an item.	Choose an item.	Choose an item.			



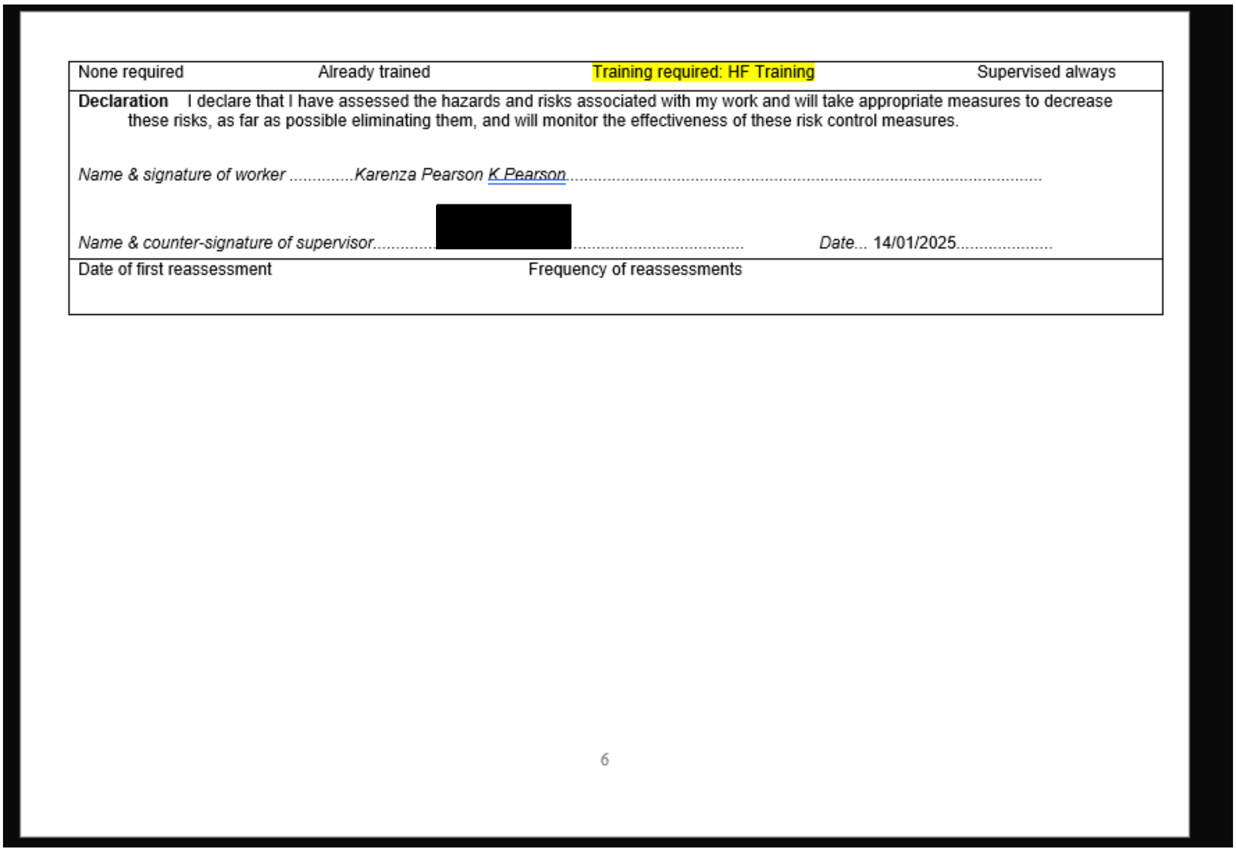
GHS symbols– SH (serious health hazard), AT (acute toxicity), H (health hazard), C (corrosive), Ex (explosive), F (flammable), O (oxidiser), Env (environment), CG (compressed gas). These should be obtained from chemical SDS documentation. See Appendix (hazard symbols).
Inhalation Group and Skin/Eyes Group- Hazard groups are classified as A/SA (least hazardous) to E/SE (most hazardous). See Appendix for hazard phrases associated with each group. Hazard phrases can be found on chemical SDS documentation.
Dustiness. Low (Pellet- does not break up), Medium (granular or crystalline), High (fine solid or light powder/dust)
Volatility. Low, medium, high, gas. Consider boiling point of liquid and operating temperature.
Disposal e.g. autoclaving of biohazard, SU chemical disposal
Primary containment: e.g. sealed flask, supplied vessel. **Storage:** e.g. secure chemical storage, fridge, freezer, general chemical storage

Note: A **specific DSEAR risk assessment** must be carried out if:

- The work activity involves the use or storage of **flammable, oxidising or corrosive gas cylinders.**
- The work activity is likely to create an **explosive atmosphere** even after the application of controls stated in the chemical risk assessment.
- The work activity involves the **use of explosives.**

PROTOCOL RISK MANAGEMENT

Secondary Containment (of protocol): e.g. open bench/fume hood/special Fume hood. Note. Storage of HF in lab in secondary containment bottles and HF storage cupboard	
Measures taken to eliminate or substitute/reduce: e.g. using less hazardous, less volume of chemicals Small volumes of chemicals are used. I will not be using HF, so will not be exposed to it.	
Personal Protective Equipment and all specific control measures Include a full description e.g. latex/nitrile/heavy gloves; safety glasses, screens; full face mask; dust mask; protective shoes; spillage tray; ear-defenders; other (state) Heavy gloves, lab goggles are used and lab coats are worn.	
Emergency procedures (include first aid, fire, spillage, communication methods) N.B. full emergency plans for each chemical are detailed in individual Chemical data Sheets In case of fire exit lab and building.	
Is exposure monitoring required? Yes (give details) or No	**Is health surveillance required?** Yes (give details) or No
Justification and controls for any work outside normal hours (N.B. UG project students cannot work outside normal hours in a laboratory) No working outside of normal hours.	
Supervision/training for worker (highlight) **N.B. All relevant training forms (e.g. for specific laboratories) should be completed**	



None required	Already trained	Training required: HF Training	Supervised always

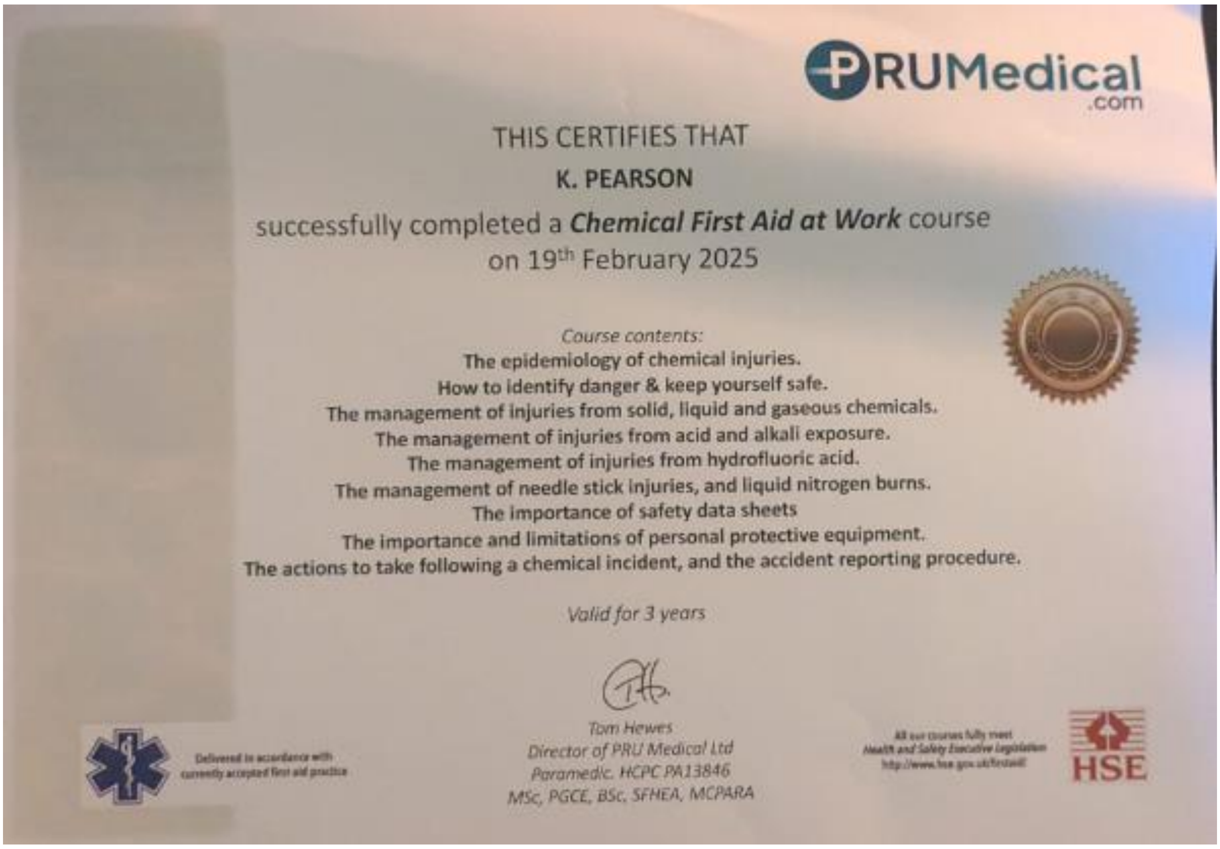
Declaration I declare that I have assessed the hazards and risks associated with my work and will take appropriate measures to decrease these risks, as far as possible eliminating them, and will monitor the effectiveness of these risk control measures.

Name & signature of worker ....*Karenza Pearson* *K Pearson*..

Name & counter-signature of supervisor............[redacted].................................... *Date*... 14/01/2025.....................

Date of first reassessment Frequency of reassessments

Completed Safe Use of HF Training on 18th February 2025 with Lorraine Wild.



PRUMedical
.com

THIS CERTIFIES THAT

K. PEARSON

successfully completed a ***Chemical First Aid at Work*** course
on 19th February 2025

Course contents:
The epidemiology of chemical injuries.
How to identify danger & keep yourself safe.
The management of injuries from solid, liquid and gaseous chemicals.
The management of injuries from acid and alkali exposure.
The management of injuries from hydrofluoric acid.
The management of needle stick injuries, and liquid nitrogen burns.
The importance of safety data sheets
The importance and limitations of personal protective equipment.
The actions to take following a chemical incident, and the accident reporting procedure.

Valid for 3 years

Tom Hewes
Director of PRU Medical Ltd
Paramedic. HCPC PA13846
MSc, PGCE, BSc, SFHEA, MCPARA

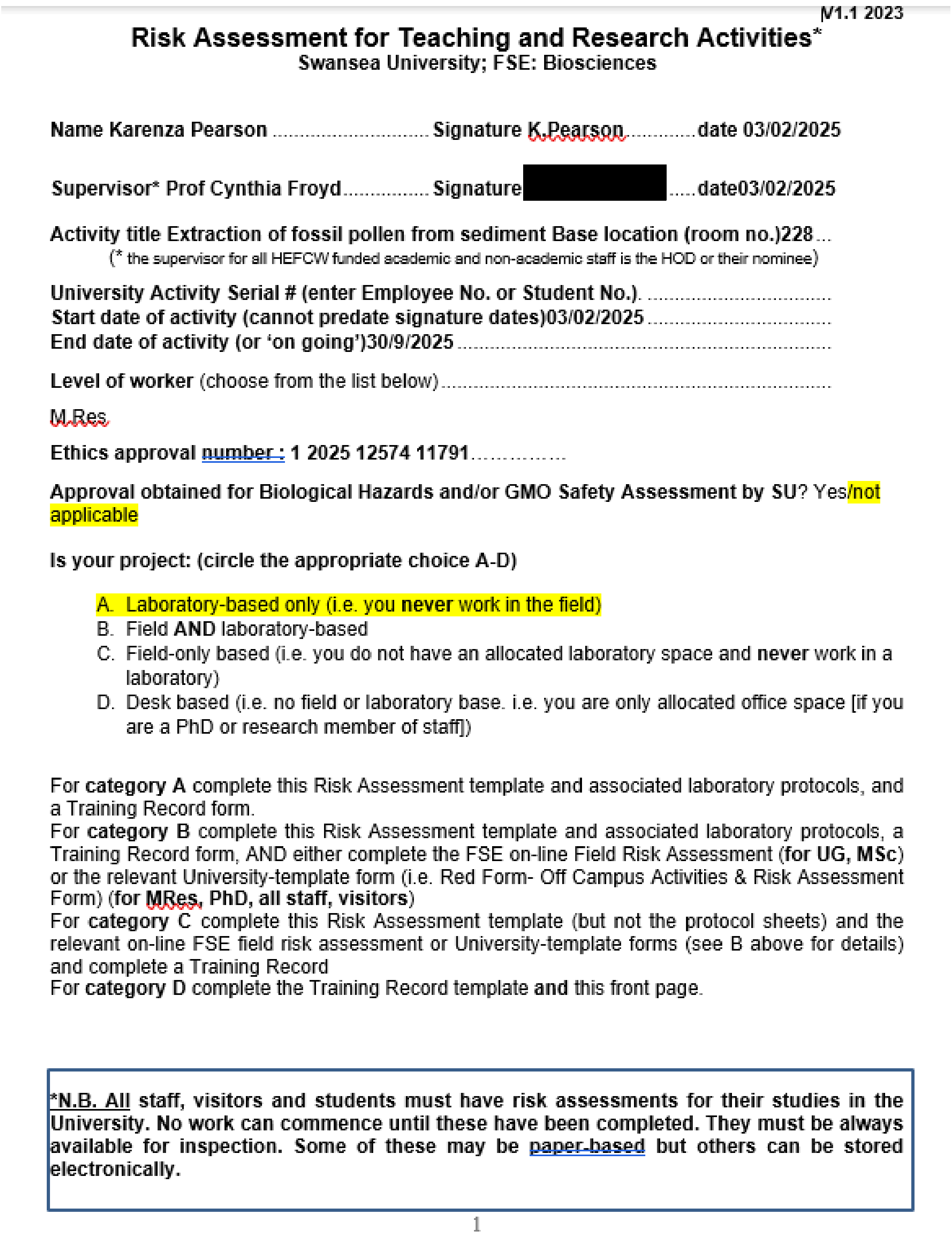
Delivered in accordance with
currently accepted first aid practice

All our courses fully meet
Health and Safety Executive Legislation
http://www.hse.gov.uk/firstaid/

HSE

Image of certificate of completion of Chemical First Aid at Work course on 19th February 2025 with Tom Hewes.

Microscopy Risk Assessment:



V1.1 2023

Risk Assessment for Teaching and Research Activities*

Swansea University; FSE: Biosciences

Name Karenza Pearson .... **Signature** K.Pearson............**date** 03/02/2025

Supervisor* Prof Cynthia Froyd............... **Signature** [redacted] **date**03/02/2025

Activity title Extraction of fossil pollen from sediment **Base location (room no.)**228...

(* the supervisor for all HEFCW funded academic and non-academic staff is the HOD or their nominee)

University Activity Serial # (enter Employee No. or Student No.). ....
Start date of activity (cannot predate signature dates)03/02/2025 ....
End date of activity (or 'on going')30/9/2025 ....

Level of worker (choose from the list below) ....

M.Res

Ethics approval number : 1 2025 12574 11791……………

Approval obtained for Biological Hazards and/or GMO Safety Assessment by SU? Yes/[✓ not applicable]

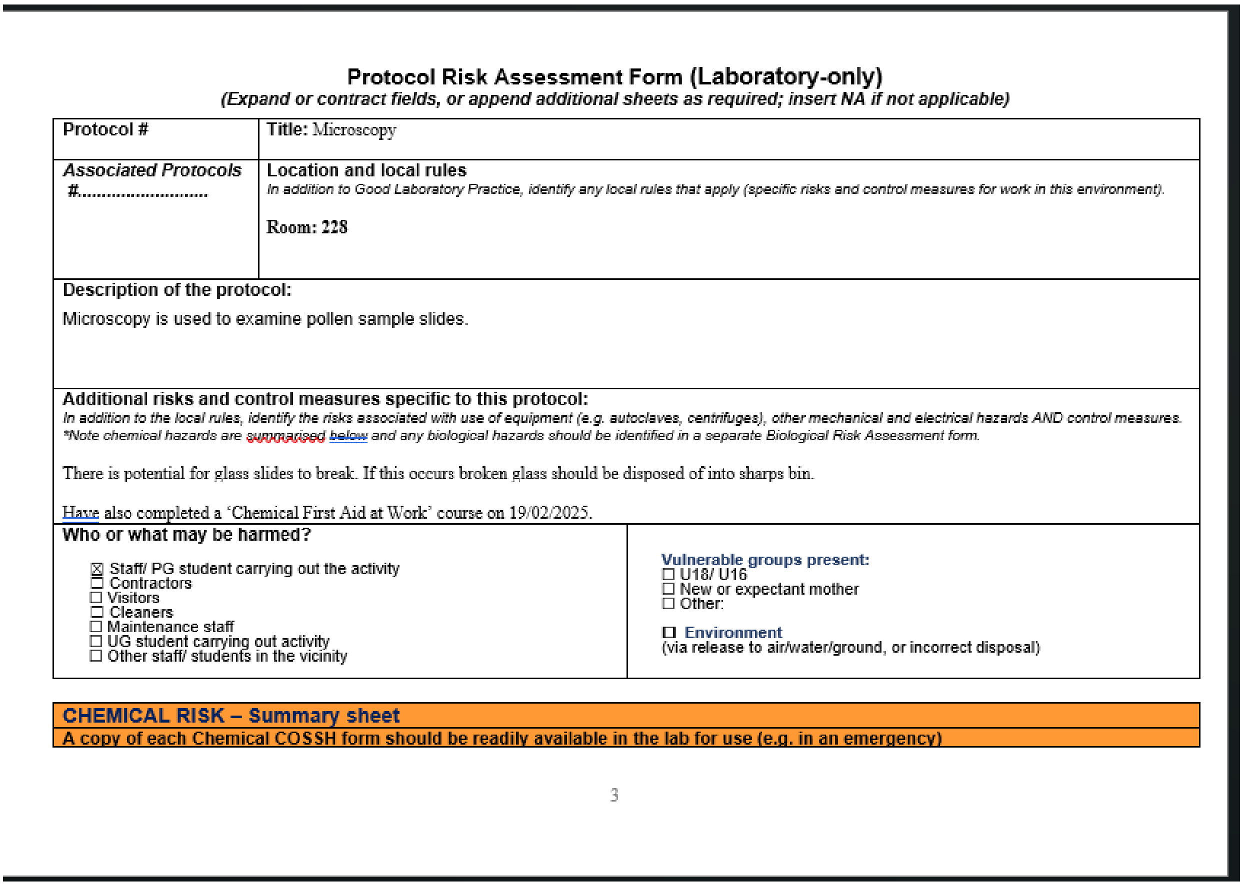
Is your project: (circle the appropriate choice A-D)

A. [✓ Laboratory-based only (i.e. you **never** work in the field)]
B. Field **AND** laboratory-based
C. Field-only based (i.e. you do not have an allocated laboratory space and **never** work in a laboratory)
D. Desk based (i.e. no field or laboratory base. i.e. you are only allocated office space [if you are a PhD or research member of staff])

For **category A** complete this Risk Assessment template and associated laboratory protocols, and a Training Record form.
For **category B** complete this Risk Assessment template and associated laboratory protocols, a Training Record form, AND either complete the FSE on-line Field Risk Assessment (**for UG, MSc**) or the relevant University-template form (i.e. Red Form- Off Campus Activities & Risk Assessment Form) (**for MRes, PhD, all staff, visitors**)
For **category** C complete this Risk Assessment template (but not the protocol sheets) and the relevant on-line FSE field risk assessment or University-template forms (see B above for details) and complete a Training Record
For **category** D complete the Training Record template **and** this front page.

***N.B. All staff, visitors and students must have risk assessments for their studies in the University. No work can commence until these have been completed. They must be always available for inspection. Some of these may be paper-based but others can be stored electronically.**

1



Protocol Risk Assessment Form (Laboratory-only)

(Expand or contract fields, or append additional sheets as required; insert NA if not applicable)

Protocol #	**Title:** Microscopy
Associated Protocols **#..........................**	**Location and local rules** *In addition to Good Laboratory Practice, identify any local rules that apply (specific risks and control measures for work in this environment).* **Room: 228**

Description of the protocol:

Microscopy is used to examine pollen sample slides.

Additional risks and control measures specific to this protocol:

*In addition to the local rules, identify the risks associated with use of equipment (e.g. autoclaves, centrifuges), other mechanical and electrical hazards AND control measures. *Note chemical hazards are summarised below and any biological hazards should be identified in a separate Biological Risk Assessment form.*

There is potential for glass slides to break. If this occurs broken glass should be disposed of into sharps bin.

Have also completed a 'Chemical First Aid at Work' course on 19/02/2025.

Who or what may be harmed?

☒ Staff/ PG student carrying out the activity
☐ Contractors
☐ Visitors
☐ Cleaners
☐ Maintenance staff
☐ UG student carrying out activity
☐ Other staff/ students in the vicinity

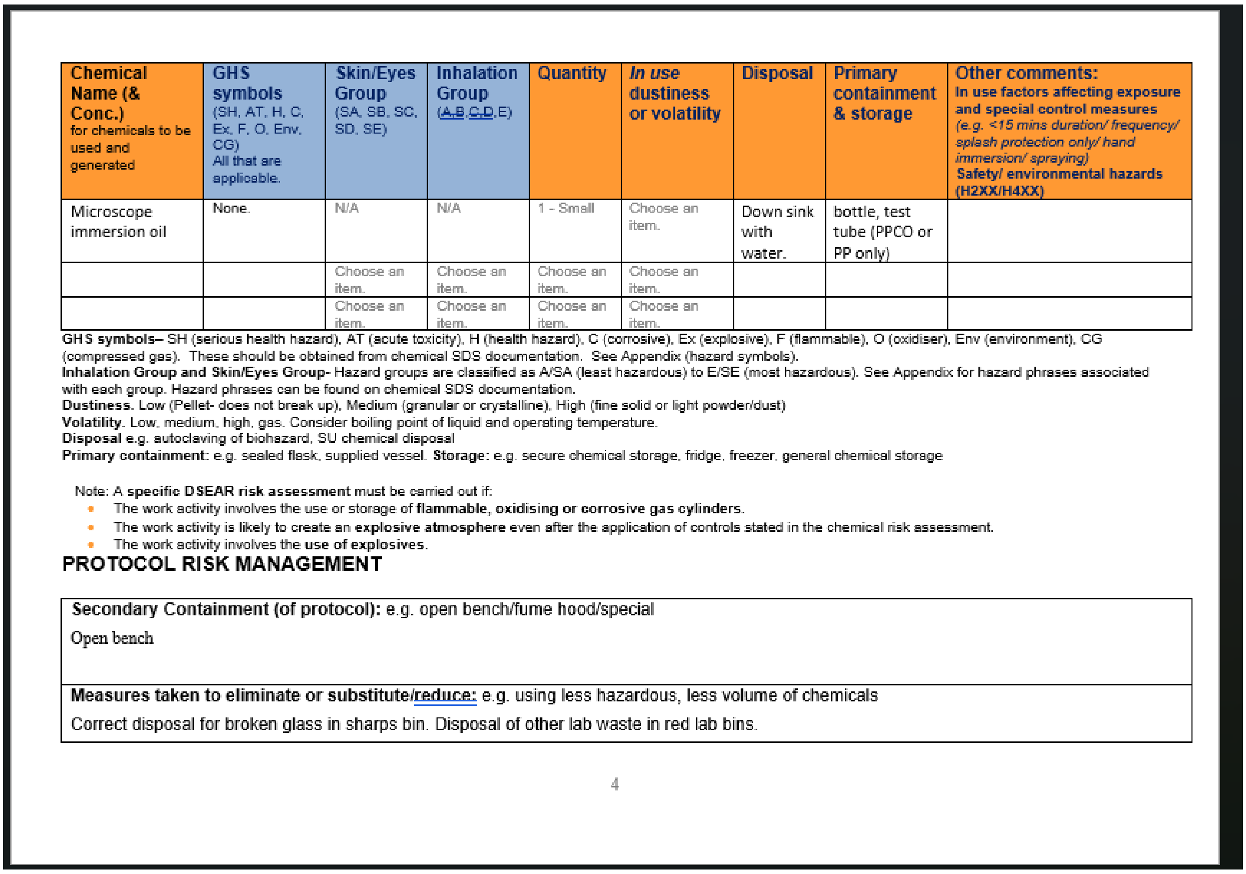
Vulnerable groups present:
☐ U18/ U16
☐ New or expectant mother
☐ Other:

☐ **Environment**
(via release to air/water/ground, or incorrect disposal)

CHEMICAL RISK – Summary sheet

A copy of each Chemical COSSH form should be readily available in the lab for use (e.g. in an emergency)

3



Chemical Name (& Conc.) for chemicals to be used and generated	**GHS symbols** (SH, AT, H, C, Ex, F, O, Env, CG) All that are applicable.	**Skin/Eyes Group** (SA, SB, SC, SD, SE)	**Inhalation Group** (A,B,C,D,E)	**Quantity**	***In use* dustiness or volatility**	**Disposal**	**Primary containment & storage**	**Other comments:** **In use factors affecting exposure and special control measures** *(e.g. <15 mins duration/ frequency/ splash protection only/ hand immersion/ spraying)* **Safety/ environmental hazards (H2XX/H4XX)**
Microscope immersion oil	None.	N/A	N/A	1 - Small	Choose an item.	Down sink with water.	bottle, test tube (PPCO or PP only)	
		Choose an item.	Choose an item.	Choose an item.	Choose an item.			
		Choose an item.	Choose an item.	Choose an item.	Choose an item.			

GHS symbols– SH (serious health hazard), AT (acute toxicity), H (health hazard), C (corrosive), Ex (explosive), F (flammable), O (oxidiser), Env (environment), CG (compressed gas). These should be obtained from chemical SDS documentation. See Appendix (hazard symbols).
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Volatility. Low, medium, high, gas. Consider boiling point of liquid and operating temperature.
Disposal e.g. autoclaving of biohazard, SU chemical disposal
Primary containment: e.g. sealed flask, supplied vessel. **Storage:** e.g. secure chemical storage, fridge, freezer, general chemical storage

Note: A **specific DSEAR risk assessment** must be carried out if:

- The work activity involves the use or storage of **flammable, oxidising or corrosive gas cylinders.**
- The work activity is likely to create an **explosive atmosphere** even after the application of controls stated in the chemical risk assessment.
- The work activity involves the **use of explosives.**

PROTOCOL RISK MANAGEMENT

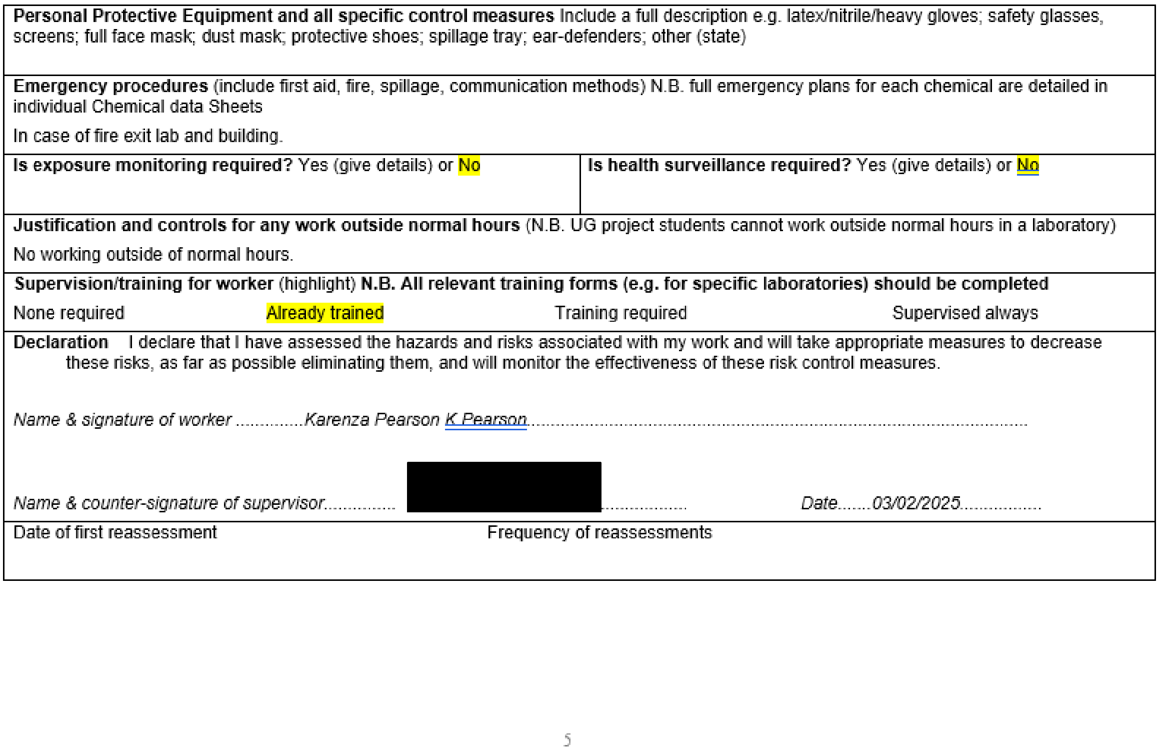
Secondary Containment (of protocol): e.g. open bench/fume hood/special

Open bench

Measures taken to eliminate or substitute/reduce: e.g. using less hazardous, less volume of chemicals

Correct disposal for broken glass in sharps bin. Disposal of other lab waste in red lab bins.

4



Personal Protective Equipment and all specific control measures Include a full description e.g. latex/nitrile/heavy gloves; safety glasses, screens; full face mask; dust mask; protective shoes; spillage tray; ear-defenders; other (state)

Emergency procedures (include first aid, fire, spillage, communication methods) N.B. full emergency plans for each chemical are detailed in individual Chemical data Sheets

In case of fire exit lab and building.

Is exposure monitoring required? Yes (give details) or [✓ No]	**Is health surveillance required?** Yes (give details) or [✓ No]

Justification and controls for any work outside normal hours (N.B. UG project students cannot work outside normal hours in a laboratory)

No working outside of normal hours.

Supervision/training for worker (highlight) **N.B. All relevant training forms (e.g. for specific laboratories) should be completed**

None required [✓ Already trained] Training required Supervised always

Declaration I declare that I have assessed the hazards and risks associated with my work and will take appropriate measures to decrease these risks, as far as possible eliminating them, and will monitor the effectiveness of these risk control measures.

Name & signature of worker ....Karenza Pearson K Pearson...

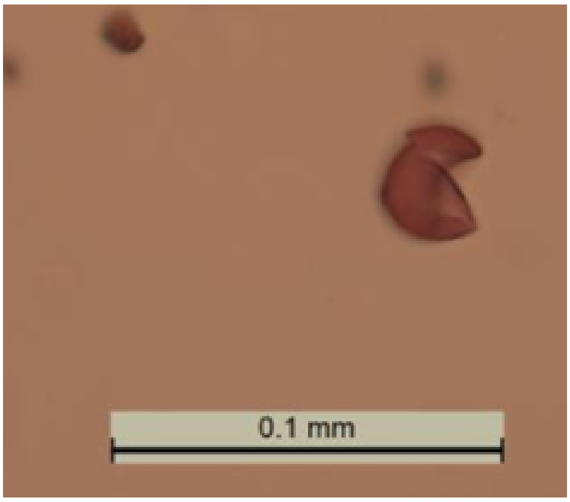
Name & counter-signature of supervisor.............. [redacted] *.................* *Date.......03/02/2025................*

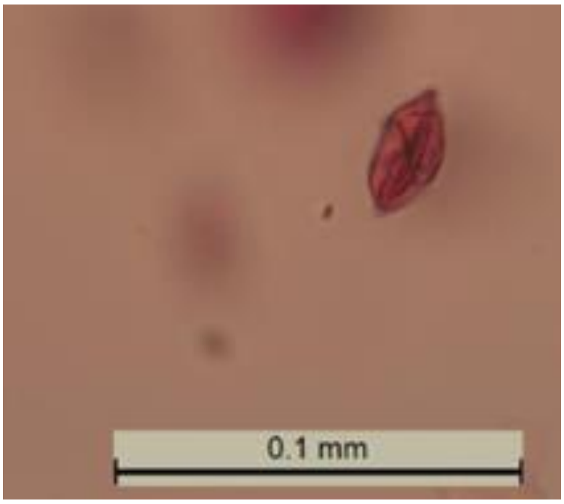
Date of first reassessment Frequency of reassessments

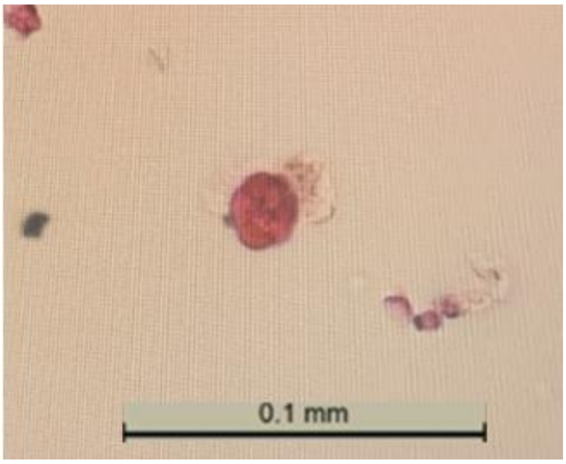
Supplementary Information 5: Pollen identification guide for *Callitropsis* and Cupressaceae

To support reproducibility and future research, this guide outlines the distinguishing characteristics of *Callitropsis nootkanensis* (Alaskan yellow cedar) pollen compared to other members of the Cupressaceae family. While both types are inaperturate and may appear superficially similar, key differences in grain size, surface ornamentation, and tear patterns allow for differentiation. *Callitropsis* grains are generally larger, exhibit denser verrucae, and frequently show a single irregular sulcoid tear, whereas other Cupressaceae grains are smaller, have scattered verrucae, and may appear torn or folded but without consistent sculpturing patterns.

Cupressaceae:



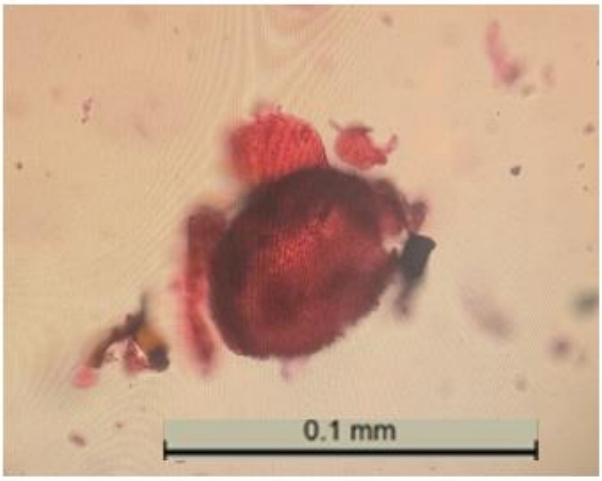


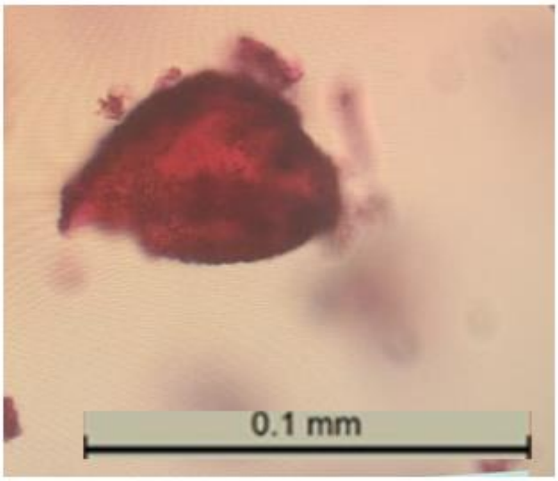


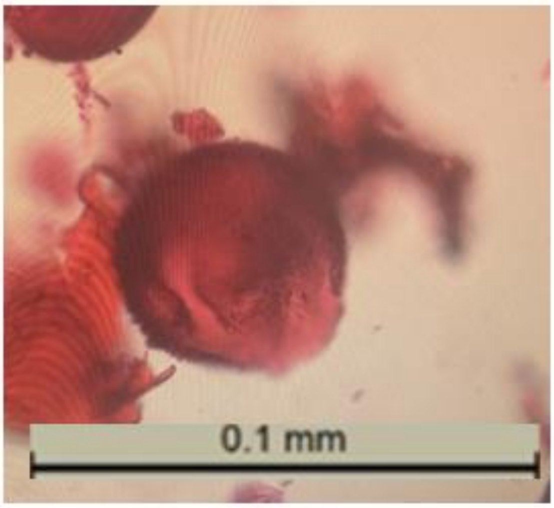
- Inaperturate type: Grains lack apertures but may appear to have irregular furrows due to tearing or folding.
- Size: Generally, 20–45 µm in diameter.
- Surface: Scattered, irregular verrucae.
- Shape: Typically, circular but may have splits or folds; folds are minor due to small size.

- Taxonomy: May include *Cupressus*, *Juniperus*, or *Thuja*; differentiation between genera is unreliable, so grouping is preferred.

Callitropsis nootkanensis (Alaskan yellow cedar):







- Inaperturate type: Grains lack apertures but a single irregular “sulcoid” tear is frequently observed.
- Size: Larger than other Cupressaceae, around 35–60 µm; can appear larger due to distortion from tears.
- Shape: Typically, circular but often has large irregular “sulcoid” tear which can distort shape.
- Surface: Verrucae are much denser; some sculpturing resembles gemmae and baculae.
- Taxonomy: Distinguishable from other Cupressaceae by size, surface density, and tear pattern.

Appendix B: R Scripts

R Script for the generation of age–depth models using the package *rBacon*

```
#### PYR Age depth model####
install.packages("rbacon")
library(rbacon)
pyr <-read.csv("Bacon_runs/PYR/PYR.csv") #File has to be within Bacon_runs


View(pyr)
Bacon("pyr", thick = 5, postbomb = 2, prob = 0.95, d.min = 0, d.max = 670, acc.mean = 10, d.lab = "Depth (mm)")
#### LML Age depth model####
install.packages("rbacon")
library(rbacon)
lml <-read.csv("Bacon_runs/LML/LML.csv") #File has to be within Bacon_runs
View(lml) #Checking data
Bacon("lml", thick = 5, postbomb = 2, prob = 0.95, d.min=0, d.max=230,acc.mean=10, d.lab = "Depth (mm)") #Depths is mm rather than cm
```

R Script for the generation of CHAR values and corresponding figures:

```
####Charcoal data for Analysis####
#Little Monon Lake used as example, suitable script for Pyramid Lake
#####tapas#####


remotes::install_github("wfinsinger/tapas")
```

```
# Load packages

library(tidyverse)
library(ggplot2)
library(tapas)

#Little Monon Lake all charcoal sizes
# Load charcoal data
charcoal <-read.csv("LMLCharcoal.csv")
charcoal
# Clean and rename columns

colnames(charcoal) <- c("depth", "Charcoal_500um", "Charcoal_500_250um",
                        "Charcoal_250_125um", "Charcoal_Total")
charcoal
#Half sediment volume for first 30mm of LML, hence counts doubled
# Double charcoal counts in the top 15 samples (first 30 mm)
charcoal[1:15, 2:5] <- charcoal[1:15, 2:5] * 2
charcoal
# Load age-depth model
ages <- read.delim("Bacon_runs/LML/LML_48_ages.txt")
ages
# Merge on depth (make sure both have the same 'depth' variable)
charage <- left_join(charcoal, ages, by = "depth")
charage
```

```
cor(charage$Charcoal_Total, charage$Charcoal_500um, use = "complete.obs")
cor(charage$Charcoal_Total, charage$Charcoal_500_250um,use = "complete.obs")
cor(charage$Charcoal_Total, charage$Charcoal_250_125um,use = "complete.obs")
cor(charage$Charcoal_500um, charage$Charcoal_500_250um,use = "complete.obs")
cor(charage$Charcoal_500um, charage$Charcoal_250_125,use = "complete.obs")

##Summary statistics ###
#LML Charcoal raw count summary statistics
summary(charage)
#Total of charcoal counts in record
sum(charage$Charcoal_Total, na.rm = TRUE)
####Violin plots of raw charcoal counts ####

library(vioplot)
par(mfrow=c(1,4))
vioplot(charage$Charcoal_Total, main = "Little Monon Lake Total Charcoal (> 125 µm)", col = "snow1", ylim = c(0, 250))
vioplot(charage$Charcoal_250_125um, main = "Little Monon Lake 125 - 250 µm", col = "snow2", ylim = c(0, 200))
vioplot(charage$Charcoal_500_250um,   main = "Little Monon Lake 250 - 500 µm", col = "snow3", ylim = c(0, 40))
vioplot(charage$Charcoal_500um, main = "Little Monon Lake > 500 µm",     col = "snow4", ylim = c(0, 6))


### Rearrange df to include mmTop, mmBot, AgeTop, AgeBot, Volume,Charcoal_Total, CHAR_Total
```

```
#Missing CHAR values will not allow tapas to run


sample_thickness <- 2  # in mm
charage <-charage %>%
  mutate(mmTop = depth - sample_thickness,
         mmBot = depth,
         AgeTop = lag(mean),
         AgeBot = mean,
         Volume = 0.5,
         Countl = Charcoal_Total) %>%
  filter(!is.na(AgeTop), !is.na(AgeBot), !is.na(Charcoal_Total)) %>%  # Remove rows with NA in AgeTop or AgeBot, remove , !is.na(CHAR_Total)
  select(mmTop, mmBot, AgeTop, AgeBot, Volume, Charcoal_Total)#0.5cm3 for all samples, remove CHAR_Total


head(charage)
tail(charage)
# Run TAPAS


#We are going to be looking at Charcoal_TotalAR


help(package=tapas)
peak_detection(series = charage, proxy = "Charcoal_Total") #This carries it out all at once, BUT we will do it step by step below


#A 500 yr interval is optimum for calculating the moving window SNI.
peakdet <- peak_detection(series = charage,
```

```
                out = "accI",
                proxy = "Charcoal_Total",
                smoothing_yr=500,#if removed then it tries all smoothing
                detr_type = "rob.loess",
                thresh_type = "local",
                thresh_value = 0.95,
                keep_consecutive = F,
                min_CountP = 0.05,
                MinCountP_window = 150,
                out_dir = "results",
                plotit = T,
                plot_crosses = T,
                plot_x = T,
                plot_neg = F,
                sens = T,
                smoothing_yr_seq = 500)#Carries it out all at once
peakdet
Plot.Anomalies(
  series = peakdet,
  plot.crosses = TRUE,
  plot.x = FALSE,
  plot.neg = FALSE
)
```

```
#Plot return intervals
Plot_ReturnIntervals(
  series = char_thresh,
  plot.x = TRUE,
  plot.neg = FALSE
)

#Fire return interval table
str(peakdet)
fri_table_pos <- data.frame(
  Event_Age_calBP = peakdet$thresh$peaks.pos.ages,
  Return_Interval_yrs = peakdet$thresh$RI_pos
)
par(mfrow = c(1, 1))
fri_table_pos
mean(fri_table_pos$Return_Interval_yrs, na.rm = TRUE)
#SNI Values
#This is detrended CHAR
#Evaluate suitability of the record for peak-detection analysis using signal-to-noise index (SNI)
SNI <- char_thresh$thresh$SNI_pos$SNI_sm #We want the smoothed SNI for positive values as the peaks are positive
SNI <- peakdet$thresh$SNI_pos$SNI_sm
mean(SNI)
median(SNI)
#A SNI value > 3 indicates that the record is suitable for peak-detection analysis
```

```
#Kolomogorov-Smirnov test
#Assess the peak detection quality by looking at contrast between empirical CHARnoise component with CHARpeak derived from Gaussian mixture model
# detrended residuals
resid <- peakdet$detr$detr$Charcoal_TotalAR
resid
# threshold (from global or local thresholding)
thr <- peakdet$thresh$thresh.pos
thr
# Extract CHARnoise and CHARpeak components

char_noise <- resid[resid <= thr]
char_noise
char_fire <- resid[resid > thr]
char_fire
# KS test
ks_test <- ks.test(char_noise, char_fire)
ks_test
#A significant p-value (p < 0.05) indicates that the two distributions are different
#If the p-value is not significant, then the peak detection may not have effectively separated CHARpeaks from CHARnoise
#D statistic indicates the maximum difference between the cumulative distributions of the two components
#A larger D value indicates a greater contrast between CHARnoise and CHARpeaks, for example D > 0.5 is considered a good separation
```

R Script for Breakpoint CHAR Analysis

```
####Breakpoint CHAR analysis ####

CHAR <- char_i$int$series.int

CHAR


#Include depth

CHAR$depth <- char_i$int$cmI

CHAR

# Remove rows where Charcoal_TotalAR == 0

CHAR_filtered <- CHAR[CHAR$Charcoal_TotalAR != 0, ]

CHAR_filtered #Doesnt contain rows without Charcoal_TotalAR values (aka CHAR)



#Changepoint package


library(changepoint)

help(package=changepoint)

cpt <- cpt.meanvar(CHAR_filtered$Charcoal_TotalAR, method = "PELT")

cpt


#Choosing cpt.meanvar means it detects changes in average level and variablity

cpt <- cpt.meanvar(

  CHAR_filtered$Charcoal_TotalAR,

  method = "PELT", #"BinSeg" is Binary segmentation method, PELT is Pruned Exact Linear Time method
```

```
  penalty = "MBIC", #modified bayesian information criterion penalty
  minseglen = 5 #Positive integer giving the minimum segment length (no of observations between
change points)
)
plot(cpt)
cpt
cpt <- cpt.meanvar(
  CHAR_filtered$Charcoal_TotalAR,
  method = "AMOC", #At most one change method
  penalty = "AIC"
)
cpt
plot(cpt)

#Plot the results of the segmentation
char <- CHAR_filtered$Charcoal_TotalAR
year <- CHAR_filtered$age
# Plot CHAR vs year
plot(year, char, type = "l",
     xlab = "Year (cal yr BP)",
     ylab = expression(CHAR~(particles~mm^{-2}~yr^{-1})),
     xlim = rev(range(year))
     )  # flip x-axis

# Add changepoints
cp_idx <- cpts(cpt)
```

R Script for the Mann-Whitney U test statistical analysis of pollen and charcoal

```
#Example is from Little Monon Lake, can be altered to fit Pyramid Lake
####Statistical analysis of pollen and charcoal ####
#Kruskall-wallace  - CHAR significantly differ between pollen zones
# Assign pollen zones based on depth
LMLcharcoal_clean <- LMLcharcoal_clean %>%
  mutate(Zone = case_when(
    depth >= 2 & depth < 34    ~ "Zone 1",
    depth >= 34 & depth <= 230 ~ "Zone 2",
    TRUE ~ NA_character_
  ))

# Convert Zone to factor
LMLcharcoal_clean$Zone <- factor(LMLcharcoal_clean$Zone, levels = c("Zone 1", "Zone 2"))
####Kruskal testing####
#Due to non-normality of residuals kruskal.test() is being used

# >500 µm
kruskal_500 <- kruskal.test(Charcoal_500um ~ Zone, data = charage)
kruskal_500
# 500–250 µm
kruskal_500_250 <- kruskal.test(Charcoal_500_250um ~ Zone, data = charage)
kruskal_500_250

# 250–125 µm
```

```
kruskal_250_125 <- kruskal.test(Charcoal_250_125um ~ Zone, data = charage)

kruskal_250_125


# Total

kruskal_total <- kruskal.test(Charcoal_Total ~ Zone, data = charage)

kruskal_total
```

Appendix C: Raw data tables

Table S.1: Raw pollen counts for Little Monon Lake

Depth (mm)	2	6	10	14	18	22	26	28	30	32	36	52	68	84	98	116	132	148	164	180	198	212	228
Abies	11	11	7	4	4	5	12	3	6	6	6	8	3	5.5	3.5	6	2	4	2.5	7.5	6	1.5	2.5
Picea	35	29	28	19	45	34	34	38	33	36	13	17	17.5	14.5	20	22	14	13	12.5	13.5	11.5	10.5	14.5
Pinus - subgenus Pinus	82	73	88	83	81	101	107	112	120	106	84	70	81	67.5	93.5	79.5	85	71	73	74.5	60	53.5	60
Pinus - subgenus Strobus	31	45	40	28	36	25	21	25	10	27	13	29	34	26.5	23.5	33.5	18.5	35.5	13.5	50	23.5	37.5	36
Pinus undifferentiated	26	34	23	20	11	6	4	10	3	4	8.5	14.5	6.5	10	16	12.5	13.5	7	6	7.5	10	9	4
Tsuga mertensiana	18	23	30	31	37	24	27	30	42	20	10.5	21	12.5	24.5	17	21.5	11.5	17	12.5	13.5	16	6.5	13
Tsuga heterophylla	18	19	13	35	24	23	14	32	18	31	21	14	9	7	6	13	4	13	5	9	12	4	10
Larix-type	8	9	0	2	1	0	2	3	0	1	2	0	3	5	3	8	3	9	3	13	3	4	0
Cupressaceae	44	41	17	41	45	33	16	14	22	10	17	6	17	4	18	3	31	12	28	16	31	22	24
Callitropsis nootkatensis	0	0	0	0	0	0	0	0	0	0	10	17	16	29	15	0	13	0	10	16	8	7	8
Populus	8	8	4	3	6	5	1	2	2	0	21	16	29	1	18	6	56	11	88	14	68	79	72
Alnus	15	25	29	37	20	27	39	23	38	49	18	7	14	17	14	7	10	13	8	0	21	9	15
Betula	1	2	1	1	1	0	0	4	1	3	0	0	1	1	0	1	1	0	1	0	2	0	1
Salix	0	3	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	1	0	0	1	1
Quercus	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	2	0	0	0	1	1	2
Acer	0	1	1	1	0	0	3	0	0	0	0	1	0	1	0	1	0	1	0	2	0	0	0
Artemesia	2	6	4	4	2	4	7	5	2	5	2	0	0	0	0	0	0	1	0	0	0	0	0
Rosaceae	1	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	1	2	0	0	0	0	1
Saxifraga	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0
Ambrosia	0	0	5	0	0	1	0	2	4	3	0	0	0	2	0	0	0	0	1	0	0	0	0
Aster-type (Asteraceae)	3	1	0	2	0	1	0	2	3	5	2	1	2	3	4	0	1	0	0	6	0	0	2
Poaceae	1	2	2	3	6	1	2	2	1	2	1	7	3	2	3	1	6	4	3	0	1	4	0
Chenopodiaceae	0	1	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Caryophyllaceae	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Vaccinium	1	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Dryopteris-type	19	5	4	1	6	14	5	3	2	5	0	2	0	0	0	4	0	2	0	3	0	0	0
Isoetes	4	1	1	2	6	4	2	2	0	2	18	2	17	2	9	4	6	4	7	5	19	10	17
Pteridium-type	5	1	0	1	6	8	5	4	1	3	2	2	0	5	0	1	0	2	0	42	0	1	1
Equisetum	10	14	15	12	8	9	9	7	5	7	34	14	50	49	43	16	48	54	41	0	32	41	35
Undifferentated spore	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	0	2	0	0	22	0	0	0
Lycopodium	0	0	0	0	0	0	0	0	0	0	18	47	3	23	9	67	7	28	9	3	8	4	6
Cyperaceae	0	0	0	0	0	0	0	0	0	0	5	3	1	9	1	6	0	0	4	0	1	2	0
Elodea	0	0	0	0	0	0	0	0	0	0	0	3	2	0	0	2	0	0	0	0	0	1	0
Sparganum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Potamogeton	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2	0	2	0	2	0	3	3	0
Nuphur	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ericaceae	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	2	2
Primaulaceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cornus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	1	0	0

Table S.2: Raw pollen counts for Pyramid Lake

Depth (mm)	2	14	34	66	98	130	162	330	360	386	418	450	482	514	546	578	610	642
Abies	6	3	9	8.5	11.5	12.5	11	15.5	11.5	15.5	16	16	19	17	14	19	22.5	20.5
Picea	6	4.5	22.5	19.5	11	18.5	13	14.5	17.5	15	18	26	22	23	21.5	28.5	21.5	23
Pinus - subgenus Pinus	29.5	16	28	62	28.5	31	34	28.5	33.5	31.5	35.5	46.5	42.5	57.5	41	41.5	27.5	38.5
Pinus - subgenus Strobus	15.5	12	21	35	17	27.5	30	22.5	30	20	30.5	44	30.5	42.5	31	25.5	26.5	36.5
Pinus undifferentiated	13	3	10	10	14	13.5	9	9	15.5	13.5	15	8.5	12	12.5	13	11	11.5	5
Tsuga mertensiana	17.5	12	22.5	28.5	13.5	20.5	19.5	18	18	16.5	21.5	25	25.5	23	33	23.5	21	33
Tsuga heterophylla	14	12	19	27	29	21	25	18	14	21	24	20	28	16	21	31	38	33
Larix-type	15	17	3	13	12	19	26	24	23	15	17	11	26	12	14	29	26	18
Cupressaceae	26	19	14	11	16	7	16	6	13	20	11	7	2	5	5	13	3	3
Populus	31	64	37	10	46	28	37	40	11	55	32	8	7	13	18	31	15	14
Alnus	37	44	14	14	26	50	39	28	36	40	30	22	25	16	20	19	17	31

Betula	0	4	1	0	1	0	3	9	2	2	1	0	0	0	2	1	0	1
Salix	4	3	1	0	1	1	2	0	3	1	1	1	1	2	2	1	3	5
Quercus	3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Acer	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Artemesia	2	3	0	1	3	0	0	0	0	3	1	0	0	0	3	1	0	0
Rosaceae	0	2	0	0	0	2	5	6	7	0	4	6	0	2	7	6	2	10
Saxifraga	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ambrosia	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aster-type (Asteraceae)	3	1	0	0	0	2	0	0	0	0	0	0	0	0	1	0	0	0
Poaceae	14	10	15	3	7	8	6	7	10	4	6	4	5	1	4	3	13	6
Chenopodiaceae	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Caryophyllaceae	1	1	1	0	2	1	0	0	0	2	1	0	0	1	0	1	1	0
Vaccinium	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dryopteris-type	7	6	16	0	0	0	1	0	0	1	1	4	3	5	4	1	0	0
Isoetes	3	2	1	4	2	1	1	0	0	0	0	0	1	1	4	0	0	0
Pteridium-type	7	7	7	2	2	2	2	2	3	2	1	0	2	0	2	3	0	1
Equisetum	38	30	19	33	26	24	28	24	32	21	24	19	25	34	47	33	28	25
Undifferentiated-spore	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	10
Cyperaceae	5	7	3	3	3	3	3	6	3	7	2	10	18	13	3	6	2	5
Potamogeton	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ericaceae	1	6	3	0	2	0	1	0	0	1	1	1	0	0	0	0	0	0
Iridaceae	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Corylus	0	0	0	0	0	0	0	2	1	0	0	2	0	1	6	2	2	0
Callitropsis nootkatensia	1	3	6	13	18	2	4	7	10	4	16	6	7	2	0	0	0	0

Table S.3: Raw charcoal counts for Little Monon Lake

Depth (mm)	>500 µm	500–250 µm	250–125 µm	Total
2	0	4	52	56
4	0	1	5	6
6	0	0	12	12
8	0	5	22	27
10	0	0	5	5
12	1	9	39	49
14	0	0	6	6
16	0	0	18	18
18	0	0	10	10
20	0	0	16	16
22	2	8	41	51
24	0	6	37	43
26	0	1	21	22
28	0	2	6	8
30	0	2	13	15
32	0	4	42	46
34	0	4	63	67
36	0	16	82	98
38	0	8	91	99
40	1	7	108	116
42	0	13	92	105
44	0	6	65	71
46	0	4	54	58
48	0	8	84	92
50	1	13	76	90
52	0	5	46	51
54	0	11	74	85
56	1	17	92	110
58	0	6	77	83
60	0	2	97	99
62	0	10	108	118
64	0	12	96	108
66	0	8	68	76
68	0	8	113	121
70	0	7	56	63
72	0			
74	0			
76	0			
78	0			
80	0	10	63	73
82	0	5	45	50

84	1	11	89	101
86	2	4	82	88
88	0	7	78	85
90	0	2	42	44
92	0			
94	0	5	84	89
96	0	4	59	63
98	0	13	68	81
100	0			
102	0			
104	0			
106	0			
108	0			
110	1	35	117	153
112	0	33	101	134
114	5	26	181	212
116	0	14	79	93
118	1	8	72	81
120	0	10	55	65
122	0	12	68	80
124	0	6	55	61
126	0	5	35	40
128	0	12	58	70
130	0	14	70	84
132	1	4	45	50
134	0	9	94	103
136	1	3	56	60
138	1	13	74	88
140	0	14	78	92
142	0	14	158	172
144	0	17	126	143
146	0	11	165	176
148	0	15	105	120
150	0	9	123	132
152	0	6	98	104
154	1	6	64	71
156	0	14	89	103
158	0	22	149	171
160	0	8	63	71
162	0	3	65	68
164	0	4	58	62
166	0	5	65	70
168	0	3	69	72
170	0	12	45	57
172	0	10	87	97
174	0	20	112	132

176	0	14	113	127
178	0	17	104	121
180	1	14	90	105
182	0	8	101	109
184	0	13	104	117
186	0	12	69	81
188	0	5	113	118
190	0	6	73	79
192	0	8	84	92
194	1	9	97	107
196	2	7	92	101
198	1	12	122	135
200	0	8	89	97
202	1	10	152	163
204	1	14	121	136
206	1	15	109	125
208	0	12	81	93
210	1	5	57	63
212	0	7	98	105
214	0	11	86	97
216	1	14	82	97
218	0	2	43	45
220	0	6	57	63
222	0	22	91	113
224	1	3	106	110
226	0	9	70	79
228	1	12	115	128
230	1	11	118	130

Table S.4: Raw charcoal counts for Pyramid Lake

Depth (mm)	>500 µm	500–250 µm	250–125 µm	Total
2				
4	0	2	21	23
6	0	1	16	17
8	0	6	72	78
10	0	0	23	23
12	0	3	27	30
14	0	13	89	102
16	0	1	56	57
18	0	4	38	42
20	1	6	36	43
22	0	8	72	80
24	0	4	51	55
26	0	1	19	20

28	0	0	10	10
30	0	0	9	9
32	0	0	36	36
34				
36				
38				
40				
42				
44				
46				
48				
50	0	3	27	30
52	0	1	68	69
54	0	1	17	18
56	0	0	18	18
58	0	4	32	36
60	0	2	41	43
62	0	2	21	23
64	1	10	88	99
66	0	12	102	114
68				
70	0	17	72	89
72	0	0	19	19
74	0	5	52	57
76	0	4	35	39
78	0	9	42	51
80	0	6	46	52
82	0	3	25	28
84	0	4	42	46
86	0	2	42	44
88	0	1	19	20
90	0	0	32	32
92	0	3	54	57
94	0	3	74	77
96	0	1	55	56
98	1	2	40	43
100	0	6	51	57
102	0	4	49	53
104	0	3	28	31
106	0	7	63	70
108	0	2	23	25
110	0	0	17	17
112	0	5	52	57
114	0	3	39	42
116	1	2	34	37
118	0	3	46	49

120	0	2	35	37
122	0	0	21	21
124	0	0	25	25
126	0	1	34	35
128	0	0	29	29
130	0	11	89	100
132	1	6	34	41
134	0	0	21	21
136	0	3	56	59
138	0	5	54	59
140	0	2	32	34
142	0	6	39	45
144	0	3	57	60
146	0	5	36	41
148	0	3	47	50
150	1	6	75	82
152	0	3	32	35
154	0	9	97	106
156	0	2	12	14
158	0	0	14	14
160	0	5	32	37
162	0	4	43	47
164	0	2	12	14
166	0	7	77	84
168	0	2	16	18
170	0	13	133	146
172	0	9	114	123
174	1	10	102	113
176	0	2	45	47
178	0	1	18	19
180	0	5	55	60
182	0	2	34	36
184	0	3	44	47
186	0	1	17	18
188	0	2	35	37
190	0	3	87	90
192	1	7	90	98
194	0	8	95	103
196	0	2	28	30
198	0	3	44	47
200	0	1	19	20
202	0	7	90	97
204	0	2	36	38
206	0	12	102	114
208	0	8	111	119
210	1	6	75	82

212	0	8	76	84
214	0	4	55	59
216	0	3	20	23
218	0	2	28	30
220	0	7	64	71
222	0	2	13	15
224	0	5	27	32
226	0	8	58	66
228	0	4	34	38
230	0	2	32	34
232	0	5	35	40
234	1	2	16	19
236	2	8	25	35
238	1	11	87	99
240	1	11	107	119
242	0	7	45	52
244	0	2	23	25
246	0	1	16	17
248	0	7	87	94
250	0	2	32	34
252	0	4	31	35
254	0	9	92	101
256	0	4	29	33
258	0	1	22	23
260	0	0	18	18
262	0	2	30	32
264	0	4	32	36
266	0	2	35	37
268	0	1	12	13
270	0	3	56	59
272	0	5	76	81
274	0	8	68	76
276	0	3	56	59
278	0	1	38	39
280	0	3	34	37
282	0	2	23	25
284	0	10	74	84
286	0	9	87	96
288	0	1	19	20
290	0	1	22	23
292	0	7	48	55
294	1	2	43	46
296	0	2	50	52
298	0	6	51	57
300	0	4	65	69
302	0	0	13	13

304	0	7	55	62
306	0	0	21	21
308	0	3	45	48
310	0	4	42	46
312	2	1	12	15
314	1	2	34	37
316	1	4	55	60
318	0	8	76	84
320	0	2	54	56
322	0	2	18	20
324	0	1	19	20
326	0	4	29	33
328	0	7	59	66
330	0	8	61	69
332	0	5	62	67
334	0	2	23	25
336	0	1	19	20

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