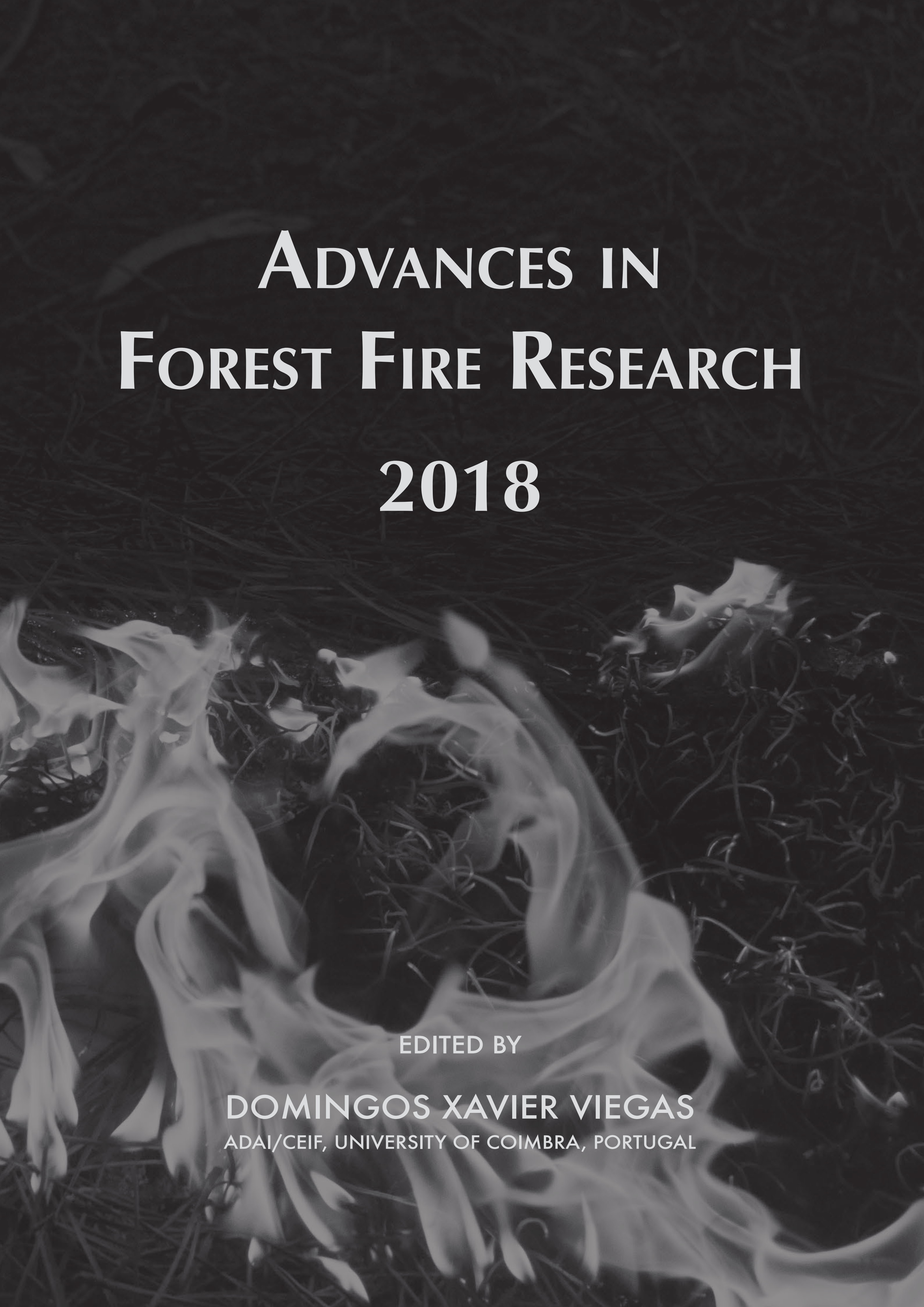

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# Integrating paleoecology into landscape management

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**Abstract**

Paleoecology has traditionally been used to examine how ecosystems evolve through time. Focusing on fossil plant reconstructions, conventional approaches examine the origin, expansion, contraction, and dynamic processes influencing plant communities over time. Recognizing that vegetation types are predominately influenced by climate, paleoecological records are frequently used to reconstruct climate through time, using both qualitative and quantitative approaches. In addition to examining vegetation and climate, evidence from natural disturbances, including charred plant remains from wilfires deposited in lake sediments, has increased in recent decades, enabling researchers to examine fire dynamics. Increasingly, there is growing urgency to integrate paleoecological studies and landscape management, rendering unique spatial (local to global) and temporal (years to millennia) perspectives that offer valuable insights for land managers today. This manuscript presents a suggested framework to acheive this goal, with emphasis on integrating paleofire data and managment applications. The framework illustrates several potential applications by scale, including direct local-scale applications within a managed municipal watershed, and medium-to-long-term perspectives on the causes and consequences of large fire events in forested ecosystems.

**Keywords:** paleoecology, fire, charcoal, Holocene, climate, management

## 1. Introduction

Traditionally, paleoecological studies aim to examine how ecosystems change through time and in response to various forcing mechanisms. Plant remains preserved in sedimentary sequences provide insights into the origin, development, and dynamics of plant communities. Recognizing that climate influences plant distribution, the utility of paleoecological records expanded to include reconstructing climate, using both qualitative and quantitative approaches (Birks *et al.*, 2010). In addition to examining vegetation and climate, analyses of charcoal fragments and other fire-derived indicators preserved in stratigraphic records have increased in recent decades (Brown and Power, 2013), enabling researchers to examine fire disturbance dynamics through time, including fire regime change and drivers.

Increasingly, there is a desire within the paleoecological community to integrate results into landscape management practices. For example, there is a growing awareness that perspectives on wildfire regimes, drivers, and effects at different scales are critical to understanding current and future fire occurrence and effects. Information about wildfire can be derived from many different sources, including administrative records, case studies, foret stand age-classes, dendrochronology, laboratory and field experiments, remote sensing, and modelling. However, fire history information extending beyond the comparatively short instrumental and observational interval is primarily derived from natural paleoenvironmental archives (Smol, 2008) and, in some cases, traditional knowledge (Lake *et al.*, 2017).

Paleofire proxies are natural materials (e.g., charcoal, pollen grains, biomarkers, minerals) or specific metrics of these materials (e.g., particle size, magnetic susceptibility, charred plant morphotypes) that have been directly generated or indirectly influenced by past fires or fire-related processes (Simoneit, 2002; Conedera *et al*., 2009; Brown and Power, 2013). These materials accumulate in lake sediments during and/or after wildfire via various pathways and linkages, creating a sequential record of physical, chemical, and biological responses to disturbance events (Birks, 1997; Conedera *et al*., 2009). These proxies can be extracted from sediment cores and systematically analyzed to enable qualitative interpretations or quantitative reconstructions of past fire dynamics based on modern fire-environment relationships.

## 2. Framework

A tentative framework for integrating paleoecological data, specifically paleofire data, into management is herein presented (Fig. 1), together with examples. While select examples are presented in this discussion, potenial opportunities for paleofire data within management contexts are more expansive, spanning multiple temporal and spatial scales. The framework presented here includes direct applications coupled with insights across scales, illustrating the robustness of the approach. Beyond management applications, paleo records documenting change through time are also valuable teaching tools for public education that resonate with wide-ranging audiences. For example, paleo studies can be used to illustrate the dynamic behavior of the earth's climate system through time, document rates and magnitudes of change in vegetation communities, and uncover the role of wildfires in shaping our modern landscape. Moreover, given that sedimentary records contain evidence of past fire, they can, if sampled at appropriate temporal resolution, provide insight into fire-induced terrestrial and aquatic effects and recovery times. The recent creation of the Global Modern Charcoal Database further aims to better calibrate recent charcoal depostion events with various $21^{st}$ century fire metrics (Hawthorne *et al*., 2017). Finally, paleoecology has much to offer conservation, providing baselines as well as measures of habitat, biodiversity, and processes, which in turn can aid the development of restoration goals (Hebda, 1998; Brown and Pasternack, 2004; 2005).

Paleoecological records can have relevance at the event-scale, where some of the largest areas burned can occur within days, by providing insights into the climate mode linked to the event, as well as other important controls (e.g., fuel types and density) and responses (e.g., geochemical and mineralogical changes). For example, the time between large charcoal peaks within a sediment archive may capture the frequency distribution of higher severity fire events (Dunnette *et al*., 2014). At annual-scales, another potential application relates to cumulative impacts. Given that paleoecological records contain biological, chemical, and physical indicators of pre- and post-disturbance conditions, they capture cumulative impacts or trends, as well as short-term responses. For example, the flammability of fuel loads in boreal or sub-boreal forests could be enhanced through insect-induced forest mortality, evidenced through changes in pollen and insect macros, increasing fire potential, assessed through changes in stratigraphic charcoal. The subsequent loss of vegetation following a fire increases overland flow and nutrient input into downstream basins, captured in sediment records by changes in grain size and diatom communities, respectively.

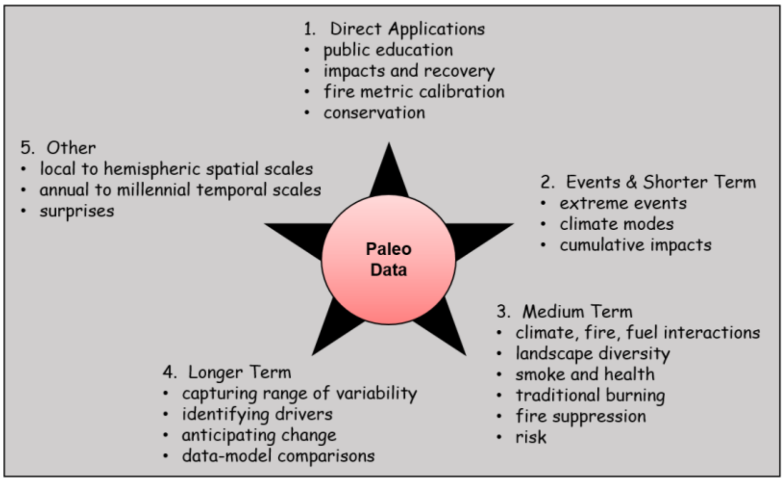


***Figure 1 - Suggested framework for integration of paleoecological research into landscape management, with an emphasis on paleofire data.***

Over the medium term (decades to centuries), paleoecology informs about the interaction between climate, vegetation, and fire. With each of these parameters interacting with the others, creating feedbacks within the system. For example, prolonged droughts may initially increase fire frequency and reduce fuel loads, but fire will utlimately become limited through an overall reduction in primary productivity in the absence of precipitation under severe drought conditions. Pollen records capture the integrated signal of the resulting landscape mosaic. Fire disturbance also creates a range of chemical products through combustion products, including slightly charred particles, residues like charcoal, condensates like soot, and a variety of other chemical markers, including fire-derived compounds (Simoneit, 2002). During a wildfire, these compounds become atmospherically lofted, transported, and later removed by wet and dry deposition. During this latter stage, some of the compounds accumulate in depositional environments, preserving a record of fire and serving as tracers of smoke. Likewise, the records are also suitable for discerning and characterizing the effects of traditional burning and fire suppression. Finally, medium- to long-term tracking of natural disturbances through time also provides insight into risk. For example, the frequency of megathrust earthquake events has been ascertained and refined using turbidites preserved in marine cores (Goldfinger *et al*., 2003), informing the public about seismic risk. Adopting a similar approach targeting lake sedimentary records could inform communities about wildfire risk in terms of the average time between large-scale wildfires, with the caveat that non-analog climate will change fuel charateristics and disturbance regimes

On yet longer timescales (centuries to millennia), paleoecological studies can reveal natural ranges of variation and identify drivers of change. Paleo data can aid model calibration and validation, and facilitate data-model comparisons (Flannigan *et al*., 2001; Marlon *et al*., 2012). Paleoecological data are used to understand landscape evolution and processes occurring at spatial and temporal scales beyond the recent establishment of geo-political boundaries and human-built systems located in regions where disturbances may skip several human generation times (e.g., fires occuring on average every 300 years). Finally, paleodata can inform about surprises in the earth system. For example, several paleoecological studies have shown that during the northern hemisphere warm mid-Holocene interval about 4000–8000 years ago, conditions were favorable for widespread burning. However, spatially explicit paleofire data show that fire actually decreased in certain parts of the circumboreal, including Quebec (Girardin *et al*., 2013) and Fennoscandia (Brown and Giesecke, 2014). This non-linear response was possibly a result of the expansion of broadleaf vegetation, which altered microclimatic conditions and fuel type, arrangement, moisture content and flammability, and lowered mid-Holocene fire activity in certain regions. In another example from boreal Alaska, the expansion of flammable black spruce resulted in an increase in fire disturbance even though climate was cooling and moistening (Lynch *et al*., 2003).

## 3. Example from a managed municipal watershed

A specific example of integrating paleoecological data into landscape management heralds from a study in the Greater Victoria Water Supply Area (GVWSA), British Columbia, Canada (Fig. 2). The Sooke Lake Reservoir (SLR) is a dammed natural lake that supplies high quality drinking water to >350,000 people at comparatively low cost. However, because the watershed is densely forested, it is susceptible to fire disturbance. Elevated post-fire erosion can contaminate water supplies by increasing delivery of suspended sediment, nutrients, and other pollutants to reservoirs for periods of days to years (Emelko *et al*., 2011; Shakesby and Doerr, 2006; Smith *et al*., 2011). Resultant changes in water turbidity, chemistry, and biology may leave it unsuitable for drinking (Smith *et al*., 2011; White *et al*., 2006), and treatment may be costly or unfeasible (Emelko *et al*., 2011). This problem is exacerbated by climate change, which is projected to drive a regional increase in wildfire severity and area burned (Haughian *et al*., 2012).

In response, GVWSA managers have identified wildfire as a major threat to drinking water supply and seek to understand how fire activity has changed within the watershed through time and in response to various forcing mechanisms. Of particular interest is the early Holocene interval, 11,700–7,000 years ago, since it represents a time when climate was warmer and drier than present, potentially providing an window into current and future fire conditions. A paleoecological investigation was initiated to characterize the long-term relationships among climate, vegetation and fire disturbance in the watershed (Brown *et al*., submitted). Lake sediment cores were collected and analysed for a suite of paleoenvironmental proxies, including pollen, charcoal, and magnetic susceptibility. The results indicate that a longer fire season and mixed-severity fire regime occurred in the warmer, drier early Holocene (Fig. 3). Futhermore, increased fire disturbance in the mid-Holocene was likely due to increased human activity and/or climate variability. Combining the results from this investigation with paleoclimate modeling, modern management practices and forecast simulations can aid the development of strategies that account for these types of ecosystem change within the watershed (*sensu* a past-present-future data continuum), leading to a more robust and informed climate adaptation strategy.

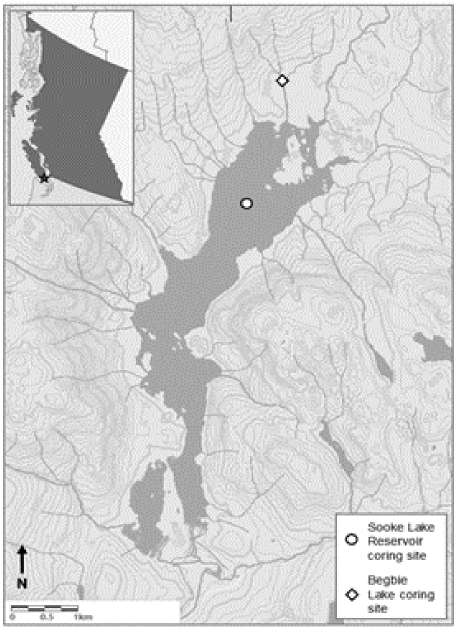


***Figure 2 - Sediment coring locations within the Greater Victoria Water Supply Area, BC, Canada.***

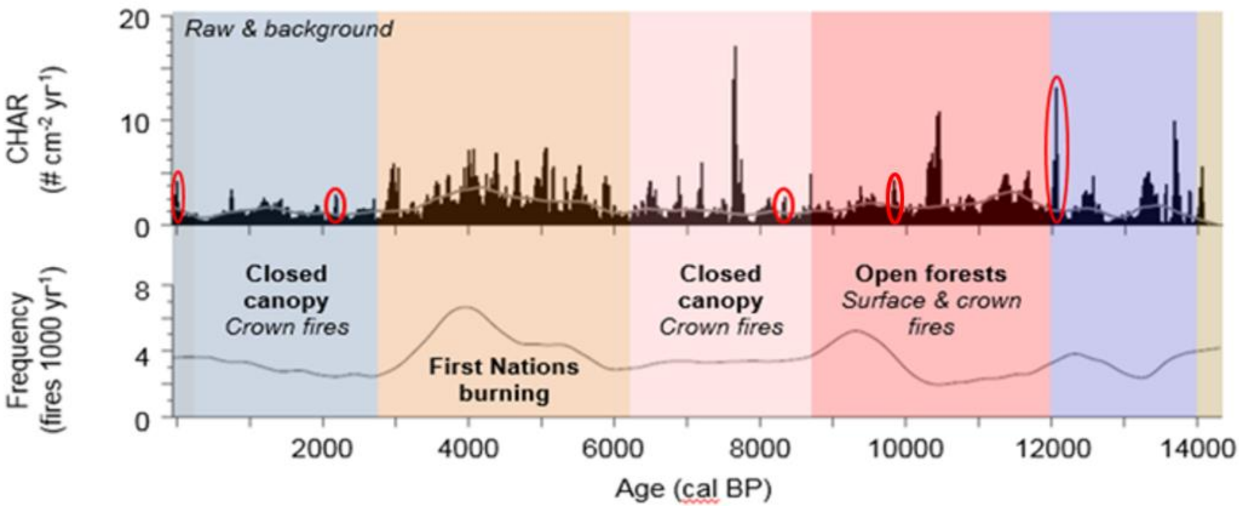


***Figure 3 - GVWSA Holocene charcoal time series showing fire regime change through time. Red ovals indicate the fire episodes being examined at high resolution.***

Furthermore, the investigation includes high-resolution analyses of select individual fire episodes recorded in the sediment to examine short-term fire effects and recovery in the terrestrial and aquatic environments (Fig. 3). Several fire events, each occurring under different past climatic conditions, are being examined in detail at high temporal resolution. The ecological and water quality effects of these fires are being evaluated using a variety of terrestrial and aquatic paleoenvironmental indicators including charcoal, pollen, diatoms, total carbon (C) and nitrogen (N), grain size, magnetic susceptibility, and trace elements. Initial results show strong evidence of fire-induced effects (Fig. 4Figure ). Charcoal, magnetic susceptibility, and total C and N exhibit clear fire responses. Coincident changes observed in the C:N ratio provide insight into post-fire changes in carbon as well as changes in aquatic productivity. Preliminary grain size results reveal apparent post-fire fining of sediment deposits. Pollen analyses show variable vegetation response, including post-fire increases in fire-adapted species abundance and concurrent decreases in fire-sensitive species. Diatom community composition likewise exhibits marked changes coincident with charcoal and magnetic susceptibility peaks. A wide variety of trace elements increase in the sediment during the post fire intervals. Although the investigation is ongoing, the targeted paleoenvironmental indicators variously exhibit compelling evidence of fire-related ecosystem impacts. As further data become available, statistical analysis and interpretation of this multi-proxy tool kit will facilitate both qualitative and quantitative reconstructions of past fire effects in the GVWSA. Viewing these data under different climate scenarios in the past will inform watershed management recommendations for mitigating future wildfire risk to the supply of drinking water.

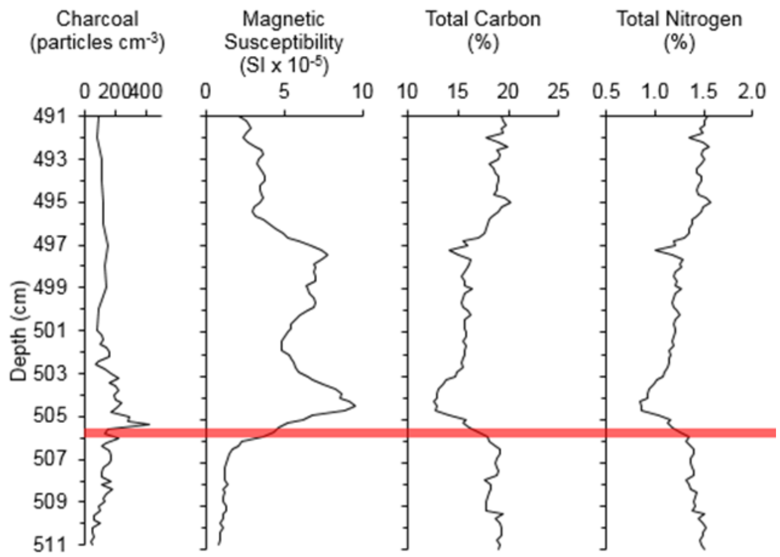


***Figure 4 - Responses of select proxies to fire disturbance. Red line indicates timing of fire event.***

## 4. Example from western USA

An example of a 13,000 year-long high-resolution pollen and charcoal record from a low-elevation record, Foy Lake, in western Montana (Fig. 5) provide novel perspectives on the evolution of fire and the relative importance of mega-fire events, like the fires of AD 1910. Following the last Ice Age approximately 20,000 years ago, low elevations in western Montana comprised subalpine parklands that supported a low incidence of fire. As the climate warmed during the late glacial and early Holocene, the region became effectively drier and more fire-prone as lodgepole pine and Douglas-fir and western larch forests developed at low elevations (Fig. 6; Power *et al*., 2011). In high-elevation forests of white pine and spruce, fires increased abruptly after 12,500 years ago in response to higher-than-present early summer temperatures and an increasing abundance of vegetation on the landscape. As fire activity increased during the early and mid Holocene, fire-adapted Douglas-fir and western larch forests developed at both low- and mid-elevations, with evidence that burning generally increased across all elevations at least until ~6000 years ago. The modern vegetation communities developed in this region during the last several millennia as the regional climate generally became cooler and wetter. The exception to this long-term trend of reduced fire occurred around ~2000 years ago, when a mixed-severity fire regime developed. A synthesis of dozens of fire records from the region show several centuries of high fire activity (Power *et al*., 2011). This time of high-fire was also when prehistoric populations expanded in the region. This abrupt increase in fire 2000 years ago was embedded within a long-term trend of climate cooling and was likely linked to short-term climate varibility and potentially amplified by human ignitions.

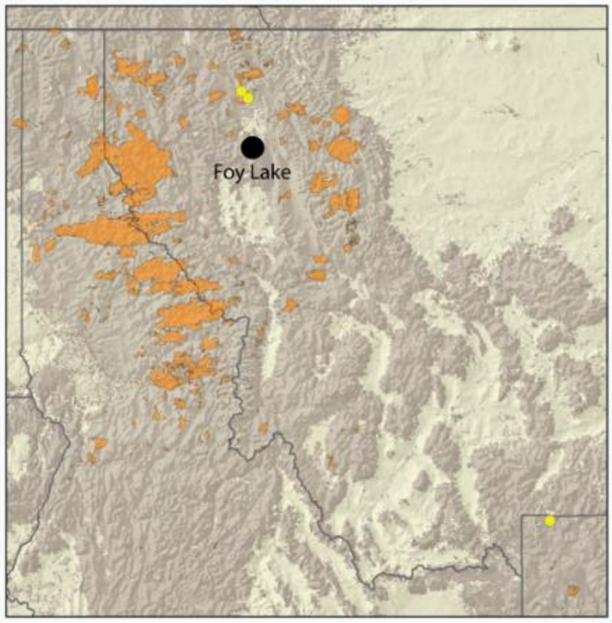


***Figure 5 - Location of study site in western Montana (black circle) and the area burn maps of the fires of 1910 (orange polygons).***

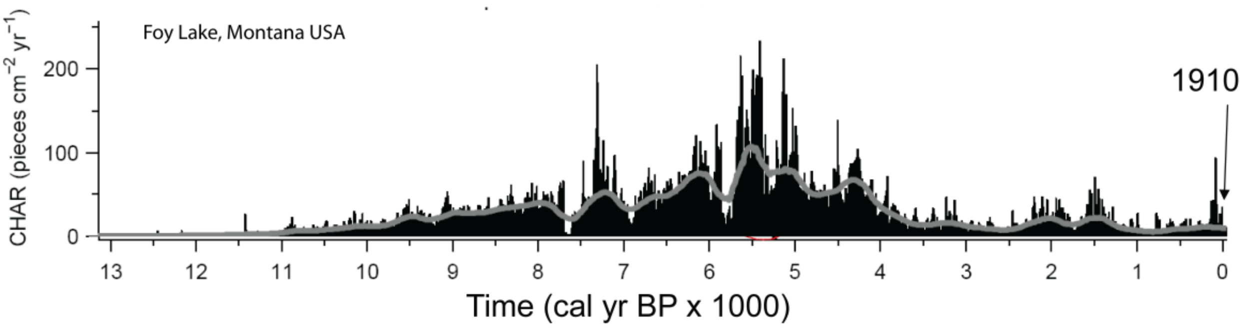


***Figure 6 - A 13,000-year long fire history reconstruction from Foy Lake, Montana, showing the relative scale of the AD 1910 fire when compared to the mid-Holocene period of extreme fire conditions.***

This research also provides a context to the AD 1910 fires that were responsible for numerous deaths and policy changes within the U.S. Department of Agriculture. When the 1910 fires are placed in the context of the last 13,000 years (Fig. 6), the significance of the disturbance event is obscured by the magnitude and frequency of fire events throughout the middle Holocene. In recent years, fires have increased across the region at both high and low elevations, suggesting the interplay among climate conditions (e.g., seasonal temperature, moisture, and snowpack), a century of fire-supression management practices, and an increasing abundance of ignition sources, both human and natural. Understanding the range of variability in western forests will ultimately help forest managers prepare and potentially mitigate worse-case scenarios under future climate conditions.

## 5. Conclusion

Paleoecological records, including paleofire proxies, provide a rich and varied archive of ecosystem and fire history information reaching back millennia, integrating information from local to global spatial scales. A more thorough understanding of current and future fire incidence and impacts can be gained by studying past natural fire variability, patterns, drivers, and consequences. By combing insights from paleodata with present-day monitoring efforts, management practices and future simulations, it is possible to generate a past-present-future data continuum (Brown *et al*., 2017), each rendering unique spatial and temporal insights. The combined information can be consulted when developing best practices and policies, especially during times of rapid change.

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