

Scale, Representation and a Utility Paradox for Applied Paleoecology

by

Geoffrey M. Johnson

A dissertation accepted and approved in partial fulfillment of the

requirements for the degree of

Doctor of Philosophy

in Environmental Sciences, Studies and Policy

Dissertation Committee:

Daniel G. Gavin, Chair

Richard F. York, Core Member

Patrick Bartlein, Core Member

Gyoung-Ah Lee, Institutional Representative

University of Oregon

Summer 2025

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DISSERTATION ABSTRACT

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In the accompanying dissertation, I submit a collection of three studies to address and expand the relevance of paleoecological science to human-land relations in the Pacific Northwest of the United States. Each of these studies is important for ecological management and long-term environmental change research around the world. In the first of these studies, I conducted a critical analysis of relationships between forest resources management and paleoecological reconstruction at the scale of The Northwest Forest Plan (primarily Region 6 of the United States Forest Service, Oregon and Washington, USA). In the second and third studies, I developed case studies of paleoecological reconstruction applied at the temporal and spatial scales of natural resources governance.

In the first study I emphasize the importance of understanding what social and biophysical factors mediate the relevance of paleoecological science to ecological management as applied within the Northwest Forest Plan. Through interviews with natural resource professionals and analysis of natural resource planning documents related to the Northwest Forest Plan, this study helps to clarify the relationship between paleoecology to the practice of ecological management. Document analysis and participant interviews suggest growing awareness of paleoecology within the ecosystem management community of practice, yet substantial obstacles to the incorporation of historical perspectives in the management of forest resources are evident. I proposed a utility paradox for paleoecology as applied to ecosystem management in light of these findings and the emphasis that participants placed on unprecedented novelty of present conditions and the economic imperative of work in natural resources.

In the second study, I addressed whether signals of fire size and severity can be detected in late Holocene records of biomass burning in the Western Cascades of Oregon. With a new multisite reconstruction of fire using sedimentary charcoal stratigraphy and existing records, I compared geospatial fire size data and charcoal particle accumulation rates at varying topographic positions. I find evidence of ‘missing’ charcoal influxes from land management activities and rare occurrences of specific fire events in the sedimentary record. Moreover, analyzed records show substantial variation in influx of different charcoal size classes and morphologies with topography and fire weather, emphasizing that large potential source areas for charcoal are highly modified by fire event conditions and fire size.

The third study examined canopy openness of dry pine forest and changes in response to fire and climate from the Late Pleistocene to present with a new lake sediment record. I first tested pollen-vegetation relationships with a pollen-ratio proxy and the REVEALS statistical vegetation reconstruction method using surface pollen data and a geospatial vegetation structure dataset. REVEALS outperforms the pollen-ratio proxy significantly and shows the strongest relationship to forest canopy cover at 50 km and above. REVEALS reconstruction of historic vegetation suggests that forest canopy cover has changed little over the past 9000 years, peaking around 4600 years before present. Despite climate that should favor trees, herbaceous cover has incrementally increased for the last 4000 years supporting inference that the pre-Euro-American settlement frequent low-to-moderate severity fire regime has been operating for millennia.

With these studies I evaluate and contextualize linked social and technological horizons for paleoecological research. I use sociological methods and theory to situate paleoecology within the natural resource sciences considering current discourse about the relationships between science, society and environment. I follow this analysis with two socially informed case studies of fire and

vegetation to advance the scope of applied paleoecological theory and practice.

ACKNOWLEDGMENTS

I gratefully acknowledge the incredible wealth of knowledge upon which this dissertation is firmly rooted; without the care and curiosity of uncountable brilliant and meticulous minds, this work would not have been possible. I particularly recognize the singular influence of Daniel G. Gavin, my advisor and mentor, who continued to guide me with his kind intelligence despite all obstacles. I additionally recognize Michael Coughlan for providing funding for field and laboratory analyses and the overarching project framework for my work in the West Cascades. I also recognize my committee and a broad group of students, scholars and workers who tended carefully to the Department of Geography and the Environmental Science, Studies and Policy Doctoral Program. These bodies were the crucible for this work, where cross-disciplinarity in its many forms was not an afterthought. Other specific individuals who contributed substantively include Drs. Lauren Hendricks and Schyler Reis in the field at North Twin Lake, Erik Johnson as a scouting companion in the West Cascades, and Rose Nittler and her astonishing laboratory technician skill.

DEDICATION

This work is dedicated to those who serve each other, enrich their communities and bring meaning to the world through mutual aid and appreciation. There is no higher calling in this world.

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I

INTRODUCTION

1.1. Paleoecology of the Present

Paleoecology is a hybrid subdiscipline of ecological and geological sciences concerned with the reconstruction of past ecological processes and states. Observations are necessarily made by proxy from traces left in natural archives such as peats, sediments, glacial ice, or animal middens. While I focus on paleoecology in this dissertation, I consider this field one component of a meta-discipline which I refer to as a science of long-term environmental change (LTEC) characterized by the reconstruction of environmental characteristics over long (centennial-to-millennial) time scales, variable temporal resolution and associated levels of uncertainty (Delcourt & Delcourt, 1991; Jackson, 2004). In the last decade the study of LTEC is at an inflection point produced by shifting social priorities (Seddon et al., 2014a) and novel analytical tools and techniques (Brewer et al., 2012; Jackson, 2004). In the following document, I describe a dissertation which examines this inflection across two axes: 1. evolving computational methodologies for reconstruction of past environmental characteristics and 2. application of inferred Quaternary ecological information in ecosystem management. These axes situate the study of LTEC in the present scientific and political moment, and I use that understanding to outline a research agenda designed to advance LTEC science and expand our understanding of the stakes and stakeholders in LTEC science. While I emphasize Quaternary (the last 2.6 million years encompassing the period of glacial cycles) LTEC, deep time (pre-Quaternary) LTEC is recently invoked in academic and non-academic circles as a source of information about a projected warmer Earth (Burke et al., 2018; Haywood et al., 2016) likely to be brought about by fossil carbon emissions and land-use change given current trends (Pachauri et al., 2015).

1.1.1 Future of Pacific Northwest Paleoecology

I explore the interaction of these emerging quantitative and applied directions through the study of sedimentary records of fire and vegetation across the crest of the Cascade Range in the Pacific Northwest (PNW) of Western North America and the social process of science-based fire and vegetation management in which these scientific products may or may not become entrained. This landscape is a useful study system in important ways. Biophysically, the Cascade Range produces a rain-shadow biogeography, resulting in distinct ecological communities, and contrast in vegetation structure over a few kilometers. Historical and contemporary fire regimes and vegetation responses to fire management also differ greatly across this gradient. Finally, the western side of this study system is home to a large human population, development and investment, while the eastern side is sparsely populated; a geography molded by biophysical patterns and infrastructure projects (Vogel, 2007). Thus, proximity and difference provide a contrast not only of ecological systems, but also of socio-ecological dynamics of modern-day constituent ecological communities as sources of economic and cultural value. While ignoring these considerations may have been a dubious luxury for ecologists of the past, the present is not so simple. These factors are no longer confounding variables, but rather nuanced overlays in which the conduct of science takes place (Latour, 1987).

To contribute to evolving computational and applied LTEC, I choose three topics in the context of PNW environments which address these linked technical and social challenges for LTEC research. Each of these topics contributes to understanding fire and its effects on natural and cultural resources through a long-term lens. In the first, a sociological critique of applied

millennial-scale environmental change science, I link LTEC to the concept of historical range of variation (HRV) (Keane et al., 2009; Swetnam et al., 1999) as applied in natural or cultural resources management in the context of The Northwest Forest Plan, a landmark ecosystem management strategy covering 24 million acres in California, Oregon and Washington. For the second topic, I present new data and interpretation on Late Holocene fire history in the West Cascades, a diverse and productive sub-region with complex climatic and human influences. The third and final topic is the effect of fire frequency and severity on vegetation structure in dry interior conifer forests of the U.S. Pacific Northwest.

1.1.2 Critique of Applied Paleoecology: Long-Term Environmental Change and Natural Resources

LTEC has the potential to inform a variety of applied natural resource management activities. Ecosystem reference conditions (Jackson & Hobbs, 2009; Watson et al., 2011), ecosystem or assemblage resilience (Barak et al., 2016; Gillson et al., 2019; Pearson et al., 2015), and setting ecological restoration goals (Manzano et al., 2020; Willis & Birks, 2006) are all ways that the LTEC community has suggested LTEC data may inform ecosystem management today. To acknowledge the pivotal role of society in guiding ecological sciences (Hirsch, 2020; Norgaard & Baer, 2005; Palmer et al., 2016; Sutherland et al., 2013; Urgenson et al., 2018), I ask first, **what social and biophysical factors mediate the relevance of LTEC to fire and vegetation management in Oregon and Washington (USFS Region 6)?** By centering the role of society and its structures, I integrate and contextualize a lineage of paleoecological thought which suggests that long-term perspectives are vital to the management of ecological (Barak et al., 2016; Jackson & Hobbs, 2009; Whitlock et al., 2018) and cultural (Ekblom et al., 2019; Ekblom & Gillson, 2017) resources.

In the tradition of critical social science (McCright & Dunlap, 2010), science studies (Klenk & Meehan, 2017), and emergent subdisciplines of environmental science (Lave et al., 2014), I suggest the applicability of LTEC data to questions of ecosystem management requires a deeper understanding of how LTEC exists in relation to the practice of ecosystem management and its political and economic engagements - an area that has received very little attention globally (Davies, 2011; Davies et al., 2014; Durham & Dietl, 2015), and none with respect to ecosystem management in the United States natural resource management apparatus. Although the global community of researchers with stated and active research into applied LTEC direction is small, this fundamental gap in understanding currently limits the application of all LTEC to socioecological problems in ways that go unrecognized by LTEC researchers and thus are not integrated into the practice of LTEC research or the framing of LTEC data. Furthermore, it leaves open the question of whether LTEC is relevant in the context of ecological governance as put into practice through ecosystem management.

1.1.3 Topic 1 | Avenues for Relevance

I posit that the concept of Historic Range of Variation (HRV) (Keane et al., 2009) is a fundamental component of the issue of LTEC's relevance. HRV as applied in ecological management of the United States is a uniquely important temporal construct linking LTEC with ecosystem management (Swetnam et al., 1999), however, the scope is commonly limited to the historical record and certain recent (<1000 years) forms of proxy data. Thus, I also ask simply, **How is millennial-scale LTEC *relevant* in defining historic range of variation (HRV) in ecosystem management as it pertains to ecological resilience and climate impacts?** I address this question through critical analysis of interviews with individuals in natural resources

organizations and of planning documents. In doing so, I place LTEC in relation to its socio-ecological context in PNW North America. I then use this placement to explore structural influences - institutional and economic - upon LTEC and its products, and how such influences suggest opportunities and obstacles for LTEC research. Furthermore, I define a utility paradox for applied paleoecology which emerges from scalar mismatch along the temporal axes of paleoecology and politicized natural resource governance. To frame this utility paradox, I adopt principles of historical materialism – an intellectual tradition which attributes much of society’s relationship to nature, its institutions, and their dynamism to the physical manifestations of production and exchange (Foster, 2011). The environmental branch of historical materialism has, I believe, proven to have a commensurate epistemology with those of natural sciences on the subject of environmental change (Foster et al., 2011; Malm, 2018) and to have unique theoretical abilities with respect to the relationship between modern societies and their environments (York & Mancus, 2009).

1.2 Applied Paleoecology in Practice

Topics 2 and 3 arise from the contextual framing of LTEC as a component of science-based ecosystem management in the PNW. Furthermore, I narrow my focus to relationships between vegetation and fire in forested landscapes of the Cascade Range in Oregon, USA. Substantial uncertainty characterizes our understanding of the frequency and severity of fires in the past in both the Western (Dunn & Bailey, 2016) and Eastern (Fulé et al., 2014; Williams & Baker, 2014) Cascades. These studies address key issues facing the management of fire, characterizing the relationships between vegetation, climate and fire over millennia. Past ecological processes and states, including the little-understood impacts of traditional and indigenous societies on landcover

(Foster et al., 2003; Hayashida, 2005), are considered by many LTEC practitioners to act as baseline information (Carter et al., 2018; Gillson et al., 2019; Whitlock et al., 2018; Willis et al., 2010) in science-based ecosystem management now practiced across public and private lands of WNA (Christensen et al., 1996; Manring, 1993) and increasingly around the world.

1.2.1 Topic 2 | Late Holocene Fire in the West Cascades

Along the western side of the Cascades Cordillera feedbacks among fire, climate, human activities and vegetation are known from multiple lines of evidence including historical documents, dendrochronological time-series, sedimentary proxies, archeological site descriptions, and oral history. In this context, these sources of information rarely inform each other, and, while perhaps not incommensurable, suggest partial histories which may occasionally appear contradictory. A notable example is the characterization of the natural Western Cascade fire regimes as dominated by large, severe fires by some authors (Franklin & Johnson, 2012; Whitlock et al., 2015), while others suggest that extensive moderate and low severity fires may have been more common (Dunn & Bailey, 2016; Tepley et al., 2013), and still other researchers suggest widespread use of cultural fire, typically low severity (Derr, 2014; Lake & Christianson, 2019), to open forest canopies for various purposes in the pre-Euro-American settlement landscape (Boyd, 1999b; Walsh et al., 2010). Given these diverse assertions and to assess the role of LTEC in understanding the nature of fire on this landscape, I believe it is necessary to ask **what do charcoal influx, morphology, and size distribution suggest about the late Holocene history of fire size, severity, and frequency in the Western Cascades?** Furthermore, if different charcoal attributes can be related to fire events and temporal patterns, **what are the spatial relationships between fire size and charcoal accumulation?**

I reconstructed fire activity using sedimentary charcoal from morainal ponds and peat deposits at hillslope seeps, where sites were chosen to reflect a patch-and-corridor model of culturally maintained resource distribution. Additionally, I revisit the representation of charcoal in sediment as a function of fire in the West Cascades – a widely utilized basis of quantitative reconstruction of the fire regime. To address this I ask, **can charcoal as a proxy of fire from sedimentary archives in Pacific Northwest forests west of the Cascades be calibrated to the extent and frequency of historical fire?** I evaluate charcoal accumulation of new and existing records with respect to source area, as topographic complexity and effects on fire are not accounted for in regional syntheses of millennial fire history at multiple scales (Marlon et al., 2012; Walsh et al., 2015) and play a crucial role in fire dynamics (Krawchuk et al., 2016).

1.2.3 Topic 3 | East Cascades Holocene Stand Structure and Composition

My last topic is the reconstruction of fire severity and vegetation structure on the East slope of the Cascades Range. East Cascades forests are comprised of mixed-conifer and ponderosa pine communities, which are differentiated largely by moisture variability and topography and which also have distinctive fire regimes (Franklin & Dyrness, 1988). These dry conifer forests are one of the most spatially extensive forest types in the continental US, covering over 25.5 million ha (Baker, 2015). Emerging consensus of a frequent low-severity fire regime in these forests (Heyerdahl et al., 2008; Johnston et al., 2016; Merschel et al., 2018a) is the product of several decades of research (Hessburg & Agee, 2003), however there is also some evidence of infrequent high-severity fires in the past (Williams & Baker, 2014). The long-term (millennial scale) frequency of high-severity fire in this environment is relatively unknown as are any effects on the positive feedback between fire frequency and understory cover.

Dendrochronological studies describe the last several hundred years and are marked by changes in forest density following shifts in land-management practices associated with settlement. However, due to extensive tree harvest, it may no longer be possible to identify the landscape extent of low and high severity fire regimes in much of the ponderosa pine forest of the US West. I suggest a Holocene-scale perspective is required to address the occurrence of large, severe fires in the past, and their effects on forest structure, and I begin by asking **what does Holocene vegetation community structure and canopy openness of East Cascades dry pine forest suggest about changes in post-glacial fire regimes?** Coupled to this question is an implicit assumption that pollen as a record of vegetation contains information regarding the structure of vegetation. Thus, I also ask, **can vegetation structure be inferred from sedimentary pollen assemblages?**

Ponderosa pine forests occur in dry regions and at low elevations typically in unglaciated areas with few lake basins, thus sedimentary records from interior WNA are typically in higher-elevation mixed conifer or sub-alpine forest where glacial landforms produce cirque lakes. The result is that the late Quaternary history of ponderosa pine forests is known from very few sites, particularly in their western-most range along the Cascades, due to the rarity of continuously accumulating sedimentary basins in these arid environments. In this study, I develop and validate chronology of vegetation and environmental change from lake cores obtained in 2016 from North Twin Lake (NTL) in Deschutes National Forest, OR, USA, and I present a calibration of pollen-vegetation relationships in dry-interior forest types to reconstruct paleo-forest structure around NTL as evidence of fire severity in the past 15 ka. I hypothesize that fluctuations in forest-structure proxies capture variations in observed fire-vegetation relationships such that forest structure (vegetation composition and canopy openness) reconstruction may be used to infer fire activity.

1.3 Background

As is true of many ecological sciences, the distribution of LTEC study locations is not uniform around the Earth. One of many legacies of 19th and 20th century European and American scientific hegemony is a preponderance of these pre-historical studies in the eastern United States and Europe. Thus, while regional characterizations of vegetation and fire are the legacy of mid to late 20th century paleoecology, a finer-scale, systematic description of Western North America's ecological history has been in early stages of development for the past four decades. These spatial limitations propagate through applied LTEC insofar as place-based information is considered crucial for ecosystem management (Colavito, 2017; Ellison et al., 2019). Likewise, efforts to unify neoecology and paleoecology (Buma et al., 2019) may be limited by the distribution of LTEC studies relative to the distribution of land cover and ecological systems. The process of 'filling in the gaps', while not complete, has continued steadily to the present. Currently there are few ecological regions that remain unrepresented, and in some systems replication is an emerging opportunity for comparative analysis. In general, however, the late Quaternary history of many ecological settings is still known from only single-site reconstructions. For the more recent past (ca the last 10-15 thousand years) there is increasing spatial density of records from the orogenies of the Western Cordillera (Cascade-Sierra and Rocky Mountains), where glacial landforms have allowed numerous depositional environments to persist since the last glacial maximum.

One of the two new developments in LTEC I've chosen to explore with this dissertation is the scientific opportunity emerging from expanding data availability on ecological variation over time and space. This development is constituted by evolving quantitative methods, emerging technologies in informatics, and associated cultures of open data which are launching LTEC research into the data science revolution, with as yet unknown opportunities and consequences

(Mah, 2017). On a purely technical note, however, this transition raises difficult questions about comparability of site records and the way these proxy records represent real phenomena. I suggest the shift from descriptive, systematic and theoretical research to computational and data science paradigms in LTEC research (Williams et al., 2018) presents new challenges and emphasizes certain well-known issues such as the density of records, the likelihood of spatial bias, and the semi-comparability of site-scale reconstructions due to site-level factors. Regarding application of LTEC data in ecosystem management – the second axis of inflection for LTEC – the last decade has seen a dramatic increase in interest from LTEC researchers around the world. Yet, the relationship of LTEC research to ecosystem management remains unclear, and I suggest this is cause for careful consideration. Human societies, institutions, and individuals are deeply embedded into ecological systems and exercise power over and through nature (Agrawal, 2005). Ecosystem management is thus never value neutral but rather entangled in socio-environmental processes at all applicable geographical scales (Cash et al., 2006). To the degree that ecosystem management involves the production of goods and services, it is also driven by global capitalism (Foster et al., 2011). Ecosystem management is thus influenced on a fundamental level by financial interests, notably the timber industry in the Pacific Northwest (Prudham, 1998), and State-sponsored infrastructure projects to facilitate extractive resource management (Vogel, 2007). In USFS Region 6, these influences are pervasive having formed the basis for nature-society relations in the post-Euro-American settlement landscape (Prudham, 2007).

Christensen et al. (1996) define ecosystem management as “management driven by explicit goals, executed by policies, protocols, and practices, and made adaptable by monitoring and research based on our best understanding of the ecological interactions and processes necessary to sustain ecosystem composition, structure, and function.” According to this widely cited definition,

millennial LTEC may indeed be relevant to a variety of management goals, and LTEC researchers also suggest insights from their studies will help in setting ecosystem goals themselves. However, there is little empirical evidence to support this or any other assertion about how LTEC research might inform the practice of managing ecosystems (but see Groff et al., 2023; Wingard et al., 2017).

Intrinsic properties of LTEC data may cause substantial difficulty with respect to informing ecosystem management (Birks, 2019), and such technical issues may be important and easily addressed. Certainly, the observation-by-proxy data paradigm which characterizes palaeoecological research; as well as the temporal scale, resolution and uncertainty of proxy data must be the fundamental focus of any effort to translate LTEC perspectives to policy-relevant insights. Despite their prevalence in this science, surprisingly little effort has been put into understanding how measurements of pollen and charcoal abundance from Western North America translate into absolute quantities on-the-ground (i.e. species composition or fire return intervals). Certain notable exceptions I review below, but I argue that the relative framing of proxy data will structurally limit the applicability of the empirical data of LTEC to the sustainable management of ecosystem services such as climate stability, biodiversity, water, and soil.

II

LONG-TERM ENVIRONMENTAL CHANGE AND NATURAL RESOURCES

What social and biophysical challenges and opportunities mediate the application of LTEC to understanding natural resources?

How is millennial-scale LTEC relevant in defining historical range of variation (HRV) in ecosystem management as it pertains to ecological resilience and climate impacts?

2.1 Introduction

Forests serve many functions for society and these vary widely in spatial and temporal scope and are frequently in conflict (Buckles, 1999). However, the history of forests and forest management in the PNW has been influenced greatly by the growth of and changes in the timber industry over the past 100 years (Prudham, 1998; Warf, 1988a). In the PNW, and much of Western North America (WNA), vast tracts of forested land are under federal administration; natural-resource economies dependent upon these lands are prevalent in this region. Substantial portions of forest land in these landscapes are also privately owned – particularly in close proximity to communities and surrounding zones of arable land. The importance of non-academic actors in management of these lands thus suggests that research with the express intent to inform natural resource management falls under the category of transdisciplinary research – a strange territory for LTEC researchers.

An emerging consensus suggests a transdisciplinary research approach requires intensive, transparent, reflexive discussion with stakeholders, and further, a critical assessment of what's at stake and for whom (Klenk & Meehan, 2015a). The complex mosaic of forest land governance requires careful assessment of stakeholders as land-management decision-making occurs in firms, households, agencies, and organizations. Moreover, the US West, while frequently characterized through regional commonalities and a changing modernity exhibits both integrity in nature-culture

relationships through time and substantial internal variation (Robbins et al., 2009). Federal agencies, State agencies, industry collaboratives, non-profit organizations, and Tribes are all important actors and many post positions requiring training in ecological sciences to support evidence-based management approaches – the dominant ecosystem management model today (Christensen et al., 1996).

Part of the rationale for this study is rooted in recent claims about the potential utility of long-term ecological data in achieving or even defining long-term land management goals (Dietl et al., 2015; Durham & Dietl, 2015; Gillson et al., 2019; Whitlock et al., 2018; Willis et al., 2007). This relatively new and growing development in the discourse of LTEC (Figure 1) has received little critical evaluation from within or without, yet numerous LTEC studies with express intent to inform resource management exist (Groff et al., 2023; Manzano et al., 2020; Willis & Birks, 2006).

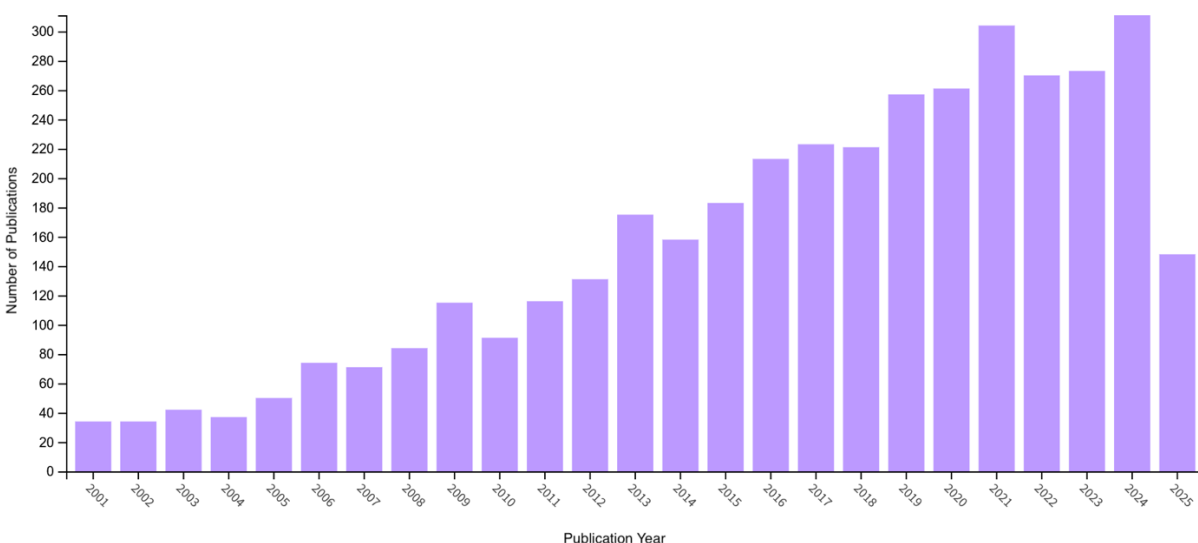


Figure 1 Clarivate Web of Knowledge search results (June 2025) for the query¹: *TS=((paleo* OR palaeo*) AND (*ecology OR *biology OR ecolog* OR biolog*)) AND (conserv* OR restor* OR manag*))* which yielded a total of 3,371 documents.

¹ This query was implemented by Groff et al. (2023) as the first step in their analysis of the studies themselves.

A small, but growing, number of studies have begun to acknowledge the complexity of realizing policy-relevance for LTEC (Davies et al., 2014; Durham & Dietl, 2015; Groff et al., 2023; Siggery et al., 2023), however, these studies generally do not consider the various forms of political and economic power exercised through resource management and governance (Agrawal, 2005), nor the nuances of variety and character of projects and viewpoints that are encompassed in ecosystem management (Buckles, 1999; Colavito, 2017; Keane et al., 2009).

With this study, I have two broad goals which address the little-understood relationship between LTEC and ecological management. First, I aim to provide guidance to the LTEC community for future efforts in framing LTEC data (proxy data from natural archives, as opposed to modern instrumental records) for use by agencies and organizations actively engaged in managing landscapes. Second, I aim to provide these same land and resource management science professionals with tools to access long-term perspectives on the management issues they face. Linking these goals is an imperative to invoke the processes of knowledge (re)production within this community of practice and how those processes are directed by the execution of political and economic power.

To advance the understanding of social and political implications of seeking relevance within ecosystem management, I assess the case of the Northwest Forest Plan (NWFP), a highly contentious and well-studied example of large-scale forest planning and restoration in the Pacific Northwest of the United States. I recruited and interviewed participants with expert knowledge of the NWFP and the forest resource management community of practice to gain greater insight into the utility of historical information in planning for resilience and climate impacts. Additionally, I analyzed documents associated with the NWFP science base and guidance for future revisions of land management plans of the USFS National Forests. The context of United States environmental

and natural resource policy and legal frameworks are well represented by the NWFP, as are spatial and ecological ambitions of ecosystem management to use scientific management as the basis for establishing resilient, sustainable relationships between human societies and natural environment. For context, I review the NWFP and its history below.

2.1.1 Northwest Forest Plan

The NWFP was crafted in response to concerns over the balance between conservation of biological resources and the provision of economic benefits from forest resources in the Pacific Northwest (PNW). Beginning in the late 1980's, tension over the biological consequences of the timber industry's high rate of harvest came to a head in 1990, when the Northern spotted owl was listed as threatened under the Endangered Species Act (ESA). The listing of this owl species led shortly to an injunction halting timber harvests on federal land in the range of the owl by Federal District Court Judge William Dwyer (Dietrich & Schaeffer, 1991). This culmination of what became known colloquially as the Timber Wars (Bari, 1990) followed more than a decade of protests and lawsuits pitting 'owls against jobs.'

Against this backdrop, the Clinton Administration was interested in making environmental issues a key component of their policy agenda, and President Clinton called the Forest Summit in 1993 in Portland, OR to address the problem of social and environmental needs in PNW forests. At this summit the President and his cabinet laid out a set of priorities and criteria which guided the development of the NWFP. The Forest Summit initiated a process of evaluation and science synthesis by the Forest Ecosystem Management Assessment Team (FEMAT). The FEMAT report, based on its predecessor the Scientific Analysis Team (SAT; Thomas et al., 1993), made recommendations for a science-based plan for forest management into the future that would be

equitable and environmentally responsible.

The requirements laid out by the Clinton Administration applied first to the federally managed habitat of the Northern spotted owl where the policy was required to (1) consider human and economic dimensions of the problem; (2) protect the long-term health of forests, wildlife, and waterways; (3) be scientifically sound, ecologically credible, and legally responsible; (4) produce a predictable and sustainable level of timber sales and nontimber resources that would not degrade the environment; and (5) emphasize collaboration among the federal agencies responsible for management of these lands (FEMAT, 1993). In recognition of the complexity of forest ecology, the guidance that came out of the Forest Summit attempted to address additional management issues related to the marbled murrelet and several species of salmon. Clinton's mandate thus applied more broadly to federal forests as ecological systems. To achieve these goals, the FEMAT was tasked to outline an ecosystem-based management strategy, rather than a species-centered approach. Thus, in addition to providing for the Northern spotted owl, the policy was also required to (1) maintain and restore habitat conditions to support all viable populations, well-distributed across current ranges, of all species known or reasonably expected to be associated with old-growth habitat conditions; (2) maintain and/or restore spawning and rearing habitat to support recovery and maintenance of viable populations of anadromous fish species and other fish species considered "sensitive" or "at risk" on federal lands; and (3) maintain or create a connected, interactive, old-growth forest ecosystem on federal lands (Thomas et al., 2006).

Fundamentally, the problem that the Clinton Administration attempted to solve with the NWFP was an impasse with respect to federal forest management in the range of the Northern spotted owl. The divisiveness of the Timber Wars made PNW forest management an issue of national attention as environmental advocates and loggers clashed violently (Bari, 1990). Blame on

the side of the forest products industry, fueled by media attraction (Liebler & Bendix, 1996), was targeted at the environmental movement, although decline in timber production has since been attributed to causes other than the ESA listings. In particular, the boom-bust cycle of global forest products economies and changes in demand for and supply of PNW timber are also prominent factors (Thomas et al., 2006; Warf, 1988b).

The cessation of federal timber harvest in 1991 was, however, a sudden and difficult reality for many timber-dependent communities already strained by changes in the timber industry involving advances in technology which reduced the need for labor (Lansing, 2005). With Justice Dwyer's injunction stalling harvests indefinitely, this problem was in part fueled by a lack of consensus surrounding the ecology of these species. This problem was in part addressed by the formation of FEMAT, and has been further remedied by the monitoring programs required by the NWFP (Thomas et al., 2006).

The complexity of this problem and its intractability required a new policy because existing governance systems and strategies were unable to adequately deal with the problem of conflicting priorities and policies. The ESA and National Forest Management Act (NFMA) of 1976 'viability clause' mandates to maintain and protect species were in direct opposition to the multiple-use mandates of the Bureau of Land Management (BLM) and United States Forest Service (USFS). These organizations had supplied as much as 50% of timber harvest in the post-World War II period according to records from Western Oregon (Andrews & Kutara, 2005). The conflicts between the institutional mandates of the USFS and BLM and the requirements of federal policy meant that intervention was necessary.

An additional factor, suggesting the need for new policy to address the issues facing federal forest managers in the early 1990's, was the potential for multiple additional listings and the

associated uncertainty. The ecosystem-based approach of the NWFP is a direct result of the complexity of providing for the listed owl species while also being cognizant of marbled murrelet, salmon species needs laid out in the Aquatic Conservation Strategy (AQS) of the ROD, and the Survey and Manage mandate (Thomas et al., 2006). Complex ownership mosaics and multispecies conservation interactions have been some of the most difficult issues for the ESA to address effectively. Traditional listing and recovery plans do not suit many social and ecological contexts (Scarlett, 2010), further supporting the need for innovative policy tools to address this shortcoming of the ESA (Bosworth & Brown, 2007; Christensen et al., 1996).

Covering over 24 million acres of public land in Washington, Oregon and California, the NWFP is one of the single most comprehensive ecosystem management policies ever written and implemented. Division of the federal estate in the affected area into different zones according to its varying ecological properties is a primary function of the NWFP. The percentages of the NWFP land area allocated to land-uses can change over time and can be summarized into two categories: reserves (~77%) and managed forest (~23%). Reserves are further subdivided into congressionally reserved areas/administratively withdrawn areas with prior protection to the NWFP; late-successional reserves set aside as owl habitat; and riparian reserves, which are designated to provide water quality protections for the watershed health goals of the NWFP. The managed portions are divided into managed late-successional reserves to buffer owl habitat; adaptive management areas that can be flexibly allocated year-by-year experimentally; and matrix, which provides most potential harvest annually.

The other key component of the NWFP is the Survey and Manage mandate: the ecological management function of the plan requiring an additional 404 species and 4 invertebrate taxa to be monitored and managed. Under the Record of Decision (United States

Department of Agriculture & United States Department of the Interior, 1994), monitoring trends in NWFP forest and surrounding communities has been one of the most prominent ongoing activities for participating institutions. Common monitoring protocols for Northern spotted owl population and habitat, late-successional extent, watershed condition (according to the AQS), marbled murrelet population, socioeconomic trends, and tribal-federal collaborations have been conducted at 10, 15, 20 and 25 years from the inception of the plan. This monitoring protocol has been modified in small respects, but effort has been made to maintain comparability between monitoring periods.

The NWFP is fundamentally a conservation strategy, but it does include provisions for the sustained yield of economic and social benefits of federal forests to support timber-dependent communities (Charnley et al., 2006). According to the ROD, the maximum amount of timber that can be offered for sale is set at 6.4 million m³/year (United States Department of Agriculture & United States Department of the Interior, 1994). For the first 5 years of the plan, the Northwest Economic Adjustment Initiative (NEAI) funneled ~\$1 billion into economic development in the NWFP region to offset costs associated with reduced harvest (United States Department of the Interior & United States Department of Agriculture, 1994).

The primary benefits associated with the NWFP have been in slowing the decline of Northern spotted owl populations and habitat (Davis et al., 2017), and improvements in watershed condition over the period of the plan (Lanigan, 2015). Benefits during the implementation of the NWFP have also likely accrued to recreation industries in the NWFP planning area, although data is not sufficient to attribute causality to the NWFP (Grinspoon et al., 2016).

Benefits in terms of avoided habitat loss and improved watershed condition scores are not straightforward, complicated by patterns of natural forest disturbance and the regrowth of previously harvested land. With respect to nesting and roosting habitat, this benefit metric has declined over the period of the NWFP. The decline in habitat can be attributed primarily to wildfire, which has occurred roughly at the rate planned for in the ROD ($\sim 2.5\%$ /decade), although at higher rates (3.9-7.4%/decade) in drier parts of the NWFP range than expected (Davis et al., 2017). Net losses of the late-successional forest type needed for owl nesting and roosting on federal lands during the first two decades of the NWFP was $\sim 1.5\%$. This net loss was small compared to gross losses of 7.2% over the same period offset by gains from regrowth, especially in Siuslaw National Forest of Oregon. Regrowth to late-successional class should increase in the coming decades.

Watershed condition scores improved over the first two decades of NWFP. Sampled watersheds in the planning area with at least 25% USFS or BLM jurisdiction $\sim 70\%$ improved over the first 15 years of NWFP (Lanigan, 2015). These estimates have been revised down for the 20-year monitoring results, but there is still a statistically significant increase in watershed condition scores (Miller et al., 2017). This increase in condition scores across the planning area are in spite of large decreases in certain watersheds that experienced large, severe wildfires in Washington, Oregon and California. Like the Northern spotted owl habitat measurements over the same time-period, these gains are important because of the relatively short time scale for forest recovery and the fact that they are offset by predicted levels of forest disturbance.

The most important costs have been to timber-dependent communities in the plan area, however these are also very difficult to isolate from larger economic and geopolitical trends. As originally conceived in the ROD, the NWFP would have resulted in a 75% reduction in the

annual harvest on the federal lands administered under the plan, from over 4.5 billion board feet (bbf) to 1.1 bbf (Burns et al., 2011). There have also been direct financial burdens from monitoring and restoration, which amounted to \$50 million and \$90 million respectively in the first 10 years of the NWFP (Davis, 2017; Haynes et al., 2006). The reduction in harvest has resulted in numerous secondary costs, most related to employment.

Secondary costs associated with the plan, which are more difficult to tease apart in practice, are the reduction in employment in forest products industries and federal agencies and the reduction in income from forest related employment (Grinspoon et al., 2016). Region 6 (Oregon and Washington) Forest Service employment has had the most substantial reductions falling from 5700 employees in 1993 to 2300 employees in 2012. Interestingly, BLM and Region 5 (California) employment did not fall in the same way, suggesting uneven processes or staffing priorities.

Non-federal employment has also been heavily impacted over the decades since NWFP began. As many as 50,000 timber-related jobs were lost and 261 mills closed in the PNW from the peak in the 1970s and 80s (Burns et al., 2011). How much of this loss is attributable to the NWFP is difficult to assess, however the trend in declining employment has persisted since NWFP from over 100,000 in 2001 to ~65,000 in 2012 (Grinspoon et al., 2016). Over this same time-period timber harvests declined on non-federal lands, while federal harvest has increased slightly. Although federal harvest increases recently have not been sufficient to offset reductions in non-federal harvest, the overall decline in non-federal harvest calls into question a regulatory cause for this long-term decrease and suggests external pressure is playing a role in this outcome.

Despite relatively stable roosting/nesting habitat, Northern spotted owl populations have declined since 1994. This is in part due to unforeseen factors, perhaps most significantly, the in-

migration and proliferation of barred owls, a successful competitor with spotted owls. This decline has been substantial (3.9% since 1985) as monitored at 9 forest areas throughout the range (Dugger et al., 2016). A declining trend in was expected in the ROD to continue for several years as habitat recovered throughout the range, however slowing ameliorating declines over the NWFP period reversed between 2008 and 2013. The success of barred owl removal experiments in fostering Northern spotted owl population growth suggest that barred owls are the primary factor, and that continued declines are likely in the absence of further mitigation.

A similar story characterizes the marbled murrelet conservation efforts, which focus on habitat as a means of encouraging population regeneration. Habitat loss from fire and timber harvest on non-federal land accompanied decreased populations in Washington by 4.6%, although populations in Oregon and California showed no significant trend (Falxa & Raphael, 2016). Due to its ecology, the murrelet relies not only on large stands of old trees within 35 miles of the coast, but also on abundant prey fish such as Pacific herring. Comparison of terrestrial and oceanic factors suggest that the conservation of habitat alone will not always produce positive outcomes for the murrelet as low prey availability may still lead to mortality of young birds in the nest.

Another unanticipated issue has arisen around differences in predicted saleable quantity (PSQ) of lumber on federal land and the amount offered for sale. The federal harvest since NWFP implementation has rarely met the quotas set out in the ROD, or about 1.1 bbf (Burns et al., 2011; Grinspoon et al., 2016). This is largely a result of ongoing litigation of proposed sales with perceived adverse consequences for listed species or those in the Survey and Manage protocols, or for the watershed goals of the ROD. The structure of the NWFP has been blamed for this problem, because the complexity of its ecosystem-based management strategy allows so

many potential legal arguments to stall timber sales in court (Grinspoon et al., 2016). As a result, the amount of timber sold has been <40% of the 1.1 bbf per year allowed under the NWFP, eroding already tenuous relationships with the timber industry.

Lastly, several of the economic and social effects had disproportionate effects on the least well represented communities in the region. Although reductions in federal employment have direct effects on communities that rely on those jobs, diminished presence of federal agencies in rural areas has likely exacerbated this effect. Agency offices in the most remote areas closed due to employment reductions leading to reduced access of community members to agency staff, which has implications for community dynamics outside of the direct financial burden. Another similar effect was observed in the mitigation program of the NWFP, the NEAI. Through this program, funding was dispersed more to communities with better resources for organizing applications and understand the requirements of the program (Christensen et al., 1999).

The command-and-control tactics of the NWFP, which have characterized much of the forest policy in the era of environmental laws (i.e. ESA, NFMA), are coming under fire for neglecting local knowledge and social capital resources as well as failing to meet the needs of conservation and development (Bosworth & Brown, 2007). Community-based forestry offers a different paradigm for managing forest resources which emphasizes the ability of local to regional bottom-up organization rather than the top-down approach of most US federal forest policy. In the PNW, substantial obstacles in the form of residual resentment and ideological alignment along pro-environmental and pro-industry lines will make community-based approaches difficult for the foreseeable future. In his examination of forest policy in the region, (Winkel, 2014) found that collaboration is “mostly assessed strategically by different interest groups, and only supported to the degree that it may help to achieve distinct ideological goals and interests” (93).

This suggests that although (Bosworth & Brown, 2007) claim the timber wars have ended, there is still much to be done to mend the rifts torn by this conflict. This may also be a critical step to foster the social learning necessary for collaboration to succeed (Schusler et al., 2003) as there is evidence of widespread, deep-seated disagreement about what goals are important and worth pursuing on public land.

2.1.2 Historic Range of Variation (HRV)

A key heuristic which I employ is the historic range of variability (HRV).² The concept was developed and described in the 1990's (Keane et al., 2009) and became interwoven with the practice of environmental policy set out in the 2012 Planning Rule and the Omnibus Public Lands Management Act of 2009. Its inclusion as a requirement of National Environmental Policy Act (NEPA) documents, specifically environmental impact statements (EIS) and environmental assessment (EA) as a component of the 'best available science' has ensured the continued use of the term (Egan & Dubay, 2013), despite the problematic nature of HRV in practice (Keane et al., 2009).

2.2 Methods

The overarching framework of this study is what Baxter (2016) calls a cross-sectional, theory-generating case study. This format is suitable for this research topic in that little work has been done to address the issue of knowledge exchange between LTEC science and land management, thus developing an in-depth case is required describing the challenges of epistemology that may exist between short term ecosystem management goals and long-term patterns. This format is widely accepted in planning literature as well (Eisenhardt & Graebner,

² Also called historic range of variation, natural range of variation/variability and past range of variation/variability.

2007). For practical reasons of research feasibility, a single point in time is necessary, although proposed archival research will elucidate the history of management strategies and situate the current management context within a historical point of view. A similar set of epistemic concerns lead (Manring, 1993) to choose Grounded Theory (Strauss & Corbin, 1997). My methodology differs from this template but emphasize the bottom-up approach to generating theory about how LTEC relates to ecosystem management. In common with Grounded Theory, I begin by identifying core theoretical categories to guide data collection and analysis (Hallberg, 2006). Initial categories for this research include key elements of LTEC (Seddon et al., 2014a) and natural resource planning: climate change and ecological resilience as applied to HRV.

2.2.1 Data Sources

The data I analyzed fall into two general sources of information: first, a series of interviews with land management scientists; and second, analysis of resource management planning documents and documents identified by interview participants. The research plan was evaluated by the University of Oregon's Research Compliance Services filed as Institutional Review Board (IRB) submission 06202019.035.

I conducted interviews beginning in Summer 2019 and continuing through Spring 2021. The final sample included a total of 7 participants. I used a snowball sampling approach to recruit participants from land management science communities beginning with Federal regional ecologists in Region 6 (Oregon and Washington), researchers at the Pacific Northwest Research Station, and staff ecologists at the Nature Conservancy. I restricted participants to professionals with ecological training and research or science synthesis and communication roles. My interviews follow a semi-structured format (Baxter, 2016) to match the theory-generating approach – a

common methodological choice for addressing questions of social process within organizations (Dutterer, 2016; Manring, 1993; White et al., 2008a). To initially frame both the participant data and analysis of texts, prompts revolved around the following (and see Appendix I for the complete interview guide):

1. In what ways do long-term perspectives pertain to land and resource management issues facing local, regional, and national organizations?
2. When management plans are being written, who contributes to the pool of scientific knowledge considered, how is that knowledge integrated, by whom and how are different priorities balanced?
 - Sub question: how are long-term perspectives represented in these decision processes?
3. Can long-term perspectives be retooled and reframed to better address the existing challenges of land management groups?

Interviews were transcribed, coded and analyzed with the context of job position and geographic duty of the participant, however all reference to administrative unit and organization was removed prior to reporting. Transcripts were analyzed for reference and allusion to core categories³, and these references used to derive secondary categories which emerged from comparison (Hallberg, 2006). I identified secondary categories from the participant responses, coding common ideas expressed by multiple participants and assigned category names

³ These categories of meaning were defined a priori by the research questions. These constitute assumptions about important concepts within the participants' community of practice given my positionality as a natural scientist and initial research regarding the nature of the community's work and its lexicon.

corresponding to their content. These secondary categories were then assessed to identify the nature of associated meanings across participants. Finally, secondary categories were cross-referenced to determine the relationships between these categories and to construct theory concerning their underlying themes (Strauss & Corbin, 1997). With these tertiary arrangements, or closely and repeatedly associated secondary categories, I assessed the relational meaning of the secondary categories and connect these categorized responses to the broader context of work in natural resources management within the NWFP.

Analysis of documents followed interviews, with document selection primarily identified by association with the NWFP planning and evaluation process, and the forthcoming revision of National Forest Land and Resource Management Plans. All documents used in this analysis were publicly available and none contained private, identifiable information about the participants. The primary texts are the Synthesis of Science to Inform Land Management within the Northwest Forest Plan (Spies et al., 2018), the Synthesis hereafter; and the Bioregional Assessment of Northwest Forests (Casamassa, 2020), the Assessment hereafter. The Synthesis and the Assessment are key documents to this analysis due to the role they play in the revision to the NWFP and the forthcoming revisions to all 19 National Forest Land Management Plans. The Synthesis is an authoritative statement of the science considered relevant to ecosystem management in the Pacific Northwest. The Synthesis is collection and integration of more than 4000 peer-review publications covers a wide range topics ranging from old growth ecology, species of concern to the NWFP, and socioecological contexts and consequences. It was compiled by 50 expert authors in the various subject areas, included submissions of relevant sources through public comment and was externally reviewed by the Ecological Society of America. The Assessment, in contrast, is a high-level guidance document for National Forest administrators to

communicate their common goals for resource management plan revision scheduled for the coming decade. Certain additional documents identified by participants and through antecedent literature review are described as they provide additional context in the Discussion below.

I surveyed these key documents for reference to LTEC research and evaluate context of these references. I focused the analysis of documents through the lens of core categories used to evaluate interviews. HRV, resilience, and climate change were key terms to analyze reciprocally with interview content to link lines of evidence and determine differences and similarities between the written narrative of resource management logics and motivations and the embodied testimony of individuals within the resource management community of practice.

2.3 Results

Interviews with participants ranged from 38 to 65 minutes, and the sample of participants included primarily current employees of the US Forest Service, and a single representative of the Nature Conservancy at the time these data were collected. Participants represented a wide range of position descriptions including administrative, operations, planning and research; and diverse areas of focus such as wildlife habitat, fire and fuels, plant ecology, and silviculture. Duty area geography both present and past varied widely as well, covering an area from Shasta-Trinity National Forest in northern California to Fremont-Winema National Forest in south-central Oregon, Siuslaw National Forest in the Oregon Coast Range, and Okanogan-Wenatchee National Forest in Washington. Most participants had held multiple positions within the USFS and had duty histories ranging from 5 to over 25 years. Some participants had previously worked for other agencies (e.g. Bureau of Land Management, US Fish and Wildlife Service), and three held doctorates in natural sciences. Four of the participants identified part of their work as currently

involving the active creation of knowledge to support decision-making guided by the internal priorities of their respective organizations.

Participants' areas of focus were far less isolated than position titles, and most had experience working with more than one program within their respective job histories. Each participant had worked on, sat in with or reviewed the work of interdisciplinary teams (IDTs) responsible for assembling pre-NEPA environmental assessments (EA) and environmental impact statements (EIS).

2.3.1 Participant Interviews: Emergent Themes

Core categories of historical perspectives, resilience and climate change were well understood by all participants and frequently required no elicitation. Each category was produced and represented in each conversation sometimes within a single prompt. The core group yielded secondary categories which I identified as 1) Novelty, 2) Urgency, 3) Opposing Priorities, 4) Economic Imperative, 5) Cultural Knowledge, and 6) Resilience/Ecosystem State.

In this analysis, I defined Novelty as references to current or future social and ecological conditions that are different from what we know from past observations or history. This theme emerged alongside multiple core categories from each participant and frequently resulted from discussion of each core category. The subject varied widely, although the most common attribute was connection to changing climatic conditions or the effects of human management and interference with 'natural' processes. Generally, this was expressed by participants with concern and the sense that unknown future conditions and unprecedented patterns in existence today were presenting management of natural resources with an increasingly difficult set of circumstances within which constituent organizational practice operates.

Urgency was mainly shown in three different ways about what knowledge is most needed. I defined these as Lack of Knowledge, a Research-Application Gap, and Science of Necessity. Participants expressed urgency as Lack of Knowledge according to multiple features of their work, but frequently as it related to historical conditions and processes, and the ‘appropriateness’ of past conditions as benchmarks. Examples were topics such as drivers of forest structure as it pertains to the provision of habitat and the relationships between non-forest and forest states under varying levels of fire activity. The concept of a Research-Application Gap was closely related permutation of Urgency. This idea was expressed by three of the participants in different contexts, but the common underlying theme of a disconnect between the wider research community and the needs, priorities and understandings of natural resource practitioners was consistent. Science of Necessity, closely related to the Research-Application Gap, was expressed as the need for clearly defined benchmarks that could be applied at a range of scales from the stand, to the watershed, to the landscape. Urgency was broad, but confined to the provision of information, and it was characterized by both discomfort and optimism.

Opposing Priorities was the single most common theme, and this category exhibited several permutations, or non-inclusive sub-categories, as well. I broadly define this category as reference to contestations of knowledge or action. The sub-categories were variously: Differing Opinion – Individual Opinion and Geographic Difference. The common thread united these concepts is that multiple viewpoints, knowledge systems, capacities, spatial and temporal scales, and priorities are consistently in operation during both the routine planning processes and accumulation of information to justify any set of prescriptions or actions.

The Economic Imperative manifested in a relatively narrow set of concepts but was also ubiquitous in the testimony of participants. This category was closely associated with discussion of

roles and responsibilities and emphasized in relation to emergent hazards associated with wildfire. Fundamentally, it was expressed most frequently in relation to efficiency, limited time and personnel, and the priority of meeting project timelines. Challenges of proactively addressing common threats across the duty geographies while maintaining abilities, personnel and infrastructure to meet emergency situations with swift action was a common theme.

In the context of this analysis, I define Cultural Knowledge broadly as an implicit set of understandings which characterize the communities of practice of my participants in professional networks, duty stations, training programs or other communal traditions. A unique case which emerged in conversation with several participants was traditional ecological knowledge (TEK). TEK is a complex subject in its own right, and in this context it was referred to in the ‘knowledge mobilization’ form described by Whyte (2013). One of the participants is an enrolled member of a sovereign tribal nation, while several other participants discussed aspects of TEK, particularly cultural burning. Thus, the category of Cultural Knowledge as I interpret it was reference to institutional knowledge and professional network knowledge-base only. In this case, Cultural Knowledge includes TEK both as it has been interpreted by the ecosystem management community primarily as an adaptive management strategy (e.g. Berkes et al., 2000) but also as lived experience of one participant.

Although the concept of resilience was in the core categories, I assigned it to a secondary category as well. Additional context for the notion of resilience was provided in its relationship to ecosystem state, and particularly ‘desired future condition’ as a technical heuristic device employed in EIS preparation. Broadly, I associate this dualistic concept of Resilience/Ecosystem State with the topologies of historical reference and change through time. Participants descriptions of the fluidity of natural processes and ecological conditions at points in time (present, past, and

near future) characterize this category.

Table 1 Categories of thematic content in interviews with participants. Core Categories were the initial conceptual framework for both data collection and analysis. Secondary Categories are the concepts developed within this analysis and are defined in the text. Two of the Secondary Categories are further divided into Sub-Categories that contain nuances which differentiate them, while still closely associated by conceptual content of their parent Secondary Category.

Core Categories	Secondary Categories	Sub-Categories
Historic Range of Variability	Novelty	
Ecological Resilience	Urgency	Lack of information, Research-Application Gap, Science of Necessity
Climate Change Impacts	Opposing Priorities	Differing Opinion - Individual Opinion, Geographic Difference
	Economic Imperative	
	Cultural Knowledge	
	Resilience/Ecosystem State	

2.3.2 Participant interviews: Relational Thematic Analysis

Several notable relationships between secondary categories emerged from identifying them in context. The most common tertiary arrangements are described here.

Novelty was most closely linked with Opposing Priorities, Resilience/Ecosystem State, and Cultural Knowledge; but occurred in relation to all secondary categories, sometimes in complex arrangements. As a set of boundary-spanning technical and social challenges, Novelty both exacerbates the effect of Opposing Priorities and conversely pushes through the milieu of perspectives and priorities to a point of unifying behind the negotiated manifestation of best available information, which I construe as Cultural Knowledge. While several participants alluded to maintaining an active awareness of new and emerging trends in relevant literature and the wider research community, reliance on internal organizational processes, precedent and established or routinized prescriptions was linked repeatedly to the concept of Novelty. This was particularly evident in the context of diverging opinions from different focus area programs or external review by engaged publics or the chain of command. Novelty was frequently referenced with respect to Resilience/Ecosystem State, as defined through HRV, monitoring, and vulnerability assessment modeling exercises.

The category of Opposing Priorities and its sub-categories, except for Geographic Difference, were most closely linked across all participant testimonies with Urgency. Lack of Knowledge was the single most closely linked sub-category occurring in relation to both Opposing Priorities and Differing Opinion – Individual Opinion, as a special case. Urgency, in general, was apparent as a resolving influence where priorities were in conflict. This trend held across the Lack of Information sub-category: when and where the perceived and acknowledged opposition of different priorities exists, critical lack of understanding about how ecological or social patterns are interacting mediates divisions.

Urgency, and particularly the Lack of Knowledge sub-category, was most frequently associated with the category of Cultural Knowledge. This theme was nearly ubiquitous as imperfect knowledge and pressing need emphasized reliance upon the established understandings held in common within each participants' professional network, epistemic frame and worldview. Urgency was also expressed frequently with respect to Resilience/Ecosystem State, both as Lack of Knowledge and Research/Application Gap. Multiple participants indicated a belief that there might be more information available, but that it was not adequately integrated into the forms that could be brought effectively into planning, prescription and implementation. The resulting oversimplification of ecological processes and conditions as spatial and temporal ranges of variation is adaptive rather than ideal.

The category of Economic Imperative was connected in context with more other categories than any other excepting Novelty. The strongest connection, however, was to Urgency expressed as Science of Necessity – particularly with respect to the flow of information regarding Resilience/Ecosystem State. The consistent underlying theme of limited resources – time, personnel, and budget – to meet the demands of policy requirements was emphasized as pressure

to produce results with the best available information in the clearest, most defensible manner possible. Multiple participants expressed this theme with respect to breadth of position duties and or geographical duty areas, contextualizing the challenge of accumulating relevant information in a timely fashion across geographies with vastly different social, ecological and economic realities.

2.3.3 Published Texts

LTEC research is well represented in certain chapters of the Synthesis (Spies et al., 2018), with references and discussion closely related to two of the core categories initially used in participant interview analysis: HRV and climate change (Table 1). Chapters where references are common and play pivotal roles in framing of content are Chapter 2 - Climate Change, Disturbance, and Vulnerability to Vegetation Change; and Chapter 3 - Old Growth, Disturbance, Forest Succession and Management. Minor, single references to LTEC are present in Chapter 7 – The Aquatic Conservation Strategy and in Chapter 11 - Tribal Ecocultural Resources and Engagement. A notable fact regarding Chapter 3 particularly, and the Synthesis as a whole, is the presence of an LTEC researcher in the author list.

The scope of references to LTEC varied in depth and geographic scope considerably, with particular emphasis on insights from the southern range of the NWFP: the Klamath Mountains, the Willamette Valley and the Oregon Coast Range. With respect to climates of the past (Synthesis, Chapter 2), the authors assess a range of studies from the Olympic Peninsula to the Klamath Mountains. These references establish the millennial scale shifts in vegetation and fire as tightly coupled to the large fluctuations in climate since the Last Glacial Maximum (LGM) and furthermore note the geographic differences in these trends over time. However, LTEC studies do not become integrated into discussion of fire history, disturbance regimes, vulnerabilities of

vegetation to change or current and projected climate change. Little connection to core categories is evident, with the exception of climate change. Core categories are however present throughout the chapter and in the research gaps and management implications identified in the concluding material.

With respect to vegetation communities and old growth forests of the NWFP (Synthesis, Chapter 3), LTEC references are again represented, and with a broader range of integration. Fire regimes of the present were defined in reference to the Holocene record, and substantial effort to frame HRV of forest succession and landscape dynamics in terms of the LTEC perspective is evident. Geographic nuances in the pre-Euro-American settlement landscapes of the NWFP are addressed, with certain emphasis on the southern portion of the planning area. The authors also explicitly note that “mimicking historical conditions is not an end in itself, but is a means of accomplishing objectives (e.g., resilience to fire), and therefore appropriate only when it meets those objectives,” and that “past conditions may not fully reflect future climate-vegetation-disturbance-topography linkages as a result of pervasive climate and land-use changes” (Synthesis, p. 145-146).

Additional reference to LTEC regarding restoration and conservation again highlights the link with HRV as a conceptual framework (Synthesis, p. 143-144). In this context, the LTEC contributions to historical understandings of vegetation and fire are closely linked with the core category of resilience, but partly in opposition. Historical ecology – with LTEC as a component of this knowledge system – although potentially useful where it aligns with management goals, may not suit the spatial scales of management needs and the direction of change.

The Assessment (Casamassa, 2020), does not refer to LTEC explicitly although core categories are expressed both explicitly and implicitly. Chapter 2 – Management

Recommendations (Assessment, p. 20) contains the only references to HRV, and these are associated primarily with the concept of resilience, closely linking these core categories in the context of recommendations for National Forest Land Management Plan revisions. The core categories of resilience and climate change are ubiquitous in the report in association with ecosystem states, management challenges, successes in NWFP planning areas and social dimensions of forest management as provision of ecosystem services and cultural value. These concepts cross all topical boundaries within the general approach to forest resource management outlined in this document.

2.4 Discussion

Within the long-term environmental change (LTEC) community of practice there have been increasingly common claims of relevance to policy and decision-making. These claims are most often framed with respect to natural resources such as freshwater availability and biodiversity (Meko & Woodhouse, 2011; Seddon et al., 2014b; Willis, Araújo, et al., 2007). While I suggest these claims represent a promising direction for LTEC, I believe they are largely made without a conceptual, let alone pragmatic, knowledge of how interfacing with the policy and management communities is constrained. As a response to what I perceive as an ‘ontological lack’ on the part of LTEC, I outline three of the most relevant insights from a co-productionist framework as developed from the work of (Jasanoff, 2004). These are 1) There are two distinct strains – realist and constructionist – of theorizing the science-policy interface, which come to very different conclusions about how to best proceed in research; 2) Politics is pervasive at the science-policy interface with profound consequences for the application of science to problems of social impact; 3) Interventions of science in social realms must be scale-aware, suited to the needs of users, and

require substantial time to transcend the imposition of political forces. Before delving into these crucial lessons, I first contextualize the LTEC knowledge claim.

Underlying the claim of LTEC are epistemic and economic considerations which propagate from discourse about the evolving roles of environmental science in society – for example describing complexity in socio-ecological systems, defining the dimensions of global environmental change, and fulfilling the need for multi-, inter-, trans- disciplinary solutions to intractable, ‘wicked’ problems. Epistemic considerations arise from a growing understanding within the academy that traditional science falls short in addressing these and other issues characterizing the Anthropocene (Marshall & Picou, 2008). Economic considerations follow the epistemic, in that funding organizations show preference for questions and approaches with the potential to address those same issues. While taking these considerations seriously has only just begun for LTEC, other segments of the environmental science community have been more engaged in meeting grand challenges that align with this evolving global regime.

In fact, the scale of the response has been massive, mobilizing new scientific agendas (Kates et al., 2001) in unprecedented national and international coordination (Felt et al., 2016; Mauser et al., 2013). In tandem with these large institutional and academic efforts, calls for science to attend to its social dimensions – to increase its salience, credibility and legitimacy (Cash et al., 2003). Recently this call is framed as a response to the perceived shortcomings of science produced in the new global regime to adequately address with the express goal of augmenting the usability of science (Dilling & Lemos, 2011) particularly by reconciling the demand for and supply of science (Sarewitz & Pielke, 2007). However, critique of primarily Western-institutional solutions originating from the constructionist domain of social science in general, and of Science and Technology Studies (STS) in particular, hold these intellectual projects to task. This is the first of

three relevant insights for an LTEC intervention with respect to natural resource sustainability: there is not a single story of how to proceed, but instead a nuanced dialectic made up of realist and constructionist viewpoints. Most importantly perhaps, realist conceptions of the world should not be given preference and can be seen as having deep-seated limitations with respect to making “sense of the untidy, uneven processes through which the production of science and technology becomes entangled with social norms and hierarchies” (Jasanoff, 2004).

The tension within STS between realist and constructionist perspectives describes an important set of considerations for LTEC, because the realist strain might be the most inherently accessible from the ontology of a Western positivist science. Due to ontological similarity, it could appear to be easier, or even advisable, to maintain an arms-length approach to the social and political dimensions of more applied areas of research such as resource management and sustainability. Notably, the epistemological push-pull in STS is mirrored in concerns within the ecological sciences over the existential threats posed by engagement with politics through advocacy (Pielke, 2004; Wilhere, 2012). Given this political reality there may be substantial incentive for researchers in LTEC and elsewhere to prioritize approaches that purport to map out the science-policy interface (Cash et al., 2003; White et al., 2008b). However, new and emerging lines evidence in the constructionist vein emphasize the highly contextual nature of science-policy interfaces. With respect to complex socio-environmental issues such as climate change adaptation, efforts to smooth out the integration of knowledges may inadvertently “restrict...alternative and experimental ways of understanding and adapting [to climate change]” (Klenk & Meehan, 2015b). This emerging understanding of how science and science producers (scientists) interact with science users begins to render a very different picture of the science-policy interface, and one that I will argue is particularly relevant to LTEC knowledge claims.

I aim to situate the knowledge-claim of LTEC science in relation to the co-production idiom (Jasanoff, 2004). At its core “co-production is shorthand for the proposition that the ways in which we know and represent the world (both nature and society) are inseparable from the ways in which we choose to live in it.” (Jasanoff, 2004). This simple framing has profound implications for the analysis of the production and circulation of environmental knowledge, and its pervasive attendant responsibilities and contingencies that flow into and from the science-policy interface. I pay particular attention to work that has arisen out of this mode of inquiry around the use of science to inform the management of natural resources (e.g. climate resources, biological resources), but I necessarily highlight work that has centered sciences of climate change. This focus is partly due to the relatively small number of LTEC engagements with STS, although examples do exist (Rice et al., 2009; Schinkel, 2016). In contrast, a long tradition aligned with the co-production idiom deals with the characterization of climate change, and in many respects LTEC is an integral component of climate change research. As such, much can be gained from carefully examining this research for insight into the social processes of circulation and stabilization of ideas about the world.

2.4.1 The LTEC-NWFP Interface: Insights from Interviews and Document Analysis

There are certain parallels between interviews with participants and the published record of information and concepts considered relevant to planning and management in the area of the NWFP. Core categories were common to both lines of evidence, and in the context of the key documents HRV and Climate Change were closely associated with LTEC products in certain frames of reference. These observations support the initial selection of these concepts as the basis for establishing a grounded understanding of the common and divergent themes, approaches,

metrics and logics (Strauss & Corbin, 1997) between LTEC and ecosystem management as represented by the NWFP. At the most basic level, this is confirmation that LTEC is present in the discussion of NWFP natural resource management, yet clear limitations of the application of LTEC insights are evident. From the results of participant interview and document analysis, I identify three themes.

First, LTEC, as understood in the Synthesis is primarily relevant to HRV in the practice of restoration and conservation of ecosystem structure and function. The inclusion of this perspective is remarkable and can be conceived of as the outcome of social processes and knowledge transfer not captured by this analysis, or perhaps the role of a single LTEC actor involved in the writing of the document. Twenty-three studies of LTEC science were included across four chapters of the synthesis, and while this is a small portion of the studies that could be reasonably associated with the NWFP (Figure 2), it is also substantial. Participant interviews verify that these ecosystem states of the past are perceived as resilient, an essential component of the mandate of the 2012 Planning Rule. Furthermore, despite the awareness that each participant expressed of LTEC as a source of information, without exception participants did not have examples of this information being used to help understand HRV in practice. In other words, alignment of LTEC with the HRV concept does not ensure the relevance of LTEC but rather suggests a perceived alliance between LTEC and the environmentalist agenda that emphasizes restoration and conservation.

Second, participants did, however, frequently express urgent need (Urgency – Lack of Information) for information leading to a greater understanding of how to create resilience in the context of novel conditions. In the absence of sufficient information about past conditions and what aspects of those ecosystem states could be replicated successfully, participants' tendency was to rely upon internal precedent (Cultural Knowledge) even when it was unsatisfactory. This

observation was particularly strong when stalemate produced by the various program area priorities (fuels, habitat, forest products etc.) or conflicting public comment was present and irresolvable.

Third, the pervasive effects of climate change, land-use, and wildfire as well as the shifting social and institutional landscape were referred to by participants as being far removed from the resilient past. The near-universal perception among my participants, was that external present and future conditions – with climate and human induced change – mediates the applicability of historical reference. This expression of Novelty as anti-historical and as a source of great uncertainty within a system of competing demands and priorities suggests that this is a very strong influence on the ability of LTEC to inform ecosystem management as practiced in the NWFP.

Additionally, participants' view that limited resources were consistently dictating the pace, scale and breadth of information gathering, synthesis and delivery fundamentally underpins all other themes. This observation exceeds the bounds of both the LTEC-NWFP interface and will be addressed further below, however the three themes I identify above situate LTEC as a component of HRV in the context of multiple-use ecosystem management. This is corroborated by my analysis of the Bioregional Assessment. As a high-level guidance statement, the Assessment offers a different view than the Synthesis, which is a starting point for the construction of next generation Land and Resource Management Plans. The Assessment rather is prepared to provide overarching guidance, and the absence of HRV in that framing is significant. A similar simplification is evident in the executive summary of the Synthesis, which also removes most reference to HRV and explicitly considers a shorter climate history of ~1000 years as preceding conditions, rather than a relevant set of observations to better understand resilience.

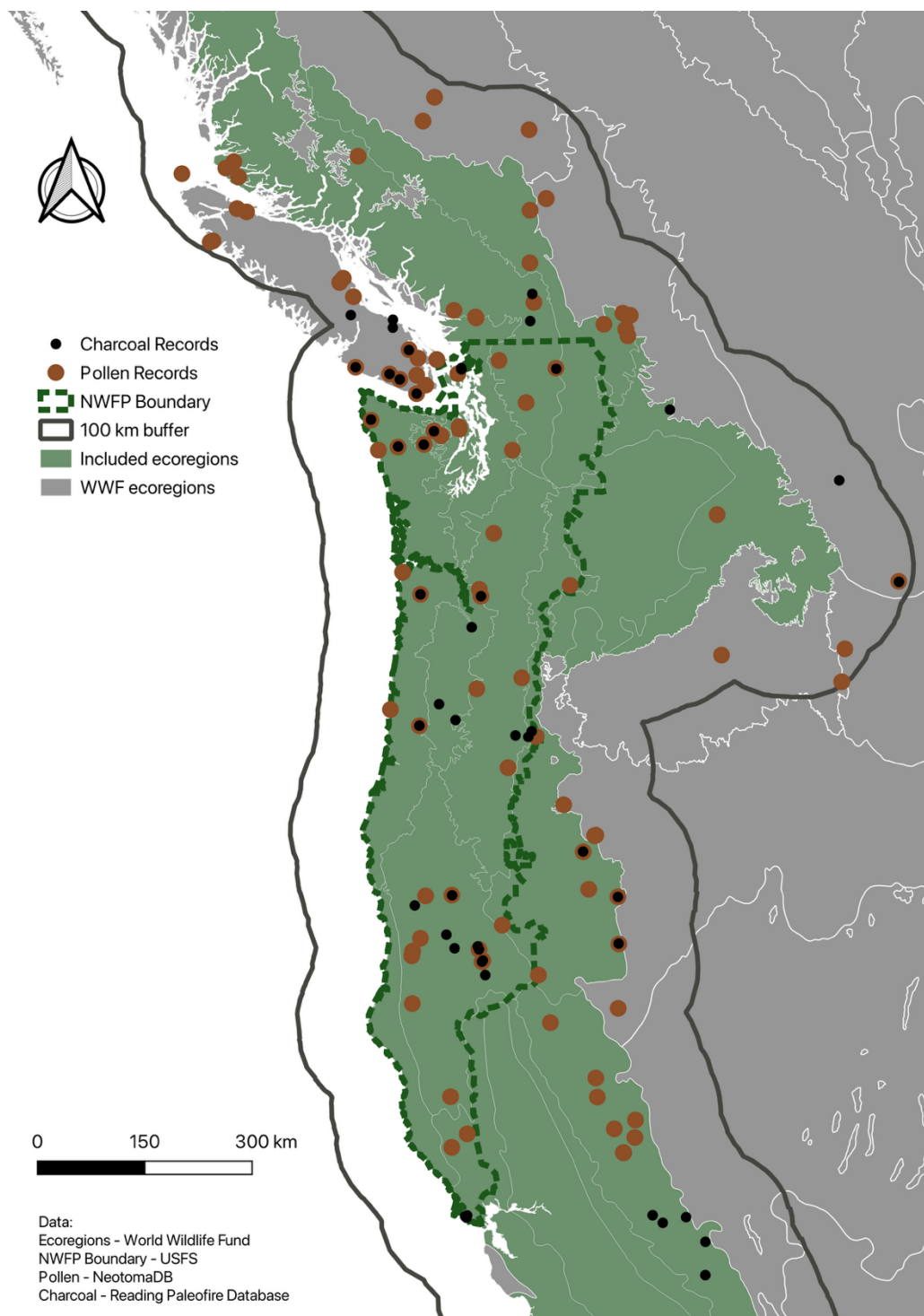


Figure 2 Map of lake sediment-based reconstructions of vegetation (pollen, orange points) and fire (charcoal, black points) located within 100 km of World Wildlife Fund ecoregions (light green) intersecting the boundary of the Northwest Forest Plan (green dashed line). 100 km buffer used to select sites shown as a solid gray line. Pollen reconstruction locations sourced from the Neotoma Paleocology Database (Williams et al., 2018; <https://www.neotomadb.org>) and charcoal reconstruction locations from the Reading Paleofire Database (Harrison et al., 2022; <https://researchdata.reading.ac.uk/319/>).

2.4.2 Political-Institutional Context: Comparison of Cases

The relationships between cultures of knowledge production (e.g. LTEC) and policy enactment (e.g. NWFP), has been the subject of considerable research in the STS traditions, and certain insights derived from investigating the dimensions of these science-policy interfaces are common. Perhaps the key insight from a co-productionist lens is that science is always political. This is certainly not to say that science should be abandoned to politics, rather, the inescapability of the political in the practice, materials and discourses of science is a call to action, or perhaps first, a call to awareness. The political influences are not necessarily benign, but rather than seeing this as a reason to demonize politicization as (Pielke, 2004) suggests, a co-productionist lens implies that there are ways to be scientific that allow scientists to make claims about the way the world is while also being cognizant of the political dimensions of their work. In fact, it has been posited for practitioners of conservation science that adhering to ideologies of value-free objectivity risks obsolescence or, worse, misuse in public debate (Garrard et al., 2016). The take-home for LTEC, as an ecological science, is that critical examination of the political as it pertains to the future directions of its work is overdue.

Thus, toward interpreting the implication of LTEC knowledge claims in the arena of environmental management, a close look at the diverse political contexts of any given project is warranted. While this is most pertinent for the branches of LTEC which claim relevance to applied problems, it may be important to consider in the basic research agenda as well due to the widespread use of LTEC data in climate modeling and the pervasive politics of that practice discussed later.

To illustrate this insight, I draw on work describing the role of science in the understanding of water availability (Kirchhoff et al., 2013; Rayner et al., 2005). Importantly, these examples are

oriented to sub-national scales, at the site of institutions which manage water projects from small regions or metropolitan zones. Due to the relatively large investment in seasonal climate forecasts (SCF) and their supposed policy relevance, these scientific objects and their uptake and use in management have received substantial attention (Dilling & Lemos, 2011; Kirchhoff et al., 2013; Rayner et al., 2005). Initial optimism about the utility of SCF in water resources management was subsequently attenuated by the realization that few water managers were using this data in their day-to-day operations. Rather, Rayner et al. (2005), found institutional politics and particularly a systemic conservatism designed to maintain invisibility of the water sector and resultant disincentives to innovate constituted one of the most prominent obstacles for SCF use.

Trans-national comparison between the US and Brazil (Kirchhoff et al., 2013) suggests that political influences on SCF use interacts with technical and financial capacity, but that political considerations from institutional conservatism again have a substantial effect on use patterns both across spatial and temporal contexts. Interestingly, in both national contexts, the occurrence of political pressure to use novel, innovative sources of information (i.e. SCF), is related to climatic anomalies such as drought or flooding. However, political pressure originating from these events is short-lived in the absence of across national contexts (Kirchhoff et al., 2013). The apparent contradiction between conservatism and upheaval following anomalous conditions, belies an inherent tension in the political dimensions of resource management. Whether, or how well, the insights from climate information use in water management travel to other management contexts, and particularly others that fall within LTEC knowledge claims such as understanding fire regime or change in biodiversity and biogeography, is a subject that should be addressed. However, it seems likely that in any resource management context with political dimensions, politics will have substantial effects on the way that new information or an innovative epistemological approach are

incorporated into existing structures.

2.4.3 Scales/sites of intervention, global narratives, and relevance for LTEC

The political considerations that permeate the site of the water management districts of the US and Brazil have corollaries at all scales, from the individual to the international, and all sides of the science-policy interface (Meehan et al., 2017). For the purpose of informing LTEC efforts to attain relevance at the interfaces of science and policy, it is important to conceive of scale as a social construct (Marston, 2000), rather than an ontologically given spatial reality. Analyzing the performance of science at scale of the individual can uncover the ways in which interpersonal interactions reproduce broader patterns. Importantly, political influence does not stop on the user side described by (Rayner et al., 2005). An example from (Monteiro & Rajão, 2017) describes the experience of remote-sensing labs and their analysts and managers in the deforestation monitoring program of the Brazilian Institute of Space Research (INPE). In this case, national and international politics filtered into the day-to-day operations of classifying land as more or less deforested. National political discourse in the form of ongoing tension over illegal logging and soybean agricultural development transcends the science-policy interface leading to conservatism in the scientists themselves. Meehan et al. (2017) corroborate this claim, suggesting that transdisciplinary research encounters with stakeholders may lead to transformation at the site of the scientist. Crucially, relevance for stakeholders is the product of sufficiently long-term commitment on all sides and acknowledgement of knowledge claims and needs on all sides of science-policy interfaces (Buizer et al., 2011; Klenk et al., 2015; Klenk & Meehan, 2017b). This may be particularly true when national and international politics are in play, through which power dynamics may be exercised intentionally or not.

Importantly, again, these scales, or sites, are not nested in a hierarchy. They exist in different settings, which, though linked, are not influenced in the same dimensions or directions. (Monteiro & Rajão, 2017), for instance, observed the long arm of the Western scientific establishment in the Amazon through Brazilian interests in the Kyoto Protocol. These scalar considerations become even more pertinent for LTEC knowledge claims in light of the global change narrative that has taken over society's imagination of a changing world and environment (Demeritt, 2001; Wynne, 2010). Most importantly, the undeniable role for LTEC in the global climate science project as a source of data for checking global circulation model (GCM) skill (Demeritt, 2001; Masson-Delmotte & Schultz, 2013), should not be considered the sole contribution from this diverse field (Seddon et al., 2014b; Willis & MacDonald, 2011). This is both because of more nuanced abilities of LTEC, and due to the issues inherent in the universalizing narrative of global change prevalent in the international research establishment.

Increasing recognition at the largest levels of global-international organization (Felt et al., 2016; Mauser et al., 2013) that a more engaged form of environmental change science is needed to address concerns related global sustainability have yet to acknowledge the empirical evidence of climate science generation and uptake at the local level (Klenk & Meehan, 2017b; Lahsen & Nobre, 2007). Similarly, the framing of climate change causes and solutions within the narrative of physically-based GCMs constitutes an unjustified assumption that the nuanced, contingent nature of smaller scale understandings is less important than the grand narrative (Demeritt, 2001). Downscaling from global to the regional and local has rightly become a crucial topic in the conception of climate adaptation (Adger et al., 2005), but doing so in terms that are regionally or locally appropriate is crucial and the scale of LTEC may be well suited to this project. The place-based nature of LTEC primary data has appealing qualities regarding the necessarily local and

regional nature of adaptation strategies. However, the placial or regional focus again highlights the politics and power dynamics inherent in science and its engagement with socially impactful issues.

Evidence from the Large-scale Biosphere Atmosphere (LBA) experiment in Amazonia (Lahsen, 2009), and the NEXUS Fulbright program (Meehan et al., 2017) suggest that particularly in international collaboration between Global South and Global North, geopolitical concerns over scientific colonialism, positioning for international agreements, and the privileging of Global North research priorities over local interests make trust-building more challenging. As LTEC begins to work on projects with more clear connections to problems of geopolitical concern, these considerations will become more present as well. For intra-national efforts, such as the National Oceanic and Atmospheric Administration's (NOAA) Regionally Integrated Science Assessments (RISAs), the observations of (Lahsen, 2009) and (Meehan et al., 2017) beg the question of whether similar political dynamics are at play in local and regional politics, on urban-rural gradients, and between academic and resource management-oriented subcultures. Because the metaphor of geopolitics is adept at describing the dimensions of science-policy interfaces, available evidence suggests the answer will imply diplomacy is a crucial organizing metaphor for science-policy interface dynamics.

2.4.4 A utility paradox for LTEC in the context of the NWFP

The Northwest Forest Plan is a case that exemplifies a particular set of ecological, historical, and political contexts with respect to LTEC. Yet, these considerations bear substantial resemblance to other science-policy interfaces outlined above and the consistent challenge of bringing LTEC insights to various problems of natural resources management (Groff et al., 2023; Siggery et al., 2023). Considering these observations, and the analysis I provide above, I approach

the case of the NWFP as an example of a broader phenomenon.

Diffusion of scientific knowledge is non-linear (Jasanoff, 1990; Latour, 1987) and the inflections or obstacles to diffusion are rendered through the structures of systems involved on both sides of any science-policy interface. While the set of analytical tools I use provide specific details about the social construction of this interface with the three constituent themes I identify above, they do not provide much explanation of these structures.

LTEC claims relevance to the management of ecological capital. Implicit in this claim is assumption that resources can be *managed* in accordance with decision-making that prioritizes ecological processes and thus ignores a crucial element of natural resource management: the dominant relationship between human society and the ecological world is characterized by the production and extraction of value. This mode of relating has characterized the post-Euro-American colonization period of the Pacific Northwest with respect to forest resources (Prudham, 2007; Prudham, 1998), and I draw further inspiration from the critical realism tradition of environmental sociology which has been particularly concerned with the nature of the relationship between modern (Western) human society and the natural environment and (Foster et al., 2011; Moore, 2003). Several important ideas from this tradition shed light on the underlying reasons for the patterns I observe in the LTEC-NWFP interface.

The critical realist environmental sociology coalesced around the argument against the Human Exemptionalist Paradigm (HEP) in favor of a New Environmental Paradigm (Catton Jr & Dunlap, 1978; Dunlap & Catton Jr, 1979). The HEP is conceived as the notion that humanity's exceptional qualities "somehow *exempt* humans from *ecological principles* and from environmental influences and constraints" (Dunlap & Catton Jr, 1979). The discussion of this principle has continued to characterize the field of environmental sociology (York & Dunlap,

2012), and could be considered one of its most closely held tenets – fundamentally acknowledging the limits of the earth system (Foster, 2012). This tenet underpins the logic of ecosystem management enacted in the NWFP, which in a sense hypothesizes that there is a sustainable mode of relating to the environment. The antithesis of this mode, the HEP, which has persisted as ecological modernization theory (Buttel, 2000), claims that when new conditions arise, humans circumvent or adapt through innovation. The association between the theme of novelty as identified in the participant interviews – as well as in the literature of ecological (Hobbs et al., 2006) and climatic (Williams & Jackson, 2007) novelty – and the notion of HEP is remarkable.

Furthermore, and perhaps more importantly, critical realist environmental sociology gives new dimensions of analytical depth to notions of ‘environment’ or ‘natural resources,’ (Pellow & Nyseth Brehm, 2013) for global systems certainly, but perhaps more importantly for localities and locally contextualized issues or problems of environment or ecology. For instance, with respect to genetic resources, analysis of animal diversity and endangerment status (Clausen & York, 2008; Naidoo & Adamowicz, 2001) suggests that national economic growth is associated with greater likelihood of increased threats to biodiversity. It is the nature of capitalism, as described through a critical realist lens, to ramp the ‘treadmill of production’ up and let it exhaust resources until they are gone or cannot be further exploited (Foster et al., 2011).

A relevant distinction is the relative ‘renewable-ness’ of the resource in question. Forests generally regrow after they are deforested and, in this respect, biological resources are far different than non-renewables such as fossil energy sources or other forms of mineral wealth. An area of research in environmental sociology that has approximated the incorporation of long-term ecological thinking into sociological study is the topic of forest transitions (Rudel, 2009; Rudel et al., 2005). The sequence of forest-society relationships suggested by Rudel is particularly relevant

to the NWFP. He finds the initial rapid land-cover changes associated with large capital investment and large-scale exploitation are followed by a patchier, small-firm mosaic of forest farming along with conservation lands produced out of the activities of coalitions between activists and residents. In the Pacific Northwest, this sequence was interrupted with the 1994 timber sale injunction and the subsequent development of the NWFP. In light of resource use paradoxes (York, 2006, 2017; York & McGee, 2015), which suggest long-term exploitation is often not attenuated over time by technological innovation or resource substitution, the continued interest of large corporate interests (Baral & Mei, 2022) and the persistent emphasis we observe in the NWFP planning area is not surprising, and are functionally linked by social theory (Catton & Dunlap, 1978).

This critical realist perspective concretizes my findings within a more holistic social context. The NWFP, as a state project, reinforces and legitimizes the extraction of forest resources while attempting to exist within the ecologically aware purview of the environmental laws, ESA and NEPA – the necessary precursors to the NWFP. The common threads of novel conditions in both environmental and institutional contexts, association of LTEC with environmental concerns, and the multiple-use mandate of the federal land management apparatus collectively form the basis of utility paradox for applied paleoecology, essentially composed of three observations:

1. In a natural resource management context production of value as the extraction of natural capital and the combined limitations of personnel time and opposing priorities collectively require swift and clear justification for management activities.
2. In the NWFP, this pressure is particularly evident in a tightly regulated legal framework, where justifications are measured against precedent, thus ‘best available science’ is construed in practice to mean most defensible science and is limited to a set of more secure notions about the past and present.

3. Emphasis on the novelty of the present and future, particularly as understood alongside the Human Exemptionalist Paradigm and Ecological Modernization (Foster, 2012) exacerbates the tendency to relinquish the dispensable concept of historical range of variability (HRV).

While it may be tempting to seek the perfect silver bullet of collaboration and methodology in a transdisciplinary approach (Groff et al., 2023), the twin obstacles of ideological opposition from extreme polar influences in the extractive and restorative end members that characterize natural resource management leaves LTEC with a highly politicized spectrum in which to engage. The inherent attraction of novelty for the status quo renders the applicability of historical conditions questionable. However, the potential contributions of LTEC are much broader than description of past ecosystem states. The strengths of LTEC are in the explanatory power of change through time. Thus, process analogy, or the identification of similar trends across ecological contexts, may be a key focus where HRV is less effective in resource management today and into the future. Furthermore, the alliance with climate change research agendas which offer primarily a dim view of the future and paint the past in a chiaroscuro that alienates the present do not serve the application of LTEC to questions of social concern. More effort towards translation of proxy data into the target metrics of those proxies is a vital research principle for LTEC (Buma et al., 2019), which may define the persistence of LTEC as a discipline.

There are some cases in which LTEC data do inform the practice of natural resource management (Groff et al., 2023; Wingard et al., 2017). While these are exceptions to the general trend of excising the present and future from historical context, they are useful as demonstrations of interdisciplinary and translational research which deserve attention. The logics that underly the success of LTEC research in these cases is particularly instructive (Groff et al., 2023). LTEC

research itself, the practice, training and institutional placement are perhaps equally implicated in the construction of the utility paradox I describe in these pages, further work may provide better understanding of how or if that can be understood and remedied.

2.5 Conclusions

Where natural resources and their management is concerned, the present moment calls for clarity more than ever. Products of LTEC may be relevant to the management of ecological capital, however, the extent to which relevance is achieved is contingent upon political processes far removed from the practice of LTEC and ecological science.

Analysis of participant testimony and key published and publicly available texts provided several pieces of information, which provide the context for further investigation. While my analysis demonstrates there is a range of exposure to LTEC and there are several important ways that LTEC may be well-positioned to provide important contributions to the science-base of ecosystem management. These data likewise suggest that there are institutional drivers regarding the overall agenda of the resource management agencies which may or may not transfer to other organizations but are likely reflected in other regional, national and institutional contexts.

- Science professionals in the research and management ecology branches of the USFS and TNC are aware of LTEC research. This varies from thorough knowledge of at least one senior management ecologist to cursory knowledge in others.
- For management scientists, LTEC research is a crucial tool, but recent histories from dendrochronology or historical ecology are used exclusively to establish historic range of variability in practice.

- Rather than being driven to explore the past further, these participants emphasize a novel future undergoing climate change is a factor mitigating the relevance of the past rather than expanding it. These participants appear to have less knowledge of analogs beyond immediate pre-Euro-American settlement of process or conditions that contextualize future changes.
- Scale of management and planning efforts has changed rapidly in recent years, with participants each reflecting on the importance of the ‘landscape scale.’ This shift was suggested by multiple informants as a way LTEC could be better applied.

III

SPATIAL REPRESENTATION AND RECONSTRUCTION OF LATE HOLOCENE FIRE IN THE WEST CASCADES OF OREGON

What do sedimentary charcoal influx, morphology, and size distribution suggest about the late Holocene history of fire size, severity, and frequency in the Western Cascades?

What are the spatial relationships between fire size and charcoal accumulation?

Can charcoal as a proxy of fire from sedimentary archives in Pacific Northwest forests west of the Cascades be calibrated to the extent and frequency of historical fire?

3.1 Introduction

The forests of the Western Cascade Range (hereafter “Western Cascades”) are known for their old growth forests and the great size and age of Douglas-fir trees (*Pseudotsuga menziesii*). From central Oregon and northward through western Washington, old-growth stands, typically between 300 and 500 years old, established after forest fires (Weisberg & Swanson, 2003a). Currently, the most widely accepted conceptual fire regime model is of infrequent (100-300 year fire return intervals) high-severity fires resulting in an observed pattern of even-aged stands and initiating patches of forest succession across broad landscapes (Franklin & Johnson, 2012; Weisberg & Swanson, 2003a). This conceptual model is further supported by an observed pattern of low lightning ignitions west of the High Cascades (Rorig & Ferguson, 1999). More recently, scholars of fire history (Johnston et al., 2023; Tepley et al., 2013; Weisberg, 2004), anthropology (Shelvey & Boyd, 2000), and ecology (Dunn & Bailey, 2016) have produced evidence of more frequent mixed- and low-severity fire, especially at the drier southern extent of the Cascade Range. These fire history studies contrast and contextualize the simplified infrequent, high-severity model across a biogeographic and climatic north-south gradient. On longer multi-centennial to millennial time scales relevant to tree lifespans and forest landscape dynamics, this model at best only

approximates fire activity in this landscape for the last five centuries of the late Holocene.

It is unclear whether extensive pre-settlement old-growth forest of the Western Cascades was contingent on climate fluctuations (e.g., Little Ice Age cooling that depressed fire in recent centuries) or did a different fire regime existed during earlier centuries (Sprugel 1991; Crausbay et al., 2017)? Many studies have shown that, in general, fire regimes are non-stationary (Whitlock et al., 2010). This longer-term view is best addressed using sedimentary charcoal records of fire across a climatic gradient. However, the late Quaternary history of the Western Cascades fire regime has been evaluated less rigorously than those of the drier forests to the east or south, or in the interior valleys. Vegetation history of the region, however, is known from pollen-based vegetation reconstructions at only three sites within Western Cascades Douglas-fir forests: Blair Lake (Cox, 2016), Indian Prairie Fen (Sea & Whitlock, 1995), and Gordon Lakes (Grigg & Whitlock, 1998), although the latter was only analyzed for the Late Glacial period (10-15 ka⁴). The Indian Prairie Fen and Blair Lake records indicates the pre-settlement forest had largely assembled by 4000 ka, and charcoal analysis at Blair Lake suggests large areas nearby burned every 250-500 years over that period (Cox, 2016).

The low spatial coverage of paleofire studies and its resulting uncertainty in the reconstructed fire regime is only one reason for revisiting these assumptions. Anthropological and indigenous scholarship emphasizes that cultural fire use served many purposes – separately or in combination – which include reinforcing vegetation feedbacks to improve wildlife habitat, increase productivity of resources, shift local water availability, and reduce the local risk of high-severity wildfires (French, 1999; Kimmerer & Lake, 2001; Lake & Christianson, 2019). Thus, management

⁴ An abbreviation of kilo-anum, signifying 1000 years.

practices based on this infrequent-high-severity model operationalize the production of wildfire risk under future climate conditions likely to result in more frequent high-severity fire across western North America (Westerling, 2006).

While the infrequent-high-severity fire regime model suggests uniform effects across the region, three key factors may add significant complexity to the fire regime. One factor is the topographic complexity of the Western Cascades, and western Oregon in general, which is understood to influence both fire and vegetation composition and structure (Krawchuk et al., 2016). In particular, south-facing slopes, valley bottoms, and ridges are known to exhibit characteristics and evidence of more frequent, lower severity fire systems (Carloni, 2005; Hadley, 1999). Edaphic (Takaoka & Swanson, 2008) and hydrological (Christy & Alverson, 2011) explanations for these topographic differences may be important, however fire likely played a decisive role in the forest composition and structure of these landscape positions (Christy & Alverson, 2011). The second factor, which is linked through cultural feedbacks to landscape pattern and process, is that predominantly low-severity cultural burning throughout history and outside of history is widely accepted to have been a factor in setting the lower elevation bounds of conifer forest in the alluvial valleys west of the Cascades (Walsh et al., 2008; Walsh et al., 2010), and has been suggested to play a role in patches and corridors throughout the wet forests of the PNW region (Boyd, 1999b; Carloni, 2005; Derr, 2014; Hadley, 1999; Lacourse et al., 2007). The integration of these factors suggests the dominant fire regime model may be broadly inaccurate as a baseline for ecological conditions in the Western Cascades prior to Euro-American settlement. Third, and finally, the 2020 Labor Day fires, resulting from a very large east wind event that, because of unnatural ignition during peak winds via power lines, may fall outside the range of historic variability in their size and extent (Reilly et al., 2022). These three factor together

emphasize the need to understand the occurrence of similar events in history, but also the relationships between fire events and patterns through time.

Environmental heterogeneity, specifically topographic complexity, thus likely affects cultural fire and wildfire and emphasizes importance of study design and site selection. In addition, characteristics of source area for fire or vegetation proxies, which vary greatly between sites and contexts (Marlon et al., 2006; Vachula, 2020), could be factored into any multisite composite analysis. Small lake basins (<10 ha) have microfossil source areas of 20-50 km (Prentice, 1985; Vachula et al., 2018), and larger macro-charcoal (>250 micron) particles will have a much smaller source area except under extreme wind (Higuera et al., 2007; Vachula, 2020). Thus, to understand the spatial variation of fire regimes across the western Oregon landscape, we require several sedimentary reconstructions, which is challenging given the dearth of sedimentary basins in the unglaciated Western Cascades.

In addition, insight into cultural burning signals via a comparison of a set of proximate fire reconstructions would greatly benefit from a better understanding the charcoal source-area analysis. Paleofire researchers recognize that site characteristics affect charcoal accumulation in depositional environments: lake area, watershed area, and watershed slope all contribute to between-site differences in mean charcoal concentrations (Marlon et al., 2006). Thus, to maximize comparability of charcoal records it is routine to statistically transform each charcoal series (Marlon et al., 2008; Power et al., 2008). This approach standardizes mean and variance of individual site records and then averages the resulting series to create composite records for ecological settings (Walsh et al., 2015), subcontinental regions (Marlon et al., 2012), and the Earth system (Marlon et al., 2008; Power et al., 2008). At the landscape scale, this approach, while powerful to extract general trends, de-emphasizes ecologically meaningful between-site variability.

While some of this variability may be the result of stochastic ignition and spread factors, additional variation is the result of scalar factors such as watershed area and slope (Gavin et al., 2006; Mustaphi & Pisaric, 2014). These factors can be assessed quantitatively to better understand the implications of individual records and collections of individual records to characterize regional and subregional fire activity with sedimentary proxies.

With this collection of data and analyses I address issues of scale and representation crucial to the advancement of applied and computational sedimentary paleoecology. I use two linked lines of evidence to critically evaluate the history of fire regimes in the western Cascade Range of Oregon. Site selection in paleoecology is opportunistic by necessity, thus potentially introducing significant bias to both multisite studies (Calder et al., 2015) and meta-analysis involving the creation of composite records (Walsh et al., 2015). I thus first explore spatial representation of historical fire in new and existing sedimentary charcoal records from lakes, ponds, and peat deposits (i.e., the spatial scales represented by these records) in the Western Cascades and ecologically similar regions across the rain shadow belt of the Cascade Range. This work expands upon methods for differentiating local and regional components of individual sedimentary charcoal records (Higuera et al., 2010; Long et al., 1998) and assessing their spatial fidelity (Adolf et al., 2018; Higuera et al., 2007; Higuera et al., 2011; Vachula et al., 2018).

The second line of evidence is a set of four late Holocene (<4 ka) reconstructions from peats and morainal ponds (Figure 3). We located these sites using landscape archeological evidence to capture environmental signals from pre-Euro-American settlement human activities. The process of locating sites included multiple criteria. We sought out sites that were along known or suspected travel routes and where there was forest structure or environmental history indicating frequent low-severity fires prior to settlement (Boyd, 1999a). The type of sedimentary records

contained in these sites is expected to have certain limitations and advantages. Small sites such as these are hypothesized to record local changes in vegetation and fire more accurately than lakes (Prentice, 1985). Yet, the slower sediment accumulation rates in mid-latitude peatlands and smaller water bodies mean that the temporal resolution will be low, >10 years/cm, rather than 1-5 years/cm typical of productive lakes.

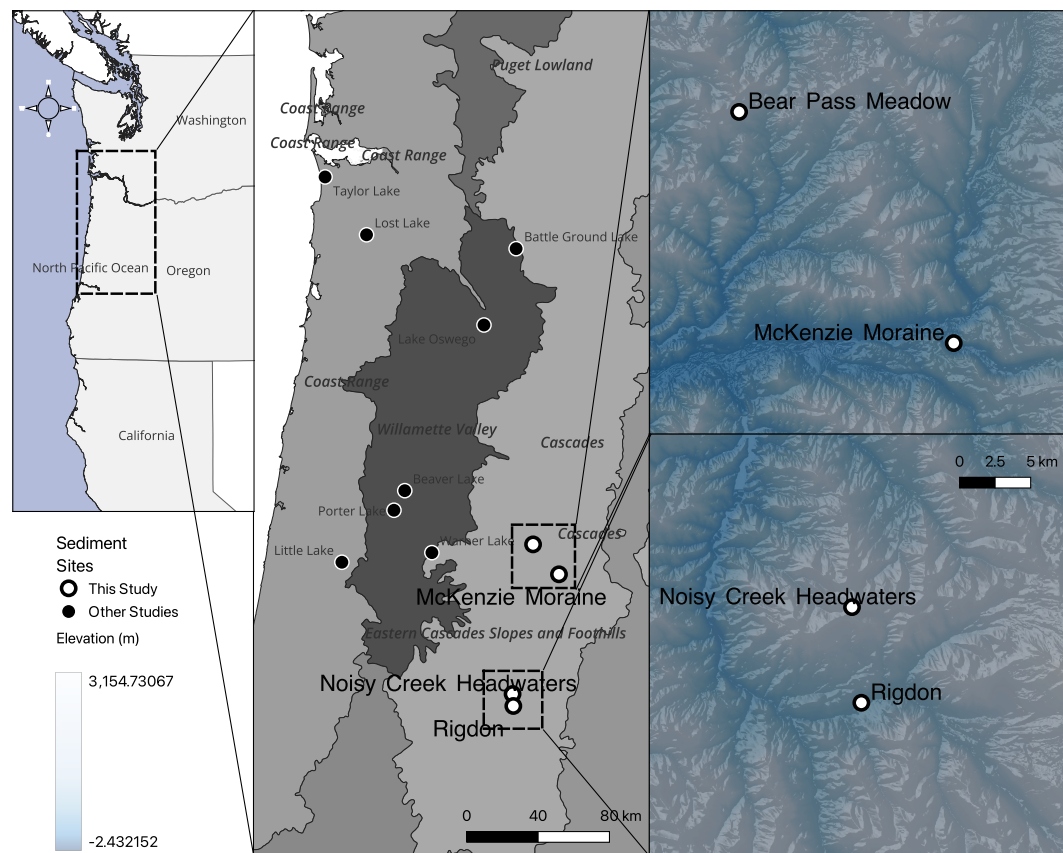


Figure 3 Sediment core sites included in this study: Bear Pass Meadow (BPMA), McKenzie Moraine (MKZM), Noisy Creek Headwaters (NOIS) and pre-existing paleofire sites. Ecoregions are EPA Level III; USGS, elevation.

3.2 Methods

3.2.1 Fire history of the Western Cascades

We identified four study sites using a landscape archeological approach by selecting sediment-accumulation sites that are proximal to pre-contact trails (Michael Coughlan,

unpublished data), and the extant archeological record. The sites span 91.3 km north-south perpendicular to the primary climatic gradient and range from valley bottom end-moraine depressions (McKenzie Moraine and Rigdon Pond) to montane meadows in small cirques or slumps (Noisy Creek and Bear Pass; Table 2). The sites reflect a range of topoclimatic, and potentially cultural, impacts on vegetation composition and a range of fire history that is not captured by the lakes in this region typically sampled for sedimentary paleoecological reconstructions, which tend to be in the larger glacial cirques on north-facing slopes.

Table 2 Site characteristics assessed in the field (Latitude, Longitude, Dominant Vegetation) and generated by the PRISM model (Mean Annual Precipitation, Mean July Temperature, Mean January Temperature; retrieved from <https://prism.oregonstate.edu/explorer/> on 03/07/2025).

Site	Latitude	Longitude	Elevation (m)	Dominant Vegetation	Mean Annual Precipitation (mm)	Mean July Temperature	Mean January Temperature
Bear Pass Marsh	44.31953	-122.2521	1311	Psuedotsuga, Abies	2391	16.9	1.7
McKenzie Moraine	44.17585	-122.0589	740	Psuedotsuga, Tsuga	2008	19.6	2.5
Noisy Creek Headwaters	43.55949	-122.3358	1368	Tsuga, Abies	1839	16.5	1.2
Rigdon Pond	43.49928	-122.3259	937	Pinus, Psuedotsuga	1526	18.5	2.2

Sediment cores were collected in summer 2020. At meadow coring sites, BPMA and NOIS, we first carefully removed a monolith with a field shovel to a depth of ~20 cm at 2 locations within a few meters of each other at the center of the meadow opening. We then used a 5-cm diameter Livingstone-type piston corer attached to a tripod to remove parallel and overlapping drives to collect a continuous stratigraphy.

At the end-moraine pond sites, MKZM and RIGD, we collected sediment cores from a platform constructed spanning two rafts and anchored at two locations on the shore. We collected surface cores with an 8 cm diameter piston corer fitted to a polycarbonate tube to minimize

deformation of the sediment water interface. We also used a 5-cm Livingstone corer to retrieve samples at these locations. At RIGD we retrieved sediment cores exclusively with the 5 cm Livingstone-type corer due to the density of sediment and aquatic vegetation.

I constructed age models for these cores using AMS radiocarbon-dated identifiable, terrestrial plant macrofossils and the ages of known tephras using Bacon 2.5.0 (Blaauw & Christen, 2011). I constructed age models for three of the four cores recovered during field excursions in Summer and Fall 2020 (BPMA, MKZM, and NOIS). All samples were analyzed at either Direct AMS (D-AMS; since closed) or the Woods Hole Oceanographic Institution's National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS; <https://www2.whoi.edu/site/nosams/>).

At BPMA, we acquired six reliable dates from eight samples submitted. Results included age reversals at the samples from 102 cm and 250 cm, and those samples were excluded from age model development due to model fit. I chose to include a sample from 251 cm to reflect the possibility of contamination and difficulty of interpretation for the lower section. I obtained four usable dates from the five submitted samples from MKZM and eliminated the sample at 136 cm due to an age reversal. For the NOIS core, I obtained three reliable dates out of four submitted samples. The most likely explanation for all age reversals is a probable lab contamination with ^{14}C radiolabeled materials in January 2021. The 1 sample from Rigdon Pond (RIGD) returned modern levels of ^{14}C . It is likely the material submitted included roots of plants; however, we did not pursue further submissions for RIGD and it is not included in any further analysis.

I measured magnetic susceptibility and macrocharcoal concentrations on contiguous down-core samples. Magnetic susceptibility is a measure of the minerogenic component of sediment (Thomson, 1973). Volume-specific magnetic susceptibility was measured with a Sapphire

Instruments cup meter using 1 cm³ wet sediment placed in a clean vial. To quantify the charcoal component, I subsampled each core at 1 cm continuous intervals and treated each sample with sodium hexametaphosphate to disperse colloids. I then sieved at least 1 cm³ using sieves of 125, 250 and 500 μm , and tallied charcoal particles in three size fractions (12-250 μm , 250-500 μm , and >500 μm) and according to woody or grass/forb (herbaceous) morphology as proxies of past fire (Mustaphi & Pisaric, 2014; Whitlock & Larsen, 2001). As the charcoal stratigraphies at these sites lacked temporal precision for statistical peak identification (Higuera et al., 2010), I subjectively evaluated evidence of local fire events as increased charcoal concentrations of the larger size fractions.

3.2.2 Calibration of Sedimentary Charcoal

To calibrate sedimentary charcoal with historical fire in western Oregon, Washington and northern California, I collected sedimentary charcoal data sets from published studies in an area equivalent to the *Tsuga heterophylla*, *Pseudotsuga menziesii* and Cool Mixed potential vegetation zones, and spatial historical fire data for Oregon and Washington (Table 3, Figure 3). Sediment core data sets were retrieved from the Global Paleofire Database (GPD, <https://paleofire.org/home>) and the Reading Charcoal Database v1.0 (RCD, [Harrison et al., 2022](#)). Data included depth below sediment surface, a charcoal measurement (either counts or influx, which varied between sites), and an age model estimate used in the original publication. Final selection criteria for sites required a reliable age-control within the last 100 years, either via ²¹⁰Pb radiometric dates or via at least one stratigraphical marker (e.g. abrupt pollen change from land-use, fire or erosion layer) that was matched to a historical event in the original publication. All age models were recalculated with Bacon (Blaauw et al., 2007; Blaauw & Christen, 2011), a Bayesian age-depth modelling program

for the R statistical computing environment (R Core Team, 2020). Age models were constructed using published age-control points (^{210}Pb , ^{14}C , known tephtras) combined with additional known historical events.

Table 3 Published sedimentary charcoal study sites, their locations, and original publication.

Site Name	Latitude	Longitude	Citation
Battle Ground Lake	45.804788	-122.494118	(Walsh et al., 2008)
Beaver Lake	44.550122	-123.177874	(Walsh et al., 2010a)
Lake Oswego	45.410495	-122.691861	(Walsh, et al., 2010b)
Little Lake	44.16745	-123.584088	(Long et al., 1998)
Lost Lake	45.825	-123.577778	(Long, 2003)
Porter Lake	44.447815	-123.244694	(Walsh et al., 2010b)
Taylor Lake	46.100484	-123.907973	(Long & Whitlock, 2002)
Warner Lake	44.246947	-122.95845	(Walsh et al., 2010b)

To fit the age models, I first added age control points to each core starting with the published radiometric dates. Then, I examined the matching stratigraphic evidence to known calendar years converted to cal yr BP with the sediment core collection year.

Little Lake, Taylor Lake and Lost Lake core data in the repositories did not include surface-core sections. For these cores, I took digital images of the original publication figures plotted as influx versus calendar year and used WebPlotDigitizer, a computer-vision graphical-analysis package which helps extract accurate numerical values from plots (WebPlotDigitizer, <https://automeris.io>). I then visually correlated large variations and trends in the long core and short core data sets in both magnetic susceptibility and charcoal influx to merge a common stratigraphy from the sediment-water interface to the core base. In all three records, this resulted in adjusted depths for long-core sections, and this depth amendment was applied to all radiocarbon sample depths. This resulted in adding 16 cm to Little Lake, 17 cm to Taylor Lake and 17 cm to Lost Lake stratigraphies.

We obtained spatially explicit fire history data from multiple sources. A database of

Washington wildland fires from 1973-2020 is maintained by the State of Washington Geospatial Open Data Portal (<https://geo.wa.gov>). Spatial Oregon fire history data was obtained from the National Interagency Fire Center (NIFC, <https://data-nifc.opendata.arcgis.com>), Oregon Department of Forestry (ODF, <https://gis.odf.oregon.gov/ags1/rest/services>) and the Oregon Spatial Data Library (<https://hub.oregonexplorer.info/pages/osdl-archive>). These records were combined and checked for redundant features by name, location and year (Figure 4). The fire databases did not include agricultural open-field fires in the Willamette Valley. These fires between 1950s and 2008 included annual burning of 250,000 acres (1010 km^2) for grass seed production (Sinclair Broadcast Group, 2009). Fire areas were converted from native units to a common unit (m^2).

To model the potential charcoal signal at the study sites that was generated by historic fires, I calculated the distance-weighted charcoal loading (L), as the area of the fire (A) divided by the square of the Euclidean distance (d^2) from the fire centroid to the coring site within an 80 km radius.

$$L = \frac{A}{d^2} \quad (1)$$

Distance weighting the effect of each individual fire by square of distance is a simplified approach, yet functionally similar to the modelled transport mechanism for charcoal particles in the convective plume of wildfires (Clark, 1988; P. Higuera et al., 2007) and observations that air-borne charcoal deposition at sedimentary sites declines in a non-linear fashion with distance (Gardner & Whitlock, 2001; Whitlock & Millspaugh, 1996).

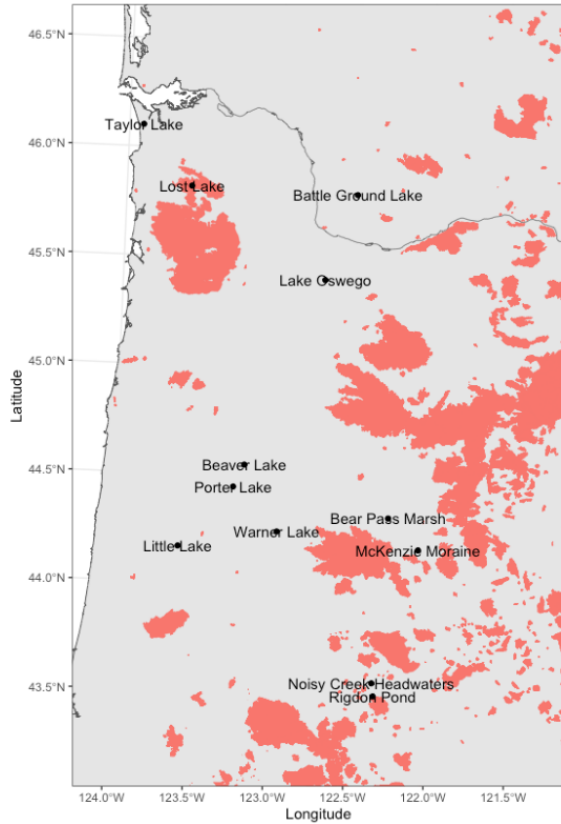


Figure 4 Historical fires in Oregon (1890-2021) and Washington (1973-2022) (red polygons) in relation to sediment core locations.

I chose a source area of 80 km to ensure that even distant fires would in aggregate exhibit a minor effect, which incorporates the possibility that strong winds potentially expand the source area for charcoal. The synchrony of charcoal influx and the charcoal loading index within and across sites was assessed by matching the modelled age of sediment sections to the charcoal loading index. Specifically, the average age of each sediment section was linearly interpolated to the top (t) and bottom (b) of the section to estimate the date range in calendar years represented. The upper bound of the surface sample was the year of coring, and the lower bound for the basal sample was estimated as t of that sample plus the accumulation rate of that sample multiplied by the sample thickness. All charcoal loading (L) for fires that occurred during that window were

summed to provide an index of fire (FI).

$$FI = \sum_{i=b}^t L \quad (2)$$

3.3 Results

3.3.1 Core Description: Physical Data

At BPMA, we recovered 268 cm of sediment. Coring depth was limited by mineral soil with gravels. The core consisted of primarily coarse fibric peats which alternated periodically from darker (10YR 3/1) to lighter (10YR 3/3) color. Clear stratigraphic markers from these changes in color provided tie points between parallel cores to establish a continuous stratigraphy. In the BPMA core, small, temporary increases in magnetic susceptibility at 26-28 cm, 46-49 cm, and 79-84 cm indicate mineral inputs (Figure 5), but show no long-term trend in changing sediment sources. Progressive increases of magnetic susceptibility magnitude and variability below 100 cm indicate a gradual process of sedimentation shifting from inorganic to organic up-core.

Multiple coring locations at MKZM revealed a consistent layer at ~2 m depth that was impenetrable to the coring device, suggesting the site may have dried up prior to sediment accumulation. We recovered 198 cm of sediment. Sediments at this site are highly organic, dominated by aquatic plant detritus, and exhibited little variation in color or texture. We made correlations between drives with magnetic susceptibility measurements to establish the final stratigraphy. The only substantial transition in sediment occurred at 143 cm from loosely consolidated darker, aquatic peat to finer, lighter peat to the base. MKZM sediments exhibit very low variability in magnetic susceptibility above 55 cm depth (Figure 5). Between 55 and 86 cm variability and magnitude of magnetic susceptibility increase slightly. Increases at 85 and 105 cm

indicate inorganic inputs, and below 170 cm higher variability indicates a different environmental condition prior to continuous accumulation of sediment.

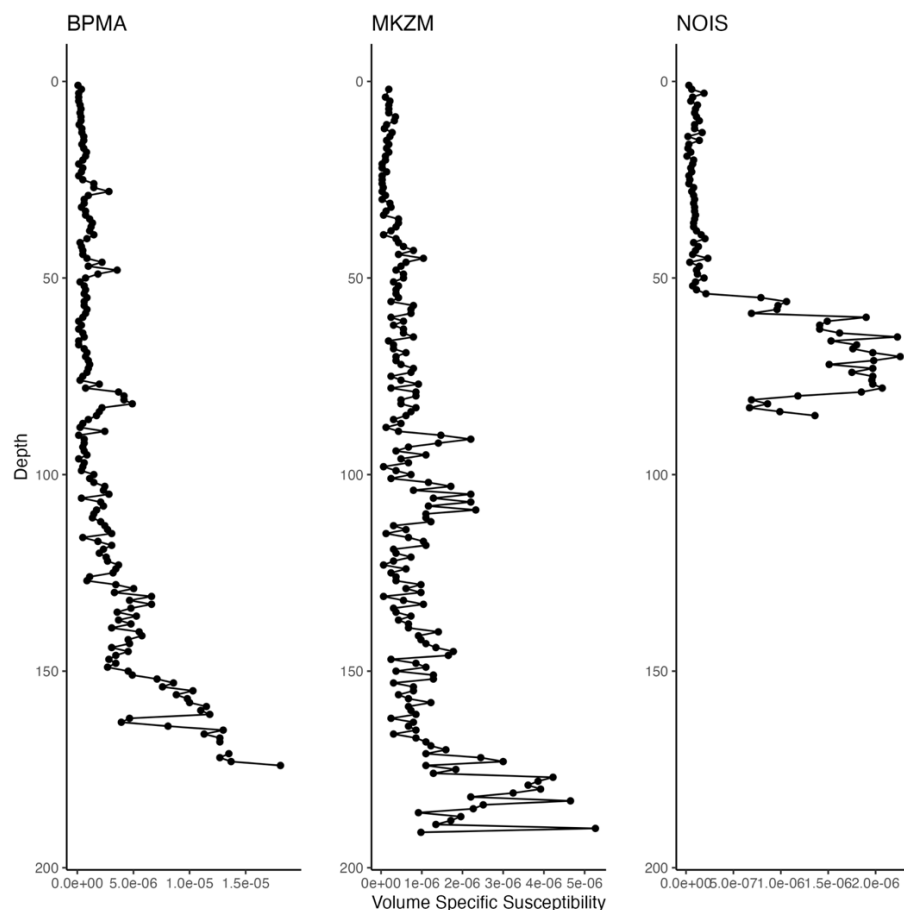


Figure 5 Continuous, 1-cm interval, magnetic susceptibility measurements for BPMA, MKZM, and NOIS reflect lithological changes over the length of each core. Basal increases for each demonstrate the potential of altered depositional and taphonomic processes operating in the lower cores.

Coring at NOIS yielded 112 cm of sediment. Dense fibric peat, with minor changes in color characterize the upper 48 cm. At 48-52 cm a very dark layer with multiple, large woody fragments was followed by dense peat to 86 cm. Below 86 cm sediments were colluvial with increasing gravels to the base. At NOIS, above 54 cm, minimal variation in magnetic susceptibility suggests a stable local pedosphere with no substantial changes in sediment accumulation or input sources (Figure 5). Below 54 cm the rapid, sustained increase is an indication that substantial changes in

inorganic inputs or overall accumulation rates took place during the time of deposition.

Magnetic susceptibility for BPMA, MKZM and NOIS identify only minor shifts in sediment sources in the upper cores, and in all cores record evidence of mineral soils prior to reaching the core base and before qualitative lithology as assessed in the lab down core.

3.3.2 Age-Depth Modeling

The age model for BPMA with six dates (Table 4, Figure 6**Error! Reference source not found.**) results in a steady accumulation rate at this site which is reasonable given the sedge-peat does not generally show taphonomic compression in the same manner as lake sediment. The greater estimated error of the date at 18 cm resulted in the widest error, the model fit still passes within a small margin of the calibration likelihood. Mean accumulation rate is 13.2 years/cm. A small change in overall slope below 120 cm indicates the possibility of a slightly higher accumulation rate prior to 2 ka. The lack of a basal age control means that inference below 165 cm (~2385 cal yr BP), necessarily will be limited.

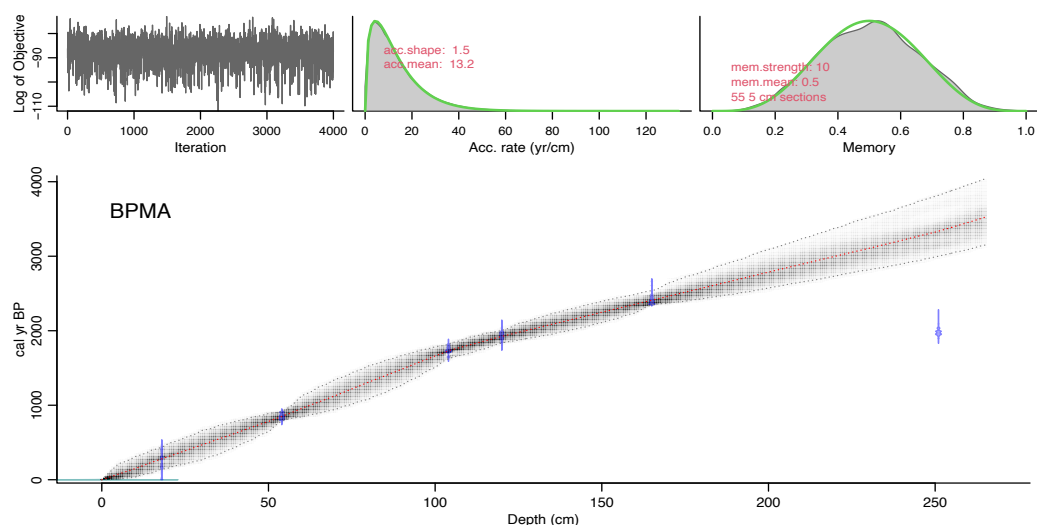


Figure 6 Age-depth model for BPMA with six radiocarbon dates. Top left: Consistency of age results across all model runs. Top center: Prior distribution for sediment accumulation rate, green line, and model results, grey fill. Top right: Prior distribution (green line) and model results (grey fill) of how well accumulation rate of a sample predicts accumulation rate of the following sample (top right).

Table 4 Radiocarbon results for Bear Pass Meadow (BPMA), McKenzie Moraine (MKZM), and Noisy Creek Headwaters (NOIS). For samples that were not used to construct age models the lab code is marked with an Asterix ().*

Lab Code	Core	Depth (cm)	Sample Type	Uncalibrated Age (ybp)	Estimated Error (SD)
NOSAMS 169242	BPMA	18	Plant/Wood	245	60
NOSAMS 169243	BPMA	54	Plant/Wood	950	15
D-AMS 041116	BPMA	102	Plant/Wood	980	25
D-AMS 044493	BPMA	104	Plant/Wood	1835	24
NOSAMS 169244	BPMA	120	Plant/Wood	2,000	30
D-AMS 041117	BPMA	165	Plant/Wood	2,385	21
D-AMS 041118	BPMA	250	Plant/Wood	1849	24
D-AMS 044494	BPMA	251	Plant/Wood	2039	21
NOSAMS 170030	MKZM	34	Plant/Wood	165	40
NOSAMS 170031	MKZM	109	Plant/Wood	1,670	20
D-AMS 044491	MKZM	135	Plant/Wood	1603	26
D-AMS 041120	MKZM	136	Plant/Wood	1032	23
NOSAMS 170032	MKZM	172	Plant/Wood	2,440	20
NOSAMS 170033	NOIS	14	Plant/Wood	110	15
NOSAMS 170034	NOIS	36	Plant/Wood	435	20
D-AMS 041119	NOIS	75	Plant/Wood	333	19
D-AMS 044492	NOIS	78	Plant/Wood	3458	25
NOSAMS 170035	RIGD	36	Plant/Wood	>Modern	

At MKZM, the three selected age control points yield an age-depth model with the characteristic upper-core decrease in accumulation rate of aquatic sediments (Figure 7). The mean accumulation rate is 15.6 year/cm over the length of the core. The second and third dates at 109 and 135 cm exhibit a small age reversal, and we selected the date at 135 cm to include in the age model. The increase in magnetic susceptibility that includes the section at 109 cm (Figure 5), suggests the possibility of redeposition, and including both dates would result in an unjustified increase in sediment accumulation rate between 135 and 109 cm.

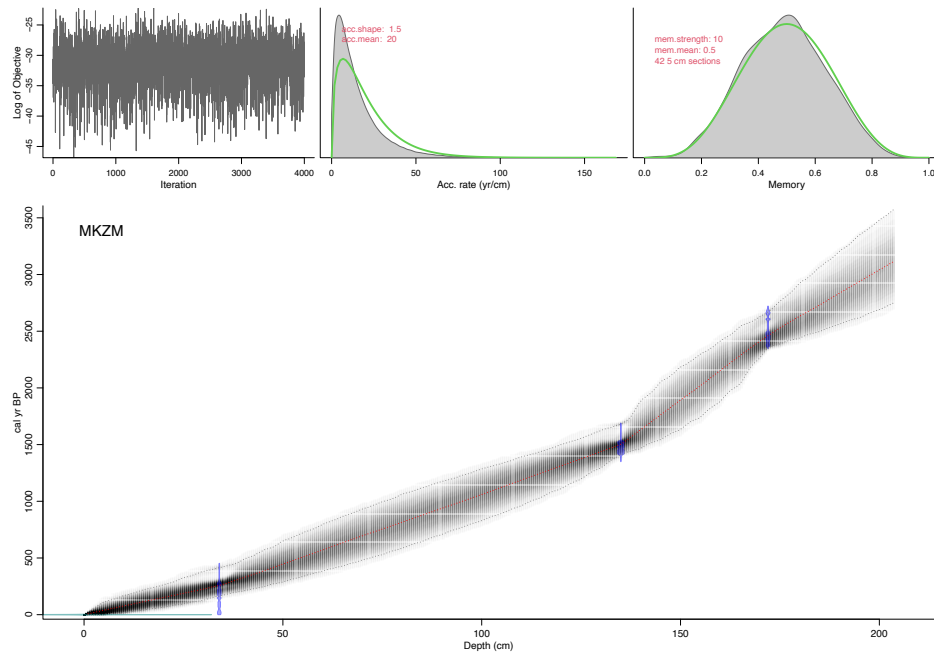


Figure 7 Age model at MKZM constructed with three final radiocarbon dates. Figure components as for Figure 6.

The only substantial change in accumulation rate is after 135 cm, which is corroborated by the lithologic change at 143 cm to more dense, lighter peat. The age control with the greatest uncertainty is the uppermost date at 34 cm ($164 \text{ cal yr BP} \pm 40 \text{ years}$). The position of this date in the IntCal curve adds some uncertainty and increases the range of likely actual ages in the upper core. The lower age control exhibits a bimodal distribution, thus while the model bisects this distribution, the modeled ages below 172 cm are subject to extrapolation in addition to this model artefact.

For the NOIS age model, the upper two age control points utilized were from individual conifer needles, precluding issues of root contamination or redeposition of older material. The lower age control indicates a substantial shift in accumulation rate below 36 cm or, more likely, at least one significant hiatus between 36 and 78 cm (Figure 8).

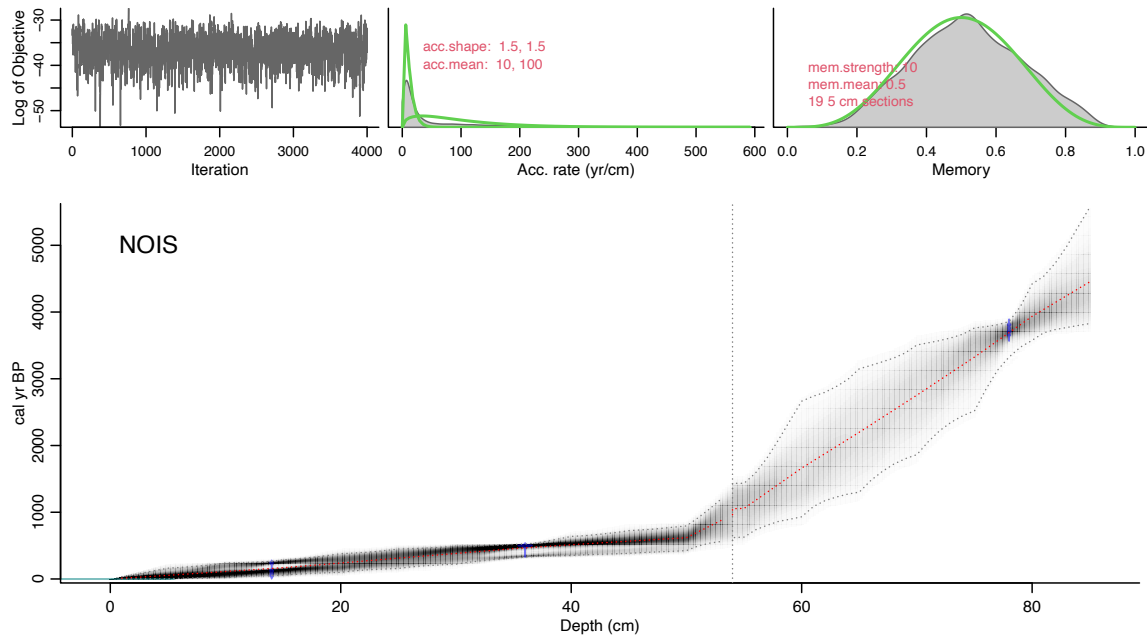


Figure 8 Age-depth relationship for the composite NOIS sphagnum peat core, with a boundary placed at 54cm to reflect the likely shift in deposition and, thus, accumulation rate. Figure components as for Figure 6.

This assumption is corroborated by the magnetic susceptibility increase in magnitude and variability for NOIS below 54 cm (Figure 5), which suggests that altered surface processes, including the transport of soil and lithospheric materials directly to the site, and taphonomic processes other than the growth of the peat lens may have been operating at the time of deposition. Given the large change in sediment accumulation rate below the date at 36 cm, and the dramatic change in lithology at 54 cm, we placed a boundary in the age model at 54 cm and provided prior mean accumulation rates of 10 years/cm above 54cm, and 100 years/cm below 54 cm.

3.3.3 Western Cascades Sedimentary Charcoal Chronologies

Charcoal concentrations and influxes exhibit large changes in all cores. At BPMA, concentrations ranged from 1 to 119 pieces/cm³ in the <125 µm (small) size fraction with a median concentration of 15 pieces/cm³. In the upper 15 cm of BPMA, corresponding to the last 220 years

in modeled age, there was a mean value of 7 ± 4.2 (SD) and no 1-cm section exhibits a concentration greater than 13 pieces/cm³. Hereafter, we treat this period as a baseline concentration for this core during times of minimal fire. Large increases in concentration to above 45 pieces/cm³ occurred 11 times in the last 2000 years (Figure 9). Prior to 200 CE, there was a large increase in overall concentrations, followed by an overall decline in values to the present. Herbaceous charcoal made up a small component of the overall concentrations.

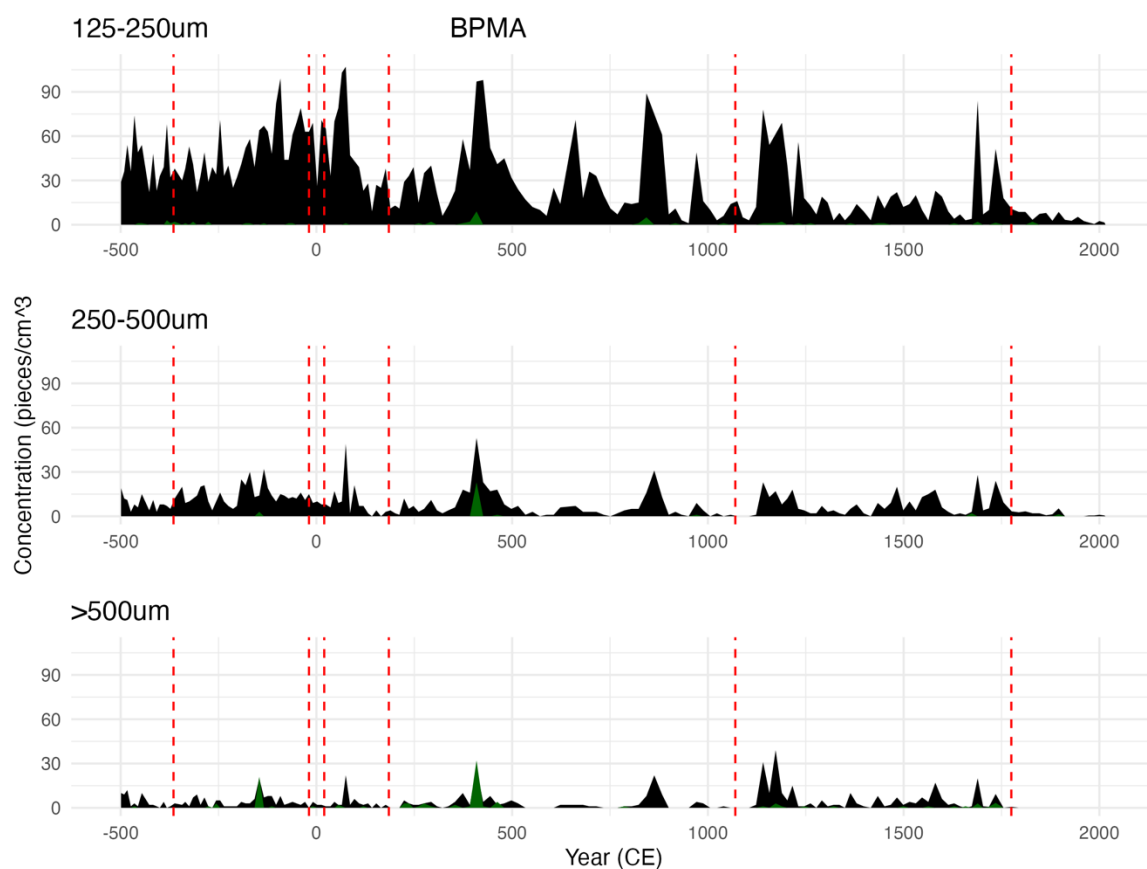


Figure 9 BPMA charcoal concentration by size class (125-250 μ m, top panel; 25-500 μ m, middle panel; >500 μ m lower panel) and morphology (herbaceous and grass-like charcoal fragment concentration shown in green, woody charcoal concentration shown in black). Red vertical dotted lines are placed at the median modeled age estimate corresponding to the depth of radiocarbon samples for dates used in age model construction.

The 250-500 μ m (medium) size fraction exhibits a similar pattern to the small fraction prior to 1800 cal yr BP, however only six of the large increases in the smaller fraction were

accompanied by increases in the medium size fraction. After 200 CE, a ~600-year period of low concentrations between the peaks differentiates this chronology from the small fraction. After 800 CE, the medium fraction concentrations increase, however, not in the sustained pattern prior to 200 CE. Overall, herbaceous charcoal is a minor contribution, except for the high concentration in the high charcoal count sample at 480 CE. In that sample the herbaceous charcoal was roughly 50% of the woody charcoal count.

In the $>500\ \mu\text{m}$ (large) fraction, the higher average concentrations prior to 1800 cal yr BP are proportionally less than either the small or medium fractions. Minimum values are still between 800 and 200 CE, and after 1800 CE, no charcoal pieces in this size fraction were identified. Herbaceous charcoal fragments in the large size fraction were rare, apart from the sample at 480 CE. In this sample, the large herbaceous fraction exceeded the concentration of the large woody fraction. Five increases in the large woody charcoal fraction correspond to increased concentrations in the small fraction in the last 2000 years. An additional increase at 1600 CE, is an exception to the pattern.

MKZM minimum concentration of >1 and maximum of 39 pieces/cm³ and median concentration of 9 pieces/cm³. The first 1 cm section of this core to reach the median value is at 34 cm (1750 CE). At no point in the MKZM record have charcoal concentrations been as low as the last 200 years (Figure 10). Prior to 1750 CE, substantial variability characterizes the last 2500 years of small fraction concentrations. Between 1250 and 1750 CE, episodes of high concentrations varied from a single sample to eight contiguous samples. These occurred at 1700-1750, 1650, 1400, and 1250-1350 CE with short gaps where concentrations decreased to post-1750 levels. Between 600 and 1250 CE, concentrations exhibit lower variation. Before 600 CE there was a period of high concentrations and high variation from approximately 350-600 CE. This period

corresponds to the greatest age uncertainty in the age-depth model for MKZM (Figure 7). Between 270 BCE and 250 CE are the highest levels of sustained concentrations in the core, with only one sample below the median. The small fraction herbaceous charcoal is a substantial component of the overall charcoal concentration and tracks with woody charcoal for the last 1700 years. The concentration of herbaceous charcoal increases over time from 300 CE to 1700 CE. Prior to ~300 CE, woody charcoal and herbaceous charcoal decouple and vary independently, with the herbaceous component lower relative to the woody component.

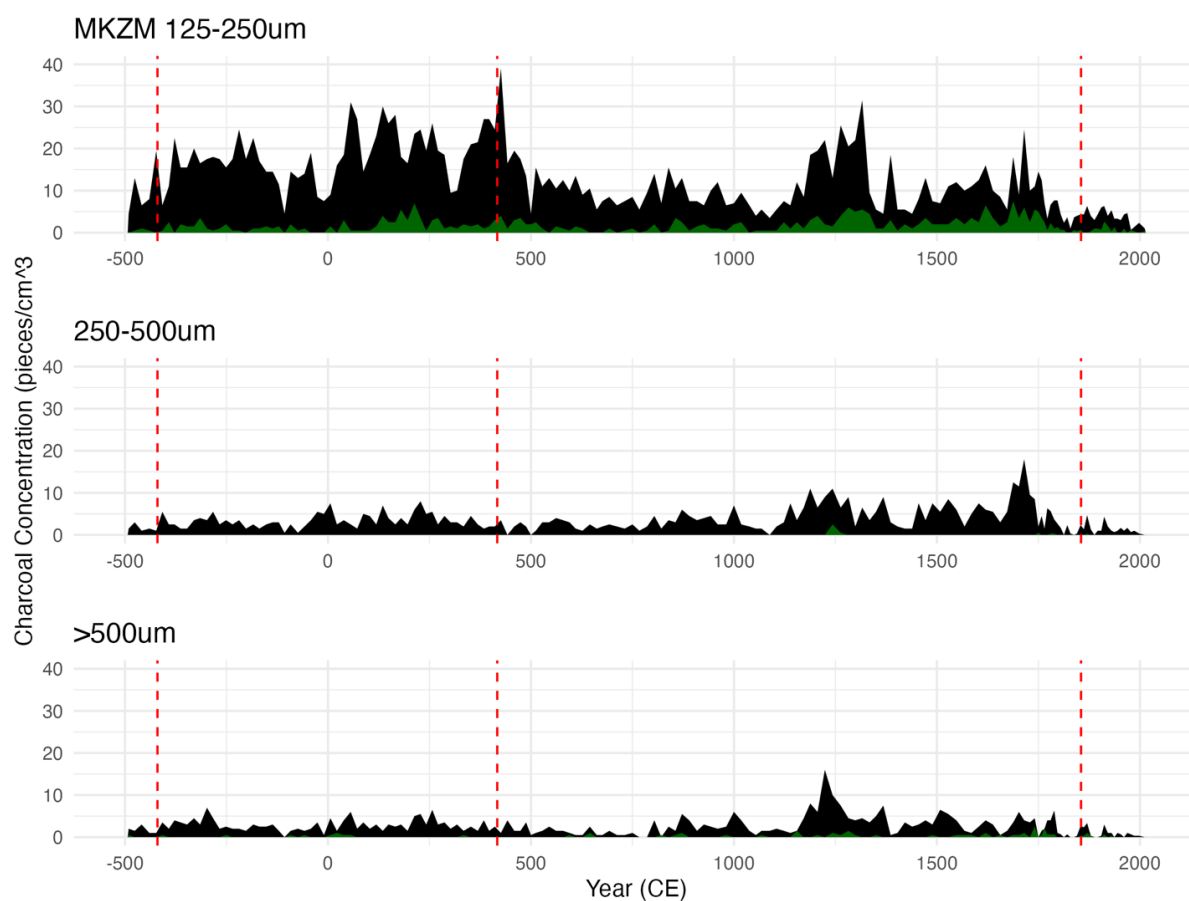


Figure 10 MKZM charcoal concentration by size class (125-250µm, top panel; 25-500µm, middle panel; >500µm lower panel) and morphology (herbaceous and grass-like charcoal fragment concentration shown in green, woody charcoal concentration shown in black). Red vertical dotted lines are placed at the median modeled age estimate corresponding to the depth of radiocarbon samples for dates used in age model construction.

The medium size fraction concentrations are low, but also variable, in the last 200 years. Between 1700 and 1750 CE is the largest increase in concentration in the MKZM record for this size fraction, and it corresponds to the most recent elevated concentrations in the small fraction. From 1200 to 1700 CE, concentrations were 2-3 times higher than the last 250 years, preceded by almost uniform low concentrations to 500 BCE. Herbaceous charcoal is nearly absent in this fraction.

Low values characterize most of the concentrations for the large fraction in the last 200 years. Higher concentrations between 1250 and 1750 CE, contain the highest concentration in this fraction at ~1270 CE. This peak concentration corresponds to a high value in the small fraction. Slight, sustained increased concentrations from 900 to 1100 CE, 200 to 400 CE, and 250 to 100 BCE; as well as slight, sustained decreases in concentration at intervals 1100-1200 CE, 700-850 CE, and prior to 250 BCE are evident in both medium and large fractions.

At NOIS, small fraction charcoal concentrations range from 0 to 37 pieces/cm³ with a median of 7.5 pieces/cm³ (Figure 11). In the core sections above 33 cm concentrations of small fraction charcoal exceeded the median value several times but have decreased overall. The most recent decrease is over the past ~50 years, which encompass the longest period of low concentrations in the past 750 years. In the last 100 years, two small, multi-sample increases in charcoal concentration, preceded by a larger increase at approximately 1750. The most prominent feature of the NOIS chronology is the increase in concentrations at 33-37 cm (446-562 cal yr BP modeled age), which is notably present in all size fractions. This time period of high woody charcoal concentrations is accompanied by increased herbaceous charcoal concentration increases, which are otherwise rare in this record. Prior to 1300 CE, the apparent large shift in sediment accumulation rate (see Figure 8) substantially changes the temporal resolution of the chronology,

and I focus primarily on the patterns since 1300 CE from here forward with respect to the NOIS record. Between 175 and 1300 CE concentrations were similar to the concentrations since ~1550 CE.

Medium and large fractions exhibit very low concentrations after ~1550 CE. Substantial increases at 1450 and 1525-1550 CE coincide with the large increase in small fraction charcoal concentrations in those samples. Prior to 1450, nearly all samples show low concentrations of medium and large fractions.

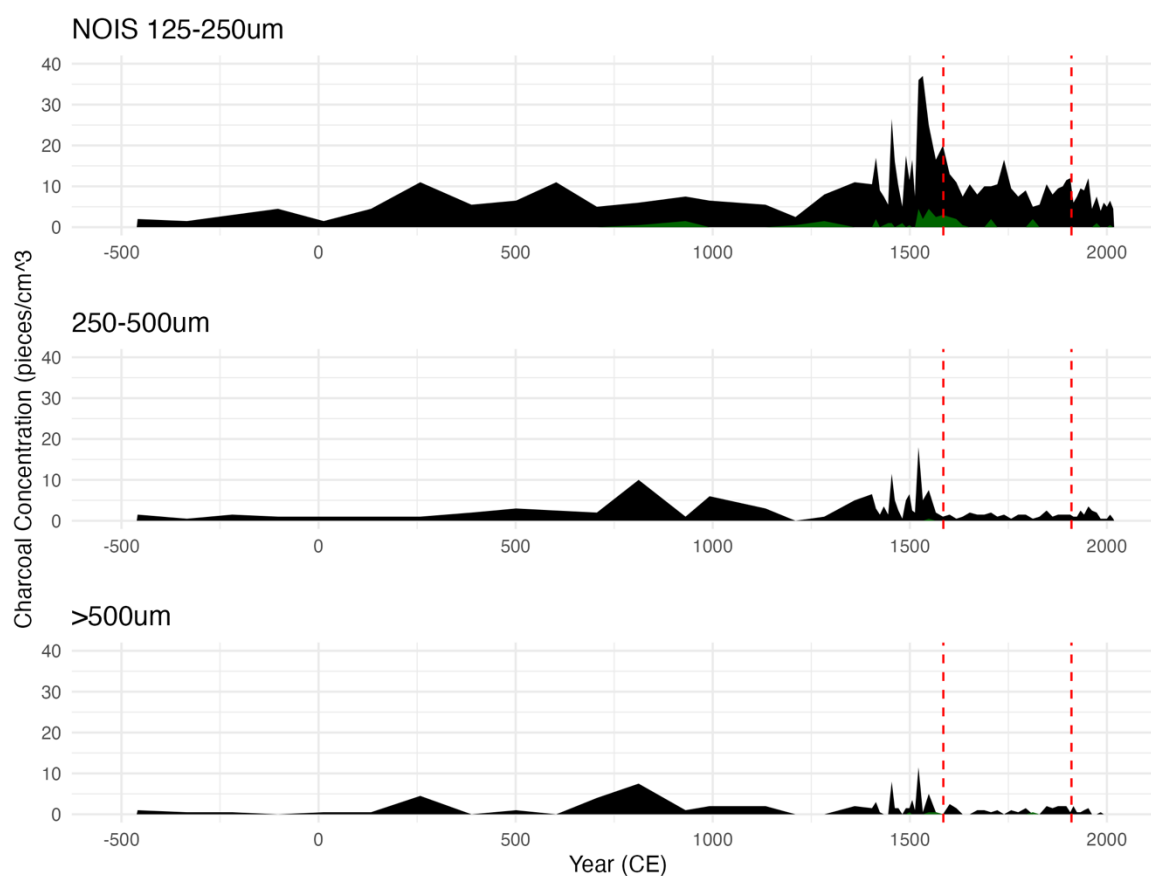


Figure 11 NOIS charcoal concentration by size class (125-250µm, top panel; 25-500µm, middle panel; >500µm lower panel) and morphology (herbaceous and grass-like charcoal fragment concentration shown in green, woody charcoal concentration shown in black) for BPMA. Red vertical dotted lines are placed at the median modeled age estimate corresponding to the depth of radiocarbon samples for dates used in age model construction.

Across the three sites, influx of small fraction charcoal varied in range and central tendency, median values were 1.0, 0.7 and 0.5 particles/cm²-yr at BPMA, MKZM, and NOIS respectively. Peak influxes at BPMA were two times the peak values at NOIS and three times those of MKZM.

The small fraction charcoal influx at BPMA (Figure 12) since 1750 has consistently fallen below the median value of 1.0 particles/cm²-yr. In the past 2000 years, charcoal influx exceeded 5 particles/cm²-yr, five times at intervals of 300 to 500 years. During that same period, influxes at or close to 2.5 particles/cm²-yr occurred eight times. Prior to ~100 CE, influxes were substantially higher and more variable mirroring the concentrations during that time at BPMA (Figure 9).

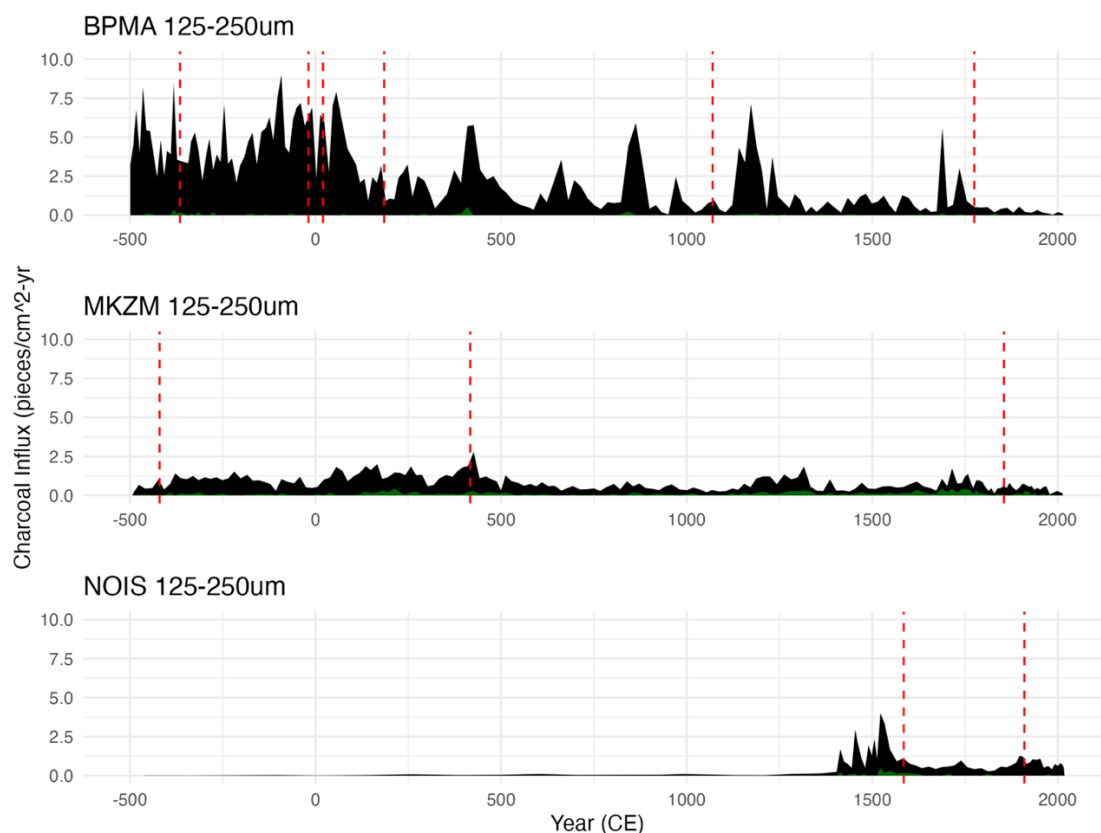


Figure 12 Charcoal influx (125-250µm size fraction; in units of pieces/cm²-yr) for BPMA, MKZM and NOIS, shown with common x- and y-axis scales.

MKZM influxes fluctuated over the past 1500 years, with periods of increased values at 1650 to 1800 CE and 1200 to 1350 CE. The highest influx in the MKZM record occurs at ~400 CE. This corresponds to the broadest increased influx at BPMA in the last 2000 years. Prior to 550 CE, and particularly between 100 CE and 500 CE, woody charcoal influx is high relative to most of the record. Between 100 and 500 CE, larger influxes of herbaceous charcoal influx persist and are low prior to this period.

At NOIS, small fraction charcoal influx has been at or above median and increased slightly over the past 50 years. Influxes were higher between 1875 and 1970 CE, preceded by 300 years of low influxes except for an increase at ~1750 CE. The highest influxes occurred between 1400 and 1550 CE. While BPMA and MKZM both exhibit overall lower influxes of over the past 200 years, NOIS influxes over that same period have been higher in both relative and absolute terms.

3.3.4 Western Oregon charcoal influx calibration

The number, size and distance to sediment core locations varied greatly across the study area, with the largest number of individual charcoal loading vectors in the southeast, decreasing to the northwest (Figure 13). The magnitude of the individual vectors was highly varied as well, with maximum values associated with the LOST site, the highest of which is 13.6. These high magnitude vectors are derived from the mapped Tillamook fires, which burned the watershed in 1933 and occurred repeatedly from 1929 to 1945. This is the only site which has been burned over out of the 11 included in this study during the temporal range of the fire data. These same fires are represented by vectors at the TAYLOR site 40 km to the Northeast of LOST. A single larger vector at LITTLE is attributable to the Oxbow fire of 1966 in the Siuslaw National Forest.

The Willamette Valley sites (Lake Oswego, Porter Lake, and Beaver Lake), the sites in the

foothills adjacent to the valleys (Battleground Lake and Warner Lake) and Little Lake are notable for the relative absence of recorded fires during the recent historical period.

The Western Cascades sites were within 80 km of far more fire events. Many of these events were fires of the high Cascades to the East, however a substantial number of fires occurred at closer distances. At BPMA, vector directions were primarily 45° (NE) to 180° (S). At MKZM, directions spread more widely from 22° to 200° and at NOIS, there was bifurcation between NE and SW oriented directions. The Warner Creek Fire of 1991 contributed to the second largest *FI* value in our analysis at NOIS.

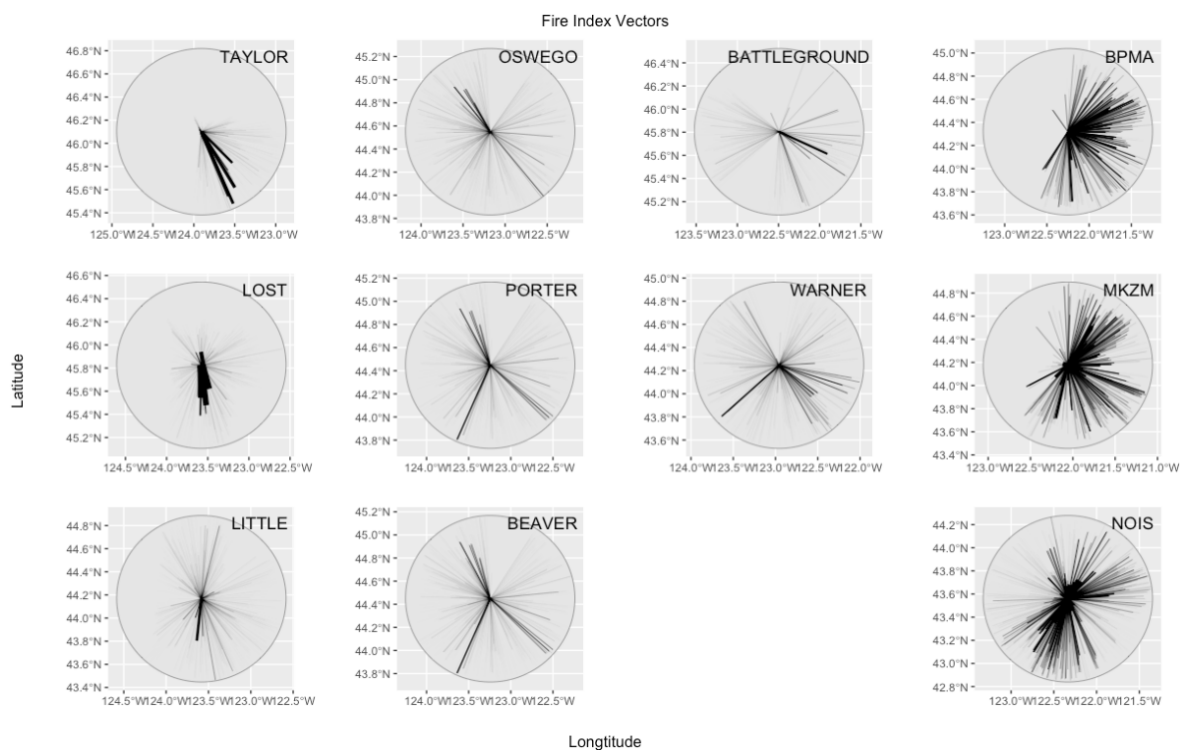


Figure 13 All charcoal loading vectors for each core site location within 80 km of the site, represented by variable width lines. Length of the line and compass direction are untransformed. The width of the lines varies with *L*, and is log transformed for visualization. Sites arranged roughly by geography (see Figure 4).

The summed magnitude of charcoal loading vectors (*FI*) has generally very poor correlation with the variation in charcoal influx at each site, with certain exceptions (Figure 14).

The Lost Lake record's highest sustained influxes from the 1875-2020 CE time period were

assigned the age of 1933 by the original author (Long, 2003) and in our analysis. At Taylor Lake, the same large fires correspond to an abrupt rise in influx. This increase in flux was not accompanied by an increase in sediment accumulation rate according to our reevaluated age model. At all Coast Range sites (Little, Lost and Taylor), influxes increase again after ~1950 CE and vary greatly. Influxes are highest at Little Lake and decrease northward to Taylor Lake.

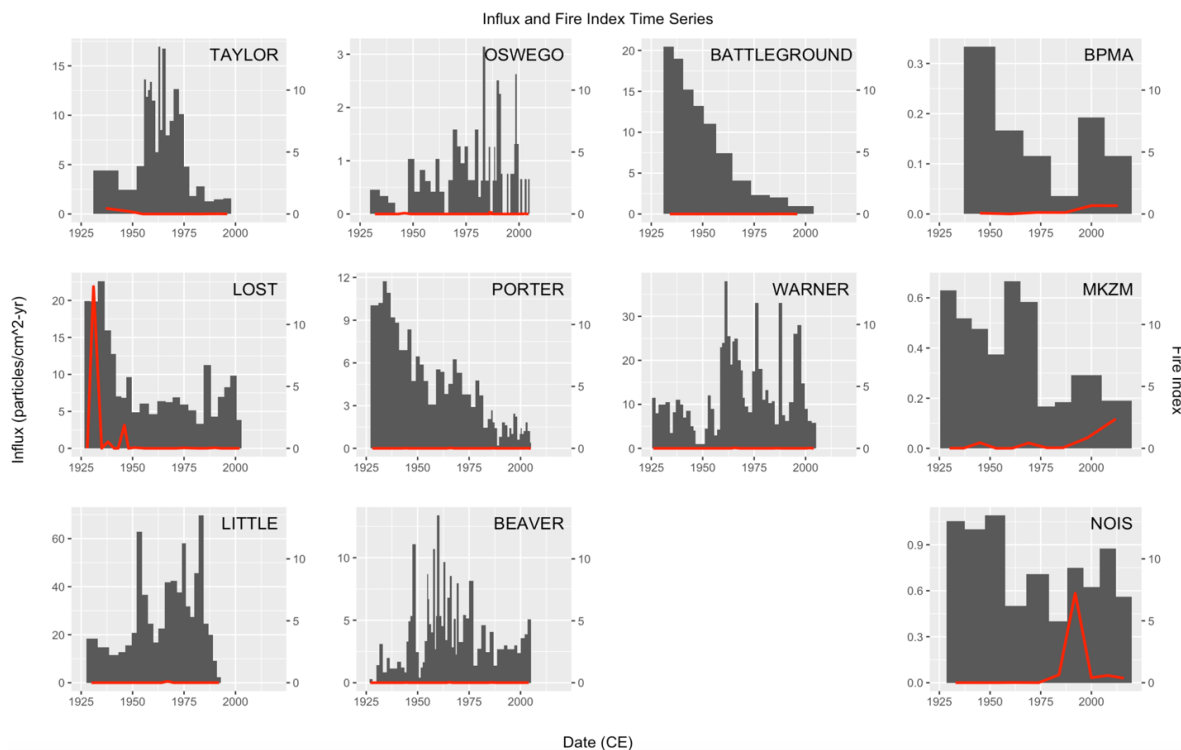


Figure 14 Comparison of charcoal influxes and fire index at all sites from 1925-2019 CE. Charcoal influxes (gray bars) are plotted as variable widths corresponding to the modeled ages of the top and base of each sediment subsample. Fire index (red line) is the sum of all charcoal loading from fire events, calculated with Equation 2, which occurred during the age interval of each core section. Field burning which began ca. 1940 and continues to the present is not represented in this figure.

The Willamette Valley sites (Beaver, Porter, and Oswego) all show a higher density of small fraction charcoal influx after ca 1940 CE. This increase is mitigated at Porter Lake where influxes in the decades prior to 1940 CE were primarily 6-12 particles/cm²-yr, followed by an increase to over 9 particles/cm²-yr in the years after ca 1960 CE. At ~1940, however, a reversal in the multi-decadal decreasing trend occurs. At Beaver Lake slightly lower influxes (1-3

particles/cm²-yr), rose to >10 particles/cm²-yr after 1940. At Porter and Beaver Lakes, increased influxes subside for the remainder of the 20th century. Lake Oswego exhibits a similar pattern, however, the increase in influx is much lower relatively, peaking at 3 particles/cm²-yr, and while overall influxes decline, high sediment accumulation rates result in greater inter-sample variation. Virtually none of this variation can be attributed to wildland fire activity as indicated by FI.

At the foothills sites (Warner and Battleground), the low recent wildland fire is common with Willamette Valley sites. Decreasing influxes characterize the Battleground Lake site. Warner Lake influxes increase substantially after 1960 and high influxes recur for the following decades, although overall and peak influxes primarily decline toward the early 2000's.

West Cascades sites' (BPMA, MKMZ, NOIS), temporal resolution is low in the meadow and small ponds but still show similar trends. Influxes decrease overall. In the past 40 years, *FI* values increased at all three sites, with corresponding increases in the small fraction influx. MKZM has the most consistent increase, while BPMA is elevated to a lesser degree. *FI* is much higher at NOIS in the date range that includes 1991, due to the Warner Creek fire which burned >2600 acres several kilometers to the North. This fire was driven by a southwest-wind event, thus it may not be represented in the NOIS record. MKZM is the only one of the West Cascade sites cored after the 2020 Labor Day fires of western Oregon and Washington. The site lies 10 km to the east of the Holiday Farm fire, which was driven by a strong east-wind event, again suggesting it may be unrepresented by charcoal influx.

3.4 Discussion

3.4.1 Historical Fire Regimes of the West Cascades

I find across my West Cascades sites sedimentary charcoal time-series that exhibit

substantial changes in both variability and central tendency through time and between sites. This general observation corroborates a growing body of literature indicating historic wildland fire in the wet forests of the Pacific Northwest is highly variable through time and occurs at a range of severities and extents (Dunn & Bailey, 2016; Johnston et al., 2023; Sensenig et al., 2013). At the local (1-3 ha) scales represented by these small sites (Calcote, 1995; Prentice, 1985), landscape patterns may be muted relative to local history, however, this theory has been more thoroughly tested with respect to pollen dispersal and preservation than charcoal. Pollen and charcoal dispersal differ greatly in their underlying physical mechanisms. In particular charcoal is injected into the overlying air column during fire events in proportion to the fire's radiative power (Higuera et al., 2007), which is tightly correlated with fire severity and size.

Moreover, the size class analysis we present here provides additional information regarding the 'localness' of biomass burning leading to charcoal arrival at the core site. Previous work suggests that our medium- (250-500 μm) and large- (>500 μm) fraction charcoal is unlikely to be transported more than a few hundred meters from the edge of even a large fire (Clark, 1988; Ohlson & Tryterud, 2000), while small fraction charcoal (125-250 μm) may be transported 10 to over 100 kilometers (Vachula, 2020; Vachula et al., 2018), and is most densely deposited at a distance from the fire which is dependent upon plume height (Clark, 1988). Given this understanding, I infer the combination of high small fraction influx and the coincident, elevated presence (concentration) of medium and large fractions indicate large, severe fires which either encompass or come within a few hundred meters of the core site.

At BPMA, this theory of charcoal transport suggests that large, severe fires have occurred during at least five periods in the last 2000 years, the most recent two periods may be constituted by as many as five separate events (Figure 9, Figure 12), indicating a mean fire return interval

(MFRI) of 250-400 years. Additionally, non-zero medium and large fraction concentrations between the local maxima suggest that these time periods were not fire-free but rather may contain low or moderate severity fires occurring nearby. Recent work by Johnston et al. (2023) using dendrochronological fire-scar evidence from similar montane forests document MFRI of non-stand replacing fires at 30 years. Due to the relatively coarse temporal resolution of the BPMA record (>15 years/cm) resolving the return interval is not possible, yet this evidence supports the inference of similar dynamics.

Correspondence between BPMA and MKZM small fraction charcoal influx chronologies suggests some events and patterns are expressed in common reflecting the long-distance transport of small fraction charcoal. Yet, substantial differences contrast the two sites which are separated by 26 kilometers map distance and nearly 1000 m in elevation. BPMA is a montane sedge peatland, where spring snowpack shortens fire season and favors montane tree taxa, primarily *Abies amabilis*. MKZM is a low elevation river valley morainal pond, currently dominated by large-diameter *Pseudotsuga menziesii* and *Thuja plicata*. Due to the shallow aquatic sedimentary environment, it is difficult to rule out sediment mixing as a possible mechanism muting high influxes by spreading accumulated charcoal out in the chronology, however the peak influxes at MKZM are 6-7 times less than BPMA. Higher concentration of medium and large-fraction charcoal during periods of elevated small-fraction influx at ~1720 and ~1250 CE could be interpreted as large, severe fire episodes. However, the drastically lower influx does not support this inference, and I interpret this as a lack of strong evidence for any large, severe fire events of the kind recorded by BPMA sediments in the past 2000 years.

MKZM influxes of small fraction charcoal are lower than BPMA, however, medium and large fraction charcoal concentrations at MKZM are much higher relative to small fraction

concentration than at BPMA. I infer from this that for most of the last 2000 years, regular fire occurred within several hundred meters of MKZM until shortly after 1750 CE. Due to the lack of strong temporal patterns in medium and large fraction charcoal, I also infer these fires likely occurred at intervals that were below the sediment accumulation rate of 15.6 years/cm. The substantial influx of small-fraction herbaceous charcoal supports the inference of high frequency, low severity fires. This pattern is compelling given that herbaceous charcoal dispersal and deposition is likely to be more diffused – with larger source area and less proximity influence – across space than woody charcoal (Vachula & Rehn, 2023).

Comparison of BPMA and NOIS, the higher elevation sites, addresses and is informed by a hypothesized geographic difference in fire regimes between the southern and northern Oregon Cascades forests that lie between the two sites at or around the divide between the Middle Fork Willamette River and the McKenzie River drainages. To the extent that lower small-fraction charcoal influx indicates lower biomass burning in the vicinity, the records from BPMA and NOIS suggest less biomass was burned at NOIS than at BPMA. Yet, interpretation of the NOIS record in light of the highly varied fire regime of this area (Johnston et al., 2023), and in light of the location of the NOIS site in a wet meadow 300-400 m above the forest with more frequent fires, requires additional consideration. While large, severe forest fires could be expected to loft small fraction charcoal into the convective column, smaller moderate or low-severity fires would not exhibit this phenomenon. Thus, if moderate and low-severity fire make up a substantial portion of total biomass burning within the charcoal source area, the small-fraction influx may not be lofted to higher elevations. Insofar as this model holds, our data support the expectation that fire frequency decreases from south to north between NOIS and BPMA.

The notion that wildfire patterns may be synchronized by large-scale climatic events and

patterns is widespread (Marlon et al., 2008; Reilly et al., 2022; Weisberg & Swanson, 2003b; Zybach, 2003). Increases in influx at BPMA, MKZM and NOIS at ca. 1750 CE are evidence of synchrony of large-scale wildfires which correspond to climatically-driven fires, determined by tree-ring analysis, reported across the same region (Weisberg & Swanson, 2003b). The most prominent increase in charcoal influx at NOIS between 1450 and 1550 CE, however, does not correspond to elevated influxes at BPMA or MKZM. Walsh et al. (2010), however, report four small-size-fraction charcoal peak-over-background events in the same period at Warner Lake, and Tepley et al. (2013) showed near MKZM the occurrence of a widespread Douglas-fir age class between 1460 and 1610.

Blair Lake, 33 km to the north, of NOIS, has similarities in small-fraction influx with the NOIS record Cox (2016). Blair Lake a pair of charcoal influx peaks at ~500 cal yr BP (ca. 1500 CE), and no peaks since other than a small, recent peak likely associated with the Warner Creek fire (1991 CE). Due to both the presence of herbaceous and medium and large fraction charcoal between 1450 and 1550 CE at NOIS, and the widespread age ca. 500-year old Douglas-fir age class in this region, we believe this is evidence of severe, fires, burning near these lake sites and elsewhere.

In summary, these three sites show a variety of fire histories. BPMA shows a history of severe fires on multi-centennial intervals but also with more frequent smaller fires. At MKZM, no large severe fires occurred, but herbaceous charcoal and consistent but low levels of large-fraction charcoal suggest low or moderate severity fires must have occurred in the region, consistent with Douglas-fir old growth dominance in the valley-bottom location.

At NOIS, frequency of large, severe fires is not possible to estimate due to the length of the record. Consistent influx of small fraction charcoal over the last 500 yr is consistent with the

frequent-fire regime found by (Johnston et al., 2023). Furthermore, lack of medium and large fraction charcoal after 1500 CE suggest even low and moderate severity fire were rare within several hundred meters of the site.

3.4.2 Evidence of Natural and Intentional Biomass Burning in Charcoal Records

The relatively modest explanatory power we observe in the fire history-charcoal influx comparisons from western Oregon and Washington raises a question: what biomass burning patterns and events are recorded in sediments of nearby depositional environments? This issue is more easily dismissed or overlooked when the purpose of paleoecological reconstruction is focused on broad centennial to millennial scale patterns of biomass burning. In western Oregon, over the past <100 years, I observed two internally consistent patterns deserving attention.

The first pattern is that of Willamette Valley small-fraction influxes (Figure 15). The valley floor and surrounding foothills have been notably devoid of large-scale wildland fires during the past 100 years. Yet, relatively high, sustained influxes at Porter Lake and to a lesser extent, Beaver Lake mark these records. Lake Oswego, 100 km to the north, does not exhibit this pattern. Initiated by growing plant pathogen issues in the Willamette Valley in the 1940s, field burning was rapidly adopted starting in 1948 (Conklin, 1970). By 1968, when regulations and the first permitting system were established, over 300,000 acres were burned. Due to public health concerns, the practice was slowly reduced after 1988, to ca. 50,000 acres, and then in 2009 limited to 15,000 acres in areas near Salem, OR.

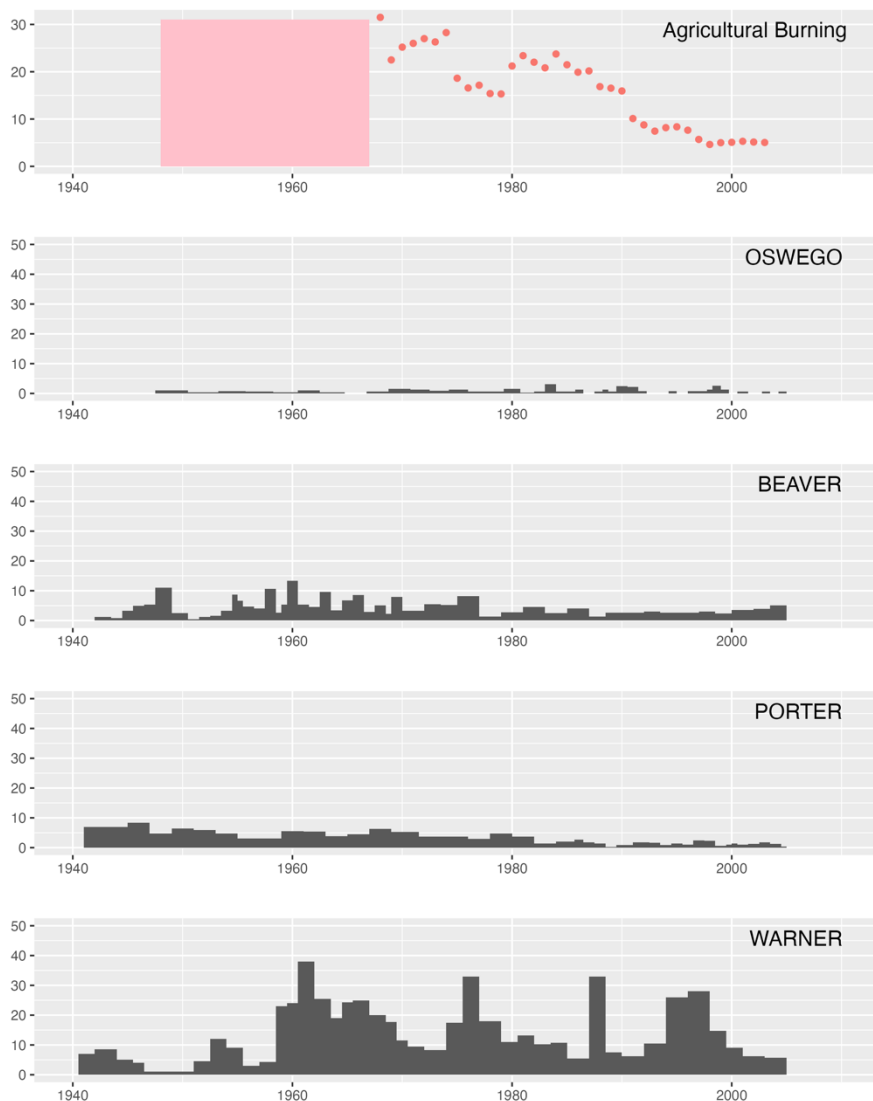


Figure 15 Relationships between agricultural burning and charcoal influx in Willamette Valley cores. Top: Field burning acreage in the Willamette Valley. Widespread burning from 1948 to 1967 was not documented and shown here as a red rectangle. Oregon Department of Agriculture issued permits beginning in 1968. Shown in units of 10,000 acres. Charcoal influx from Oswego, Beaver, Porter, and Warner are plotted on a common y-axis scale. North (Oswego) to South (Warner) influxes increase toward the geographic center of grass seed production in central Lane and Linn counties. Sustained influxes are most prevalent during the period of intense field burning.

There is strong correspondence between this historical trajectory and the fully radiometric (Pb^{210}) age-depth chronology of small fraction influx at Beaver Lake (Figure 15). The original age-depth model for Porter Lake (Walsh et al., 2010), 13 km to the south of Beaver Lake, was based on a single ^{14}C date, and thus the model was linear from present. Given the strong relationship of

Beaver Lake charcoal chronology to the field burning history, the close proximity of the two lakes, and the prevailing observation that aquatic sediments exhibit non-linear sediment age-depth curves approaching the sediment water interface, I placed an additional age control of 1968 CE (37 ± 5 years before coring) at the average depth (45.5 cm) of the sample with the maximum charcoal concentration in the series of elevated influx samples. The resulting charcoal chronology (Figure 15) for Porter Lake matches both the Beaver Lake record in overall pattern, and both the history of initiation and the post-1968 CE decline in acreage burned.

This exercise has utility in that it demonstrates key characteristics of sedimentary charcoal with respect to biomass burning both in the Willamette Valley and in grasslands in any geographic context as the combustion of field stubble likely better resembles the fire dynamics and charcoal production of low severity prescribed or cultural fire than high severity forestland fires. Despite the short map distance separating Warner Lake from the valley floor, its influx chronology does not reflect the history of field burning, suggesting that despite the spatial extent, the convective plumes of these fires were insufficient to inject even small fraction charcoal high enough to cause a response. The specific locations of each acre burned is not known, although it is possible that archival research might provide some further insight.

The second feature of Western Oregon paleofire records I observe in the recent charcoal chronologies relates to Coast Range, foothill, and West Cascades sites (Figure 14). At these sites, a combination of inflections in the age-depth relationships and periodic increases in small-fraction charcoal concentration result in patterns explained by neither the historic fire records nor the Willamette Valley field burning history. Since the early 20th century, it has been common practice to dispose of logging slash first through broadcast burning (Kraemer, 1979), and then pile burning as the risk of escaped fire was better recognized (Morris, 1934). To my knowledge, no specific

records of broadcast or pile burns are available to quantitatively address this charcoal source, all the sites in this analysis are within areas that are currently in clear-cut rotation or have been during the past several decades. While estimation of this charcoal source is theoretically possible through aerial photography analysis and estimates of slash production per area harvested, such an analysis is beyond the scope of this work.

Although I have examined recorded wildfire with sedimentary records here, any biomass burning has the potential to produce charcoal which may be transported to sediment sites. This component of sedimentary charcoal records, routinely contained within the concept of ‘background’ charcoal (Higuera et al., 2007; Long, 2003; Whitlock & Larsen, 2001), is primarily considered to be a feature to be controlled for through statistical transformation to decompose time series of charcoal accumulation in order to identify peaks which can be considered large fire events or fire episodes. Given the responsiveness we observe in these sedimentary archives, spatially explicit quantitative assessment of slash burning would benefit calibration of sediment records of biomass burning particularly with respect to moderate and low severity fires which remain enigmatic in pre-history.

3.4.3 Tuning Age Controls for Calibration of Existing and Future Records

The iterative way we constructed age models for the new and existing sedimentary sites presented here using not only the radiocarbon dates, but also known events in fire history of the area presents an important contribution to the practice of sedimentary paleoecology. The increasing necessity of calibrating sedimentary archives to modern observations of natural and anthropogenic phenomena in general and biomass burning in particular, can be supplemented through incorporating dendrochronological (Higuera et al., 2011) and historical (Long, 2003) data sets. For

example, dendrochronological estimates of fire dates may in some cases be unambiguously matched to sediment charcoal peaks and thus provide a basis to modify age model development. This approach may yield refinements to age control that are of routine difficulty due to cost, difficulty in developing precise age estimates, and in interpreting the charcoal proxy. When possible, independent age control such as radiometric isotope dating techniques is highly desirable, however, as the reuse of data of legacy studies becomes more common, utilizing alternatives may be necessary. At the time of many of the previous studies I utilize in this paper, age-depth modeling did not easily incorporate multiple sources of age information. The advent of flexible age modeling approaches such as the Bayesian process I used (Blaauw & Christen, 2011), render these combinations routine. When the purpose of analysis is to establish the best understanding of how natural and anthropogenic phenomena and proxy evidence relate in sedimentary archives, failing to utilize alternative age-control from environmental history and other paleoecological archives would risk misinterpretation.

Conducting sediment age-depth modeling in an iterative manner is crucial. I recommend that independent age control always be added first. Working backward in time is highly desirable, adding the oldest potential age-controls first. Great care is needed to utilize historical and independent paleoecological information including additional sediment core-derived information. Core lithology and data which inform sediment source inference such as magnetic susceptibility are useful to avoid unsupported changes in sediment accumulation rate. Sediment accumulation rates are uniquely important as even small inflections in these rates can produce large effects on calculated influx values that are essential to establishing physical and mathematical relationships between proxy data and real phenomena.

3.4.4 The Inter-Site Comparability Problem, Sedimentary Charcoal Source Area, and Charcoal Transport in Relation to Fire Events

Study sites similar to those we present for the West Cascades have been the subject of previous paleoenvironmental studies. Sub-alpine peats (Hope et al., 2020; van der Knaap et al., 2011) and small-hollows such as studied by Crausbay et al. (2017), have been shown to provide reliable, continuous chronologies. Our results expand on the growing number of studies which are emphasizing the importance of understanding how charcoal records in sedimentary archives represent fire regimes and patterns through time not only at individual sites, but across landscapes and environmental gradients. Yet comparison of even similar sized sites such as BPMA and MKZM presents clear challenges. This problem is exacerbated when comparing charcoal influx recorded in a peat deposit such as NOIS with the lake sediment record of Blair Lake (Cox, 2016), or my small Western Cascade sites with the small lakes of the Coast Range. Firstly, influxes are upward of an order of magnitude different, with lakes exhibiting the larger influxes. It is not justified to infer that there is an equivalent increase in biomass burning from this observation. The existing theory of particulate proxy evidence whether exogenous (e.g. charcoal, pollen) or endogenous to the depositional environment (e.g. diatom tests), is that lake area and morphometry of the lake basin and the bathymetry of the lake bottom have some relationship to observed influx, potentially magnifying influxes as transport is focused to the deepest part of the sedimentary basin. This suggests there is some continuum of sediment focusing in lakes, but this process has not been applied to collections of sites like the one I present here. Peat deposits are the extreme end of this continuum, with an effective basin size of the sediment core longitudinal area.

The most widely used method to coerce different sedimentary archives to comparability is to statistically transform charcoal data (Power et al., 2008; Walsh et al., 2015) or express pollen as

percentages. However, quantitative reconstruction necessary for interpreting proxy evidence in terms of units relevant to neoecology and environmental management relies on the absolute influxes. Many other studies have confirmed that peaks in charcoal accumulation could be linked to fire events within a source area, which has variously been identified as the watershed of the sedimentary site, a 7 km radius (Whitlock & Millspaugh, 1996) or over 100 km (Vachula et al., 2018) and the size fraction evidence I present here provides additional insight.

Yet, no established method exists for normalizing charcoal influx by basin characteristics, which is necessary to compare influx values to a common, independent variable such as my fire index (*FI*). This is a crucial and unrealized step in developing quantitative reconstruction of biomass burning and other paleoenvironmental information relying on proxy evidence contained in sedimentary abundance of identifiable, aurally deposited particles.

3.5 Conclusions

Assembly of records across wet forests west of the Cascade Mountain Range indicates several important insights into the nature of wildland fire in these forests. Large fires are not unprecedented; these events have occurred in both wetter and drier areas throughout the Holocene. The periodicity of these events for the last 3 ka has been on the order of 200-500 years. In addition, by differentiating charcoal size fractions and biomass source from sites in the West Cascades, I found substantial evidence of low and moderate severity fires occurred at or below the temporal resolution of the sediment cores. We also find that the past ~250 years has been characterized by low charcoal influx corresponding to the decline in ignitions and fire suppression – separating this period from the remainder of the last 2500 years. Improvement in estimation of biomass burning related to agriculture and forestry operations is needed to further understand the dynamics of low

and moderate severity fires in the sedimentary charcoal records of western Oregon and other landscapes with similar land use histories.

IV

EAST CASCADES RANGE HOLOCENE STAND STRUCTURE AND COMPOSITION

What does Holocene vegetation community structure and canopy openness of East Cascades dry pine forest suggest about changes in post-glacial fire regimes?

Can vegetation structure be inferred from sedimentary pollen assemblage?

4.1 Introduction

Historical fire severity in mixed conifer and ponderosa pine dry forests of the Pacific Northwest and its implications for forest composition and demography has become a contested subject in recent years (Fulé et al., 2014; Hagsmann et al., 2018; Williams & Baker, 2014) with implications for setting management targets (Spies et al., 2018). The dominant view of the pre-European settlement fire regime in this ecosystem, supported by tree-ring dated fire-scar studies, is of frequent (<15-year interval) low severity fires which maintain park-like stands of large diameter ponderosa pine (*Pinus ponderosa*). In contrast, a controversial study of Williams & Baker (2012) based on novel interpretation of settlement-era land surveys suggests large areas of high-severity stand-replacing fires in the ponderosa pine zone. Other scholars have found that intermittent moderate-to-high severity fires occur in virtually all seral stages in the ponderosa pine ecosystem although the evidence is not conclusive for Oregon (Johnston et al., 2016).

Attempts to reconstruct the pre-settlement era fire regime with fire history derived from the analysis of tree-rings depend only on living trees thus introducing bias toward sites where old trees have survived past disturbances (Hessburg et al., 2007). Companion historical techniques use strip survey records from early forest inventories in the late 19th and early 20th centuries (Hagsmann, 2013); but these records, although spatially and temporally precise, are also sparse in both time and space. Together, these lines of evidence have pushed our knowledge of forest structure and fire

regime toward a nuanced understanding of landscape structure and topographic effects (Hagmann, 2013; Johnston et al., 2017; Merschel et al., 2018a). However, projecting these insights beyond the late Holocene, toward a future that holds climate states dissimilar from those of the recent past, is a fundamental challenge to this research agenda (Mote & Salathé, 2010; J. W. Williams & Jackson, 2007). A well understood and tested method for mitigating this uncertainty is to expand the temporal frame of reference for understanding linked shifts in vegetation, fire, and climate. The analysis of pollen from lake cores coupled with sub-continental scale pollen-vegetation modeling to address this gap is one such approach. With this study, I build and examine a history of vegetation structure of ponderosa pine forest in the Eastern Cascade Range (hereafter, East Cascades) across the last glacial maximum (LGM) to the present. Given the well-understood response of vegetation structure to changes in fire frequency and severity (Hessburg & Agee, 2003; Johnston et al., 2017; Merschel et al., 2018a), and the perceived inability for charcoal records to adequately preserve fire events from a frequent low-severity fire regime (Whitlock & Larsen, 2001), in this study I take a forest-structure approach (i.e. pollen-based vegetation reconstruction) rather than focusing on evidence of fire in sedimentary charcoal (e.g. Whitlock & Larsen, 2001). Infrequent stand-replacing fires would show evidence of both shade-tolerant taxa and early successional shrub taxa, but frequent low severity fire would have a more constant representation of pine and an understory without the shade-tolerant component. This approach is tested in a calibration study by comparing surface pollen assemblages with the surrounding vegetation, where I employ the REVEALS model, a statistical method for estimating landcover from pollen assemblage data (Sugita, 2007a). Specifically, I ask:

- 1) What is the scale at which pollen records land cover?
- 2) How has forest vs open vegetation changed and what can be inferred about the

fire regime from this pollen record in the context of the scale represented by the pollen record.

To address the first question, I employ a spatial analysis of surface sediment pollen (Whitmore et al., 2005) and forest structure as represented by imputed, continuous global nearest neighbor estimates of vegetation (Ohmann & Gregory, 2002) to evaluate the spatial representation of pollen across a continuum of vegetation cover types. I use this analysis to inform the interpretation of a new sedimentary pollen record of vegetation located in the ponderosa pine zone of the East Cascades in Oregon.

4.2 Methods and Materials

4.2.1 Site Description and Environmental Setting

The high-desert plateau east of the Cascade Range crest is characterized today by a persistent rain shadow created by the adjacent mountain range (Figure 16) that resulted from the tectonic and volcanic history of the Eastern Pacific margin. This topographic context predates the Quaternary, and orogeny continues to the present day. North Twin Lake (NTL; N 43.7273°, W 121.7658°) and South Twin Lake 1.5 km to the south are true volcanic maar lakes located in the Deschutes National Forest, Oregon, USA, believed to have been formed during a period of increased volcanic activity at ~20 ka⁵ (Cashman et al., 2009; Dean & Bradbury, 1993; Peterson & Groh, 1963). Existing, highly permeable soils of the surrounding area developed on dacite pumice and rhyolitic deposits of the Mt Mazama and Newberry Caldera eruptions in the last <10 ka (Volland, 1988), and topography is characterized by broad shallow basins interrupted by basalt scarps and numerous cinder cones and buttes.

⁵ Kilo-anum (ka) signifies thousands of years before present.

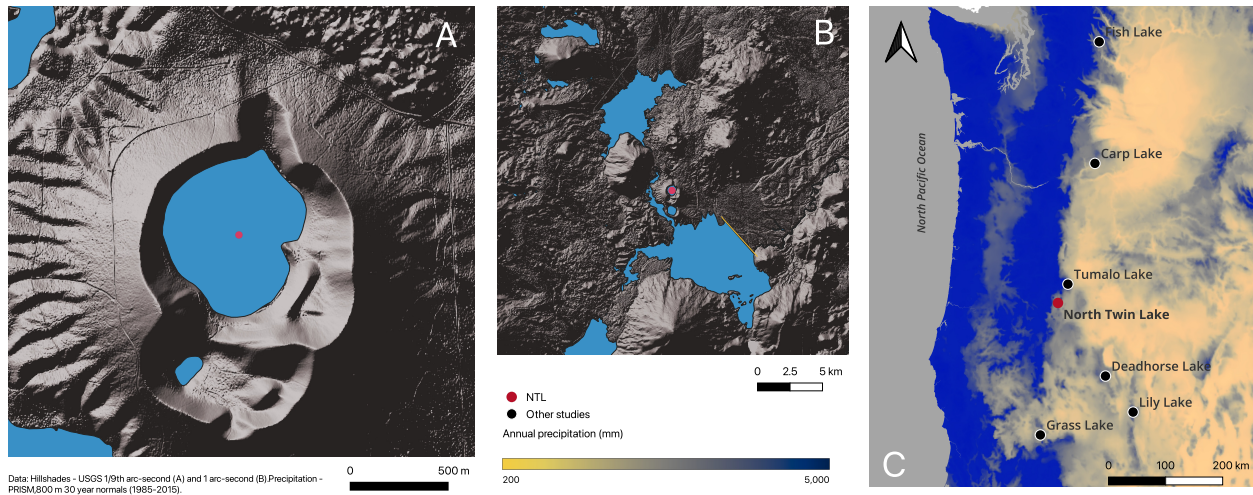


Figure 16 North Twin Lake (NTL, A) site level and (B) local topography represented as hill shade, and (C) regional climate context with other nearby sedimentary pollen-based reconstructions of vegetation east of the Cascade crest and characterized by the topographically defined precipitation gradient toward the North Pacific Ocean.

NTL lies at an elevation of 1,324 m above sea level within the East Cascades Slopes and Foothills Level III Ecoregion (Sorenson, 2012; US EPA, 2015). Climate normals 1991-2020 from the US National Oceanic and Atmospheric Administration (NOAA) station at Wickiup Dam (Elevation 1328 m, N 43.6825°, W 121.8687°) show mean annual temperature is 7.5 °C and mean temperature of the warmest and coldest month are 18.2 °C and -1.4 °C respectively. Mean annual precipitation from the same station is 49.6 cm. which nearly all occurs from October to May. Mean precipitation June-September is low (<1.25-2.5 cm/month) and is associated with convective storms which bring moisture from the south. A large contribution to annual precipitation falls as snow with 188 cm mean annual accumulation, primarily from November to April.

Dominant vegetation associations of the area, botanically referred to as Pumice Zone associations, are linked primarily with tree species *Pinus ponderosa* and *Pinus contorta* or dry mixed-conifer forest types and understories of *Purshia tridentata*, *Artemisia tridentata*, *Ceanothus* and *Poaceae* (Volland, 1988). Yet, a considerable variability in tree canopy density and understory shrub and ground cover – both with respect to taxa present and relative abundances – characterizes

the zone. Seasonal wetlands and ephemeral lakes, which form during snowmelt, are common in the surrounding area and riparian and emergent taxa associated with these locations are numerous sedges and forbs.

NTL has a small watershed and no inflowing streams (Figure 16), however, the volcanic substrate is porous indicating a high degree of subsurface hydrological connectivity. The local area is known for the numerous small to medium size lakes, as well as two large reservoirs with impoundments that may have substantially impacted subsurface flow and water table height after their construction. In the margin of NTL, I observed small diameter stumps and standing stems which substantiate the notion that water table heights changed by 1-2 m in the recent past. Dense forest canopy begins 5-10 m from the edge of the lake with a narrow band of emergent vegetation, primarily *Carex* and Equisitaceae.

4.2.2 Physical Core Collection and Measurements

We cored NTL in September 2016, retrieving an 80-cm-length short core with a 5-cm modified piston-corer to preserve the sediment water interface; and parallel 5-cm Livingstone cores to a depth of 560 cm. Water depth measured physically during coring at the core location was 1695 cm. The short core was sub-sectioned in the field at 1 cm, and long cores were returned to the lab and split into halves longitudinally. The working half was sub-sectioned at 0.5 cm, and the remaining half was wrapped in plastic and archived. Above the Mazama tephra layer, long cores produced 143 cm of highly organic sapropel with distinct alternating bands that permitted correlation between parallel core drives. Final, continuous stratigraphy was accomplished with a combination of visual correlation utilizing the banded sediment layers for all long core drives, and continuous magnetic susceptibility of the lower short core and the upper long to link collected

sediments from sediment water interface to core base. I used loss-on-ignition (Heiri et al., 2001) to estimate proportion organic matter and carbonate content every 5 cm in short and long cores. In the long core I measured sediment physical properties to quantify visually observed stratigraphic patterns. Sediment density was assessed with computed tomography (CT), measured at OSU Lois Bates Acheson Veterinary Hospital at a resolution of 0.25 mm. High resolution imagery was obtained with a GEOTEK-XZ line-scan camera at OSU Marine and Geology Repository at 0.1 mm resolution.

4.2.3 Radiocarbon and Age-Depth Modeling

Large, identifiable organic macrofossils for radiocarbon dating are rare in the NTL cores, particularly where organic matter is very low in the lower core. We thus used a suite of techniques to select organic matter in sufficient quantities and with the desired properties with respect to the carbon cycling in lakes. We initially collected some scarce, identifiable wood and charcoal particles ($> 250 \mu\text{m}$ size fraction). In addition, we extracted pollen from sediments using a modified approach to the methods used by LacCore (<http://lrc.geo.umn.edu/laccore/assets/pdf/sops/AMSPollen.pdf>), for depths in the lower core. The majority of materials submitted for radiocarbon age analysis were bulk sediment carbon. We submitted a single bulk sediment sample from core drive NTL II-b, which included the boundary between the well-dated Mazama tephra and the underlying sediment to verify that aquatic food web cycling or carbonates from groundwater springs would not lead to systematic overestimation of radiocarbon age. I submitted 10 samples for radiocarbon analysis to the Woods Hole Oceanographic Institution's National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS; <https://www2.whoi.edu/site/nosams/>). All samples were cleaned with HCl and KOH,

dried at 40° C and sealed in new 15 ml test tubes prior to submission.

I modelled the relationship between sediment age and depth below the sediment-water interface using a Bacon 2.3.0 (Blaauw & Christen, 2011), a Bayesian autoregressive gamma process package implemented in R (R Core Team, 2020). Bacon accepts radiometric and alternative age control points as well as priors for sediment accumulation rate, which can be adjusted at significant inflection points to best represent the shifts in sediment accumulation, measured in cm/year, which can occur as response to various environmental events and patterns. Bacon natively estimates these accumulation rates at equally spaced intervals, determined by the length of the core and number and distribution of age control points used.

I used standard model run parameters (4000 iterations and prior distributions for accumulation rate and sample-to-sample predictive memory), accepted to produce robust estimates of age uncertainty. I defined ad hoc boundaries in accumulation rates at 300 and 385 cm, and supplied accumulation rate priors of 45, 65, and 20 yrs/cm to the resulting 3 core sections. I verified model performance by the qualitative assessment of prior distributions and model results.

4.2.4 Pollen Extraction, Identification and Analysis

I subsampled sediment volumes of 1.0 cm³ for pollen extraction at 10-15 cm intervals for much of the continuous stratigraphy, with additional samples in the upper 20 cm and above and below the Mazama tephra. I extracted pollen from 48 subsamples using an augmented process (available at <https://pages.uoregon.edu/dgavin/sop/>) similar to standard procedures detailed in Faegri et al. (1989), including acid-base-acid, acetolysis, and treatment with hydrofluoric acid to reduce high silica content.

At least one tablet containing *Lycopodium* spores was added to each sediment subsample

prior to extraction and pollen samples were stained with safranin after extraction to facilitate identification. Extracts were blended with silicone oil and slides prepared with free cover slips to allow rotation of pollen grains during identification. I identified a minimum of 500 individual pollen grains at 250x and 400x magnification on a Leitz Laborlux light microscope fitted with a calibrated graticule. I tallied additional aquatic palynomorphs and charcoal particles in two size fractions: >63 µm and <63 µm. I categorized grains to the lowest possible taxonomic level matched to the common pollen taxa from the Neotoma Pollen Database (NPD, <https://www.neotomadb.org>).

I calculated sedimentary pollen concentration of pollen taxon i (C_i , grains/cm³) as the product of tally of individual pollen grains (T_i), the inverse of the tally of *Lycopodium* exotic taxon (T_e), the known quantity of *Lycopodium* spores (Q_e) and the inverse of the subsample volume (V_s).

$$C_i = \frac{T_i}{T_e} * \frac{Q_e}{V_s} \quad (3)$$

Taxon-specific pollen percentage (P_i) is calculated as quotient of the tally (T_i) and terrestrial sum (S_T) of all pollen terrestrial pollen taxa tallies (T_t), where $S_T = \sum T_t$. The terrestrial pollen taxa (T_t) exclude palynomorph spores and taxa predominantly associated with wetland or riparian environments.

$$P_i = \frac{T_i}{S_T} \quad (4)$$

In addition, I calculated pollen influx as the time-averaged measure of pollen arrival intended to correct pollen-based vegetation estimates of taxa (Faegri et al., 1989). The influx calculations relied upon final age model-determined variations in sample-to-sample average sediment accumulation (cm/year) rate over time. Influx of each taxon (I_i , grains/cm²-year) was

calculated as product of the pollen concentration (C_i) and the average sediment accumulation rates (r_{acc}) at the average stratigraphic depth of the sediment subsample.

$$I_i = C_i * r_{acc} \quad (5)$$

Pollen assemblage, as multivariate observation of each terrestrial pollen percentage, was used to separate pollen time series into discrete zones with a stratigraphically constrained cluster analysis (CONISS, Grimm, 1987). Additionally, I assessed concentration, percentage and influx values with semi-quantitative methods and descriptive statistics and compared to ecologically similar sites in California, Oregon and Washington (Figure 16c).

4.2.5 Pollen and Vegetation Structure Relationships

I examined pollen-vegetation relationships through regional lake and pond sediment-surface pollen (Whitmore et al., 2005) and local vegetation-cover estimates from remote-sensed vegetation products in the form of Gradient Nearest Neighbor (GNN) structure maps created by the Landscape Ecology, Modeling, Mapping and Analysis group (LEMMA, <https://lemma.forestry.oregonstate.edu/>). 391 surface pollen sites correspond to the GNN modeled area north of 40° N (Figure 17). These data are produced by imputation of United States Forest Service Forest Inventory and Analysis program (FIA) plot data to continuous surfaces of forest composition and structure attributes with observed relationships to remote-sensed topography and landcover at 30 m resolution for Washington, Oregon and California (Bell et al., 2023; Ohmann & Gregory, 2002).

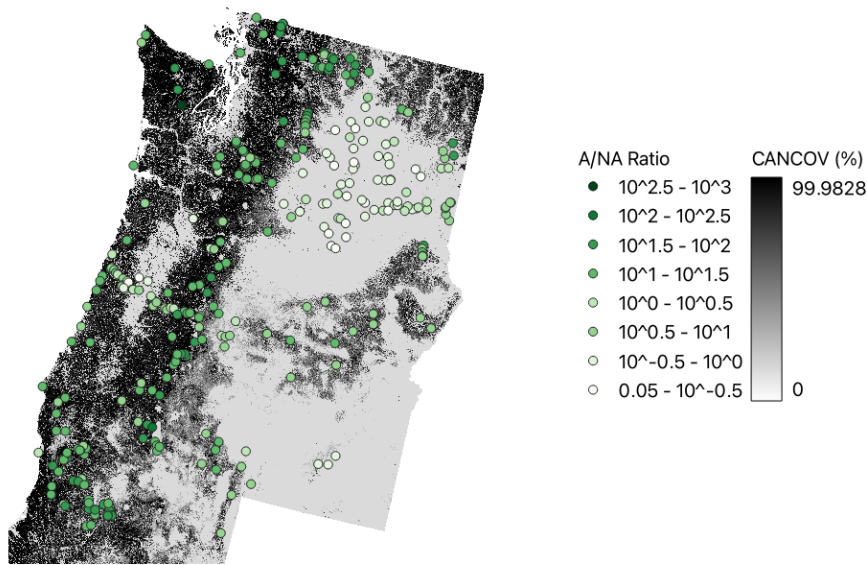


Figure 17 391 pollen surface-sample sites (Whitmore et al. 2005) that overlap the GNN model area (Bell et al. 2023). These sites include lakes, ponds, soil and moss pollsters. Points are symbolized by arboreal-nonarboreal pollen ratio (A/NA). Background is GNN tree canopy cover (CANCOV).

Pollen in surface sediments has been shown to exhibit significant relatedness to remotely-sensed vegetation cover products in other contexts (e.g. McLauchlan et al., 2007) and varies spatially with vegetation within the regional context of the Pacific Northwest (Minckley & Whitlock, 2000; Wanket, 2002). I assess the relative openness of vegetation structure with two approaches common to paleoecological research: a simple a pollen ratio index and a quantitative vegetation reconstruction using the REVEALS model (Sugita, 2007a). To create the pollen ratio index, I examined relationships between arboreal forest canopy pollen taxa (e.g. *Alnus*, *Quercus*, *Pinus*, *Abies*, and *Pseudotsuga*) and shrub and herbaceous pollen taxa (e.g. *Poaceae*, *Rosaceae*, and *Artemisia*), as the indicators of canopy openness given the observed inverse relationship between dense canopy cover and understory and ground cover in dry pine forests of the interior western United States (Abella & Springer, 2015). To accomplish this analysis, I assign each pollen taxon to a single morphological category: one of arboreal, shrub, or herbaceous (Table 6, Appendix

III). I calculate summed percent non-arboreal taxa (T_{NA}), where T_{NA} is equal to the sum of pollen percentages for primarily herbaceous and shrub taxa. Summed percent of associated arboreal taxa (T_A), where T_A is equal to the sum of observed pollen percentages of primarily arboreal taxa. I then calculate an arboreal-nonarboreal normalized difference pollen ratio as an index of canopy openness (O_p):

$$O_p = \frac{T_{NA} - T_A}{T_{NA} + T_A} \quad (6)$$

I estimated quantitative relative cover of pollen taxa with the REVEALS model (Sugita, 2007a) implemented in R (Theuerkauf et al., 2016). REVEALS makes use of taxon-specific pollen fall speed and relative pollen productivity estimates to determine what percent cover of each taxon on the landscape can produce the pollen assemblage observed in a sediment sample. Moreover, REVEALS accepts error terms associated with pollen parameters and estimates the error of model predictions. To model REVEALS estimates of vegetation cover at surface pollen sampling sites, I adapted taxon-specific pollen productivity and fall speed parameters from Wieczorek & Herzschuh (2020). No parameter estimates are available for PNW-specific taxa, thus for all high abundance taxa ($> 0.5\%$), I selected global average parameter estimates for common pollen taxa (Table 6, Appendix III). For less abundant taxa ($< 0.5\%$) where taxon-specific parameter estimates were not available, I employed a stratified approach by applying a) phylogeny to assign nearest-related taxon estimates to each unassigned taxon, and then b) mean values of parameter estimates of taxa with similar pollination strategy and growth habit where no close relative was available. These estimates of pollen representation are a source of considerable uncertainty as they are gleaned from studies of sites and taxa in China, eastern North America and Europe and thus are not specific to the pollen taxa found in my study region. However, these parameter values are routinely used in

vegetation reconstructions not local to the taxa and environments from which they originate, and have been shown to function in a variety of environments including California (Klimaszewski-Patterson et al., 2018; Knight et al., 2021), the Northwest Alps (Julien et al., 2025), Czech Republic (Mazier et al., 2012), and across the Northern Hemisphere (Dawson et al., 2024). For REVEALS model runs I used parameter settings of GPM as “unstable” due to the selection of lake sedimentary environments⁶, and I set the basin diameter to 100 m to reflect the small lakes and ponds sampled. 1000 model runs were completed, and the results generate error estimates of pollen cover from the error associated with pollen parameters.

I subset surface pollen sampling locations (Whitmore et al., 2005), within a group of Level 3 Ecoregions that contain mixed conifer, ponderosa pine and sagebrush steppe. Other surface sample types such as moss polsters will over-represent local taxa compared to lake sites, which contain a higher proportion of regionally dispersed pollen. Therefore, I only used lake surface sediment samples in this analysis, yielding 83 sites across northern California, eastern Oregon and Washington (Figure 18). This subset of sites approximates the climate space which sets up the vegetation gradients between dry-mixed conifer and sagebrush to most closely evaluate relationships of pollen representation with GNN estimates of forest structure relevant to NTL.

⁶ The GPM (Global Pollen Model) has two settings, stable and unstable, which are designed primarily to be used at small sites such as forest hollows or bogs (stable) and large sites such as lakes (unstable). This setting modifies the pollen dispersal algorithm employed in the model runs.

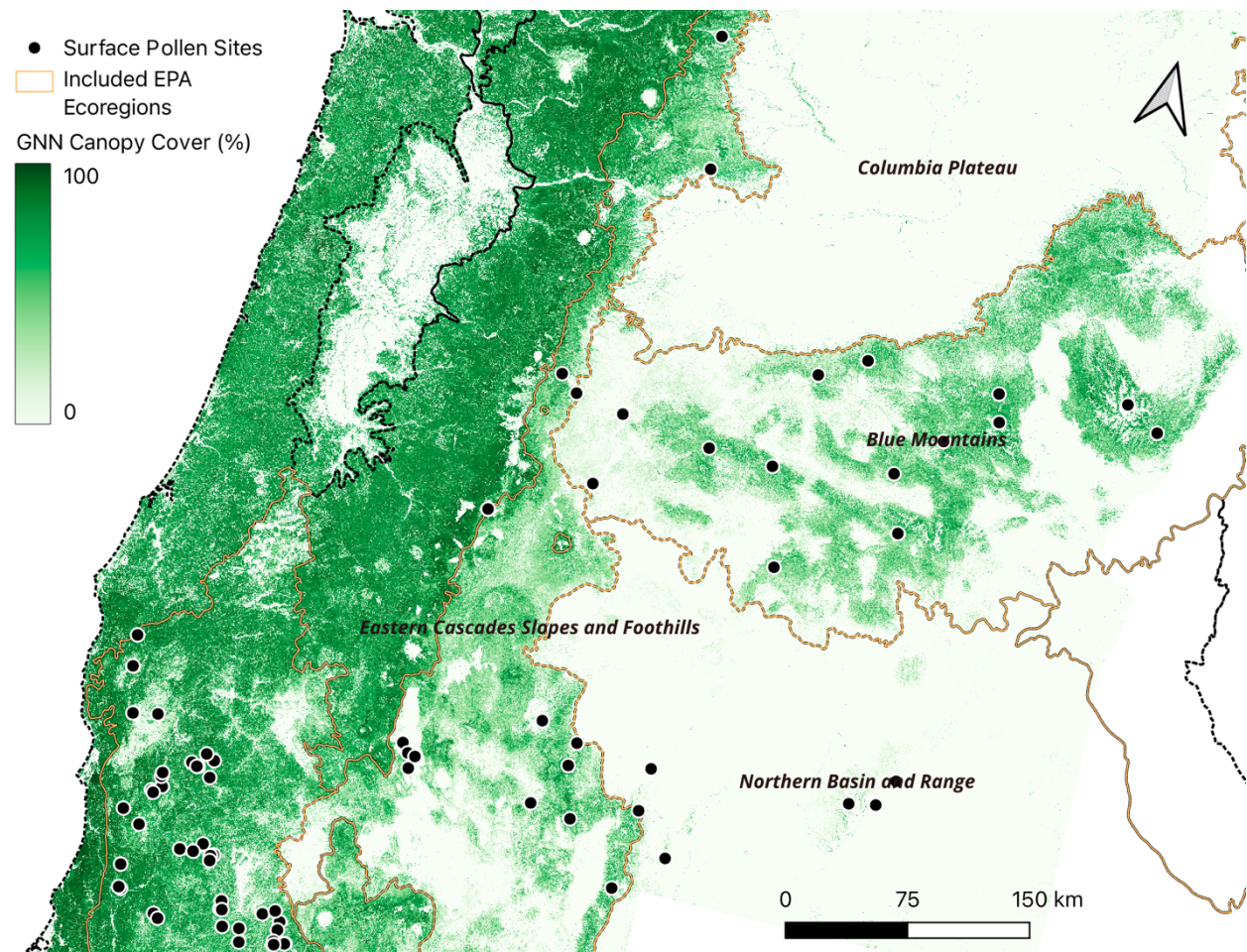


Figure 18 Map of GNN canopy cover (%), locations of the subset of surface pollen sites used in this analysis, and boundaries of US EPA Level III Ecoregions used to isolate the subset shown.

I calculated the REVEALS estimate of taxon-specific percent cover and O_p at each site. To both validate pollen-based cover estimates and assess pollen representation, I perform a source-area analysis with respect to mean canopy cover within circular zones ranging from 5 km to 150 km and Gaussian kernel-weighted means defined by the standard deviation of normal distribution (σ) distances of 10-150 km. I refer to these calculations as zonal mean cover and focal mean cover. The weights matrix for the distance-weighted focal mean extended to a distance of 2σ , thus ignoring the outermost margin of the Gaussian distribution. All extractions were performed on GNN maps, resampled to 270 m grids and projected in NAD83 Albers Equal Area. I evaluate the

pairwise relationships between pollen-derived estimates of vegetation (REVEALS and O_p), and canopy cover (zonal mean and distance-weighted mean) to understand the spatial extent of pollen representation and thus help gauge the spatial representation of forest structure history contained in sedimentary records across this temperate sub-region. I model these relationships with ordinary least squares (OLS) regression at each distance (radius and σ) primarily to assess the strength and nature of these relationships and evaluate each model for spatial autocorrelation of residuals with a Moran's I test performed using the MASS package in R (R Core Team, 2020).

4.2.6 NTL Vegetation Cover Chronology Modeling

I apply both the arboreal-nonarboreal normalized-difference pollen ratio (O_p) and REVEALS to the NTL pollen record. I follow an approach identical to the one described above for the surface pollen dataset in assigning pollen taxon-specific parameters (listed in Table 7, Appendix III). The atmospheric REVEALS parameter (GPM) for the NTL runs was “unstable” as described above, however, I assigned a basin diameter of 500 m, approximately the diameter of the lake surface at present (Figure 16).

4.3 Results

4.3.1 Physical Core Characteristics

I recovered 560 cm of sediment from NTL. Clear patterns in the measured physical properties of the NTL core identifies a rapid shift in sediment composition at 280 cm depth (Figure 19). From the core base upward to 280 cm, the core was characterized by interbedded coarse sand (>0.5 mm) and fine mud layers of varied thicknesses. Sediment density as measured by computed tomography (CT) is high and variable. Rapid oscillations between ~1000 and 1600 HU correspond to the interbedded layers, identifying the fine layers as the highest densities, and the coarse layers

as lower density materials. These layers were perpendicular to the longitudinal axis of the core to a depth of 440 cm, below which they were progressively angled relative to the cross-sectional plane indicating our basal depth approached the initial infilling of the volcanic crater. An 8 cm gap at 420 cm was the result of misaligned parallel core drives. Above 420 cm there is a decrease in overall density, central tendency and range to 350 cm. This is followed by a rapid decrease in both variability and central tendency over the next 70 cm upward. Above 280 cm, density is low (200-250 HU) and decreases slowly to a minimum at 60 cm, followed by a slight increase to 50 cm. This upper section is characterized by highly organic sapropel with distinct alternating bands of lighter and darker sediment which varied from 0.5 to 1.5 mm thickness. The Mazama tephra, from 241 to 143 cm, consisted of coarse primary deposition fining upwards for an additional 5 cm of pumiceous sand to volcanic ash. The lower bound of Mazama tephra was abrupt.

Loss-on-ignition (LOI) is very low ($<3\%$) from the core base to 400 cm. Above 400 cm, values increase in variability without substantial changes in central tendency to 360 cm. From 360 cm to 320 cm LOI increases to 17% and then declines to 3% before increasing rapidly over the following 40 cm. Values above 280 cm are high, with most values between 40 and 50%, intermittent abrupt decreases to 8-15%, and a generally increasing trend. The highest values of LOI recorded in the core are above 60 cm, and the abrupt decreases in the upper core occur at 110 cm, 60-50 cm and 10 cm.

Visual spectrum color saturation of red, green and blue bands (RGB) are highest in the lower core, with substantial range of variation and oscillations between low and high at intervals which correspond to alternating fine-coarse layers in CT data and visual assessment of the core. Red, green, and blue bands exhibit synchrony in trend pattern, however red is more saturated, followed by green and then blue generally lowest. Exceptions occur at the lowest values, where the

green band reaches lower saturation than blue at several minima. Variability in all three bands generally decreases from the core base to 400 cm. Above 400 cm central tendency of all bands shift higher to 380 cm. Over the following 100 cm all bands exhibit reduction in variability accompanied by a decrease in saturation between 320 cm and 300 cm. From 300 cm to 280 cm, blue is lower than green and red by the largest margin in the core and approaches the lower values that characterize the rest of the upper core. Above 280 cm, all bands approach a common saturation to the Mazama tephra (224 cm). Above Mazama, variability in all three band remains low, although their central tendencies spread apart progressively to the top of the long core at 50 cm.

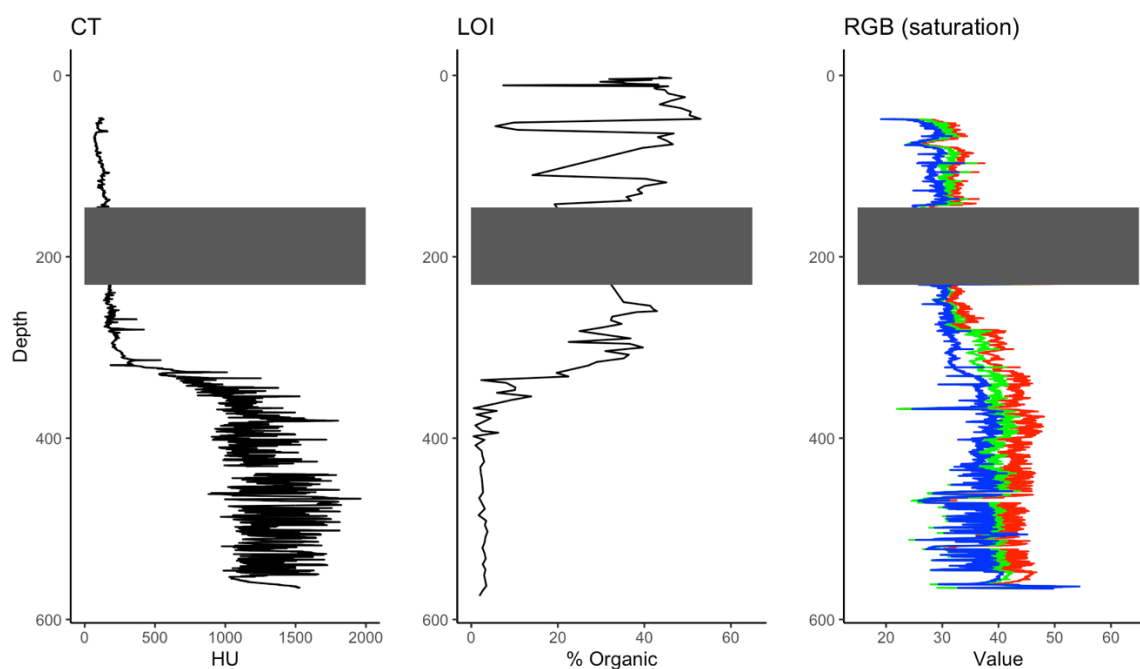


Figure 19 NTL physical core characteristics plotted on a depth axis. Sediment density estimated by CT measured in houndsfeld units (HU), LOI represents an estimate of percent organic matter by mass. RGB saturation is a percentage value indicating the strength of the red, green and blue bands extracted from digitized core imagery. Gray rectangles indicate the depths of the Mazama tephra.

4.3.2 Radiocarbon and Age Modelling

I developed the age-depth model for the NTL core in Bacon 2.3.0 (Blaauw & Christen, 2011), a flexible Bayesian framework employing an auto-regressive gamma process which permits

estimation of age error continuously along a stratigraphy. The initial age model was constructed with eight radiocarbon dates ranging from 1590 ± 20 to $15,300 \pm 450$ 14C yr BP (Table 5). Apart from an age reversal between dates at 392 cm and 458 cm, all dates conform to the expectation of increasing age with depth.

The sample submitted to assess reservoir effects on bulk sediment returned a radiocarbon age of 7310 ± 40 14C yr BP, which corresponds to calibrated date 95% confidence interval of 8184-8022 cal yr BP with no clear central tendency in the probability distribution (Figure 33, Appendix III). The Mazama tephra age is most precisely estimated at 7633 ± 25 14C yr BP, suggesting an age offset of 350-700 years.

Table 5 Radiocarbon results used for age model development of the NTL core. All samples analyzed at Woods Hole Oceanographic Institute. Depth in centimeters below sediment water interface; type of sample submitted; uncalibrated age as estimated by accelerator mass spectrometry direct counts of ^{14}C atoms; and error of count estimated by both counting statistics and replication. The age for sample 163360, marked with an asterisk () is the sample analyzed to check for carbon reservoir effects.*

Lab Code	Depth (cm)	Sample Type	Uncalibrated Age (cal yr BP)	Estimated Error (SD)
196057	29	Sediment Organic carbon	1,590	20
169239	51	Pollen Fraction	3,610	85
196058	80	Sediment Organic carbon	5,660	30
163360	125	Sediment Organic carbon	7,310	40
196059	231	Sediment Organic carbon	8,760	40
163359	264	Plant/Wood	10,250	250
166890	293	Sediment Organic carbon	10,550	85
196061	392	Sediment Organic carbon	13,950	85
196060	458	Sediment Organic carbon	14,700	95
169241	549	Pollen Fraction	15,300	450

An additional tephra at 54 cm is likely a Rock Mesa tephra given that it also occurs in Gold Lake 15 km to the West (Baig & Gavin, 2023). The date of this tephra is uncertain, but it is most likely 2743-2850 cal yr BP (Skinner & Radosevich, 1991), and the mean modeled age of this depth in the NTL core is 2666 cal yr BP (Figure 34, Appendix III). This date is not incorporated into the age model. Given the probable reservoir effect, Mazama is included in the final age model as

independent age control (Figure 20).

The age model log of objective (Figure 20, Top Left), indicates model integrity is high due to the lack of pattern across the 4000 iterations, total accumulation rate (top-center of figure) falls within the range of model priors, and memory strength (top-right) is shifted slightly positive relative to the prior.

Mean modeled accumulation rates were low in the lower core with median values of 8-11 yr/cm. The boundary definitions (300 and 385 cm) allow model accumulation rates to inflect slightly, however, accumulation rates above 385 cm are relatively stable with median values ranging from 45-55 yr/cm (Figure 20, see also

Figure 35 and

Figure 36, Appendix III). Mean modeled basal age of the core is 19,280 cal yr BP with a 95% confidence range of 18,533 to 20,416 cal yr BP (Figure 34, Appendix III).

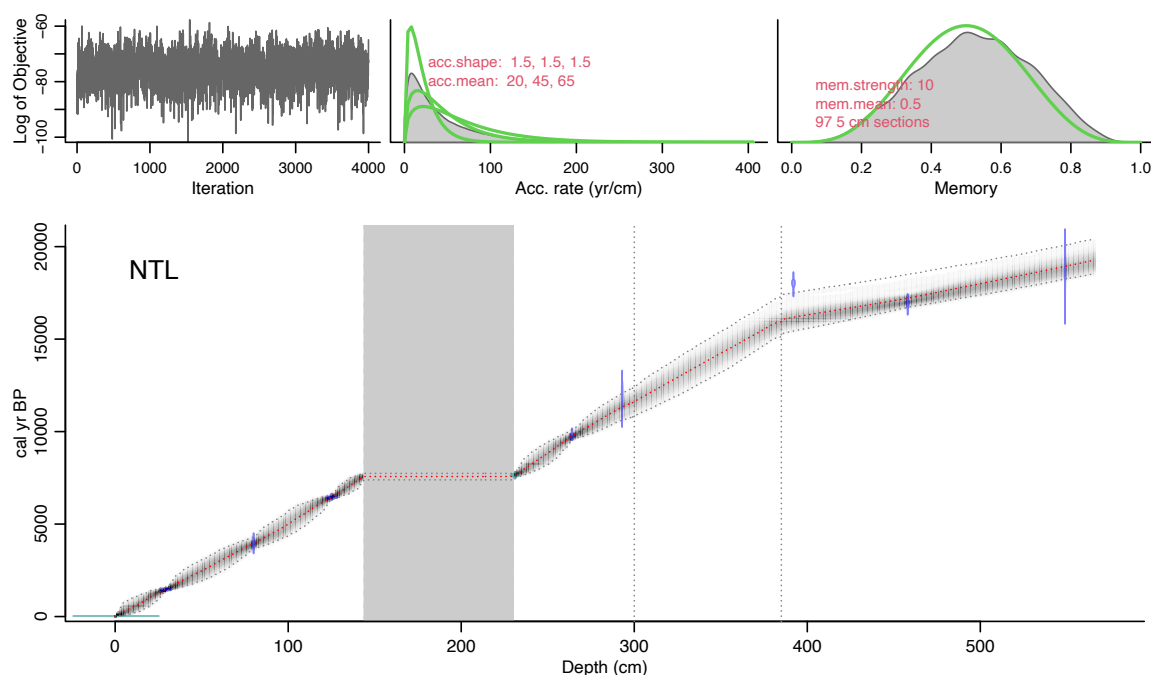


Figure 20 Age model generated with Bacon 2.3.0 (Blaauw & Christen, 2011), including eight radiocarbon dates and the dates of two well-known tephtras: Rock Mesa and Mazama. Top Left: log of objective test. Top Center: Modeled accumulation rate (grey fill), and priors (green lines). Top Right: Memory strength model results (grey fill), and prior distribution (green line).

4.3.3 NTL Pollen Record

Terrestrial pollen percentages for 38 samples have a mean modeled age from 17,280 cal yr

BP to 22 cal yr BP form the basis of the NTL vegetation reconstruction (Figure 21). The terrestrial pollen percentages are dominated by *Pinus* taxa, and the sum of all taxa in this genus does not fall below 41% throughout the duration of the record. Pollen preservation was highest in the last 5000 years, varied substantially in the NTL record, with generally increasing degradation with age. This pattern is most obvious in the relationship between percentage *Pinus undiff* (undifferentiable *Pinus* grains) and *Pinus* subg. *Pinus*⁷. The CONISS clustering algorithm of raw percentages by individual pollen taxa separates the record at the highest level of dissimilarity between modeled sample ages 15,150 and 13,380 cal yr BP. The second highest division occurs between 4,600 and 4,230 cal yr BP, driven largely by the increase in identifiable *Pinus* subg. *Pinus*. The remaining samples are differentiated most between 11,960 cal yr BP and 11,580 cal yr BP. It is notable, however, that the samples at 11,580 cal yr BP and 11,320 cal yr BP are distinctly identified by substantial dissimilarity from the samples younger than 9,515 cal yr BP.

The average pollen percentages of the oldest cluster of samples, from 17,280 - 15,150 cal yr BP, is defined by the lowest percentages of *Pinus* ranging from 43% to 61%. Several pollen taxon percentages in this section of the core exceed those otherwise observed in the record and are highly variable: *Picea* (8%-30%), Cupressaceae (0.6%-5%), Rosaceae (0%-3%), Asteraceae (1%-3%), *Artemisia* (5%-19%), and Other Herbs and Shrubs (OHS, 2%-6%). Pollen and charcoal influx are also very low in this section of the core, <1000 and <300 particles/cm²-yr respectively.

Following a 2,200-year gap in the pollen record between 15,100 to 13,300 cal yr BP, substantial changes in pollen assemblages are evident. In pollen samples after this gap, *Pinus*

⁷ *Pinus* subg. *Pinus* is a sub-genus division characterized by needle bundles of two needles. This sub-genus includes two species local to the NTL region currently: *Pinus contorta* (lodgepole pine) and *Pinus ponderosa* (Ponderosa pine). *Pinus* subg. *Strobus* refers to the sub-genus characterized by needle bundles with three to five needles, locally western white pine. Pollen of these two types can be identified accurately and differentiated when grains are well preserved.

percentages rose to the range (77%-90%) that characterizes the remainder of NTL record.

Concurrent declines in *Picea*, Cupressaceae, Asteraceae, *Artemisia*, and OHS, and a dramatic increase in pollen and charcoal influx are common to these samples.

CONISS identifies a shift the pollen percentages after 11,960 cal yr BP driven by a small decrease in *Pinus* (74%-81%), and increases in the relative abundance of *Picea*, *Psuedotsuga/Larix*, *Artemisia*, and OHS. Charcoal influx begins to increase consistently from this time, and pollen influx appears to be stabilizing at intermediate levels. Although the samples at 11,580 cal yr BP and 11,320 cal yr BP are clustered with those between 9,510 cal yr BP and 4,600 cal yr BP based on relative pollen abundances, pollen and charcoal influxes increase in magnitude and variability substantially after 9,500 cal yr BP. This trend in influxes is particularly strong in samples from 9,510 cal yr BP to 6,450 cal yr BP. After 6,450 cal yr BP to 2,400 cal yr BP pollen and charcoal influxes are much more uniform and intermediate in magnitude.

Approximately bisecting the ~4000 year period of stable influxes, CONISS identifies the uppermost cluster (4,230 cal yr BP-present), driven by the increase in identifiable *Pinus* subg. *Pinus* and *Tsuga heterophylla*, and a decrease in Cupressaceae and identifiable *Pinus* subg. *Strobus*. Immediately preceding this cluster, the sample at 4,600 cal yr BP contains the lowest relative abundance of *Pinus* in the last ~10 ka.

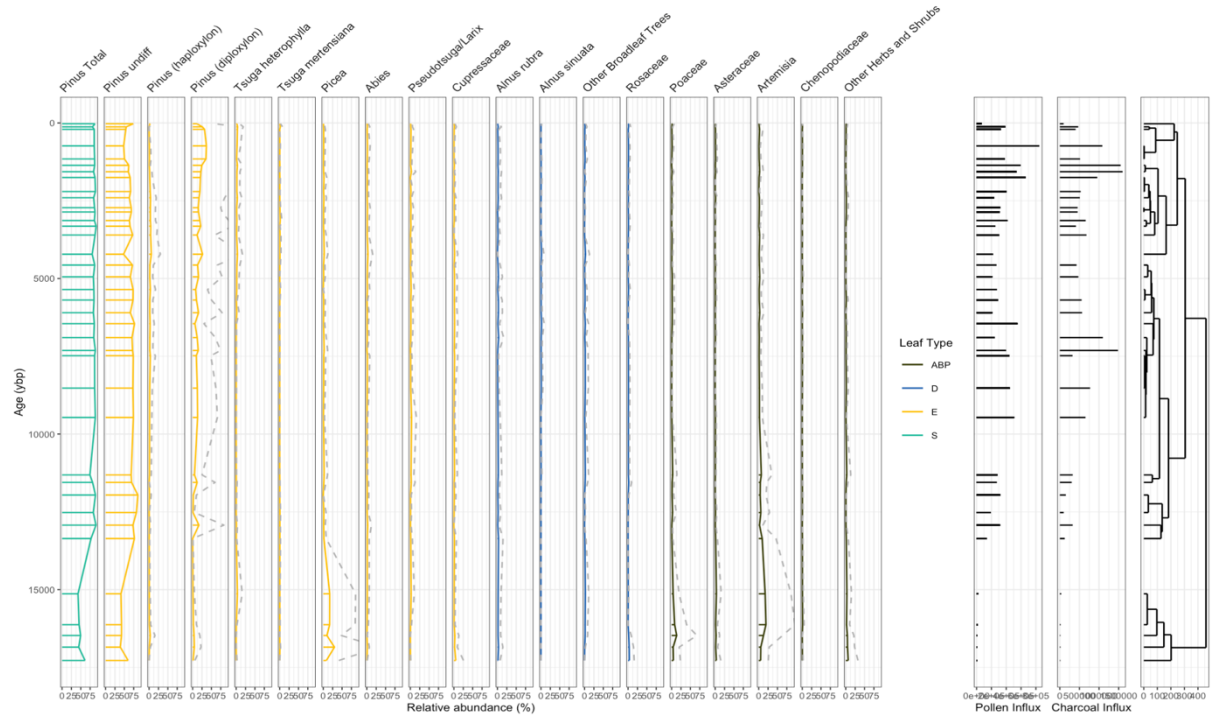


Figure 21 Terrestrial pollen percentages of major taxa ($>0.5\%$), and less common ($<0.5\%$) grouped taxa: Other Broadleaf Trees and Other Herbs and Shrubs. Taxa grouped and symbolized as: Pinus Total (S, light green, far left) is the summed percentage of all Pinus pollen taxa and is not included in the pollen sum. Evergreen trees (E, yellow), deciduous trees and shrubs (D, blue), and dry-adapted herbaceous and shrub taxa (ABP, dark green). Right panels: Total pollen influx (grains/cm²-yr), charcoal influx (particles/cm²-yr), and CONISS clustering of pollen percentages (excluding Pinus Total). 5x exaggeration of rare pollen taxa shown as dashed grey line. Charcoal and pollen presented in units of particles/cm²-yr.

4.3.4 Surface Pollen Relationships to Canopy Cover

The REVEALS estimate of percent arboreal cover and the pollen abundance-based openness index (O_p), calculated at the 83 surface pollen sites span a wide range, but the distribution of both metrics is highly skewed toward higher arboreal cover (Figure 22). REVEALS estimates of percent arboreal cover, however, include a greater proportion of the potential range of values (0 to 100%) than do the values of O_p , which may span between -1 to 1. O_p values range from -0.12 to 1, while REVEALS cover estimates range from 26% to 99%.

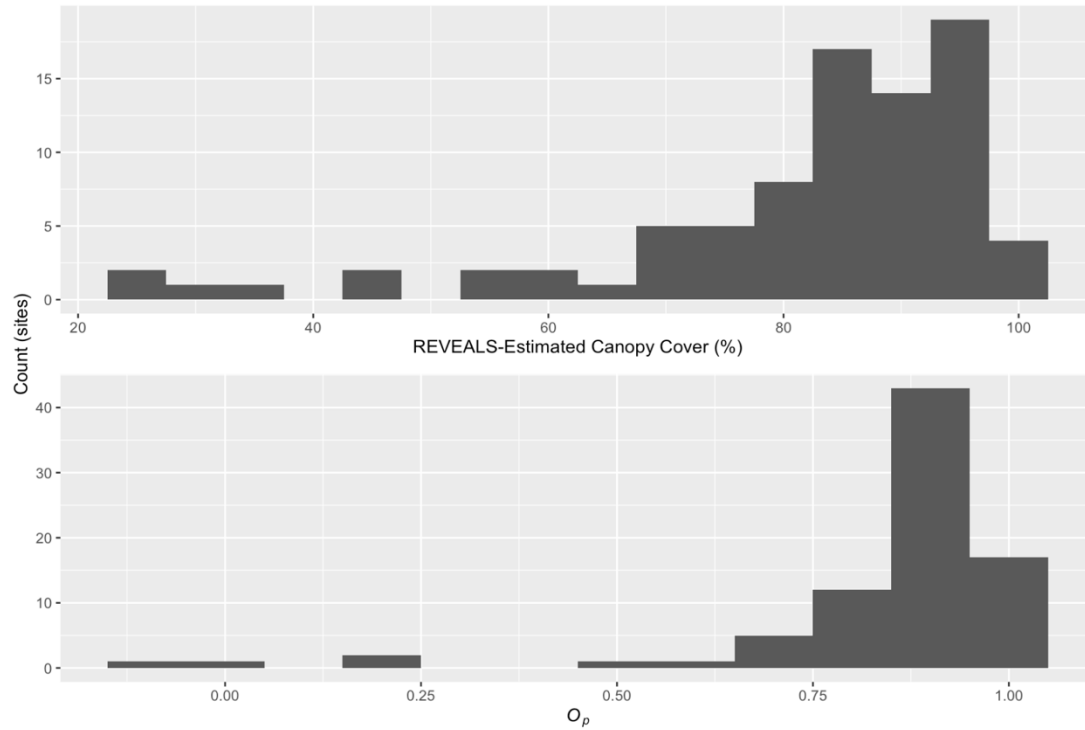


Figure 22 Distributions of pollen-derived metrics of canopy cover at the 83 sites selected from the North American surface pollen dataset (Whitmore et al., 2005). Top: REVEALS estimates of arboreal (evergreen and deciduous) cover (%), bin width is 5. Bottom: O_p , bin width is 0.1.

The distribution of Gaussian-weighted mean (focal) canopy cover at the surface sample sites is highly influenced by σ distance (Figure 23). At 10 km, the distribution is broad with a strong central tendency at 45%-55% cover. As σ increases, both high and low edges of the range are attenuated, although this occurs more quickly at higher values. Values concentrate in the 45%-55% range, and a bimodal distribution develops at intermediate σ distances, with concentrated values at 25%-20%. At high σ distances, the number of sites in the 45-55% range increases and forms the upper limit of the distribution which is skewed toward that upper range limit.

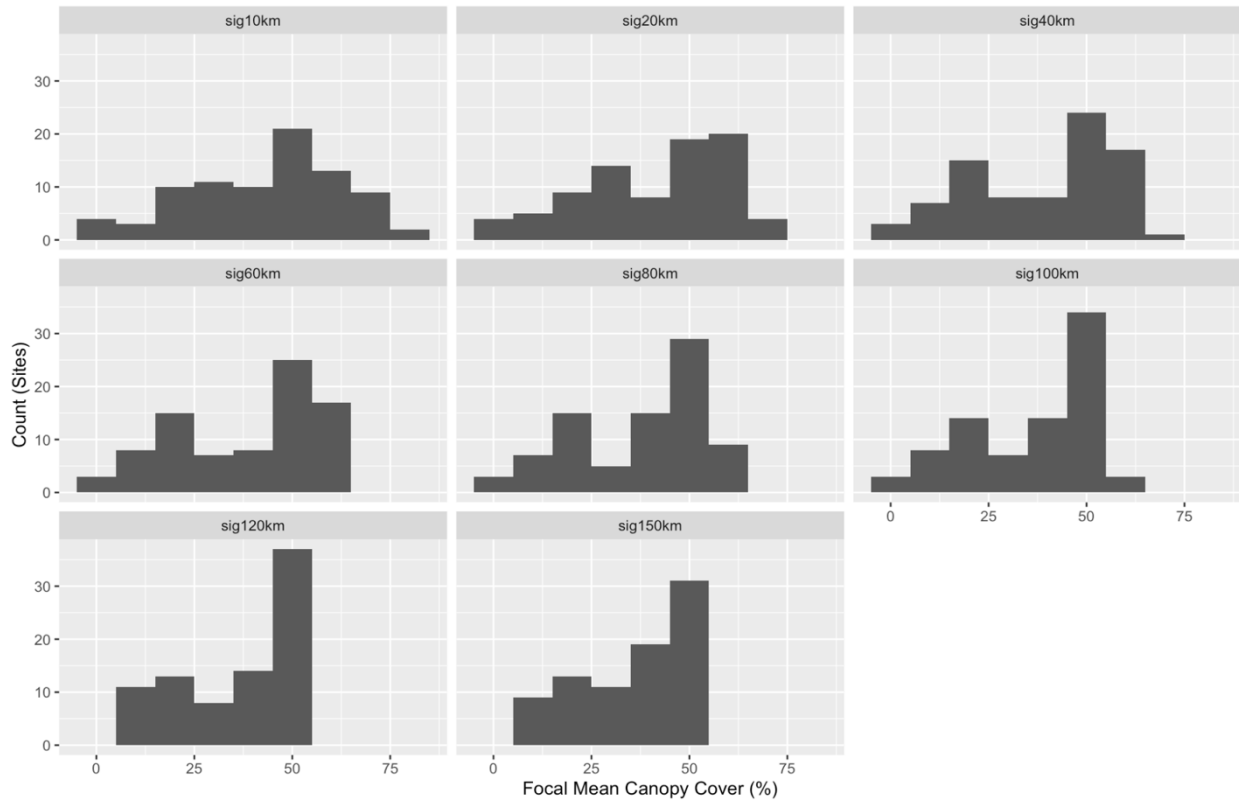


Figure 23 Distributions of Gaussian-weighted (focal) mean canopy cover (%) for the 83 surface pollen sites within a two-standard deviation (σ) distance of sample sites for eight values of σ , ranging from 10-150 km. Weights and extent of weights matrix defined by σ .

The range of zonal mean distribution of percent canopy cover is greatest at small radii and progressively decreases as the radius increases (Figure 24). At small radii (1-5 km) the distribution is bimodal with the dominant mode at 45%-55% cover and a substantial concentration of low (0%-15%) cover values. As the radius increases to 10 km the lower mode is attenuated, while the number of values at 45%-55% increases. Increasing the radius from 20 km to 50 km results in broadening of the central tendency in the upper range between 45% and 65%, and the formation of a secondary mode at 15%-20%. This pattern is only accentuated by further increases in radius.

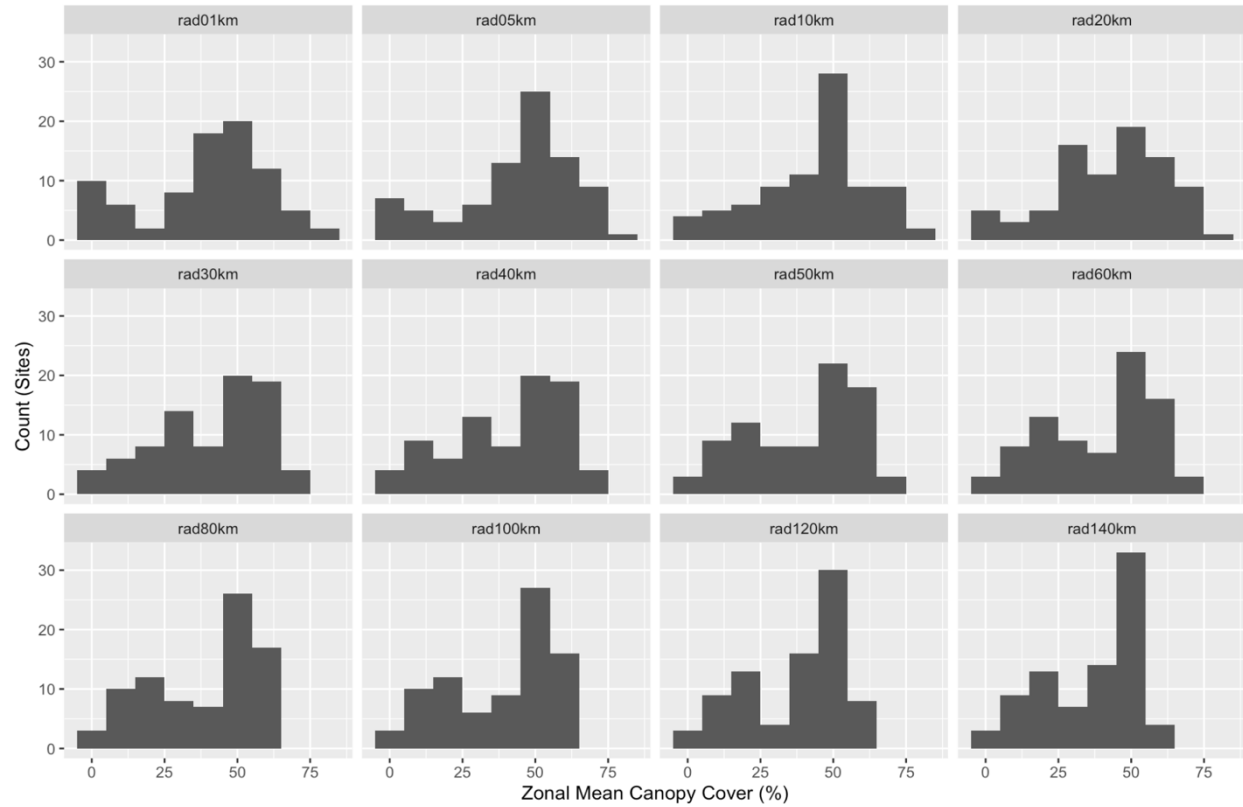


Figure 24 Distributions of mean (zonal) canopy cover (%) for the 83 surface pollen sites within circular areas defined by a radius (r) for 12 values of r , ranging from 1-140 km. Values of each cell within the circular zone were given equal weight.

The size of zonal radius (r) substantially influences the linear fit of zonal mean canopy cover as a function of REVEALS estimated canopy cover, and has comparatively little impact on linear fit of zonal mean as a function of O_p (Figure 25; Table 8, Appendix III). Scatter plots demonstrate that both focal and zonal mean values are more evenly dispersed at low radii with respect to both REVEALS-estimated canopy cover and O_p . As the radius increases clustering increases at both high and intermediate zonal mean values, while focal mean values cluster much more strongly at the upper range limit.

Across all radii, zonal mean as a function of REVEALS estimates tend to be overestimated by the linear model at low and intermediate cover and underestimated at high values. Model parameters shift incrementally with increasing radius (slope increases, and intercept decreases),

however, the effect of radius size is relatively small (Table 8, Appendix III). O_p generally differentiates zonal mean poorly, and the radius has little effect on model parameters.

*Forest cover was much better predicted by the REVEALS model than by the arboreal/non-arboreal pollen index. The strength of the fit was similar for focal Gaussian-weighted estimates of tree cover ($R^2=0.53$ at $\sigma=60$ km) as for zonal unweighted canopy cover ($R^2=0.51$ for radii >50 km). The REVEALS estimates of cover, however, were 20 to 40% lower than that observed, especially at the highest levels of canopy cover. In contrast, forest cover was not predicted at all by the O_p pollen ratio index ($r^2<0.03$) for either type of zonal or focal forest cover. Notably, low pollen ratios occurred in both low and high canopy cover settings. Even within the bulk of observations with high O_p (>0.75), no correlation was observed with canopy cover. A linear model fit of focal mean as a function of REVEALS cover estimate is significant across all σ distances (**Error! Reference source not found.**, Appendix III). Goodness of fit as assessed by r^2 increases from 10 km to 60 km and decreases thereafter to 150 km suggesting that 60 km is an optimum distance for σ (*

Figure 27, Top Left). Zonal mean linear fit increases similarly from low radii to 20 km, where a sharp inflection in r^2 improvement for increase in radius occurs, and there only moderate gains thereafter to 140 km. Local optima in r^2 occur at 50 km and 100 km.

For the REVEALS estimates, the scatter in the relationship is greatest at low σ distances and the fit improves at larger radii to 80 km, and O_p exhibits no relationship to canopy cover at any σ distance. For the REVEALS estimates, however, clustering in the upper and intermediate range diverges at σ distances over 80 km. While cluster density continues to increase above 80 km at high cover values, intermediate range exhibits increasing dispersion.

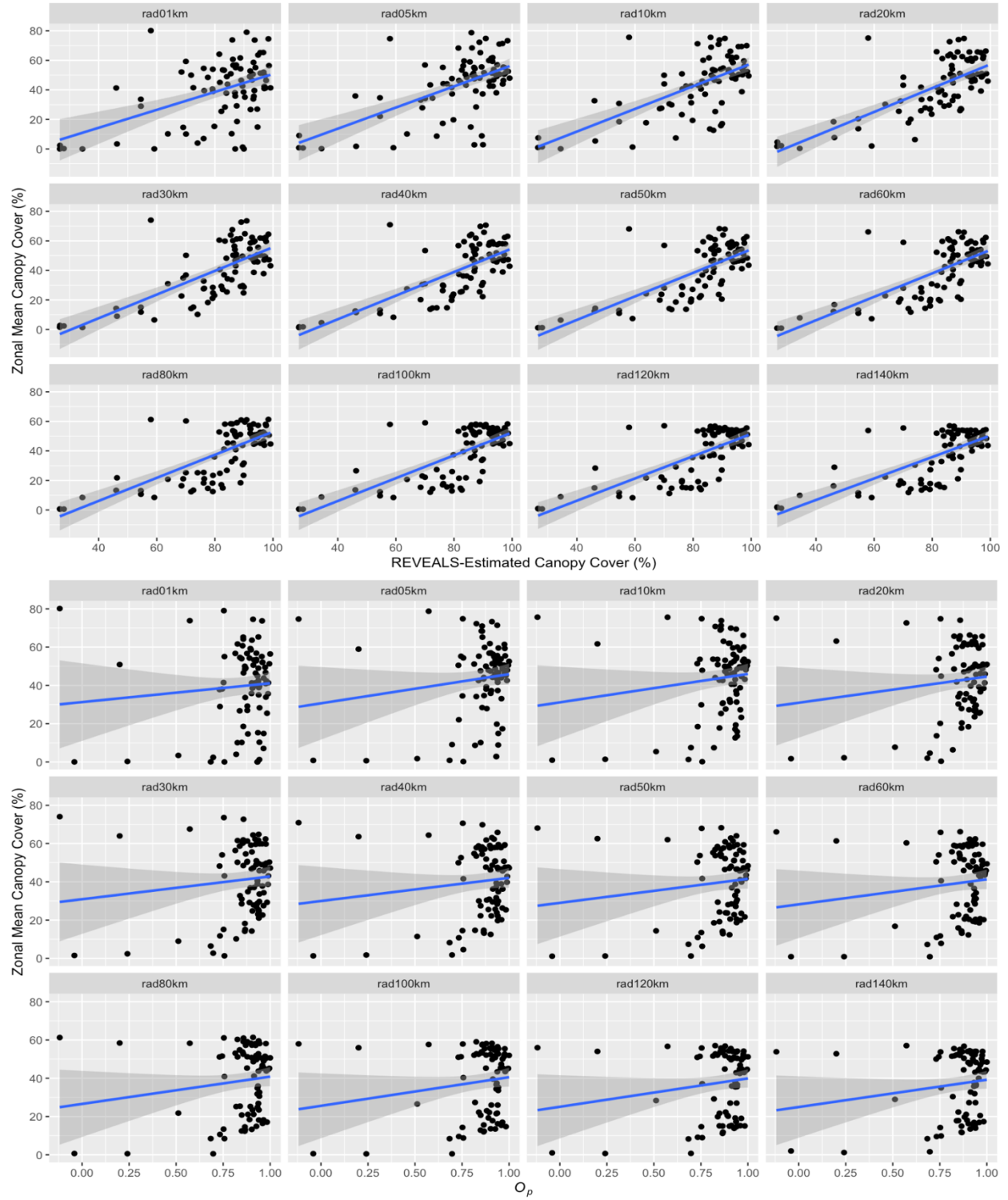


Figure 25 Top: Scatter plot and linear fit of zonal mean canopy cover (%) as a function of REVEALS estimate of canopy cover (%) at 12 radii ranging from 1 to 140 km. Bottom: Scatter plot and linear fit of zonal mean canopy cover with O_p at 12 radii ranging from 1 km to 140 km.

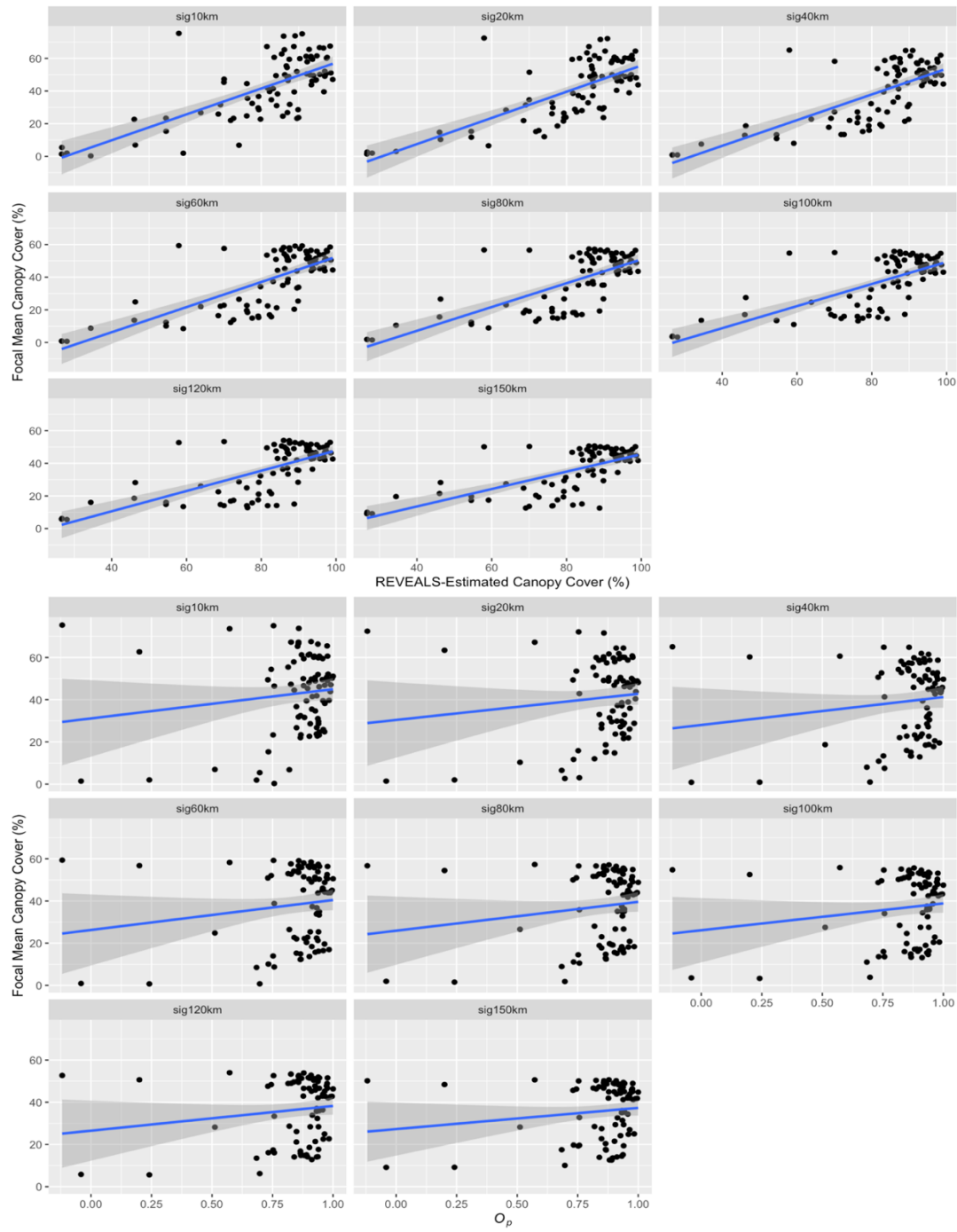


Figure 26 Top: Scatter plot and linear fit of focal mean canopy cover (%) as a function of REVEALS estimate of canopy cover (%) at eight values of σ ranging from 10 km to 150 km. Bottom: Scatter plot and linear fit of focal mean canopy cover as a function of O_p at eight values of σ ranging from 10 km to 150 km.

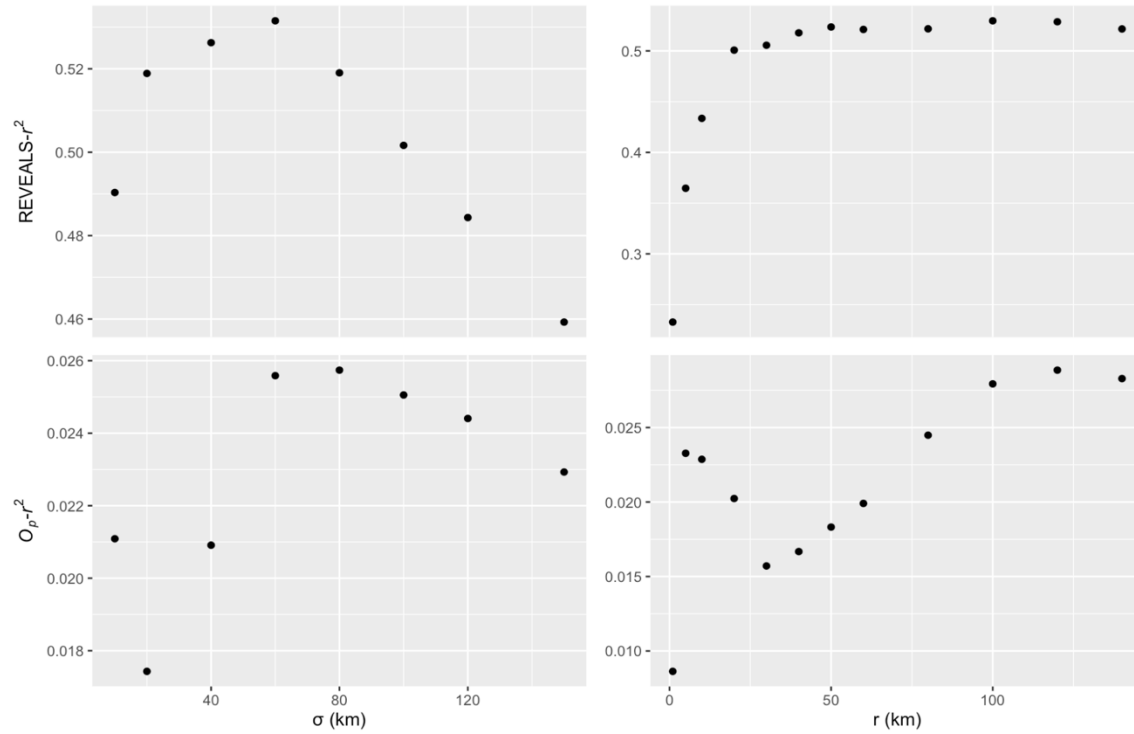


Figure 27 Goodness-of-fit (R^2) of linear models for pair-wise comparison of focal and zonal means with REVEALS cover estimate and O_p .

Spatial autocorrelation of residuals is a common feature of all regressions in this analysis (Figure 28; Figure 29; Figure 38, Appendix III; Figure 39, Appendix III). Furthermore, positive residuals (Figure 28) generally fall into the southwestern portion of the study area (northern California) close to the Pacific Ocean, while negative residuals are concentrated in the northeastern portion (central and eastern Oregon).

The positive residuals of the focal mean regression decrease with σ distance consistently. Negative residuals exhibit more nuanced spatial patterns. At low σ distances, residuals at sites in central and southeast Oregon fall into a wider range of negative values, and as σ distance increases, the residuals homogenize and generally decrease. Sites in northwest Oregon do become homogenized by spatial averaging, however the residuals tend to increase slightly at greater σ

distances.

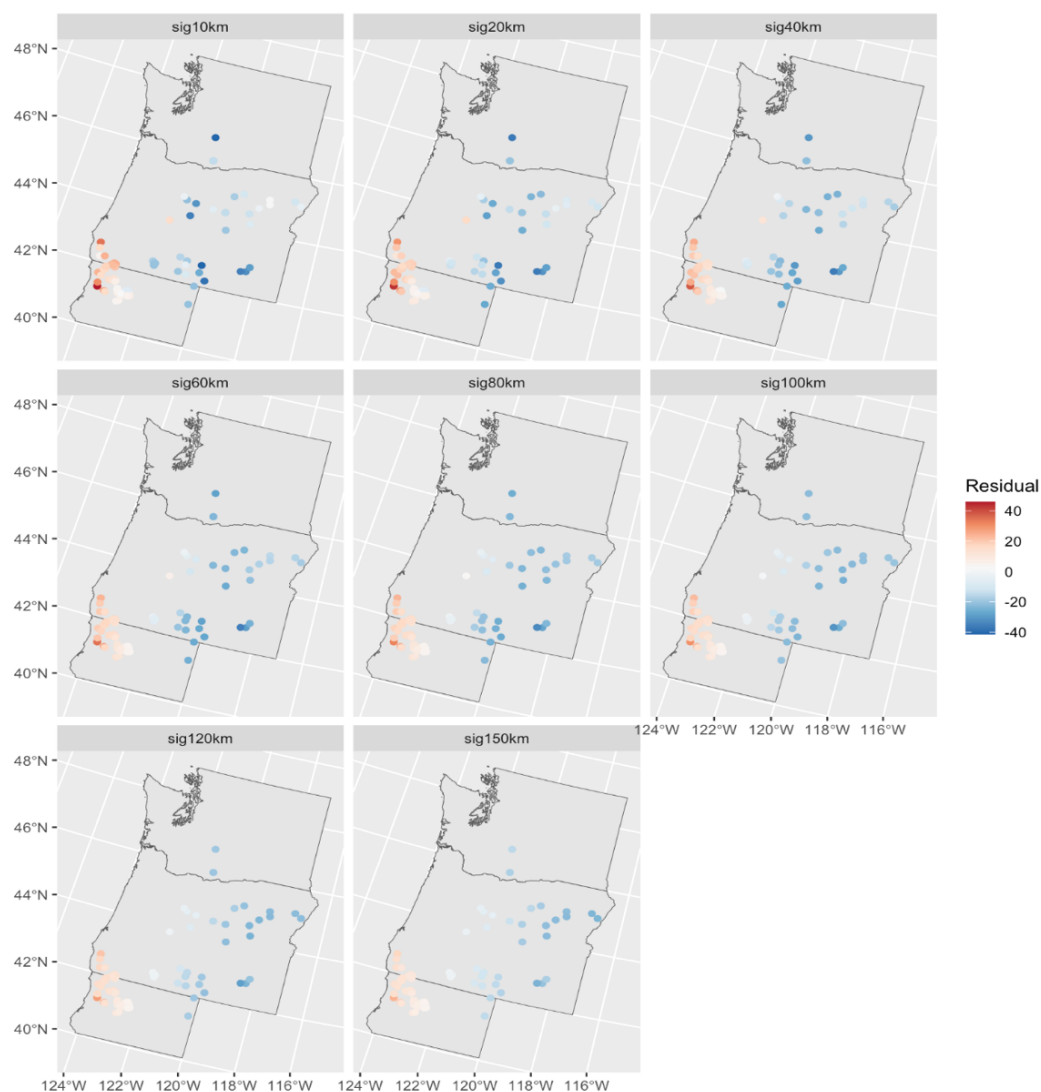


Figure 28 Residuals of linear models for focal mean canopy cover as a function of REVEALS cover estimate for eight distances of σ from 10 km to 150 km. Positive residuals indicate observed canopy cover was greater than that predicted by regression of observed vs. REVEALS canopy cover.

The spatial pattern of residuals from linear regression of zonal mean cover as a function of REVEALS estimates is highly sensitive to radius (Figure 29). At the 1 km radius, little spatial pattern is evident in the residuals either in terms of magnitude or sign. As radius increases from 5 km to 30 km, the sign of the residuals becomes more regionalized. In the northern California,

positive residuals are generally stable at radii greater than 30 km; whereas in south-central and northeastern Oregon pockets of sites exhibit increasing negative residuals while other sites nearby are stable or decrease.

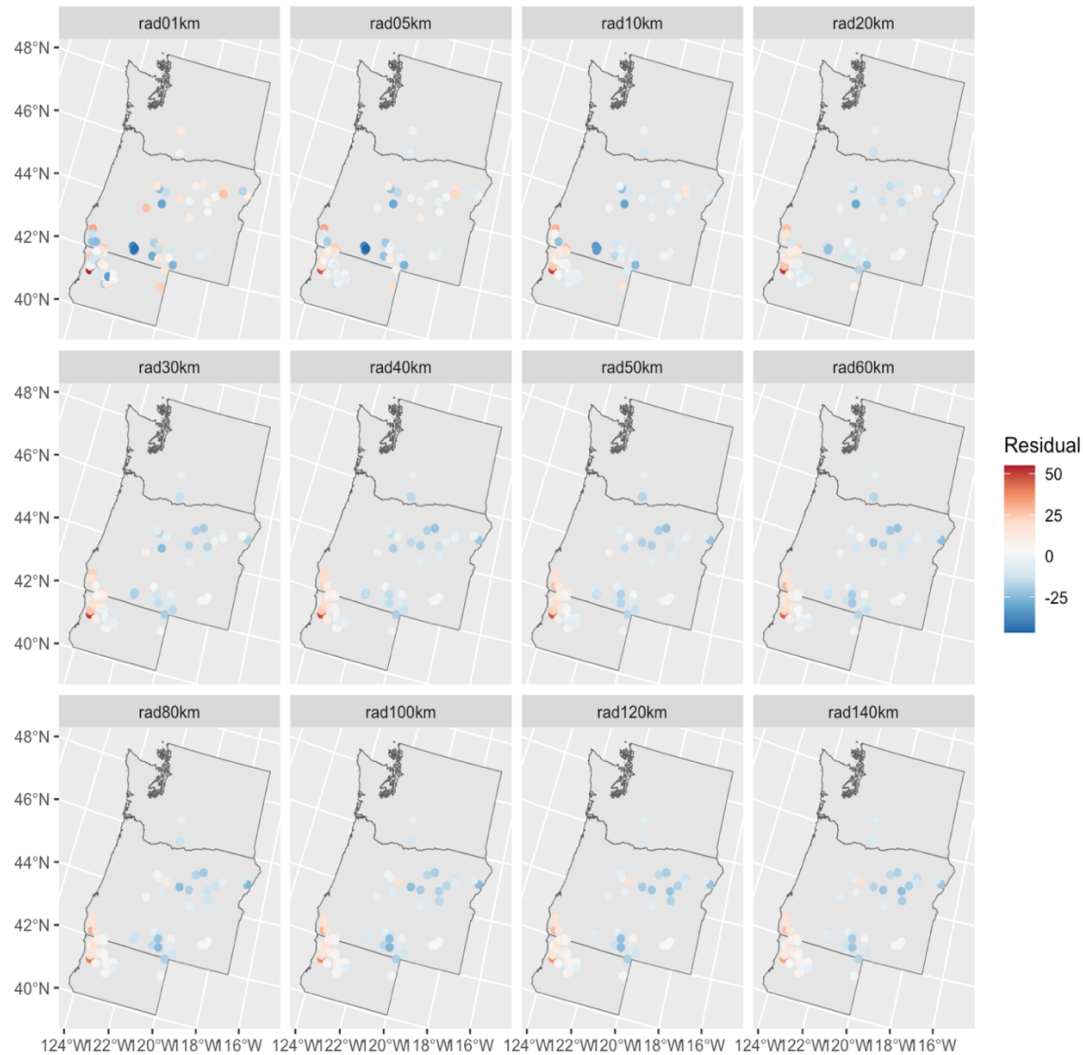


Figure 29 Residuals of linear models for zonal mean canopy cover as a function of REVEALS cover estimate for 12 distances of r from 1 km to 140 km.

4.3.5 REVEALS Cover: NTL

The chronology of terrestrial plant cover changes interpreted by REVEALS identifies many of the same transitions apparent in the pollen taxa relative abundance data, however,

substantial modifications to taxa representation and variability result from the modelling process (Figure 30). The percent cover of *Pinus* is substantially reduced due to the high pollen productivity estimate characteristic of the genus. REVEALS estimates of cover are percentages and REVEALS cannot simulate bare ground, thus reductions in the over-representation of *Pinus* drive large increases in the represented cover of all other taxa.

During Late Pleistocene conditions in the area around NTL dominant taxa were by *Pinus* (10%), *Picea* (10%-20%), Cupressaceae (8%-15%), Rosaceae (10%), Poaceae (10%-25%), Asteraceae (7%-12%), and *Artemisia* (10%-25%). Otherwise rare taxa Cruciferae, Primulaceae, Rubiaceae and Saxifragaceae were more abundant as well. Substantial decreases in *Picea*, Cupressaceae, Rosaceae, and Poaceae; and increases in *Artemisia* and Cruciferae characterize the period 15-16.5 ka. After 15 ka a large increase in *Pinus*, and slight increases in other arboreal taxa *Tsuga*, *Abies*, *Pseudotsuga*, Cupressaceae, and *Alnus* signal the establishment of contemporary forest taxa on both the eastern and western sides of the Cascade Crest.

At 13 ka, *Pinus* cover increases from 20% to over 40%. Concurrently, *Abies* increases to almost 20% and *Artemisia* and Poaceae decrease abruptly. After 13 ka, *Artemisia* and Poaceae increase temporarily and subsequently continue to decrease for the next 3 ka. During that time, *Pinus* decreases to 25% at 11.5 ka before returning to ~40%, and *Pseudotsuga*, Cupressaceae and Rosaceae increase.

Changes in pollen taxon cover after 9.5 ka are generally smaller. *Pinus* varies between 30% and 45%, with local minima at 4.5 ka and 2 ka. Other notable trends include the general decrease in Cupressaceae from 8 ka to present; the increase in *Tsuga heterophylla* starting at 6.5 ka; variable, elevated presence of *Alnus rubra* from 7.5 ka; and the temporary increase in *Abies* at 4.5 ka.

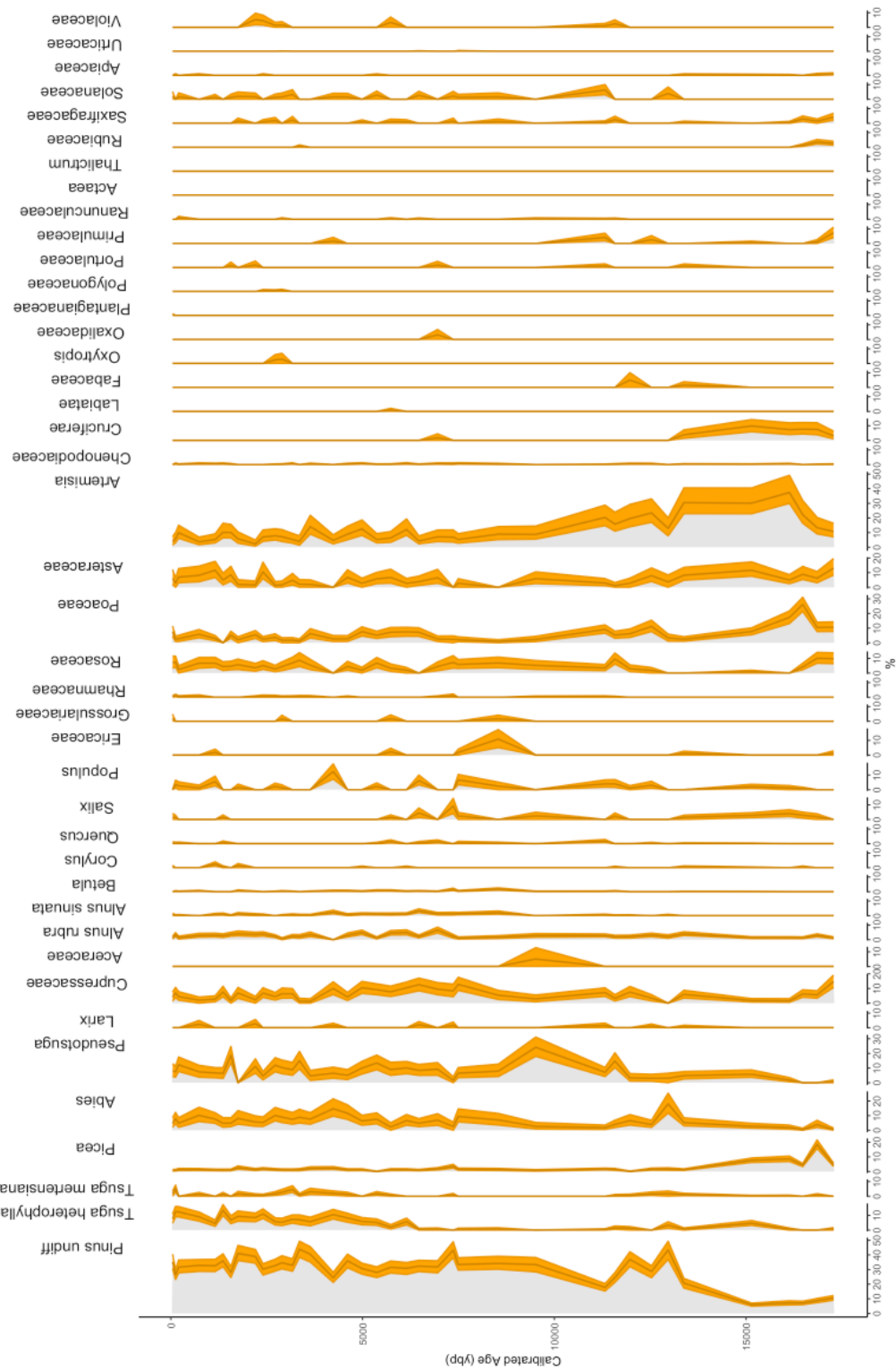


Figure 30 REVEALS estimates of pollen-taxon specific cover (%) for all taxa identified in the NTL core plotted on an age (cal yr BP) axis. Solid lines indicate the median of 1000 model runs. Orange fill represents the confidence interval containing 80% of all model runs.

Summarizing pollen abundance by assigned plant morphology category to calculate O_p for the NTL record contextualizes REVEALS estimates over the late Pleistocene and Holocene (Figure 31). O_p is highly sensitive to changes in arboreal pollen abundance, yet the minimum value at 16 ka is 0.37. Late Pleistocene REVEALS cover estimates of herbaceous cover are 35%-50%, shrub cover estimates are 20%-30%; and arboreal cover estimates are 19%-29%.

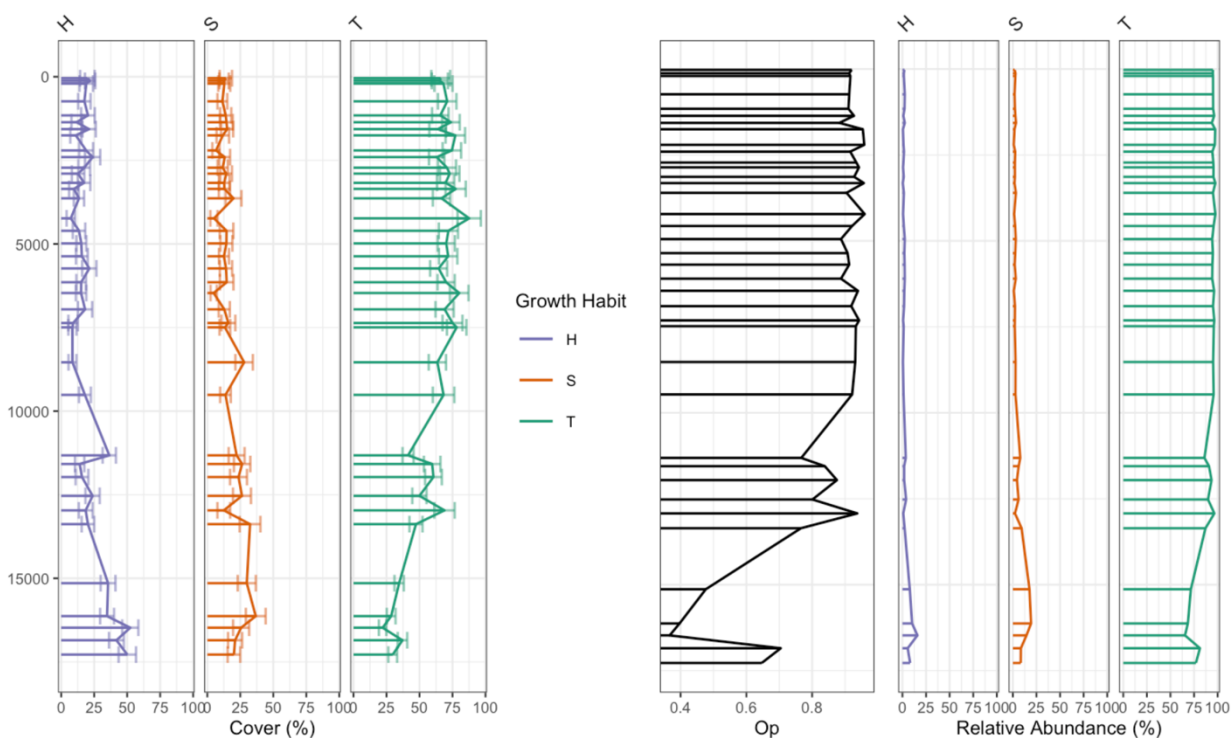


Figure 31 REVEALS-estimated percent cover chronology of morphological groups H (herbaceous), S (shrubs), and T (trees). Error bars represent 1 standard deviation. O_p (black) and the pollen group percentages used to calculate it (colors and labels as with REVEALS estimates).

Herbaceous cover decreases until 12 ka, while shrub cover is more constant, and arboreal cover increases. At 13 ka, arboreal cover replaces nearly 10% of shrub cover; and after 12.5 ka arboreal cover appears to replace herbaceous cover as shrub cover returns. The rise in herbaceous cover at 11.5 ka is coupled primarily to a corresponding decrease in arboreal cover.

From 9.5 to 7.4 ka herbaceous and shrub cover estimates decline to ca. 20%. From 7.5 ka

to present herbaceous cover varies between 12% and 25%, shrub cover between 10% and 19%, and arboreal cover between 62% and 86%. Peak arboreal cover occurs at 4 ka, with corresponding decreases in both herbaceous and shrub cover. Arboreal cover since 4 ka varied between 62% and 77% and has been lower and more stable for the past 1.5 ka than any similar length period in the past 4.5 ka. Over that period herbaceous cover has generally increased, while arboreal cover decreased, and shrub cover was a more consistent vegetation cover through time.

4.4 Discussion

4.4.1 Regional Late Pleistocene Vegetation

Physical core data clearly demonstrates the changes in the environment (Figure 19) prior to and across deglaciation. This data is validated by the age-model (Figure 20), and general pattern of vegetation composition which shows cold-adapted taxa (e.g. *Picea*) and dry-adapted taxa (e.g. Cupressaceae, as *Juniperus*; *Artemisia*; and Poaceae) strongly represented prior to 13.6 ka. The extremely low pollen accumulation rates and low organic content suggest open vegetation, little organic soil, and low aquatic productivity. However, accumulation rate estimates are sensitive to the age model, which is fit to broadly overlapping radiocarbon dates in the basal inorganic sediment. This evidence of tundra-like vegetation is consistent with a deglaciating landscapes at the margin of alpine ice-extent shortly after the Last Glacial Maximum. These conditions were likely widespread along the east side of the Cascade orogeny. A pollen record from south-central Washington (Whitlock et al., 2000) shows similarly high *Picea* pollen at the same time it was abundant at NTL, indicating open *Picea engelmannii* forest. To the south, an organic-matter and diatom assemblages from Klamath Lake, Oregon indicate cold, dry, and windy conditions during

the Late Glacial (Platt Bradbury et al., 2004; Reynolds et al., 2004)

The late Pleistocene to Holocene transition, as recorded in NTL sediments, was a series of large, rapid changes in vegetation. Sediment organic matter, as a measure of ecosystem productivity, tracks the changes in vegetation community as shown by multiple shifts during the period between 17.3 and 9.5 ka (Figure 19), especially with respect to key arboreal taxa (*Pinus*, *Picea*, and Cupressaceae), and the relationships between cover of morphological groups (Figure 31). Basal *Picea* cover was 5%, rising to ~20% in a single sample and then declining until 13.5 ka. Cupressaceae, was elevated at the base and decreased immediately.

Other records of the Pleistocene-Holocene transition record similar shifts between 15.5 and 13 ka. The Klamath Lake sedimentary organic matter record (Platt Bradbury et al., 2004) indicates the first increases in lake productivity at 15.5 ka, apparently synchronous with the timing of changes in physical characterization of NTL sediments at ~400 cm depth (Figure 19). At Carp Lake (Whitlock et al., 2000), a transition in pollen assemblages from cold and dry-adapted to thermophilic taxa occurs at or prior to 13 ka, contemporaneous with the initial rise in *Pinus* recorded in NTL sediments. Carp Lake sedimentary pollen records similar changes in certain taxa, notably *Artemisia*, Poaceae, Cupressaceae and *Picea*. Concurrent decrease in Cupressaceae is common to both records as well. However, the relative abundance of *Artemisia* and Poaceae in the Carp Lake cores during full glacial conditions exceeds those of the NTL record substantially. Correspondingly high rates of change in the Carp Lake record are a sharp contrast with the relatively slow decrease in those taxa at NTL.

Late Pleistocene evidence from Grass Lake in northern California (Hakala & Adam, 2004) further contextualizes the early NTL record. In Grass Lake sediments from 20 to 18 ka, *Artemisia* (30%-40%), *Pinus* (50%-60%), Asteraceae (8%-10%) and Poaceae (8%-10%) pollen relative

abundances are more similar to NTL glacial assemblage in several respects than those of Carp Lake, indicating the possibility that a late Pleistocene latitudinal gradient in vegetation composition along the eastern margin of the Cascade Range shifted substantially north of NTL. The Grass Lake late Pleistocene assemblage does however lack *Picea* and Cupressaceae, and relative abundances of *Artemisia* are elevated relative to NTL, suggesting a smaller moisture deficit at NTL.

4.4.2 Spatial Representation of East Cascades Lakes

Spatial representation theory of pollen in lake sediments (Prentice, 1985) has shown that pollen assemblages from small lakes may represent vegetation within 10s of km of the lake. This observational theory, as well as my analysis of surface pollen and forest structure, suggests that the NTL pollen record is not only a chronology of what is today dry pine and mixed conifer, but also detects within its pollen source area some of the more mesic forests on the western side of the Cascade crest. The upper samples at NTL contain multiple taxa which do not occur locally at NTL in the recent past, notably *Tsuga heterophylla* and *Alnus rubra*, which are characteristic pollen taxa of the West Cascades. The strength of this signal in the NTL record is a function of proximity to the steep longitudinal gradient in climate across the Cascade Range, because NTL lies ~ 15 km from the edge of the *Tsuga heterophylla* distribution (co-located with *Psuedotsuga menziesii* zone, Figure 32). Thus, at NTL vegetation history must be interpreted considering vegetation on both sides of the Cascade Range.

At NTL, representation of *Tsuga heterophylla* increased steadily after 6.5 ka consistent with observations from Blair Lake (Cox, 2016), Gold Lake (Baig & Gavin, 2023) and Indian Prairie Fen (Sea & Whitlock, 1995). This strong agreement between palynological investigations on the west side of the Cascade crest supports the notion that regional pollen, defined by Prentice

(1985) as pollen originating from distances 2 km to 200 km, is a long term feature of the NTL record and that representation of West Cascades vegetation is spatially consistent through time.

Cover-estimate contributions from primarily mesic taxa (*Tsuga*, *Pseudotsuga*, *Abies*, and Cupressaceae as *Thuja*) at pre-settlement time horizons in the NTL core indicate that 30%-40% of REVEALS-estimated arboreal cover represented is regional. Furthermore, this estimate corresponds well with historic vegetation classifications within the 50 km radius (Figure 32) which my spatial analysis of surface pollen and GNN estimated forest canopy cover suggests is most appropriate for pollen representation of forest structure. In the recent past (<40 years), the forest structure dataset I used to evaluate surface pollen relationship to canopy cover in the upper elevation range of the West Cascades suggests that canopy cover more than 80% is common in these forests. REVEALS estimates of arboreal cover from the last 200 years at NTL indicate that canopy cover within the area represented by pollen deposition has been ~65% (Figure 31). If forest canopy on the east and west sides of the Cascades have not changed dramatically over the past 200 years, nearly half of the REVEALS estimated canopy cover is representing west Cascades forests. The remainder is spread across the larger proportion of the NTL pollen source area (60%-70% of the 50 km radius zone) characterized by dry pine and mixed conifer communities yielding canopy cover of 50% or less. Focal mean GNN-derived canopy cover at NTL estimate is 44%. Further work is necessary to account for this kind of edge effect in paleovegetation reconstruction within topoclimatically diverse landscapes such as the Cascade orogeny.

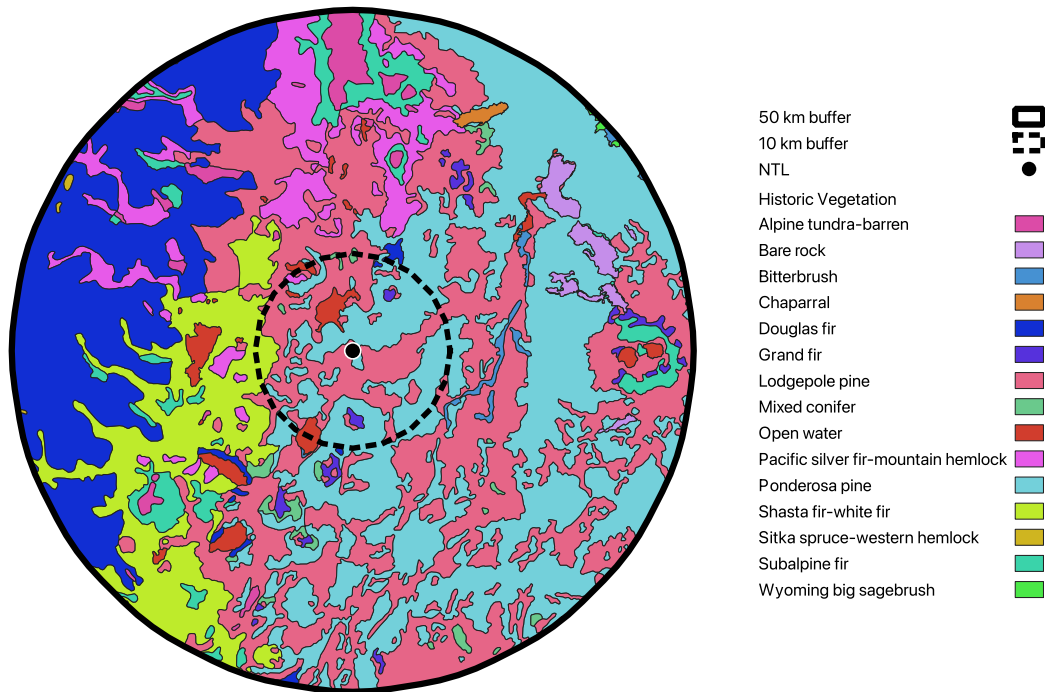


Figure 32 Historic vegetation circa 1850 CE within 10km (dashed black line) and 50 km (solid black border) of North Twin Lake. Data from Christy & Alverson (2011), generated using H. J. Andrews, General Land Office (GLO), Soil Survey Geographic (SSURGO), BLM, Oregon Gap analysis data sources, available at <https://geohub.oregon.gov/datasets/oregon-geo::historic-vegetation>.

4.4.3 East Cascades Canopy Openness as Measured by Proxy

Arboreal and non-arboreal taxa may represent different pollen source areas, complicating the interpretation of the NTL REVEALS cover estimates. As discussed above, I assessed the pollen source area only using arboreal taxa as an estimate of percent forest canopy cover which in comparison with mapped vegetation suggests a 50 km source area (or σ distance), is the most relevant for arboreal taxa. Pollen source area theory (Prentice, 1985; Sugita, 2007a) and observations (Calcote, 1995; Sugita, 1994) indicate that non-arboreal taxa are represented in pollen profiles more locally than arboreal taxa, thus while REVEALS estimates of forest canopy generally represent >40 km radius areas surrounding lake core sites (

Figure 27), the non-arboreal component should be assumed to represent a smaller area (Sugita, 2007b). Moreover, non-arboreal taxa I observed in NTL during the Holocene are common in the plant communities that characterize the East Cascade Slopes and Foothills rather than the West Cascades.

Interpreting the NTL record with the regional canopy cover and more localized non-

arboreal component, the slightly decreasing trend in arboreal cover over the past 4 ky may underestimate the changes in structure more local to NTL and the East Cascades dry pine and mixed conifer forests. REVEALS estimates of mesic Cascades forest canopy taxa for the past 4 ky show evidence of expansion (Figure 30). The necessary inference is that east Cascade arboreal canopy has decreased slowly on average for the past 4 ky, such that the open *Pinus* forests believed to be common prior to Euro-American settlement in landscapes of the region (Hagmann et al., 2018; Hessburg & Agee, 2003; Johnston et al., 2016; Merschel et al., 2018b) were the end product of a multi-millennial process. Assessing this observation quantitatively would require use of additional steps outlined in the Landscape Reconstruction Algorithm (Sugita, 2007b) of which REVEALS is merely the first. There is no agreed upon approach for conducting such a modeling exercise at sites like NTL due to the necessity of identifying the ‘regional’ pollen component with the use of sedimentary pollen from a large lake (generally > 2-5 km diameter).

Vegetation change on Holocene time scales is most readily explained by climate (Huang et al., 2021), which is closely linked with fire regime (Marlon et al., 2006; Marlon et al., 2012). The general observation that forests east of the Cascades are moisture limited (Saban & Gavin, 2025; Volland, 1988) further suggests that water balance could be a driver of the multi-millennial shift toward more open forest canopy in the east Cascades. However, Late Holocene records from other sites east of the Cascades indicate that the last 4 ky have been wetter than previous millennia. At Klamath Lake and Caledonia Marsh, Platt Bradbury et al., (2004) present diatom records indicating planktonic assemblages adapted to lower salinity, and conclude that a period of greater freshwater inputs were the most likely explanation. At the western edge of the Northern Great Basin, Saban & Gavin (2025) also note that peak aridity at Dog Lake occurred prior to 4 kypb, similar to the timing of a mid-Holocene arid period recorded widely in the Great Basin. A similar

pattern across northern California (Daniels et al., 2005) observed in a meta-analysis of sites corroborates this pattern and links these sites with synoptic scale climate patterns which drive effective moisture.

Much of the variation in interior climates of the Western US is related to sea surface temperatures in the Eastern Pacific (Barron et al., 2003, 2012). Planktonic diatom and foraminifer assemblages off the California coast suggest that the past 4000 years have been characterized by warmer oceans, greater oceanic evaporation and larger onshore movement of water. Increased fire occurrence across the region broadly agrees with a greater moisture availability leading to increased terrestrial productivity and fuel accumulation (Walsh et al., 2015). In addition, sites across northern California (Crawford et al., 2015; Daniels et al., 2005; Mohr et al., 2000) and central and eastern Oregon (Long et al., 2019; Minckley et al., 2007; Minckley & Long, 2016; Saban & Gavin, 2025) record increases in fire activity as assessed by charcoal accumulation rates.

Temperature may modify moisture availability as readily as precipitation, and chironomid-inferred summer temperature reconstruction from Gold Lake (Baig et al., 2025) suggests that the last 2.5-3 ky have been warmer than any period since the early Holocene. They note a particularly warm period at 2.5 ka, which corresponds to a substantial increase in *Pinus* (Figure 30) and the only substantial increase in total arboreal cover (Figure 31) in the NTL record in the past 4 ky. These samples also contained the highest influxes of pollen-slide charcoal in the NTL record other than the early Holocene (Figure 21). Pollen slide charcoal, although a discontinuous and coarse spatiotemporal record of fire (Vachula, 2020), suggests that fire has been a constant feature of the landscape around NTL since the late Pleistocene. Furthermore, the highest charcoal influxes I observe in the NTL record correspond to periods of elevated arboreal representation. While this evidence does not definitively confirm high severity fires like those inferred from forest structure

across the Western US (Baker, 2015; Williams & Baker, 2012, 2014), I interpret this evidence as consistent with extensive high severity fires at ~2-2.5 ka in the area surrounding NTL.

With increased summer temperature and moisture availability, the most likely outcome would be increases in forest productivity and fire (Krawchuk & Moritz, 2011). The pollen signal of fires however, is not necessarily obvious. Minckley & Long (2016), in a subalpine forest in the Oregon Cascades, examined pre- and post-fire pollen assemblages and found very little change to overall pollen representation of vegetation. At the >10 km scale of forested landscapes where fires occur frequently enough that the fire regime will not change – but rather maintains – a fire-adapted forest vegetation. Thus, at the scale of a pollen source area which aggregates vegetation over large areas, the constant forest cover like observed at NTL is consistent with a high-frequency fire regime that may include both low and high severity fires.

4.4.4 Fire Suppression, Fire Severity and Canopy Openness

REVEALS-derived pollen representations of vegetation indicates that this time-series of pollen spectra has responded in the past 250 years to changes in forest structure due to fire suppression, yet at the temporal and spatial scale of my reconstruction, these are not unprecedented shifts in the composition of pollen taxa we observe in the record at NTL in the last several millennia.

Historical (Hagmann, 2013) and dendrochronological (Johnston et al., 2016) evidence supports the model of pre-settlement forests composed of park-like stands of *Pinus ponderosa* and uneven-aged stands of mixed conifer forest were the result of frequent low and mixed severity fires prior to Euro-American settlement (Hessburg & Agee, 2003). These types of fires have been shown to maintain and even promote the diversity and abundance of understory plant communities

(Laughlin & Fulé, 2008).

While the NTL record of the past 4 ky cannot attribute the decrease in arboreal cover to a particular pattern of fire regime or climate, the increase in herbaceous cover and increasing temperature climate conditions conducive to biomass burning suggest that the inference of frequent low to moderate severity fire is supported. Use of REVEALS estimates of vegetation cover allow us to discern this trend in forest cover, indeed, this approach has been used in California (Klimaszewski-Patterson et al., 2018) to refine vegetation-fire relationships that are not as clearly described by pollen assemblage alone. Furthermore, within the pollen source area of NTL, the pre-Euro-American forest composition and structure appears to have been the outcome of an ~4 ky trend.

4.4.5 Surface Pollen Data Sets for Geospatial Analysis

Sediment core derived REVEALS estimates alone do not address openness as directly as our surface pollen analysis. The agreement between spatially explicit GNN modeling of forest canopy cover and REVEALS-based estimates of forest cover suggests that pollen assemblages do capture a significant amount of spatial variation in forest composition and structure. The poorer fit between REVEALS and GNN estimate at > 50% forest cover indicates there are factors from GNN model construction or the relative pollen productivity (RPP) estimates that are not refined, and that additional investigation is warranted. GNN model accuracy at low tree cover (Bell et al., 2023) is a potential source of error in regression, particularly for the sites with <30% mean cover. Additional confounding factors including the pollen taxon differences in RPP may be responsible for positive residuals in northern California and negative residuals in central and northeast Oregon includes.

Linear regression of this spatially extensive surface pollen set, despite being limited to

lakes, combines multiple layers of environmental heterogeneity. The extent to which this pollen source area model can be held is subject to extensive debate and my analysis contributes to this ongoing exploration of how pollen represents plants over space. Initial analysis shows that pollen spectra from existing surface pollen datasets exhibit a strong spatial relationship to structure suggesting that more rigorous quantitative modeling is warranted. If pollen taxa were attributable to species with known RPPs, then the REVEALS model may produce stronger fits with the GNN data and without spatial pattern in the residual maps.

Even with these considerations in mind, REVEALS clearly outperforms pollen ratios for assessing the representativeness of surface pollen assemblage with respect to extant vegetation across a wide area of dry pine and mixed conifer forest of the Pacific Northwest.

4.5 Conclusions

I present the first stratigraphically continuous sequence of vegetation change which includes the late Pleistocene to present east of the Coast Range in Oregon. This record of full glacial vegetation along the eastern edge of the Cascade Range further develops our understanding of the ecological, and climatic, rates of change during and after deglaciation. Millennial to sub-millennial shifts in full glacial vegetation composition, particularly shifts in taxa with greater moisture requirements (e.g. *Picea*) predate the Bølling-Allerød warm period during full glacial conditions. The timing of deglaciation, the Younger Dryas, and the onset of a warm early Holocene, are generally consistent with other records from the Pacific Northwest, however, the pace of change in vegetation composition was less abrupt than that recorded at Carp Lake (Whitlock et al., 2000), particularly with respect to dry-adapted taxa, suggesting that changes in moisture availability across the Pleistocene-Holocene transition were mediated in this location.

The quantitative reconstruction algorithm REVEALS, as utilized to evaluate surface pollen relationship to spatially explicit canopy cover, outperforms more traditional pollen ratio approaches significantly. My analysis suggests that regional differences in pollen productivity estimates do exist and influence results, however, I find that this approach to pollen reconstruction of vegetation is valuable with respect to calibration of pollen-vegetation relationships that extend beyond simple abundance to physical structure of vegetation communities of the past.

The vegetation record, interpreted with REVEALS, suggests that forest structure has shifted incrementally and with deviations related to climate over the past 4 ky. Moreover, this shift toward a more open forest structure – a pattern which is not explained by climate alone – is related to fire-climate feedbacks which support the long-term development of pre-Euro-American dry pine and mixed conifer forests east of the Cascade crest.

V

CONCLUDING REMARKS

Each of my research activities fits into its socio-ecological context in unique ways and together constitute crucial steps in understanding human and climate effects on fire and vegetation across the primary rain shadow gradient of PNW forests. These three research activities as a collection describe and then explore the challenges and opportunities for the key findings of LTEC research to inform sustainable socio-ecological relations (Steffen et al., 2015). I interweave the process of biophysical data collection and analysis from lake-core reconstruction and regional, synthesis of lake cores and the interactive process of interviewing land management personnel. The coeval process of fire activity reconstruction and science-based ecosystem management assessment provided a more comprehensive understanding of the use of long-term perspectives in ecosystem management.

This dissertation examines and develops applied paleoecology in theory and practice. I link this research agenda explicitly to recent advances in paleoecology, particularly informatics, and the challenges of adapting socio-ecological systems to rapidly changing climate and associated ecological conditions. Furthermore, as LTEC researchers make claims about utility and importance of long-term data and understanding, this dissertation helps situate paleoecology in the natural resource management landscape. I provide direct evidence of how paleoecological data has been translated to relevance for resource management communities, and how relevance is mediated by social process implicit to science and the social context of capitalism in the Northwest Forest Plan. While this is likely an appropriate moment to contribute LTEC data to local and regional natural resource decision-making across much of the world, the role of science varies greatly in different social and ecological contexts. Paleoecological researchers are only beginning to appreciate the

roles they may play in this process.

REFERENCES CITED

- Abella, S. R., & Springer, J. D. (2015). Effects of tree cutting and fire on understory vegetation in mixed conifer forests. *Forest Ecology and Management.*, 335, 281–299. <https://doi.org/10.1016/j.foreco.2014.09.009>
- Adger, W. N., Arnell, N. W., & Tompkins, E. L. (2005). Successful adaptation to climate change across scales. *Global Environmental Change*, 15(2), 77–86. <https://doi.org/10.1016/j.gloenvcha.2004.12.005>
- Adolf, C., Wunderle, S., Colombaroli, D., Weber, H., Gobet, E., Heiri, O., van Leeuwen, J. F. N., Bigler, C., Connor, S. E., Gałka, M., La Mantia, T., Makhortykh, S., Svitavská-Svobodová, H., Vannière, B., & Tinner, W. (2018). The sedimentary and remote-sensing reflection of biomass burning in Europe. *Global Ecology and Biogeography*, 27(2), 199–212. <https://doi.org/10.1111/geb.12682>
- Agrawal, A. (2005). Environmentalism: Community, Intimate Government, and the Making of Environmental Subjects in Kumaon, India. *Current Anthropology*, 46(2), 161–190. <https://doi.org/10.1086/427122>
- Andrews, A., & Kutara, K. (2005). *Oregon's Timber Harvests: 1849-2004*.
- Baig, J., & Gavin, D. G. (2023). Postglacial vegetation and fire history with a high-resolution analysis of tephra impacts, High Cascade Range, Oregon, USA. *Quaternary Science Reviews*, 303, 107970. <https://doi.org/10.1016/j.quascirev.2023.107970>
- Baig, J., Gavin, D. G., Walker, I., & Porinchu, D. (2025). Chironomid-inferred postglacial temperature reconstruction from Gold Lake, Oregon, USA. *Quaternary Research*, 1–14. <https://doi.org/10.1017/qua.2024.56>
- Baker, W. L. (2015). Are High-Severity Fires Burning at Much Higher Rates Recently than Historically in Dry-Forest Landscapes of the Western USA? *PLOS ONE*, 10(9), e0136147. <https://doi.org/10.1371/journal.pone.0136147>
- Barak, R. S., Hipp, A. L., Cavender-Bares, J., Pearse, W. D., Hotchkiss, S. C., Lynch, E. A., Callaway, J. C., Calcote, R., & Larkin, D. J. (2016). Taking the Long View: Integrating Recorded, Archeological, Paleocological, and Evolutionary Data into Ecological Restoration. *International Journal of Plant Sciences*, 177(1), 90–102. <https://doi.org/10.1086/683394>
- Baral, S., & Mei, B. (2022). Development and performance of timber REITs in the United States: A review and some prospects. *Canadian Journal of Forest Research*, 52(1), 1–10. <https://doi.org/10.1139/cjfr-2021-0085>
- Bari, J. (1990). Timber wars. *Earth Island Journal*, 5(3), 30–31.
- Barron, J. A., Heusser, L., Herbert, T., & Lyle, M. (2003). High-resolution climatic evolution of coastal northern California during the past 16,000 years. *Paleoceanography*, 18(1), 2002PA000768. <https://doi.org/10.1029/2002PA000768>
- Barron, J. A., Metcalfe, S. E., & Addison, J. A. (2012). Response of the North American monsoon to regional changes in ocean surface temperature. *Paleoceanography*, 27(3), 2011PA002235. <https://doi.org/10.1029/2011PA002235>
- Baxter, J. (2016). Case Studies in Qualitative Research. In I. Hay (Ed.), *Qualitative research methods in human geography* (Fourth edition.). Don Mills, Ontario : Oxford University Press.

- Bell, D. M., Gregory, M. J., Palmer, M., & Davis, R. (2023). *Guidance for forest management and landscape ecology applications of recent gradient nearest neighbor imputation maps in California, Oregon, and Washington* (No. PNW-GTR-1018; p. PNW-GTR-1018). U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.
<https://doi.org/10.2737/PNW-GTR-1018>
- Berkes, F., Colding, J., & Folke, C. (2000). REDISCOVERY OF TRADITIONAL ECOLOGICAL KNOWLEDGE AS ADAPTIVE MANAGEMENT. *Ecological Applications*, 10(5), 1251–1262. [https://doi.org/10.1890/1051-0761\(2000\)010\[1251:ROTEKA\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2000)010[1251:ROTEKA]2.0.CO;2)
- Birks, H. J. B. (2019). Contributions of Quaternary botany to modern ecology and biogeography. *Plant Ecology & Diversity*, 12(3–4), 189–385.
<https://doi.org/10.1080/17550874.2019.1646831>
- Blaauw, M., & Christen, J. A. (2011). Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Analysis*, 6(3), 457–474.
<https://doi.org/10.1214/11-BA618>
- Blaauw, M., Christen, J. A., Mauquoy, D., van der Plicht, J., & Bennett, K. D. (2007). Testing the timing of radiocarbon-dated events between proxy archives. *The Holocene*, 17(2), 283–288. <https://doi.org/10.1177/0959683607075857>
- Bosworth, D., & Brown, H. (2007). After the timber wars: Community-based stewardship. *Journal of Forestry*, 105(5), 271–273.
- Boyd, R. (1999a). Indians, fire and the land. *Corvallis: Oregon State University Press*, 52, 54.
- Boyd, R. (1999b). Strategies of Indian Burning in the Willamette Valley. In *Indians, fire, and the land*. Oregon State University Press.
- Brewer, S., Jackson, S. T., & Williams, J. W. (2012). Paleoecoinformatics: Applying geohistorical data to ecological questions. *Trends in Ecology & Evolution*, 27(2), 104–112. <https://doi.org/10.1016/j.tree.2011.09.009>
- Buckles, D. (Ed.). (1999). *Cultivating peace: Conflict and collaboration in natural resource management*. Ottawa : International Development Research Center.
- Buizer, M., Arts, B., & Kok, K. (2011). Governance, scale and the environment: The importance of recognizing knowledge claims in transdisciplinary arenas. *Ecology and Society*, 16(1).
<https://doi.org/21>
- Buma, B., Harvey, B. J., Gavin, D. G., Kelly, R., Loboda, T., McNeil, B. E., Marlon, J. R., Meddens, A. J. H., Morris, J. L., Raffa, K. F., Shuman, B., Smithwick, E. A. H., & McLauchlan, K. K. (2019). The value of linking paleoecological and neoecological perspectives to understand spatially-explicit ecosystem resilience. *Landscape Ecology*, 34(1), 17–33. <https://doi.org/10.1007/s10980-018-0754-5>
- Burke, K. D., Williams, J. W., Chandler, M. A., Haywood, A. M., Lunt, D. J., & Otto-Bliesner, B. L. (2018). Pliocene and Eocene provide best analogs for near-future climates. *Proceedings of the National Academy of Sciences*, 115(52), 13288–13293.
<https://doi.org/10.1073/pnas.1809600115>
- Burns, A. F., Horngren, S., Mickey, R., & Partin, T. (2011). Judging the Effectiveness of the Northwest Forest Plan: Year Eighteen. *Northwest Science*, 85(3), 504–505.
- Buttel, F. H. (2000). Ecological modernization as social theory. *Geoforum*, 31(1), 57–65.
[https://doi.org/10.1016/S0016-7185\(99\)00044-5](https://doi.org/10.1016/S0016-7185(99)00044-5)

- Calcote, R. (1995). Pollen Source Area and Pollen Productivity: Evidence from Forest Hollows. *The Journal of Ecology*, 83(4), 591. <https://doi.org/10.2307/2261627>
- Calder, W. J., Parker, D., Stopka, C. J., Jiménez-Moreno, G., & Shuman, B. N. (2015). Medieval warming initiated exceptionally large wildfire outbreaks in the Rocky Mountains. *Proceedings of the National Academy of Sciences*, 112(43), 13261–13266. <https://doi.org/10.1073/pnas.1500796112>
- Carloni, K. (2005). *The Ecological Legacy of Indian Burning Practices in Southwestern Oregon* [Doctoral]. Oregon State University.
- Carter, V. A., Chiverrell, R. C., Clear, J. L., Kuosmanen, N., Moravcová, A., Svoboda, M., Svobodová-Svitavská, H., van Leeuwen, J. F. N., van der Knaap, W. O., & Kuneš, P. (2018). Quantitative Palynology Informing Conservation Ecology in the Bohemian/Bavarian Forests of Central Europe. *Frontiers in Plant Science*, 8, 2268. <https://doi.org/10.3389/fpls.2017.02268>
- Casamassa, G. (2020). *Bioregional Assessment of Northwest Forests* (p. 92). United States Department of Agriculture. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd762774.pdf
- Cash, D. W., Adger, W. N., Berkes, F., Garden, P., Lebel, L., Olsson, P., Pritchard, L., & Young, O. (2006). Scale and Cross-Scale Dynamics: Governance and Information in a Multilevel World. *Ecology and Society*, 11(2). <https://doi.org/10.5751/ES-01759-110208>
- Cash, D. W., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., Guston, D. H., Jäger, J., & Mitchell, R. B. (2003). Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences of the United States of America*, 100(14), 8086–8091. <https://doi.org/10.1073/pnas.1231332100>
- Cashman, K. V., Deligne, N. I., Gannett, M. W., Grant, G. E., & Jefferson, A. (2009). Fire and water: Volcanology, geomorphology, and hydrogeology of the Cascade Range, central Oregon. In J. E. O'Connor, R. J. Dorsey, & I. P. Madin (Eds.), *Volcanoes to Vineyards* (pp. 539–582). Geological Society of America. [https://doi.org/10.1130/2009.fld015\(26\)](https://doi.org/10.1130/2009.fld015(26))
- Catton Jr, W. R., & Dunlap, R. E. (1978). Environmental Sociology: A New Paradigm. *The American Sociologist*, 13(February), 41–49.
- Catton, W. R., & Dunlap, R. E. (1978). Environmental Sociology: A New Paradigm. *The American Sociologist*, 13(1), 41–49.
- Charnley, S., Dillingham, C., Stuart, C., Moseley, C., & Donoghue, E. (2006). *Forest Plan Northwest Forest Plan—The First 10 Years (1994 – 2003): Socioeconomic Monitoring of the Klamath National Forest and Three Local Communities*.
- Christensen, H., Raettig, T., Sommers, P. (1999). *Northwest Forest Plan: Outcomes and Lessons Learned From the Northwest Economic Adjustment Initiative PNW-GTR-484*.
- Christensen, N. L., Bartuska, A., Brown, J. H., D'Antonio, C., Franklin, J. F., MacMahon, J. A., Noss, R. F., Parsons, D. J., Peterson, C. H., Turner, M. G., & Moodmansee, R. G. (1996). The report of the Ecological Society of America Committee on the scientific basis for ecosystem management. *Ecological Applications*, 6(3), 665–691.
- Christensen, N. L., Bartuska, A. M., Brown, J. H., Carpenter, S., D'Antonio, C., Francis, R., Franklin, J. F., MacMahon, J. A., Noss, R. F., Parsons, D. J., Peterson, C. H., Turner, M. G., & Woodmansee, R. G. (1996). The Report of the Ecological Society of America Committee on the Scientific Basis for Ecosystem Management. *Ecological Applications*, 6(3), 665–691. <https://doi.org/10.2307/2269460>

- Christy, J. A., & Alverson, E. R. (2011). Historical Vegetation of the Willamette Valley, Oregon, circa 1850. *Northwest Science*, 85(2), 93–107. <https://doi.org/10.3955/046.085.0202>
- Clark, J. S. (1988). Particle Motion and the Theory of Charcoal Analysis: Source Area, Transport, Deposition, and Sampling. *Quaternary Research*, 30(1), 67–80. [https://doi.org/10.1016/0033-5894\(88\)90088-9](https://doi.org/10.1016/0033-5894(88)90088-9)
- Clausen, R., & York, R. (2008). Global biodiversity decline of marine and freshwater fish: A cross-national analysis of economic, demographic, and ecological influences. *Social Science Research*, 37(4), 1310–1320. <https://doi.org/10.1016/j.ssresearch.2007.10.002>
- Colavito, M. M. (2017). Utilising scientific information to support resilient forest and fire management. *International Journal of Wildland Fire*, 26(5), 375. <https://doi.org/10.1071/WF16158>
- Conklin, F. S. (1970). Environmental Quality Problems: A Case Study of Field Burning in the Willamette Valley. *Proceedings, Annual Meeting (Western Agricultural Economics Association)*, 43, 279–284.
- Cox, T. G. (2016). *The Role of Fire in Montane Forest Environments in the Willamette National Forest, Oregon* [Masters]. Western Washington University.
- Crausbay, S. D., Higuera, P. E., Sprugel, D. G., & Brubaker, L. B. (2017). Fire catalyzed rapid ecological change in lowland coniferous forests of the Pacific Northwest over the past 14,000 years. *Ecology*, 98(9), 2356–2369. <https://doi.org/10.1002/ecy.1897>
- Crawford, J. N., Mensing, S. A., Lake, F. K., & Zimmerman, S. R. (2015). Late Holocene fire and vegetation reconstruction from the western Klamath Mountains, California, USA: A multi-disciplinary approach for examining potential human land-use impacts. *The Holocene*, 25(8), 1341–1357. <https://doi.org/10.1177/0959683615584205>
- Daniels, M. L., Anderson, S., & Whitlock, C. (2005). Vegetation and fire history since the Late Pleistocene from the Trinity Mountains, northwestern California, USA. *The Holocene*, 15(7), 1062–1071. <https://doi.org/10.1191/0959683605hl878ra>
- Davies, A. L. (2011). Long-term approaches to native woodland restoration: Palaeoecological and stakeholder perspectives on Atlantic forests of Northern Europe. *Forest Ecology and Management*, 261(3), 751–763. <https://doi.org/10.1016/j.foreco.2010.12.006>
- Davies, A. L., Colombo, S., & Hanley, N. (2014). Improving the application of long-term ecology in conservation and land management. *Journal of Applied Ecology*, 51(1), 63–70. <https://doi.org/10.1111/1365-2664.12163>
- Davis, R. (2017). *Northwest Forest Plan Interagency Regional Monitoring 20-Year Report Status and Trend of Watershed Condition*.
- Davis, R. J., Ohmann, J. L., Kennedy, R. E., Cohen, W. B., Gregory, M. J., Yang, Z., Roberts, H. M., Gray, A. N., & Spies, T. A. (2017). *Northwest Forest Plan—the first 20 years (1994–2013): Status and trends of late-successional and old-growth forests*. Gen. Tech. Rep. PNW-GTR-911.
- Dawson, A., Williams, J. W., Gaillard, M.-J., Goring, S. J., Pirzamanbein, B., Lindstrom, J., Anderson, R. S., Brunelle, A., Foster, D., Gajewski, K., Gavin, D. G., Lacourse, T., Minckley, T. A., Oswald, W., Shuman, B., & Whitlock, C. (2024). *Holocene land cover change in North America: Continental trends, regional drivers, and implications for vegetation-atmosphere feedbacks*. Vegetation Dynamics/Terrestrial Archives/Holocene. <https://doi.org/10.5194/cp-2024-6>

- Dean, W. E., & Bradbury, J. P. (1993). *CHARACTERISTICS OF SEDIMENTS FROM SELECTED LAKES OF OREGON AND WASHINGTON AND THEIR POTENTIAL FOR OBTAINING HIGHRESOLUTION PALEOCLIMATE RECORDS* (Open-File Report Nos. 93–212; Open-File Report).
- Delcourt, P. A., & Delcourt, H. R. (1991). *Quaternary ecology: A paleoecological perspective* (1st ed.). Springer Dordrecht.
- Demeritt, D. (2001). The Construction of Global Warming and the Politics of Science. *Annals of the Association of American Geographers*, 91(2), 307–337. <https://doi.org/10.1111/0004-5608.00245>
- Derr, K. M. (2014). Anthropogenic Fire and Landscape Management on Valdes Island, Southwestern BC. *Canadian Journal of Archaeology*, 38(1), 29.
- Dietl, G. P., Kidwell, S. M., Brenner, M., Burney, D. A., Flessa, K. W., Jackson, S. T., & Koch, P. L. (2015). Conservation Paleobiology: Leveraging Knowledge of the Past to Inform Conservation and Restoration. *Annual Review of Earth and Planetary Sciences*, 43(1), 79–103. <https://doi.org/10.1146/annurev-earth-040610-133349>
- Dietrich, W. E., & Schaeffer, D. (1991, May 24). Owl Ruling Halts Logging in Much of Northwest. *Seattle Times*, A-1.
- Dilling, L., & Lemos, M. C. (2011). Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy. *Global Environmental Change*, 21(2), 680–689. <https://doi.org/10.1016/j.gloenvcha.2010.11.006>
- Dugger, K. M., Forsman, E. D., Franklin, A. B., Davis, R. J., White, G. C., Schwarz, C. J., Burnham, K. P., Nichols, J. D., Hines, J. E., Yackulic, C. B., Doherty, P. F., Bailey, L., Clark, D. A., Ackers, S. H., Andrews, L. S., Augustine, B., Biswell, B. L., Blakesley, J., Carlson, P. C., ... Sovern, S. G. (2016). The effects of habitat, climate, and Barred Owls on long-term demography of Northern Spotted Owls. *The Condor*, 118(1), 57–116. <https://doi.org/10.1650/CONDOR-15-24.1>
- Dunlap, R. E., & Catton Jr, W. R. (1979). Environmental Sociology. *Annual Review of Sociology*, 5, 243–273.
- Dunn, C. J., & Bailey, J. D. (2016). Tree mortality and structural change following mixed-severity fire in Pseudotsuga forests of Oregon's western Cascades, USA. *Forest Ecology and Management*, 365, 107–118. <https://doi.org/10.1016/j.foreco.2016.01.031>
- Durham, S. R., & Dietl, G. P. (2015). Perspectives on Geohistorical Data among Oyster Restoration Professionals in the United States. *Journal of Shellfish Research*, 34(2), 227–239. <https://doi.org/10.2983/035.034.0204>
- Dutterer, A. D. (2016). *LEADERSHIP DYNAMICS IN COLLABORATION: LESSONS FROM THE MIDDLE FORK JOHN DAY RIVER INTENSIVELY MONITORED WATERSHED COLLABORATION* [Ph.D.]. University of Oregon.
- Egan, E. D., & Dubay, T. (Eds.). (2013). *Breaking Barriers Building Bridges: Collaborative Forest Landscape Restoration Handbook*. Ecological Restoration Institute at Northern Arizona University. https://openknowledge.nau.edu/id/eprint/2501/1/Dubay_C_etal_2013_HandbookBreakingBarriers3.pdf#page=82
- Eisenhardt, K. M., & Graebner, M. E. (2007). Theory Building from Cases: Opportunities and Challenges. *The Academy of Management Journal*, 50(1), 25–32. JSTOR. <https://doi.org/10.2307/20159839>

- Ekblom, A., & Gillson, L. (2017). The importance of paleoecology in the conservation and restoration of cultural landscapes. *Past Global Changes Magazine*, 25(2), 88–89. <https://doi.org/10.22498/pages.25.2.88>
- Ekblom, A., Shoemaker, A., Gillson, L., Lane, P., & Lindholm, K.-J. (2019). Conservation through Biocultural Heritage—Examples from Sub-Saharan Africa. *Land*, 8(1), 5. <https://doi.org/10.3390/land8010005>
- Ellison, A., Kooistra, C., Coughlan, M., & Johnson, G. (2019). *Wildland Fire Science Needs in Oregon and Washington* (Working Paper No. 94; p. 33). Ecosystem Workforce Program.
- Faegri, Knut., Kaland, P. Emil., & Krzywinski, Knut. (1989). *Textbook of pollen analysis* (4th ed. / by Knut Faegri, Peter Emil Kaland, and Knut Krzywinski.). Wiley.
- Falxa, G. A., & Raphael, M. G. (2016). *Northwest Forest Plan—The first 20 years (1994–2013): Status and trend of marbled murrelet populations and nesting habitat. Gen. Tech. Rep. PNW-GTR-933.*
- Felt, U., Igelsböck, J., Schikowitz, A., & Völker, T. (2016). Transdisciplinary Sustainability Research in Practice. *Science, Technology, & Human Values*, 41(4), 732–761. <https://doi.org/10.1177/0162243915626989>
- FEMAT (Forest Ecosystem Management Team). (1993). *Forest ecosystem management: An ecological, economic, and social assessment.*
- Foster, D., Swanson, F., Aber, J., Burke, I., Brokaw, N., Tilman, D., & Knapp, A. (2003). The Importance of Land-Use Legacies to Ecology and Conservation. *BioScience*, 53(1), 77. [https://doi.org/10.1641/0006-3568\(2003\)053\[0077:TIOLUL\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2003)053[0077:TIOLUL]2.0.CO;2)
- Foster, J. B. (2011). The Ecology of Marxian Political Economy. *Monthly Review*, 63(4), 1. https://doi.org/10.14452/MR-063-04-2011-08_1
- Foster, J. B. (2012). The Planetary Rift and the New Human Exemptionalism: A Political-Economic Critique of Ecological Modernization Theory. *Organization & Environment*, 25(3), 211–237. <https://doi.org/10.1177/1086026612459964>
- Foster, J. B., Clark, B., & York, R. (2011). *The Ecological Rift—Capitalisms War on the Earth.* Monthly Review Press.
- Franklin, J. F., & Dyrness, C. T. (1988). *Natural vegetation of Oregon and Washington.* Oregon State University Press.
- Franklin, J. F., & Johnson, K. N. (2012). A Restoration Framework for Federal Forests in the Pacific Northwest. *Journal of Forestry*, 110(8), 429–439. <https://doi.org/10.5849/jof.10-006>
- French, D. (1999). Aboriginal control of huckleberry yield. In *Indians, fire, and the land.* Oregon State University Press.
- Fulé, P. Z., Swetnam, T. W., Brown, P. M., Falk, D. A., Peterson, D. L., Allen, C. D., Aplet, G. H., Battaglia, M. A., Binkley, D., Farris, C., Keane, R. E., Margolis, E. Q., Grissino-Mayer, H., Miller, C., Sieg, C. H., Skinner, C., Stephens, S. L., & Taylor, A. (2014). Unsupported inferences of high-severity fire in historical dry forests of the western United States: Response to Williams and Baker: Correspondence. *Global Ecology and Biogeography*, 23(7), 825–830. <https://doi.org/10.1111/geb.12136>
- Gardner, J. J., & Whitlock, C. (2001). Charcoal accumulation following a recent fire in the Cascade Range, northwestern USA, and its relevance for fire-history studies. *The Holocene*, 11(5), 541–549. <https://doi.org/10.1191/095968301680223495>

- Garrard, G. E., Fidler, F., Wintle, B. C., Chee, Y. E., & Bekessy, S. A. (2016). Beyond Advocacy: Making Space for Conservation Scientists in Public Debate. *Conservation Letters*, 9(3), 208–212. <https://doi.org/10.1111/conl.12193>
- Gavin, D. G., Hu, F. S., Lertzman, K., & Corbett, P. (2006). WEAK CLIMATIC CONTROL OF STAND-SCALE FIRE HISTORY DURING THE LATE HOLOCENE. *Ecology*, 87(7), 1722–1732. [https://doi.org/10.1890/0012-9658\(2006\)87\[1722:WCCOSF\]2.0.CO;2](https://doi.org/10.1890/0012-9658(2006)87[1722:WCCOSF]2.0.CO;2)
- Gillson, L., Whitlock, C., & Humphrey, G. (2019). Resilience and fire management in the Anthropocene. *Ecology and Society*, 24(3), art14. <https://doi.org/10.5751/ES-11022-240314>
- Grigg, L. D., & Whitlock, C. (1998). Late-Glacial Vegetation and Climate Change in Western Oregon. *Quaternary Research*, 49(3), 287–298. <https://doi.org/10.1006/qres.1998.1966>
- Grimm, E. C. (1987). CONISS: A FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers & Geosciences*, 13(1), 13–35. [https://doi.org/10.1016/0098-3004\(87\)90022-7](https://doi.org/10.1016/0098-3004(87)90022-7)
- Grinspoon, E., Jaworski, D., & Phillips, R. (2016). *Social and Economic Status and Trends FS/R6/PNW/2015/0006*.
- Groff, D. V., McDonough MacKenzie, C., Pier, J. Q., Shaffer, A. B., & Dietl, G. P. (2023). Knowing but not doing: Quantifying the research-implementation gap in conservation paleobiology. *Frontiers in Ecology and Evolution*, 11, 1058992. <https://doi.org/10.3389/fevo.2023.1058992>
- Hadley, K. S. (1999). FOREST HISTORY AND MEADOW INVASION AT THE RIGDON MEADOWS ARCHAEOLOGICAL SITE, WESTERN CASCADES, OREGON. *Physical Geography*, 20(2), 116–133. <https://doi.org/10.1080/02723646.1999.10642672>
- Hagmann, R. K. (2013). Historical structure and composition of ponderosa pine and mixed-conifer forests in south-central oregon. *Forest Ecology and Management*, 13.
- Hagmann, R. K., Stevens, J. T., Lydersen, J. M., Collins, B. M., Battles, J. J., Hessburg, P. F., Levine, C. R., Merschel, A. G., Stephens, S. L., Taylor, A. H., Franklin, J. F., Johnson, D. L., & Johnson, K. N. (2018). Improving the use of early timber inventories in reconstructing historical dry forests and fire in the western United States: Comment. *Ecosphere*, 9(7), e02232. <https://doi.org/10.1002/ecs2.2232>
- Hakala, K. J., & Adam, D. P. (2004). Late Pleistocene Vegetation and Climate in the Southern Cascade Range and the Modoc Plateau Region. *Journal of Paleolimnology*, 31(2), 189–215. <https://doi.org/10.1023/B:JOPL.0000019231.58234.fb>
- Hallberg, L. R.-M. (2006). The “core category” of grounded theory: Making constant comparisons. *International Journal of Qualitative Studies on Health and Well-Being*, 1(3), 141–148. <https://doi.org/10.1080/17482620600858399>
- Harrison, S. P., Villegas-Diaz, R., Cruz-Silva, E., Gallagher, D., Kesner, D., Lincoln, P., Shen, Y., Sweeney, L., Colombaroli, D., Ali, A., Barhoumi, C., Bergeron, Y., Blyakharchuk, T., Bobek, P., Bradshaw, R., Clear, J. L., Czerwiński, S., Daniau, A.-L., Dodson, J., ... Paillard, J. (2022). The Reading Palaeofire Database: An expanded global resource to document changes in fire regimes from sedimentary charcoal records. *Earth System Science Data*, 14(3), 1109–1124. <https://doi.org/10.5194/essd-14-1109-2022>
- Hayashida, F. M. (2005). ARCHAEOLOGY, ECOLOGICAL HISTORY, AND CONSERVATION. *Annual Review of Anthropology*, 34(1), 43–65. <https://doi.org/10.1146/annurev.anthro.34.081804.120515>

- Haynes, R. W., Bormann, B. T., Lee, D. C., & Martin, J. R. (2006). *Northwest Forest Plan—The First 10 Years (1994-2003): Synthesis of Monitoring and Research Results Gen. Tech. Rep. PNW-GTR-651*.
- Haywood, A. M., Dowsett, H. J., & Dolan, A. M. (2016). Integrating geological archives and climate models for the mid-Pliocene warm period. *Nature Communications*, 7(1), 10646. <https://doi.org/10.1038/ncomms10646>
- Heiri, O., Lotter, A. F., & Lemcke, G. (2001). Loss on ignition as a method for estimating organic and carbonate content in sediments: Reproducibility and comparability of results. *Journal of Paleolimnology*, 25, 10.
- Hessburg, P. F., & Agee, J. K. (2003). An environmental narrative of Inland Northwest United States forests, 1800–2000. *Forest Ecology and Management*, 178(1–2), 23–59. [https://doi.org/10.1016/S0378-1127\(03\)00052-5](https://doi.org/10.1016/S0378-1127(03)00052-5)
- Hessburg, P. F., Salter, R. B., & James, K. M. (2007). Re-examining fire severity relations in pre-management era mixed conifer forests: Inferences from landscape patterns of forest structure. *Landscape Ecology*, 22(S1), 5–24. <https://doi.org/10.1007/s10980-007-9098-2>
- Heyerdahl, E. K., McKenzie, D., Daniels, L. D., Hessler, A. E., Littell, J. S., & Mantua, N. J. (2008). Climate drivers of regionally synchronous fires in the inland Northwest (1651–1900). *International Journal of Wildland Fire*, 17(1), 40. <https://doi.org/10.1071/WF07024>
- Higuera, P. E., Gavin, D. G., Bartlein, P. J., & Hallett, D. J. (2010). Peak detection in sediment - charcoal records: Impacts of alternative data analysis methods on fire-history interpretations. *International Journal of Wildland Fire*, 19(8), 996. <https://doi.org/10.1071/WF09134>
- Higuera, P. E., Whitlock, C., & Gage, J. A. (2011). Linking tree-ring and sediment-charcoal records to reconstruct fire occurrence and area burned in subalpine forests of Yellowstone National Park, USA. *The Holocene*, 21(2), 327–341. <https://doi.org/10.1177/0959683610374882>
- Higuera, P., Peters, M., Brubaker, L., & Gavin, D. (2007). Understanding the origin and analysis of sediment-charcoal records with a simulation model. *Quaternary Science Reviews*, 26(13–14), 1790–1809. <https://doi.org/10.1016/j.quascirev.2007.03.010>
- Hirsch, S. L. (2020). Anticipatory practices: Shifting baselines and environmental imaginaries of ecological restoration in the Columbia River Basin. *Environment and Planning E: Nature and Space*, 3(1), 40–57. <https://doi.org/10.1177/2514848619857523>
- Hobbs, R. J., Arico, S., Aronson, J., Baron, J. S., Bridgewater, P., Cramer, V. A., Epstein, P. R., Ewel, J. J., Klink, C. A., Lugo, A. E., Norton, D., Ojima, D., Richardson, D. M., Sanderson, E. W., Valladares, F., Vila, M., Zamora, R., & Zobel, M. (2006). Novel ecosystems: Theoretical and management aspects of the new ecological world order. *Global Ecology and Biogeography*, 15(1), 1–7. <https://doi.org/10.1111/j.1466-822X.2006.00212.x>
- Hope, G., Mooney, S. D., Allen, K., Baker, P., Keaney, B., Kemp, J., Martin, L., Pearson, S., Stevenson, J., & Zheng, X. (2020). Science through time: Understanding the archive at rennix gap bog, a sub-alpine peatland in kosciuszko national park, New South Wales, Australia. *Proceedings of the Linnean Society of New South Wales*, 141, 25–47. <https://doi.org/10.3316/informit.887177364867602>

- Huang, E., Chen, Y., Fang, M., Zheng, Y., & Yu, S. (2021). Environmental drivers of plant distributions at global and regional scales. *Global Ecology and Biogeography*, 30(3), 697–709. <https://doi.org/10.1111/geb.13251>
- Jackson, S. T. (2004). Quaternary Biogeography: Linking Biotic Responses to Environmental Variability across Timescales. In M. V. Lomolino & L. R. Heaney (Eds.), *Frontiers of biogeography: New directions in the geography of nature*. Sinauer Associates.
- Jackson, S. T., & Hobbs, R. J. (2009). Ecological Restoration in the Light of Ecological History. *Science*, 325(5940), 567–569. <https://doi.org/10.1126/science.1172977>
- Jasanoff, S. (1990). *The fifth branch: Science advisers as policymakers*. Cambridge, Mass. : Harvard University Press.
- Jasanoff, S. (2004). The idiom of co-production. In *States of Knowledge: Science, Power and Political Culture* (p. 11).
- Johnston, J. D., Bailey, J. D., & Dunn, C. J. (2016). Influence of fire disturbance and biophysical heterogeneity on pre-settlement ponderosa pine and mixed conifer forests. *Ecosphere*, 7(11), e01581. <https://doi.org/10.1002/ecs2.1581>
- Johnston, J. D., Bailey, J. D., Dunn, C. J., & Lindsay, A. A. (2017). Historical Fire–Climate Relationships in Contrasting Interior Pacific Northwest Forest Types. *Fire Ecology*, 13(2), 18–36. <https://doi.org/10.4996/fireecology.130257453>
- Johnston, J. D., Schmidt, M. R., Merschel, A. G., Downing, W. M., Coughlan, M. R., & Lewis, D. G. (2023). Exceptional variability in historical fire regimes across a western Cascades landscape, Oregon, USA. *Ecosphere*, 14(12), e4735. <https://doi.org/10.1002/ecs2.4735>
- Julien, A., Giguët-Covex, C., Messenger, E., Mazier, F., & Marquer, L. (2025). Performance of the REVEALS model to reconstruct present mountain vegetation cover in the North-Western Alps: A model evaluation for past land cover reconstruction. *Quaternary Science Reviews*, 349, 109089. <https://doi.org/10.1016/j.quascirev.2024.109089>
- Kates, R. W., Clark, W. C., Corell, R., Hall, J. M., Jaeger, C. C., Lowe, I., McCarthy, J. J., Schellnhuber, H. J., Bolin, B., Dickson, N. M., Faucheux, S., Gallopin, G. C., Gröbler, A., Huntley, B., Jäger, J., Jodha, N. S., Kaspersen, R. E., Mabogunje, A., Matson, P., ... Svedin, U. (2001). Sustainability Science. *Science*, 292(5517), 641 LP – 642.
- Keane, R. E., Hessburg, P. F., Landres, P. B., & Swanson, F. J. (2009). The use of historical range and variability (HRV) in landscape management. *Forest Ecology and Management*, 258(7), 1025–1037. <https://doi.org/10.1016/j.foreco.2009.05.035>
- Kimmerer, R., & Lake, F. (2001). Maintaining the mosaic—The role of indigenous burning in land management. *Journal of Forestry*, 99(11), 36–41.
- Kirchhoff, C. J., Lemos, M. C., & Engle, N. L. (2013). What influences climate information use in water management? The role of boundary organizations and governance regimes in Brazil and the U.S. *Environmental Science and Policy*, 26, 6–18. <https://doi.org/10.1016/j.envsci.2012.07.001>
- Klenk, N. L., & Meehan, K. (2017a). Transdisciplinary sustainability research beyond engagement models: Toward adventures in relevance. *Environmental Science & Policy*, 78, 27–35. <https://doi.org/10.1016/j.envsci.2017.09.006>
- Klenk, N. L., & Meehan, K. (2017b). Transdisciplinary sustainability research beyond engagement models: Toward adventures in relevance. *Environmental Science and Policy*, 78(September), 27–35. <https://doi.org/10.1016/j.envsci.2017.09.006>

- Klenk, N. L., Meehan, K., Pinel, S. L., Mendez, F., Lima, P. T., & Kammen, D. M. (2015). Stakeholders in climate science: Beyond lip service? *Science*, 743(6262), 743–744. <https://doi.org/10.1126/science.aab1495>
- Klenk, N., & Meehan, K. (2015a). Climate change and transdisciplinary science: Problematizing the integration imperative. *Environmental Science & Policy*, 54, 160–167. <https://doi.org/10.1016/j.envsci.2015.05.017>
- Klenk, N., & Meehan, K. (2015b). Climate change and transdisciplinary science: Problematizing the integration imperative. *Environmental Science and Policy*, 54, 160–167. <https://doi.org/10.1016/j.envsci.2015.05.017>
- Klimaszewski-Patterson, A., Weisberg, P. J., Mensing, S. A., & Scheller, R. M. (2018). Using Paleolandscape Modeling to Investigate the Impact of Native American–Set Fires on Pre-Columbian Forests in the Southern Sierra Nevada, California, USA. *Annals of the American Association of Geographers*, 108(6), 1635–1654. <https://doi.org/10.1080/24694452.2018.1470922>
- Knight, C. A., Baskaran, M., Bunting, M. J., Champagne, M., Potts, M. D., Wahl, D., Wanket, J., & Battles, J. J. (2021). Linking modern pollen accumulation rates to biomass: Quantitative vegetation reconstruction in the western Klamath Mountains, NW California, USA. *The Holocene*, 095968362098803. <https://doi.org/10.1177/0959683620988038>
- Kraemer, J. F. (1979). Broadcast Burning: 25-Year Effects on Forest Soils in the Western Flanks of the Cascade Mountains. *Forest Science*, 25(3), 427–439.
- Krawchuk, M. A., Haire, S. L., Coop, J., Parisien, M., Whitman, E., Chong, G., & Miller, C. (2016). Topographic and fire weather controls of fire refugia in forested ecosystems of northwestern North America. *Ecosphere*, 7(12). <https://doi.org/10.1002/ecs2.1632>
- Krawchuk, M. A., & Moritz, M. A. (2011). Constraints on global fire activity vary across a resource gradient. *Ecology*, 92(1), 121–132. <https://doi.org/10.1890/09-1843.1>
- Lacourse, T., Mathewes, R. W., & Hebda, R. J. (2007). Paleoecological analyses of lake sediments reveal prehistoric human impact on forests at anthony island UNESCO World Heritage Site, Queen Charlotte Islands (Haida Gwaii), Canada. *Quaternary Research*, 68(2), 177–183. <https://doi.org/10.1016/j.yqres.2007.04.005>
- Lahsen, M. (2009). A science-policy interface in the global south: The politics of carbon sinks and science in Brazil. *Climatic Change*, 97(3), 339–372. <https://doi.org/10.1007/s10584-009-9610-6>
- Lahsen, M., & Nobre, C. A. (2007). Challenges of connecting international science and local level sustainability efforts: The case of the Large-Scale Biosphere-Atmosphere Experiment in Amazonia. *Environmental Science and Policy*, 10(1), 62–74. <https://doi.org/10.1016/j.envsci.2006.10.005>
- Lake, F. K., & Christianson, A. C. (2019). Indigenous Fire Stewardship. In S. L. Manzello (Ed.), *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires* (pp. 1–9). Springer International Publishing. https://doi.org/10.1007/978-3-319-51727-8_225-1
- Lanigan, S. H. (2015). *Northwest Forest Plan Interagency Regional Monitoring, 15-Year Report Status and Trend of Watershed Condition*.
- Lansing, W. A. (2005). *Seeing the forest for the trees*. The Monroe Press.
- Latour, B. (1987). *Science in action: How to follow scientists and engineers through society*.

- Laughlin, D. C., & Fulé, P. Z. (2008). Wildland fire effects on understory plant communities in two fire-prone forests. *Canadian Journal of Forest Research*, 38(1), 133–142. <https://doi.org/10.1139/X07-118>
- Lave, R., Wilson, M. W., Barron, E. S., Biermann, C., Carey, M. A., Duvall, C. S., Johnson, L., Lane, K. M., McClintock, N., Munroe, D., Pain, R., Proctor, J., Rhoads, B. L., Robertson, M. M., Rossi, J., Sayre, N. F., Simon, G., Tadaki, M., & Van Dyke, C. (2014). Intervention: Critical physical geography. *The Canadian Geographer / Le Géographe Canadien*, 58(1), 1–10. <https://doi.org/10.1111/cag.12061>
- Liebler, C. M., & Bendix, J. (1996). Old-growth forests on network news: News sources and the framing of an environmental controversy. *Journalism and Mass Communication Quarterly*, 73(1), 53–65. <https://doi.org/10.1177/107769909607300106>
- Long, C. J. (2003). Holocene fire and vegetation history of the Oregon Coast Range, United States [Ph.D., University of Oregon]. In *ProQuest Dissertations and Theses* (305307940). Dissertations & Theses @ University of Oregon. <http://libproxy.uoregon.edu/login?url=https://www.proquest.com/docview/305307940?accountid=14698>
- Long, C. J., Shinker, J. J., Minckley, T. A., Power, M. J., & Bartlein, P. J. (2019). A 7600 yr vegetation and fire history from Anthony Lake, northeastern Oregon, USA, with linkages to modern synoptic climate patterns. *Quaternary Research*, 91(2), 705–713. <https://doi.org/10.1017/qua.2018.124>
- Long, C. J., & Whitlock, C. (2002). Fire and Vegetation History from the Coastal Rain Forest of the Western Oregon Coast Range. *Quaternary Research*, 58(03), 215–225. <https://doi.org/10.1006/qres.2002.2378>
- Long, C. J., Whitlock, C., Bartlein, P. J., & Millsaugh, S. H. (1998). *A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study*. 28, 14.
- Mah, A. (2017). Environmental justice in the age of big data: Challenging toxic blind spots of voice, speed, and expertise. *Environmental Sociology*, 3(2), 122–133. <https://doi.org/10.1080/23251042.2016.1220849>
- Malm, A. (2018). *The progress of this storm: Nature and society in a warming world*. Verso.
- Manring, N. J. (1993). Reconciling science and politics in forest service decision making: New tools for public administrators. *American Review of Public Administration*(, 23(4), 9.
- Manzano, S., Julier, A. C. M., Dirk, C. J., Razafimanantsoa, A. H. I., Samuels, I., Petersen, H., Gell, P., Hoffman, M. T., & Gillson, L. (2020). Using the past to manage the future: The role of palaeoecological and long-term data in ecological restoration. *Restoration Ecology*, 28(6), 1335–1342. <https://doi.org/10.1111/rec.13285>
- Marlon, J., Bartlein, P. J., & Whitlock, C. (2006). Fire-fuel-climate linkages in the northwestern USA during the Holocene. *The Holocene*, 16(8), 1059–1071. <https://doi.org/10.1177/0959683606069396>
- Marlon, J. R., Bartlein, P. J., Carcaillet, C., Gavin, D. G., Harrison, S. P., Higuera, P. E., Joos, F., Power, M. J., & Prentice, I. C. (2008). Climate and human influences on global biomass burning over the past two millennia. *Nature Geoscience*, 1(10), 697–702. <https://doi.org/10.1038/ngeo313>
- Marlon, J. R., Bartlein, P. J., Gavin, D. G., Long, C. J., Anderson, R. S., Briles, C. E., Brown, K. J., Colombaroli, D., Hallett, D. J., Power, M. J., Scharf, E. A., & Walsh, M. K. (2012).

- Long-term perspective on wildfires in the western USA. *Proceedings of the National Academy of Sciences*, 109(9), E535–E543. <https://doi.org/10.1073/pnas.1112839109>
- Marshall, B. K., & Picou, J. S. (2008). Postnormal Science, Precautionary Principle, and Worst Cases: The Challenge of Twenty-First Century Catastrophes. *Sociological Inquiry*, 78(2), 230–247.
- Marston, S. A. (2000). The social construction of scale. *Progress in Human Geography*, 24(2), 219–242. <https://doi.org/10.1191/030913200674086272>
- Masson-Delmotte, V., & Schultz, M. (2013). Information from Paleoclimate Archives. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
- Mausser, W., Klepper, G., Rice, M., Schmalzbauer, B. S., Hackmann, H., Leemans, R., & Moore, H. (2013). Transdisciplinary global change research: The co-creation of knowledge for sustainability. *Current Opinion in Environmental Sustainability*, 5(3–4), 420–431. <https://doi.org/10.1016/j.cosust.2013.07.001>
- Mazier, F., Gaillard, M.-J., Kuneš, P., Sugita, S., Trondman, A.-K., & Broström, A. (2012). Testing the effect of site selection and parameter setting on REVEALS-model estimates of plant abundance using the Czech Quaternary Palynological Database. *Review of Palaeobotany and Palynology*, 187, 38–49. <https://doi.org/10.1016/j.revpalbo.2012.07.017>
- McCright, A. M., & Dunlap, R. E. (2010). Anti-reflexivity. *Theory, Culture & Society*, 27(2–3), 100–133. <https://doi.org/10.1177/0263276409356001>
- McLauchlan, K. K., Elmore, A. J., Wyatt Oswald, W., & Sugita, S. (2007). Detecting open vegetation in a forested landscape: Pollen and remote sensing data from New England, USA. *The Holocene*, 17(8), 1233–1243. <https://doi.org/10.1177/0959683607085130>
- Meehan, K., Klenk, N. L., & Mendez, F. (2017). The Geopolitics of Climate Knowledge Mobilization: Transdisciplinary Research at the Science-Policy Interface(s) in the Americas. *Science, Technology, & Human Values*, 1–33.
- Meko, D. M., & Woodhouse, C. A. (2011). *Application of Streamflow Reconstruction to Water Resources Management* (Vol. 11). <https://doi.org/10.1007/978-1-4020-5725-0>
- Merschel, A. G., Heyerdahl, E. K., Spies, T. A., & Loehman, R. A. (2018a). Influence of landscape structure, topography, and forest type on spatial variation in historical fire regimes, Central Oregon, USA. *Landscape Ecology*, 33(7), 1195–1209. <https://doi.org/10.1007/s10980-018-0656-6>
- Merschel, A. G., Heyerdahl, E. K., Spies, T. A., & Loehman, R. A. (2018b). Influence of landscape structure, topography, and forest type on spatial variation in historical fire regimes, Central Oregon, USA. *Landscape Ecology*, 33(7), 1195–1209. <https://doi.org/10.1007/s10980-018-0656-6>
- Miller, S. A., Gordon, S. N., Eldred, P., Beloin, R. M., Wilcox, S., Raggon, M., Andersen, H., & Muldoon, A. (2017). *Northwest Forest Plan—The first 20 years (1994–2013): Watershed condition status and trends. Gen. Tech. Rep. PNW-GTR-932*.
- Minckley, T. A., & Long, C. J. (2016). Paleofire severity and vegetation change in the Cascade Range, Oregon, USA. *Quaternary Research*, 85(2), 211–217. <https://doi.org/10.1016/j.yqres.2015.12.010>

- Minckley, T. A., Whitlock, C., & Bartlein, P. J. (2007). Vegetation, fire, and climate history of the northwestern Great Basin during the last 14,000 years. *Quaternary Science Reviews*, 26(17–18), 2167–2184. <https://doi.org/10.1016/j.quascirev.2007.04.009>
- Minckley, T., & Whitlock, C. (2000). Spatial variation of modern pollen in Oregon and southern Washington, USA. *Review of Palaeobotany and Palynology*, 112(1–3), 97–123. [https://doi.org/10.1016/S0034-6667\(00\)00037-3](https://doi.org/10.1016/S0034-6667(00)00037-3)
- Mohr, J. A., Whitlock, C., & Skinner, C. N. (2000). Postglacial vegetation and fire history, eastern Klamath Mountains, California, USA. *The Holocene*, 10(5), 587–601. <https://doi.org/10.1191/095968300675837671>
- Monteiro, M., & Rajão, R. (2017). Scientists as citizens and knowers in the detection of deforestation in the Amazon. *Social Studies of Science*, 47(4), 466–484. <https://doi.org/10.1177/0306312716679746>
- Moore, J. W. (2003). The Modern World-System as environmental history? Ecology and the rise of capitalism. *Theory and Society*, 32, 307–377.
- Morris, W. G. (1934). Forest Fires in Western Oregon and Western Washington. *Oregon Historical Quarterly*, 35(4), 313–339.
- Mote, P. W., & Salathé, E. P. (2010). Future climate in the Pacific Northwest. *Climatic Change*, 102(1–2), 29–50. <https://doi.org/10.1007/s10584-010-9848-z>
- Mustaphi, C. J. C., & Pisaric, M. F. J. (2014). A classification for macroscopic charcoal morphologies found in Holocene lacustrine sediments. *Progress in Physical Geography: Earth and Environment*, 38(6), 734–754. <https://doi.org/10.1177/0309133314548886>
- Naidoo, R., & Adamowicz, W. L. (2001). Effects of economic prosperity on numbers of threatened species. *Conservation Biology*, 15(4), 1021–1029. <https://doi.org/10.1046/j.1523-1739.2001.0150041021.x>
- Norgaard, R. B., & Baer, P. (2005). Collectively Seeing Complex Systems: The Nature of the Problem. *BioScience*, 55(11), 953. [https://doi.org/10.1641/0006-3568\(2005\)055\[0953:CSCSTN\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2005)055[0953:CSCSTN]2.0.CO;2)
- Ohlson, M., & Tryterud, E. (2000). Interpretation of the charcoal record in forest soils: Forest fires and their production and deposition of macroscopic charcoal. *The Holocene*, 10(4), 519–525. <https://doi.org/10.1191/095968300667442551>
- Ohmann, J. L., & Gregory, M. J. (2002). Predictive mapping of forest composition and structure with direct gradient analysis and nearest- neighbor imputation in coastal Oregon, U.S.A. *Canadian Journal of Forest Research*, 32(4), 725–741. <https://doi.org/10.1139/x02-011>
- Pachauri, R. K., Mayer, L., & Intergovernmental Panel on Climate Change (Eds.). (2015). *Climate change 2014: Synthesis report*. Intergovernmental Panel on Climate Change.
- Palmer, M. A., Zedler, J. B., & Falk, D. A. (2016). Ecological Theory and Restoration Ecology. In M. A. Palmer, J. B. Zedler, & D. A. Falk (Eds.), *Foundations of Restoration Ecology* (pp. 3–26). Island Press/Center for Resource Economics. https://doi.org/10.5822/978-1-61091-698-1_1
- Pearson, S., Lynch, A. J. J., Plant, R., Cork, S., Taffs, K., Dodson, J., Maynard, S., Gergis, J., Gell, P., Thackway, R., Sealie, L., & Donaldson, J. (2015). Increasing the understanding and use of natural archives of ecosystem services, resilience and thresholds to improve policy, science and practice. *The Holocene*, 25(2), 366–378. <https://doi.org/10.1177/0959683614558650>

- Pellow, D. N., & Nyseth Brehm, H. (2013). An Environmental Sociology for the Twenty-First Century. *Annual Review of Sociology*, 39(1), 229–250. <https://doi.org/10.1146/annurev-soc-071312-145558>
- Peterson, N. V., & Groh, E. A. (1963). MAARS OF SOUTH-CENTRAL OREGON. *The ORE BIN*, 25(5), 16.
- Pielke, R. A. (2004). When scientists politicize science: Making sense of controversy over The Skeptical Environmentalist. *Environmental Science and Policy*, 7(5), 405–417. <https://doi.org/10.1016/j.envsci.2004.06.004>
- Platt Bradbury, J., Colman, S. M., & Dean, W. E. (2004). Limnological and Climatic Environments at Upper Klamath Lake, Oregon during the past 45 000 years. *Journal of Paleolimnology*, 31(2), 167–188. <https://doi.org/10.1023/B:JOPL.0000019232.74649.02>
- Power, M. J., Marlon, J., Ortiz, N., Bartlein, P. J., Harrison, S. P., Mayle, F. E., Ballouche, A., Bradshaw, R. H. W., Carcaillet, C., Cordova, C., Mooney, S., Moreno, P. I., Prentice, I. C., Thonicke, K., Tinner, W., Whitlock, C., Zhang, Y., Zhao, Y., Ali, A. A., ... Zhang, J. H. (2008). Changes in fire regimes since the Last Glacial Maximum: An assessment based on a global synthesis and analysis of charcoal data. *Climate Dynamics*, 30(7–8), 887–907. <https://doi.org/10.1007/s00382-007-0334-x>
- Prentice, I. C. (1985). Pollen Representation, Source Area, and Basin Size: Toward a Unified Theory of Pollen Analysis. *Quaternary Research*, 23(01), 76–86. [https://doi.org/10.1016/0033-5894\(85\)90073-0](https://doi.org/10.1016/0033-5894(85)90073-0)
- Prudham, S. (2007). Sustaining Sustained Yield: Class, Politics, and Post-War Forest Regulation in British Columbia. *Environment and Planning D: Society and Space*, 25(2), 258–283. <https://doi.org/10.1068/d2104>
- Prudham, W. S. (1998). Timber and Town: Post-War Federal Forest Policy, Industrial Organization, and Rural Change in Oregon's Illinois Valley. *Antipode*, 30(2), 177–196. <https://doi.org/10.1111/1467-8330.00073>
- R Core Team. (2020). *R: A language and environment for statistical computing* [Manual]. <https://www.R-project.org/>
- Rayner, S., Lach, D., & Ingram, H. (2005). WEATHER FORECASTS ARE FOR WIMPS: WHY WATER RESOURCE MANAGERS DO NOT USE CLIMATE FORECASTS. *Climatic Change*, 69(2–3).
- Reilly, M. J., Zupan, A., Halofsky, J. S., Raymond, C., McEvoy, A., Dye, A. W., Donato, D. C., Kim, J. B., Potter, B. E., Walker, N., Davis, R. J., Dunn, C. J., Bell, D. M., Gregory, M. J., Johnston, J. D., Harvey, B. J., Halofsky, J. E., & Kerns, B. K. (2022). Cascadia Burning: The historic, but not historically unprecedented, 2020 wildfires in the Pacific Northwest, USA. *Ecosphere*, 13(6), e4070. <https://doi.org/10.1002/ecs2.4070>
- Reynolds, R. L., Rosenbaum, J. G., Rapp, J., Kerwin, M. W., Platt Bradbury, J., Colman, S., & Adam, D. (2004). Record of Late Pleistocene Glaciation and Deglaciation in the Southern Cascade Range. I. Petrological Evidence from Lacustrine Sediment in Upper Klamath Lake, Southern Oregon. *Journal of Paleolimnology*, 31(2), 217–233. <https://doi.org/10.1023/B:JOPL.0000019230.42575.03>
- Rice, J. L., Woodhouse, C. A., & Lukas, J. J. (2009). Science and decision making: Water management and tree-ring data in the western United States. *Journal of the American Water Resources Association*, 45(5), 1248–1259. <https://doi.org/10.1111/j.1752-1688.2009.00358.x>

- Robbins, P., Meehan, K., Gosnell, H., & Gilbertz, S. J. (2009). Writing the New West: A Critical Review. *Rural Sociology*, 74(3), 356–382. <https://doi.org/10.1526/003601109789037240>
- Rorig, M. L., & Ferguson, S. A. (1999). Characteristics of Lightning and Wildland Fire Ignition in the Pacific Northwest. *JOURNAL OF APPLIED METEOROLOGY*, 38, 11.
- Rudel, T. K. (2009). How Do People Transform Landscapes? A Sociological Perspective on Suburban Sprawl and Tropical Deforestation. *American Journal of Sociology*, 115(1), 129–154. <https://doi.org/10.1086/597794>
- Rudel, T. K., Coomes, O. T., Moran, E., Achard, F., Angelsen, A., Xu, J., & Lambin, E. (2005). Forest transitions: Towards a global understanding of land use change. *Global Environmental Change*, 15(1), 23–31. <https://doi.org/10.1016/j.gloenvcha.2004.11.001>
- Saban, C., & Gavin, D. G. (2025). Reconstruction of Holocene aridity, fire, and vegetation patterns using lake sediments from Dog Lake, Oregon, USA. *The Holocene*, 35(4), 420–433. <https://doi.org/10.1177/09596836241307301>
- Sarewitz, D., & Pielke, R. A. (2007). The neglected heart of science policy: Reconciling supply of and demand for science. *Environmental Science and Policy*, 10(1), 5–16. <https://doi.org/10.1016/j.envsci.2006.10.001>
- Scarlett, L. (2010). *Reshaping the Endangered Species Act: A Holistic Approach Needed ?* (Issue June).
- Schinkel, W. (2016). Making climates comparable: Comparison in paleoclimatology. *Social Studies of Science*, 46(3), 374–395. <https://doi.org/10.1177/0306312716633537>
- Schusler, T. M., Decker, D. J., & Pfeffer, M. J. (2003). Social learning for collaborative natural resource management. *Society and Natural Resources*, 16(4), 309–326. <https://doi.org/10.1080/08941920390178874>
- Sea, D. S., & Whitlock, C. (1995). Postglacial Vegetation and Climate of the Cascade Range, Central Oregon. *Quaternary Research*, 43(3), 370–381. <https://doi.org/10.1006/qres.1995.1043>
- Seddon, A. W. R., Mackay, A. W., Baker, A. G., Birks, H. J. B., Breman, E., Buck, C. E., Ellis, E. C., Froyd, C. A., Gill, J. L., Gillson, L., Johnson, E. A., Jones, V. J., Juggins, S., Macias-Fauria, M., Mills, K., Morris, J. L., Nogués-Bravo, D., Punyasena, S. W., Roland, T. P., ... Witkowski, A. (2014a). Looking forward through the past: Identification of 50 priority research questions in palaeoecology. *Journal of Ecology*, 102(1), 256–267. <https://doi.org/10.1111/1365-2745.12195>
- Seddon, A. W. R., Mackay, A. W., Baker, A. G., Birks, H. J. B., Breman, E., Buck, C. E., Ellis, E. C., Froyd, C. a., Gill, J. L., Gillson, L., Johnson, E. a., Jones, V. J., Juggins, S., Macias-Fauria, M., Mills, K., Morris, J. L., Nogués-Bravo, D., Punyasena, S. W., Roland, T. P., ... Witkowski, A. (2014b). Looking forward through the past: Identification of 50 priority research questions in palaeoecology. *Journal of Ecology*, 102(1), 256–267. <https://doi.org/10.1111/1365-2745.12195>
- Sensenig, T., Bailey, J. D., & Tappeiner, J. C. (2013). Stand development, fire and growth of old-growth and young forests in southwestern Oregon, USA. *Forest Ecology and Management*, 291, 96–109. <https://doi.org/10.1016/j.foreco.2012.11.006>
- Shelvey, B., & Boyd, R. (2000). Indians, Fire, and the Land in the Pacific Northwest. *The Western Historical Quarterly*, 31(2), 225. <https://doi.org/10.2307/970071>

- Siggery, B., Bennion, H., Morse, S., Murphy, R., & Waite, M. (2023). Practitioner perspectives on the application of palaeoecology in nature conservation. *Frontiers in Ecology and Evolution*, 11, 1304510. <https://doi.org/10.3389/fevo.2023.1304510>
- Sinclair Broadcast Group. (2009, June 29). *A history of field burning: 1948 to 2009* [News]. KVAL. <https://kval.com/news/local/a-history-of-field-burning-1948-to-2009>
- Skinner, C. E., & Radosevich, S. C. (1991). *HOLOCENE VOLCANIC TEPHRA IN THE WILLAMETTE NATIONAL FOREST, WESTERN OREGON: DISTRIBUTION, GEOCHEMICAL CHARACTERIZATION, AND GEOARCHAEOLOGICAL EVALUATION* (p. 231). Transworld Geology.
- Sorenson, D. G. (2012). Eastern Cascades Slopes and Foothills Ecoregion: Chapter 12 in Status and trends of land change in the Western United States--1973 to 2000. In *Professional Paper* (Nos. 1794-A-12; pp. 133–139). U.S. Geological Survey. <https://doi.org/10.3133/pp1794A12>
- Spies, T. A., Stine, P. A., Gravenmier, R. A., Long, J. W., & Reilly, M. J. (2018). *Synthesis of science to inform land management within the Northwest Forest Plan area* (No. PNW-GTR-966; p. PNW-GTR-966). U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. <https://doi.org/10.2737/PNW-GTR-966>
- Steffen, W., Richardson, K., Rockstrom, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sorlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, 347(6223), 1259855–1259855. <https://doi.org/10.1126/science.1259855>
- Strauss, A., & Corbin, J. (Eds.). (1997). *Grounded theory in practice*. Thousand Oaks : Sage Publications.
- Sugita, S. (1994). Pollen Representation of Vegetation in Quaternary Sediments: Theory and Method in Patchy Vegetation. *The Journal of Ecology*, 82(4), 881. <https://doi.org/10.2307/2261452>
- Sugita, S. (2007a). Theory of quantitative reconstruction of vegetation I: Pollen from large sites REVEALS regional vegetation composition. *The Holocene*, 17(2), 229–241. <https://doi.org/10.1177/0959683607075837>
- Sugita, S. (2007b). Theory of quantitative reconstruction of vegetation II: All you need is LOVE. *The Holocene*, 17(2), 243–257. <https://doi.org/10.1177/0959683607075838>
- Sutherland, W. J., Freckleton, R. P., Godfray, H. C. J., Beissinger, S. R., Benton, T., Cameron, D. D., Carmel, Y., Coomes, D. A., Coulson, T., Emmerson, M. C., Hails, R. S., Hays, G. C., Hodgson, D. J., Hutchings, M. J., Johnson, D., Jones, J. P. G., Keeling, M. J., Kokko, H., Kunin, W. E., ... Wiegand, T. (2013). Identification of 100 fundamental ecological questions. *Journal of Ecology*, 101(1), 58–67. <https://doi.org/10.1111/1365-2745.12025>
- Swetnam, T. W., Allen, C. D., & Betancourt, J. L. (1999). APPLIED HISTORICAL ECOLOGY: USING THE PAST TO MANAGE FOR THE FUTURE. *Ecological Applications*, 9(4), 1189–1206. [https://doi.org/10.1890/1051-0761\(1999\)009\[1189:AHEUTP\]2.0.CO;2](https://doi.org/10.1890/1051-0761(1999)009[1189:AHEUTP]2.0.CO;2)
- Takaoka, S., & Swanson, F. J. (2008). Change in Extent of Meadows and Shrub Fields in the Central Western Cascade Range, Oregon*. *The Professional Geographer*, 60(4), Article 4. <https://doi.org/10.1080/00330120802212099>

- Tepley, A. J., Swanson, F. J., & Spies, T. A. (2013). Fire-mediated pathways of stand development in Douglas-fir/western hemlock forests of the Pacific Northwest, USA. *Ecology*, 94(8), 1729–1743. <https://doi.org/10.1890/12-1506.1>
- Theuerkauf, M., Couwenberg, J., Kuparinen, A., & Liebscher, V. (2016). A matter of dispersal: REVEALSinR introduces state-of-the-art dispersal models to quantitative vegetation reconstruction. *Vegetation History and Archaeobotany*, 25(6), 541–553. <https://doi.org/10.1007/s00334-016-0572-0>
- Thomas, J. W., Franklin, J. F., Gordon, J., & Johnson, K. N. (2006). The Northwest Forest Plan: Origins, components, implementation experience, and suggestions for change. *Conservation Biology*, 20(2), 277–287. <https://doi.org/10.1111/j.1523-1739.2006.00385.x>
- Thomas, J. W., Raphael, M. G., Anthony, R. G., Forsman, E. D., Gunderson, A. G., Holthausen, R. S., Marcot, B. G., Reeves, G. H., Sedell, J. R., & Solis, D. M. (1993). *Viability assessments and management considerations for species associated with late-successional and old-growth forests of the Pacific Northwest* - (p. 530). U.S. Department of Agriculture Forest Service, National Forest System.
- Thomson, R. (1973). Palaeolimnology and Palaeomagnetism. *Nature*, 242(5394), 182–184. <https://doi.org/10.1038/242182a0>
- United States Department of Agriculture, & United States Department of the Interior. (1994). *Record of Decision for Amendments to Forest Service and Bureau of Land Management Planning Documents Within the Range of the Northern Spotted Owl* (pp. 1–78).
- United States Department of the Interior, & United States Department of Agriculture. (1994). *Standards and Guidelines for Management of Habitat for Late-Successional and Old-Growth Forest Related Species Within the Range of the Northern Spotted Owl*.
- Urgenson, L. S., Nelson, C. R., Haugo, R. D., Halpern, C. B., Bakker, J. D., Ryan, C. M., Waltz, A. E. M., Belote, R. T., & Alvarado, E. (2018). Social perspectives on the use of reference conditions in restoration of fire-adapted forest landscapes: Perspectives on reference conditions. *Restoration Ecology*, 26(5), 987–996. <https://doi.org/10.1111/rec.12640>
- US EPA, O. (2015, November 25). *Level III and IV Ecoregions of the Continental United States* [Data and Tools]. <https://www.epa.gov/eco-research/level-iii-and-iv-ecoregions-continental-united-states>
- Vachula, R. S. (2020). A meta-analytical approach to understanding the charcoal source area problem. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 110111. <https://doi.org/10.1016/j.palaeo.2020.110111>
- Vachula, R. S., & Rehn, E. (2023). Modeled dispersal patterns for wood and grass charcoal are different: Implications for paleofire reconstruction. *The Holocene*, 33(2), 159–166. <https://doi.org/10.1177/09596836221131708>
- Vachula, R. S., Russell, J. M., Huang, Y., & Richter, N. (2018). Assessing the spatial fidelity of sedimentary charcoal size fractions as fire history proxies with a high-resolution sediment record and historical data. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 508, 166–175. <https://doi.org/10.1016/j.palaeo.2018.07.032>
- van der Knaap, W. O., Lamentowicz, M., van Leeuwen, J. F. N., Hangartner, S., Leuenberger, M., Mauquoy, D., Goslar, T., Mitchell, E. A. D., Lamentowicz, Ł., & Kamenik, C. (2011). A multi-proxy, high-resolution record of peatland development and its drivers

- during the last millennium from the subalpine Swiss Alps. *Quaternary Science Reviews*, 30(23), 3467–3480. <https://doi.org/10.1016/j.quascirev.2011.06.017>
- Vogel, E. (2007). *THE COLUMBIA RIVER'S REGION: POLITICS, PLACE AND ENVIRONMENT IN THE PACIFIC NORTHWEST, 1933-PRESENT* [Doctoral]. University of Oregon.
- Volland, L. (1988). *Plant Associations of the Central Oregon Pumice Zone* (Nos. R6-ECOL-104–1985; p. 216). United States Forest Service. <https://ir.library.oregonstate.edu/downloads/fn107397s>
- Walsh, M. K., Marlon, J. R., Goring, S. J., Brown, K. J., & Gavin, D. G. (2015). A Regional Perspective on Holocene Fire–Climate–Human Interactions in the Pacific Northwest of North America. *Annals of the Association of American Geographers*, 105(6), 1135–1157. <https://doi.org/10.1080/00045608.2015.1064457>
- Walsh, M. K., Pearl, C. A., Whitlock, C., Bartlein, P. J., & Worona, M. A. (2010). An 11 000-year-long record of fire and vegetation history at Beaver Lake, Oregon, central Willamette Valley. *Quaternary Science Reviews*, 29(9–10), 1093–1106. <https://doi.org/10.1016/j.quascirev.2010.02.011>
- Walsh, M. K., Whitlock, C., & Bartlein, P. J. (2008). A 14,300-year-long record of fire–vegetation–climate linkages at Battle Ground Lake, southwestern Washington. *Quaternary Research*, 70(2), 251–264. <https://doi.org/10.1016/j.yqres.2008.05.002>
- Walsh, M. K., Whitlock, C., & Bartlein, P. J. (2010). 1200 years of fire and vegetation history in the Willamette Valley, Oregon and Washington, reconstructed using high-resolution macroscopic charcoal and pollen analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 297(2), 273–289. <https://doi.org/10.1016/j.palaeo.2010.08.007>
- Wanket, J. A. (2002). *Late Quaternary Vegetation and Climate of the Klamath Mountains* [Ph.D.]. University of California, Berkley.
- Warf, B. (1988a). Regional transformation, everyday life, and Pacific Northwest lumber production. *Annals of the Association of American Geographers*, 78(2), 326–346.
- Warf, B. (1988b). Regional Transformation, Everyday Life, and Pacific Northwest Lumber Production. *Annals of the Association of American Geographers*, 78(2), 326–346.
- Watson, E. B., Wasson, K., Pasternack, G. B., Woolfolk, A., Van Dyke, E., Gray, A. B., Pakenham, A., & Wheatcroft, R. A. (2011). Applications from Paleoecology to Environmental Management and Restoration in a Dynamic Coastal Environment. *Restoration Ecology*, 19(6), 765–775. <https://doi.org/10.1111/j.1526-100X.2010.00722.x>
- Weisberg, P. J. (2004). Importance of Non-Stand-Replacing Fire for Development of Forest Structure in the Pacific Northwest, USA. *Forest Science*, 50(2), 14.
- Weisberg, P. J., & Swanson, F. J. (2003a). Regional synchronicity in fire regimes of western Oregon and Washington, USA. *Forest Ecology and Management*, 12.
- Weisberg, P. J., & Swanson, F. J. (2003b). Regional synchronicity in fire regimes of western Oregon and Washington, USA. *Forest Ecology and Management*, 172, 17–28.
- Westerling, A. L. (2006). Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. *Science*, 313(5789), 940–943. <https://doi.org/10.1126/science.1128834>
- White, D. D., Corley, E. A., & White, M. S. (2008a). Water Managers' Perceptions of the Science–Policy Interface in Phoenix, Arizona: Implications for an Emerging Boundary Organization. *Society & Natural Resources*, 21(3), 230–243. <https://doi.org/10.1080/08941920701329678>

- White, D. D., Corley, E. A., & White, M. S. (2008b). Water Managers' Perceptions of the Science–Policy Interface in Phoenix, Arizona: Implications for an Emerging Boundary Organization. *Society & Natural Resources*, 21(3), 230–243. <https://doi.org/10.1080/08941920701329678>
- Whitlock, C., Colombaroli, D., Conedera, M., & Tinner, W. (2018). Land-use history as a guide for forest conservation and management: Land-Use History. *Conservation Biology*, 32(1), 84–97. <https://doi.org/10.1111/cobi.12960>
- Whitlock, C., Higuera, P. E., McWethy, D. B., & Briles, C. E. (2010). Paleoecological Perspectives on Fire Ecology: Revisiting the Fire-Regime Concept. *The Open Ecology Journal*, 3(2), 6–23. <https://doi.org/10.2174/1874213001003020006>
- Whitlock, C., & Larsen, C. (2001). Charcoal as a Fire Proxy. In J. P. Smol, H. J. B. Birks, W. M. Last, R. S. Bradley, & K. Alverson (Eds.), *Tracking Environmental Change Using Lake Sediments: Terrestrial, Algal, and Siliceous Indicators* (pp. 75–97). Springer Netherlands. https://doi.org/10.1007/0-306-47668-1_5
- Whitlock, C., McWethy, D. B., Tepley, A. J., Veblen, T. T., Holz, A., McGlone, M. S., Perry, G. L. W., Wilmshurst, J. M., & Wood, S. W. (2015). Past and Present Vulnerability of Closed-Canopy Temperate Forests to Altered Fire Regimes: A Comparison of the Pacific Northwest, New Zealand, and Patagonia. *BioScience*, 65(2), 151–163. <https://doi.org/10.1093/biosci/biu194>
- Whitlock, C., & Millspaugh, S. H. (1996). Testing the assumptions of fire-history studies: An examination of modern charcoal accumulation in Yellowstone National Park, USA. *The Holocene*, 6(1), 7–15. <https://doi.org/10.1177/095968369600600102>
- Whitlock, C., Sarna-Wojcicki, A. M., Bartlein, P. J., & Nickmann, R. J. (2000). Environmental history and tephrostratigraphy at Carp Lake, southwestern Columbia Basin, Washington, USA. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 155(1–2), 7–29. [https://doi.org/10.1016/S0031-0182\(99\)00092-9](https://doi.org/10.1016/S0031-0182(99)00092-9)
- Whitmore, J., Gajewski, K., Sawada, M., Williams, J. W., Shuman, B., Bartlein, P. J., Minckley, T., Viau, A. E., Webb, T., Shafer, S., Anderson, P., & Brubaker, L. (2005). Modern pollen data from North America and Greenland for multi-scale paleoenvironmental applications. *Quaternary Science Reviews*, 24(16–17), 1828–1848. <https://doi.org/10.1016/j.quascirev.2005.03.005>
- Whyte, K. P. (2013). On the role of traditional ecological knowledge as a collaborative concept: A philosophical study. *Ecological Processes*, 2(1), 7. <https://doi.org/10.1186/2192-1709-2-7>
- Wieczorek, M., & Herzschuh, U. (2020). Compilation of relative pollen productivity (RPP) estimates and taxonomically harmonised RPP datasets for single continents and Northern Hemisphere extratropics. *Earth System Science Data*, 12(4), 3515–3528. <https://doi.org/10.5194/essd-12-3515-2020>
- Wilhere, G. F. (2012). Inadvertent Advocacy. *Conservation Biology*, 26(1), 39–46. <https://doi.org/10.1111/j.1523-1739.2011.01805.x>
- Williams, J. W., Grimm, E. C., Blois, J. L., Charles, D. F., Davis, E. B., Goring, S. J., Graham, R. W., Smith, A. J., Anderson, M., Arroyo-Cabrales, J., Ashworth, A. C., Betancourt, J. L., Bills, B. W., Booth, R. K., Buckland, P. I., Curry, B. B., Giesecke, T., Jackson, S. T., Latorre, C., ... Takahara, H. (2018). The Neotoma Paleoecology Database, a multiproxy,

- international, community-curated data resource. *Quaternary Research*, 89(1), 156–177. <https://doi.org/10.1017/qua.2017.105>
- Williams, J. W., & Jackson, S. T. (2007). Novel climates, no-analog communities, and ecological surprises. *Frontiers in Ecology and the Environment*, 5(9), 475–482. <https://doi.org/10.1890/070037>
- Williams, M. A., & Baker, W. L. (2012). Spatially extensive reconstructions show variable-severity fire and heterogeneous structure in historical western United States dry forests: Historical landscape reconstructions show heterogeneity. *Global Ecology and Biogeography*, 21(10), 1042–1052. <https://doi.org/10.1111/j.1466-8238.2011.00750.x>
- Williams, M. A., & Baker, W. L. (2014). High-severity fire corroborated in historical dry forests of the western United States: Response to Fulé *et al.* : Response to Fulé *et al.* *Global Ecology and Biogeography*, 23(7), 831–835. <https://doi.org/10.1111/geb.12152>
- Willis, K. J., Araujo, M. B., Bennett, K. D., Figueroa-Rangel, B., Froyd, C. A., & Myers, N. (2007). How can a knowledge of the past help to conserve the future? Biodiversity conservation and the relevance of long-term ecological studies. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 362(1478), 175–187. <https://doi.org/10.1098/rstb.2006.1977>
- Willis, K. J., Araújo, M. B., Bennett, K. D., Figueroa-Rangel, B., Froyd, C. a, & Myers, N. (2007). How can a knowledge of the past help to conserve the future? Biodiversity conservation and the relevance of long-term ecological studies. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, 362(1478), 175–186. <https://doi.org/10.1098/rstb.2006.1977>
- Willis, K. J., Bailey, R. M., Bhagwat, S. A., & Birks, H. J. B. (2010). Biodiversity baselines, thresholds and resilience: Testing predictions and assumptions using palaeoecological data. *Trends in Ecology & Evolution*, 25(10), 583–591. <https://doi.org/10.1016/j.tree.2010.07.006>
- Willis, K. J., & Birks, H. J. B. (2006). What Is Natural? The Need for a Long-Term Perspective in Biodiversity Conservation. *Science*, 314(5803), 1261–1265. <https://doi.org/10.1126/science.1122667>
- Willis, K. J., & MacDonald, G. M. (2011). Long-Term Ecological Records and Their Relevance to Climate Change Predictions for a Warmer World. *Annual Review of Ecology, Evolution, and Systematics*, 42(1), 267–287. <https://doi.org/10.1146/annurev-ecolsys-102209-144704>
- Wingard, G. L., Bernhardt, C. E., & Wachnicka, A. H. (2017). The Role of Paleoecology in Restoration and Resource Management—The Past As a Guide to Future Decision-Making: Review and Example from the Greater Everglades Ecosystem, U.S.A. *Frontiers in Ecology and Evolution*, 5. <https://doi.org/10.3389/fevo.2017.00011>
- Winkel, G. (2014). When the pendulum doesn't find its center: Environmental narratives, strategies, and forest policy change in the US Pacific Northwest. *Global Environmental Change*, 27(1), 84–95. <https://doi.org/10.1016/j.gloenvcha.2014.04.009>
- Wynne, B. (2010). Strange Weather, Again. *Theory, Culture & Society*, 27(2–3), 289–305. <https://doi.org/10.1177/0263276410361499>
- York, R. (2006). Ecological paradoxes: William Stanley Jevons and the Paperless Office. *Human Ecology Review*, 13(2), 143–147. <https://doi.org/10.2307/24707585>

- York, R. (2017). Why Petroleum Did Not Save the Whales. *Socius: Sociological Research for a Dynamic World*, 3, 1–13. <https://doi.org/10.1177/2378023117739217>
- York, R., & Dunlap, R. E. (2012). Environmental Sociology. In *The Wiley-Blackwell Companion to Sociology* (pp. 504–521). <https://doi.org/10.1002/9781444347388.ch27>
- York, R., & Mancus, P. (2009). Critical Human Ecology: Historical Materialism and Natural Laws. *Sociological Theory*, 27(2), 122–149. <https://doi.org/10.1111/j.1467-9558.2009.01340.x>
- York, R., & McGee, J. A. (2015). Understanding the Jevons paradox. *Environmental Sociology*, 2(1), 1–11. <https://doi.org/10.1080/23251042.2015.1106060>
- Zybach, B. (2003). *The Great Fires: Indian Burning and Catastrophic Forest Fire Patterns of the Oregon Coast Range, 1491-1951* [Oregon State University]. https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/0p096972r

APPENDIX A

INTERVIEW GUIDE

I will be working to understand of the local/regional management issues related to fire and biodiversity and how those might have long-term ecosystem trajectory characteristics relevant to management. During this phase, I will pay special attention to how participants frame their own duties with respect to management goals, and how concepts of natural range of variability and long-term trends manifest in discourse about contemporary issues.

What is job title and what are your primary responsibilities?

- Do you collect data? Do you analyze data? Do you plan research or monitoring? Do you deal with the press or the public? Do you write internal or external reports?
- How often do you do these different things throughout the year, is there a yearly rhythm to your work?

What are the top 3 concerns or issues that you deal with related to the management of wildfire in your job? Fire effects, habitat snags, prescribed fire didn't go through

- How much of your time is spent on them?
- Would you say these issues are recognized by your institution and your colleagues?
- What would you want to know about the history of these? Do you think it would be available? Where would you look for information?

When was the last time you referred to forest or fire history or thought about it? How do you use forest or fire history, and/or other information about historic range of variability as part of your job to address these concerns (specifically fire)?

- What function does fire history have in your work?
- How does it inform planning for the future?

In what ways is your understanding of forest or fire history limiting?

- Do you find that you wish you had more information about fire history? What more would like to know?
- Does fire history you use seem to be sufficient for describing a ‘baseline’ fire condition, if so, what that take into account changing climatic conditions? If not, how is it insufficient?

How is your job related to fire planning?

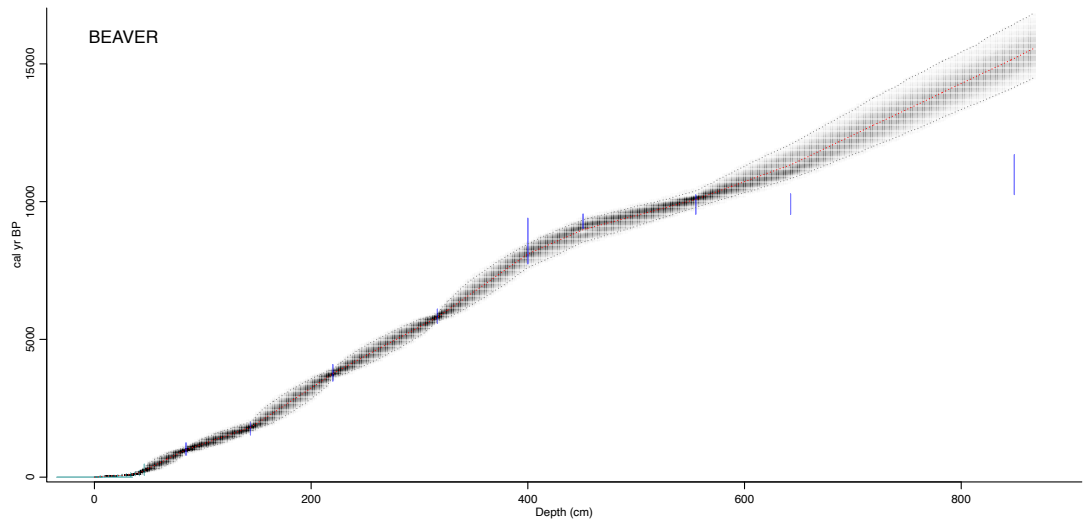
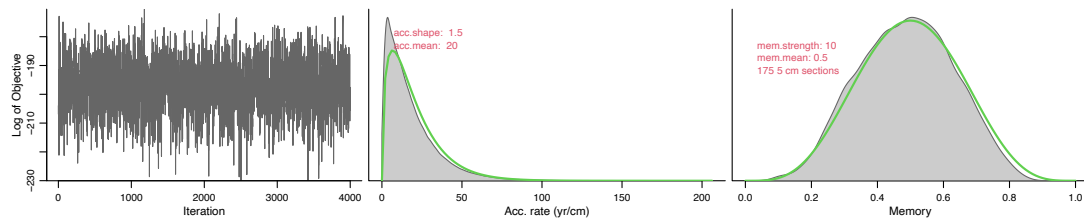
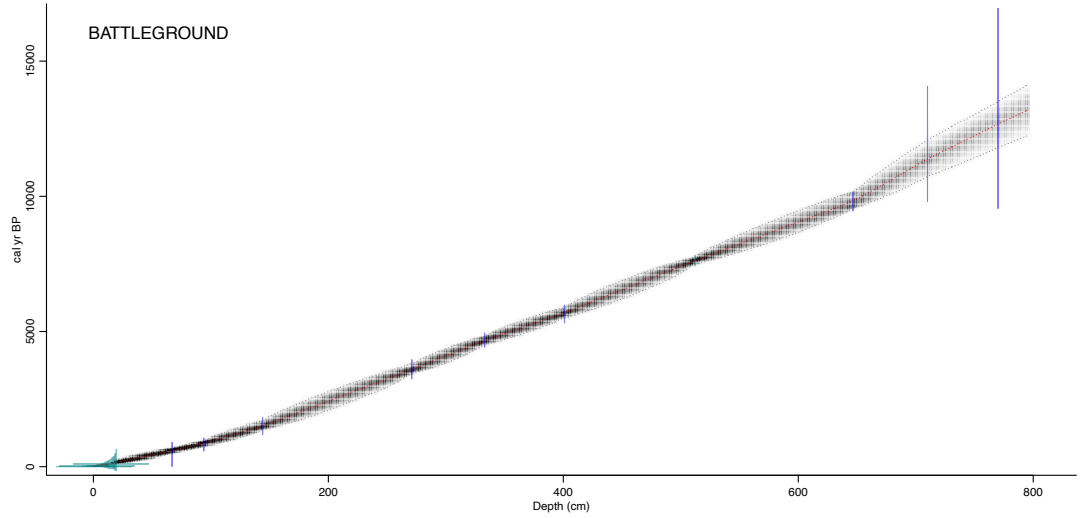
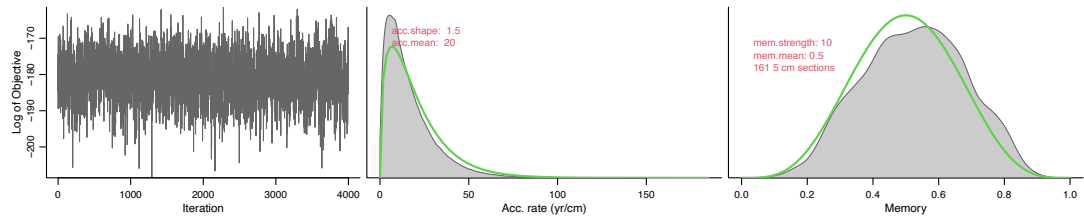
- Do you advise people who write forest plans (or other planning documents) and the fire plans that are part of them? How are these codified, and how often?
- Who else do you work with on these plans?

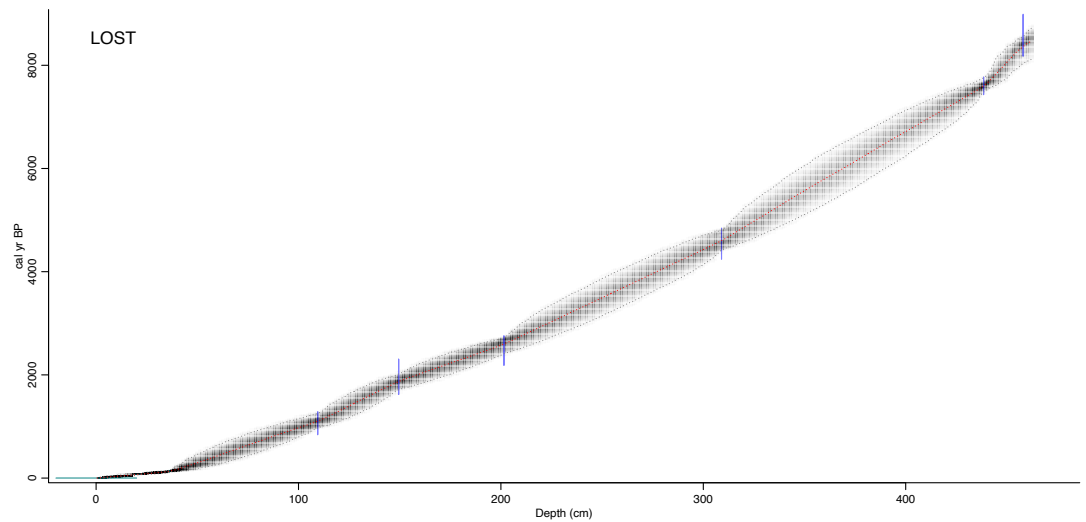
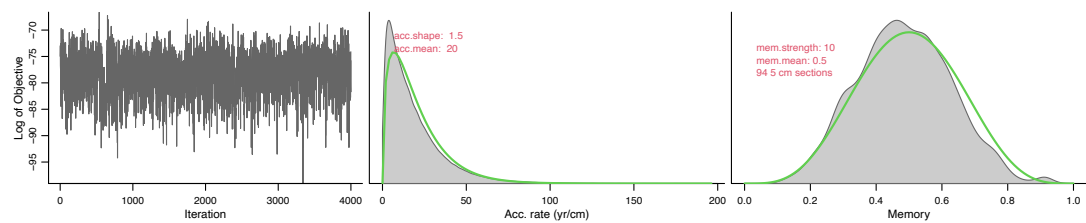
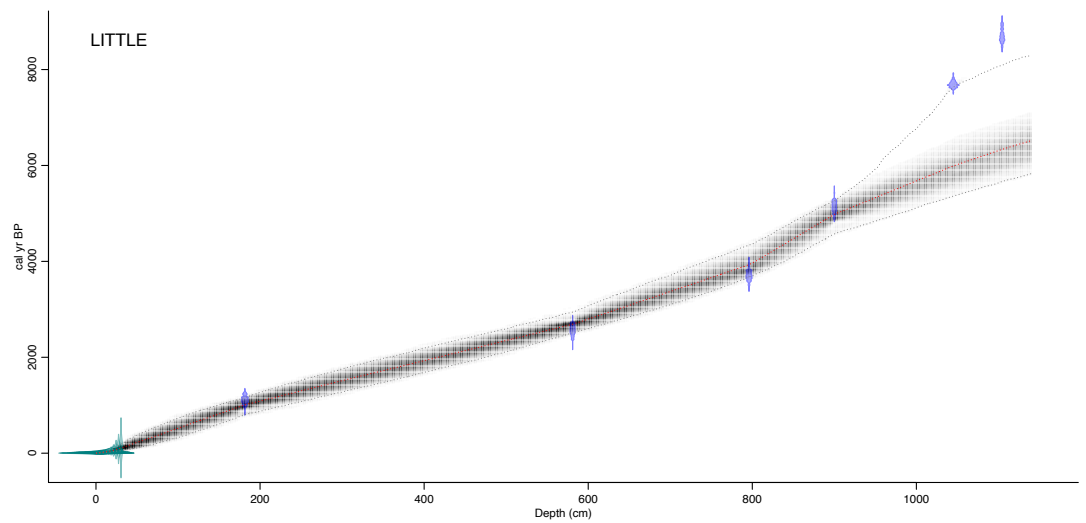
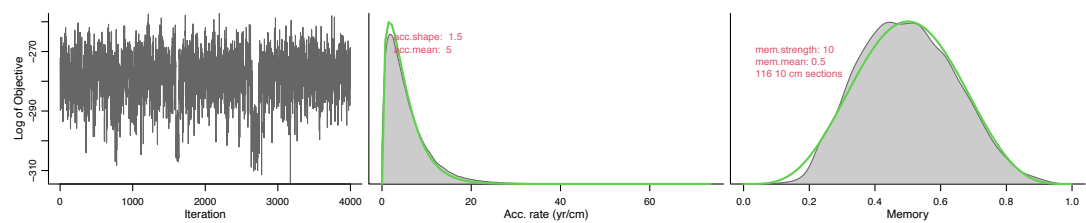
Is fire history useful for planning for fire now and in the future?

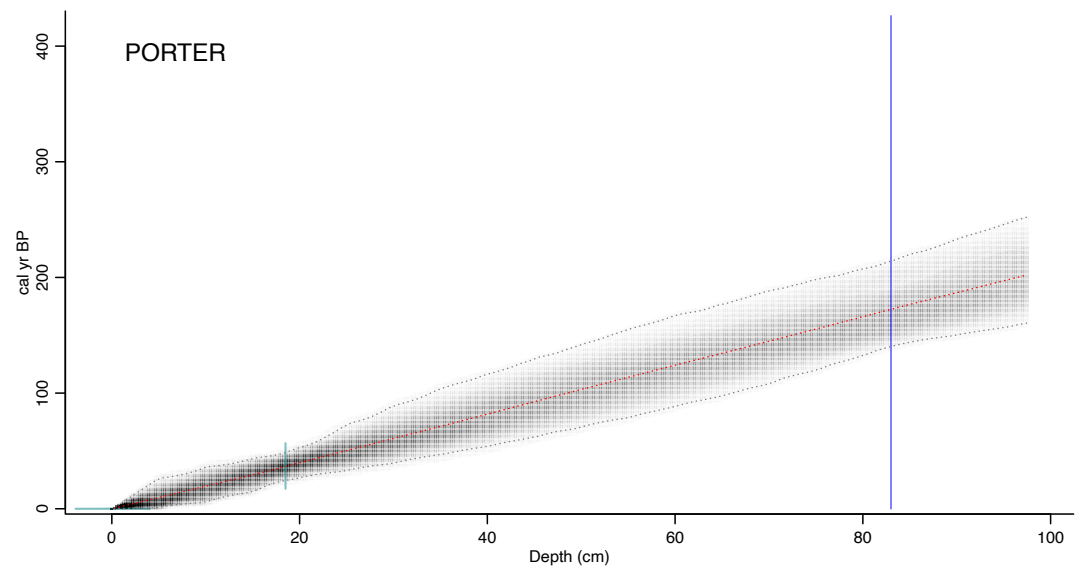
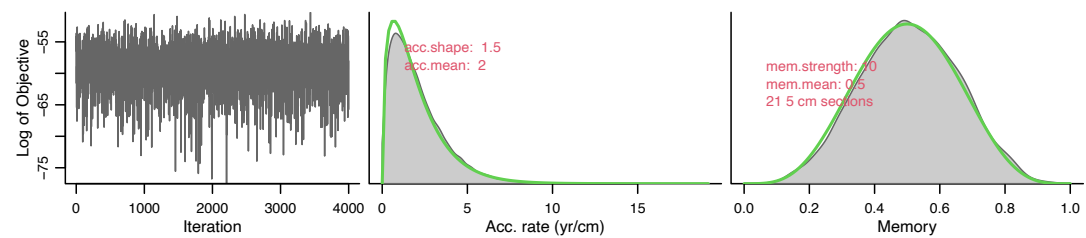
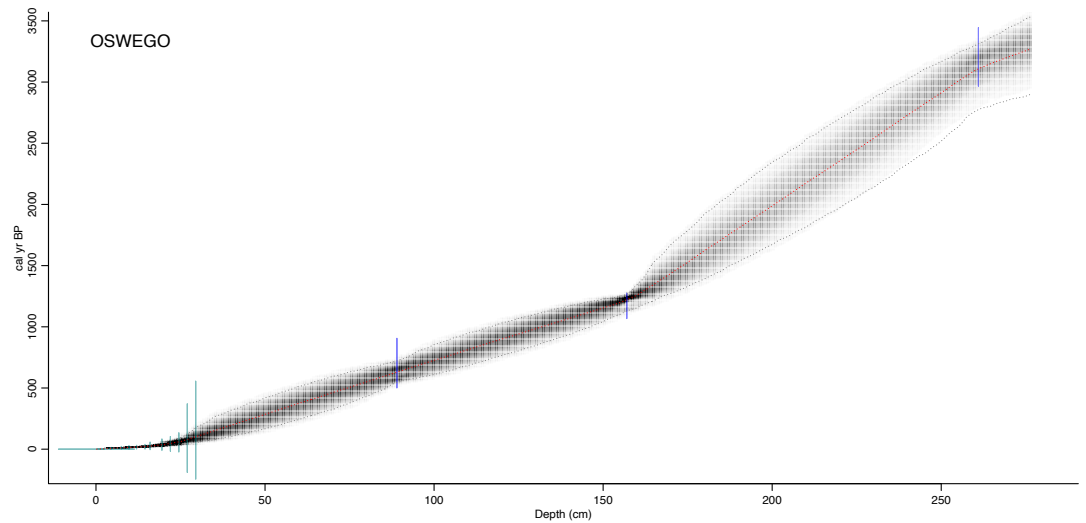
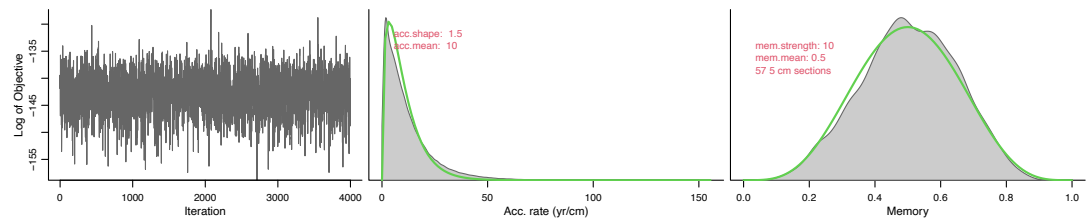
- Do other people you work with have insights?

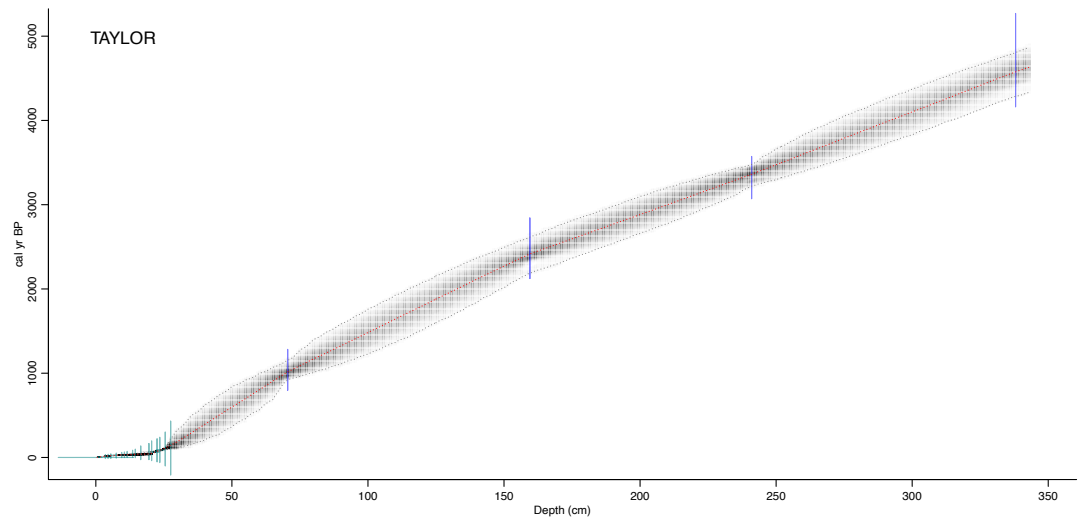
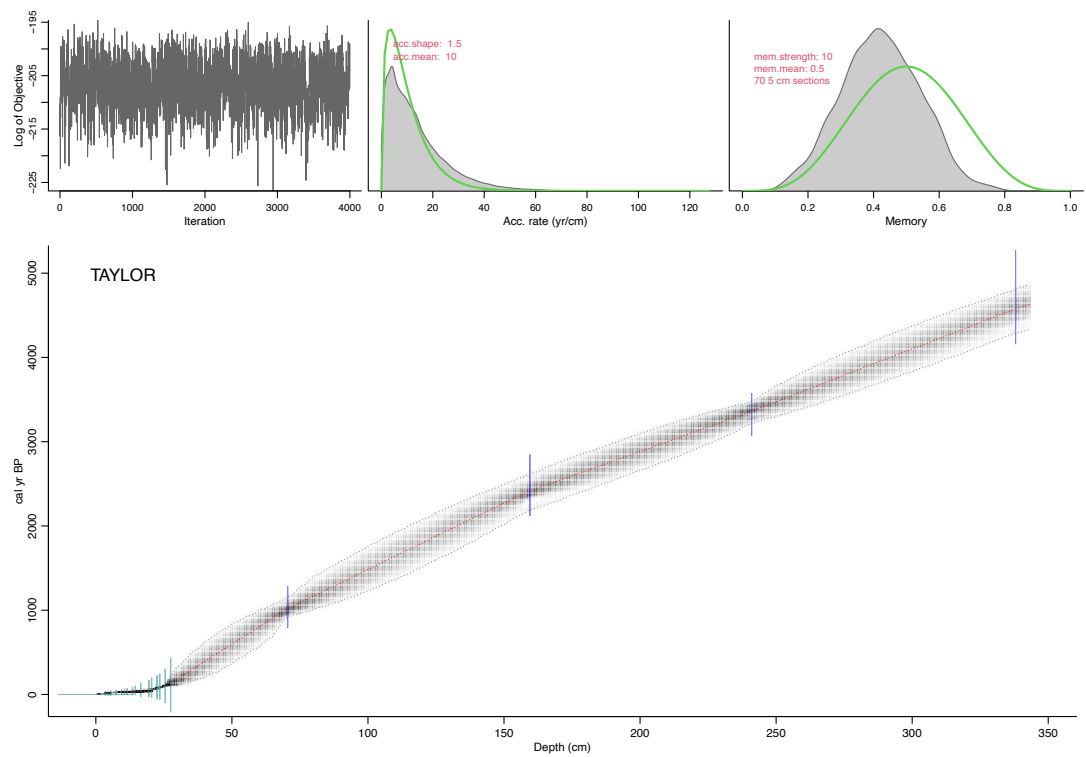
APPENDIX B

RECALCULATED AGE MODELS FOR PRIOR STUDIES









APPENDIX C

SURFACE POLLEN, COMPOSITION AND STRUCTURE SPATIAL ANALYSIS

This appendix contains supplemental information for Chapter 4.

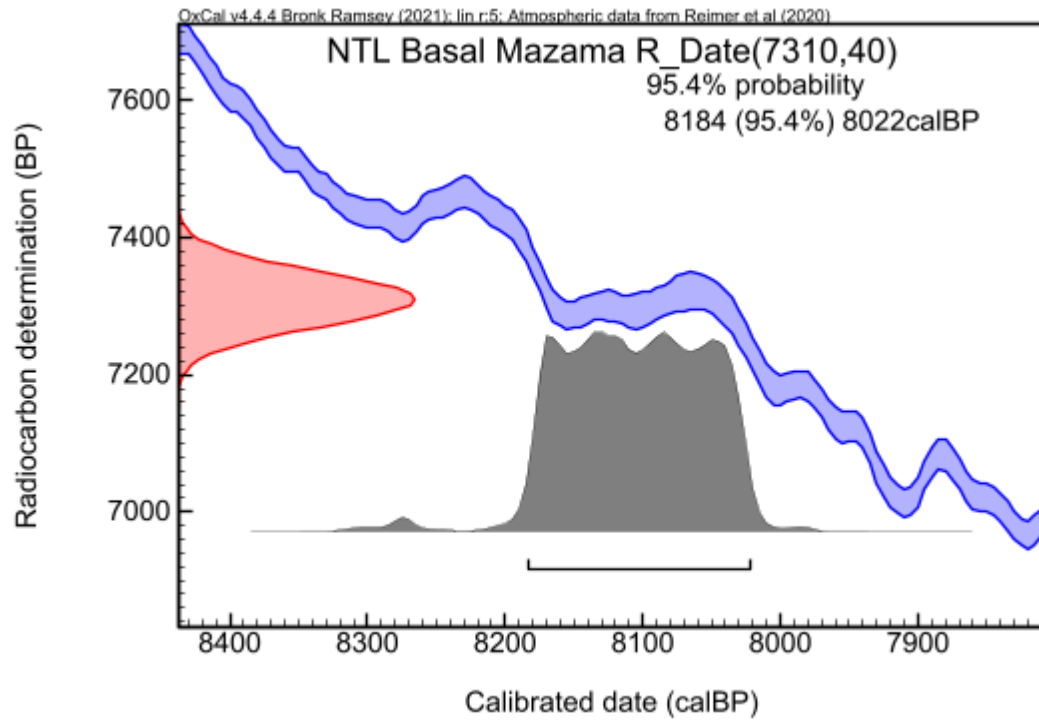


Figure 33 Calibration results for the radiocarbon sample from 231 cm submitted to assess the potential reservoir effects which, if present, would lead to overestimating bulk sediment radiocarbon age. Uncalibrated age is 7310 ± 40 .

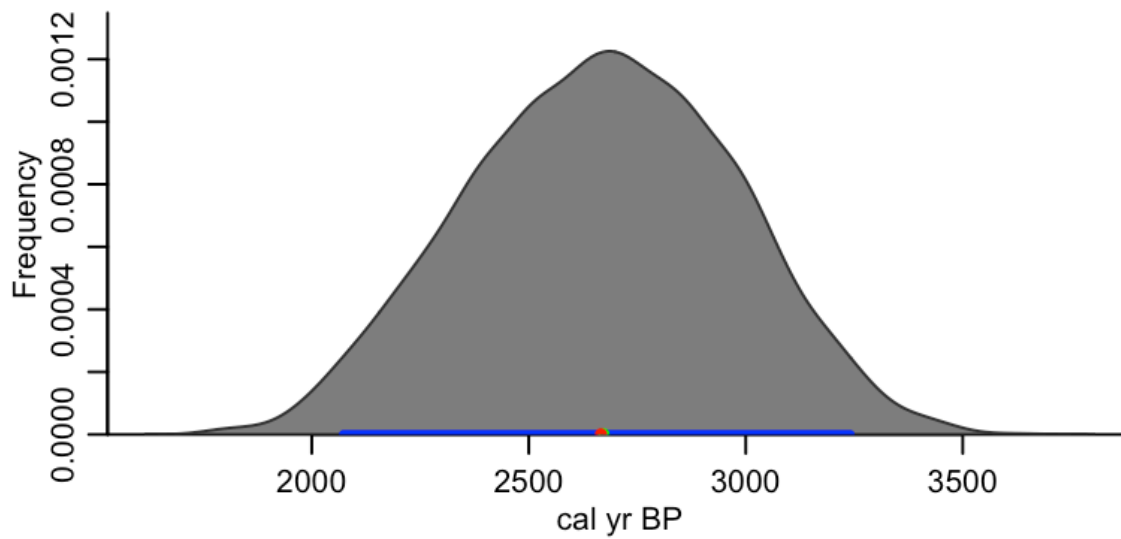


Figure 34 Probability distribution produced by Bacon age-depth model for NTL at 54 cm depth, where an observed tephra layer occurs. Rock Mesa tephras occurred at 2742 and 2850 calibrated cal yr BP, dated by dendrochronology (Skinner & Radosevich, 1991). Mean (red) 2666.4 cal yr BP, median (green): 2672.3 cal yr BP. 95% range (blue): 2072.9 to 3240.8 cal yr BP.

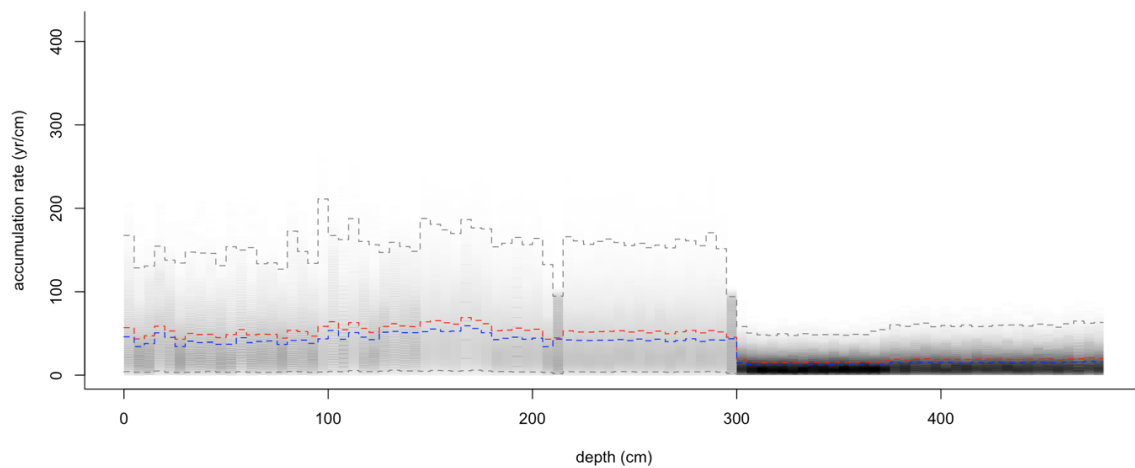


Figure 35 Accumulation rates produced by age-depth modeling of the NTL core by depth. Mean of model iterations (dashed red line), and median (dashed blue line).

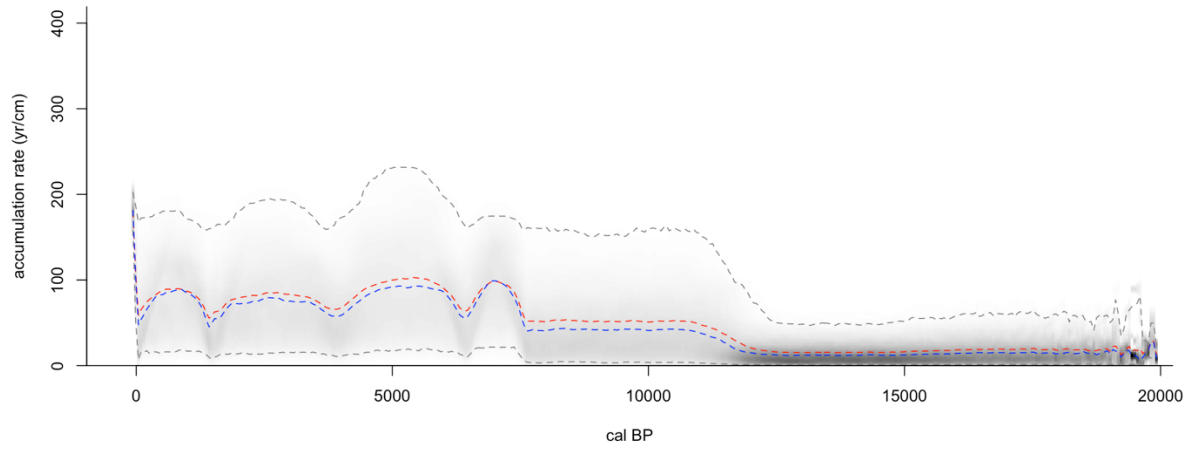


Figure 36 Accumulation rates produced by age-depth modeling of the NTL core by modeled age. Mean of model iterations (dashed red line), and median (dashed blue line).

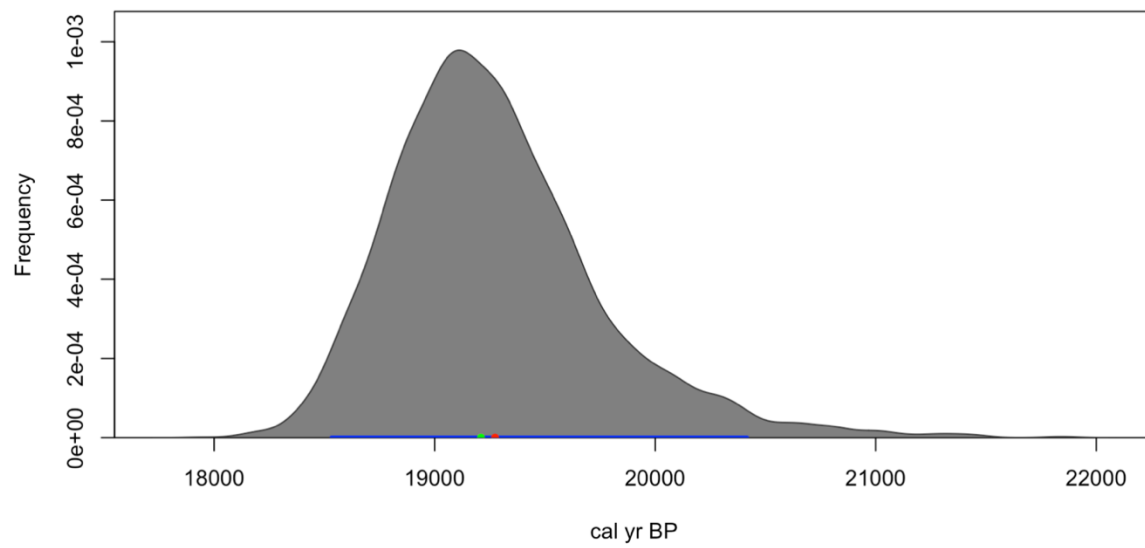


Figure 37 Probability distribution of modeled ages for basal depth (566 cm) of NTL core.

Table 6 Surface pollen taxon assigned morphology and input parameter estimates for computing percent cover with REVEALS

Arboreal				Shrub				Herbaceous			
Taxon	Fall speed (m/s)	PPE	PPE error (SE)	Taxon	Fall speed (m/s)	PPE	PPE error (SE)	Taxon	Fall speed (m/s)	PPE	PPE error (SE)
ABIES	0.12	6.88	1.44	ARTEMISIA	0.01	1.36	0.36	AMBROSIA	0.01	1.36	0.36
ACERX	0.056	0.23	0.04	CAPRIFOLIA	0.03	0.52	0.08	APIACEAE	0.04	0.41	2.13
ALCRISPA	0.021	2.7	0.12	CEANOTHUS	0.03	0.52	0.08	ARCEUTHOBI	0.03	0.52	0.08
ALRUBRA	0.021	2.7	0.12	CHENOAMX	0.01	5.24	0.50	ASTERX	0.03	0.59	0.13
ALNUSX	0.021	2.7	0.12	CORNUS	0.04	1.72	0.14	ASTERCICHO	0.03	0.59	0.13
BETULA	0.051	6.19	0.149	CORYLUS	0.02	1.78	0.07	BRASSICACEAE	0.02	0.48	0.09
CUPRESSA	0.01	1.11	0.09	ERICACEX	0.03	0.83	0.07	CAMPANULACEA	0.02	2.29	0.14
FRAXINUX	0.02	2.42	0.187	ERICALES	0.03	0.83	0.07	CARYA	0.03	3.28	0.12
JUGLANSX	0.032	3.28	0.119	MYRICACX	0.03	3.28	0.12	CARYOPHYLL	0.04	0.60	0.05
LARIXPSEU	0.065	1.24	0.15	RHAMNACEAE	0.03	2.24	0.46	CERCOCAR	0.01	0.88	0.11
MORACEAX	0.016	1.1	0.55	ROSACEAX	0.01	0.88	0.11	CHRYSOLEP	0.06	2.92	0.13
PICEAX	0.056	6.46	0.18	SARCOBATUS	0.01	5.24	0.50	CYPERACE	0.03	0.98	0.03
PINDIPLO	0.033	14.64	0.352	SHEPHERDIA	0.01	13.64	0.69	EPHEDRA	0.03	0.52	0.08
PINHAPLO	0.033	14.64	0.352					ERIOGONUM	0.03	2.92	0.07
PINUSX	0.033	14.64	0.352					EUPHORB	0.03	0.52	0.08
PLATANUS	0.012	13.64	0.686					FABACEAE	0.02	0.30	0.03
POPULUS	0.026	0.67	0.085					LAMIACEAE	0.02	1.06	0.13
QUERCUS	0.035	2.08	0.43					LILIACEAE	0.01	1.49	0.11
SALIX	0.016	2.02	0.188					MALVACEAE	0.01	0.88	0.11
TAXUS	0.01	1.11	0.09					ONAGRACEAE	0.02	0.48	0.09
TSUGHETE	0.08	3.4	0.13					PLANTAGINX	0.03	3.54	0.19
TSUGMERT	0.08	3.4	0.13					POACEAE	0.03	1.00	0.05
TSUGAX	0.08	3.4	0.13					POLEMONI	0.03	0.83	0.07
								POLYGONAX	0.04	0.60	0.05
								POLYGBIS	0.04	0.60	0.05
								POLYGONMX	0.04	0.60	0.05
								RANUNCUL	0.01	2.40	0.40
								RUBIACEAE	0.02	1.67	0.13
								RUMEX	0.01	2.79	0.17
								SXFRAGAX	0.01	0.88	0.11

Table 7 NTL pollen taxon assigned morphology and input parameter estimates for computing percent cover with REVEALS

Arboreal				Shrub				Herbaceous			
Taxon	Fall speed (m/s)	PPE	PPE error (SE)	Taxon	Fall speed (m/s)	PPE	PPE error (SE)	Taxon	Fall speed (m/s)	PPE	PPE error (SE)
Pinus undiff	0.03	14.10	0.45	Ericaceae	0.04	0.45	0.01	Poaceae	0.03	1.00	0.05
Pinus (haploxyton)	0.03	14.10	0.45	Grossulariaceae	0.03	0.52	0.08	Cyperaceae	0.03	0.98	0.03
Pinus (diploxyton)	0.03	14.10	0.45	Rhamnaceae	0.03	2.24	0.46	Asteraceae	0.02	0.59	0.13
Tsuga heterophylla	0.08	3.40	0.13	Rosaceae	0.01	0.88	0.11	Ambrosia	0.01	1.36	0.36
Tsuga mertensiana	0.08	3.40	0.13	Artemisia	0.01	1.36	0.36	Liguliflorea	0.02	0.59	0.13
Picea	0.06	6.46	0.18					Tubuliflorea	0.02	0.59	0.13
Abies	0.12	6.88	1.44					Chenopodiaceae	0.01	5.24	0.50
Pseudotsuga	0.07	1.24	0.15					Cruciferae	0.02	0.49	0.09
Larix	0.07	1.24	0.15					Labiatae	0.02	1.06	0.13
Cupressaceae	0.01	1.11	0.09					Fabaceae	0.02	0.30	0.03
Aceraceae	0.06	0.23	0.04					Oxytropis	0.02	0.30	0.03
Alnus undiff	0.02	2.70	0.12					Oxalidaceae	0.03	0.52	0.08
Alnus rubra	0.02	2.70	0.12					Plantagianaceae	0.03	3.54	0.19
Alnus sinuata	0.02	2.70	0.12					Polygonaceae	0.01	2.70	0.17
Betula	0.05	6.19	0.15					Portulaceae	0.03	0.52	0.08
Corylus	0.02	1.58	0.06					Primulaceae	0.03	0.52	0.08
Quercus	0.04	2.08	0.43					Ranunculaceae	0.01	2.40	0.40
Salix	0.02	0.68	0.01					Actaea	0.01	2.40	0.40
Populus	0.03	0.67	0.09					Thalictrum	0.01	4.65	0.30
								Rubiaceae	0.02	1.67	0.13
								Saxifragaceae	0.01	0.88	0.11
								Solanaceae	0.03	0.52	0.08
								Apiaceae	0.04	2.13	0.41
								Urticaceae	0.01	10.52	0.31
								Violaceae	0.03	0.52	0.08

Table 8 Model fit parameters for zonal fit.

Model	r (km)	r ²	F	p	l	AIC	BIC	D
zm ~ Ca	1	0.21	21.33	1.44E-05	-361.11	728.22	735.48	29215.05
	5	0.33	39.36	1.63E-08	-349.50	704.99	712.25	22082.66
	10	0.43	60.06	2.33E-11	-341.45	688.90	696.16	18190.92
	20	0.51	83.59	4.15E-14	-333.24	672.48	679.74	14925.95
	30	0.52	86.83	1.87E-14	-331.54	669.08	676.34	14326.51
	40	0.54	95.95	2.14E-15	-328.13	662.27	669.53	13197.98
	50	0.56	102.73	4.60E-16	-325.77	657.55	664.80	12468.06
	60	0.57	106.20	2.14E-16	-324.91	655.81	663.07	12210.06
	80	0.58	110.52	8.44E-17	-322.55	651.09	658.35	11535.51
	100	0.58	112.12	6.00E-17	-320.70	647.40	654.66	11033.21
	120	0.57	109.27	1.10E-16	-319.32	644.64	651.89	10672.25
	140	0.56	103.18	4.16E-16	-318.18	642.35	649.61	10382.38
zm ~ Op	1	0.06	5.41	2.25E-02	-368.13	742.26	749.51	34596.65
	5	0.11	10.52	1.72E-03	-360.86	727.73	734.98	29041.62
	10	0.13	11.96	8.70E-04	-358.76	723.51	730.77	27603.98
	20	0.13	11.72	9.72E-04	-357.06	720.11	727.37	26495.30
	30	0.11	10.19	2.01E-03	-356.85	719.70	726.96	26365.53
	40	0.11	9.95	2.25E-03	-355.75	717.51	724.77	25677.28
	50	0.11	9.98	2.22E-03	-354.94	715.88	723.14	25178.52
	60	0.11	10.20	2.00E-03	-354.75	715.50	722.76	25063.62
	80	0.12	10.83	1.48E-03	-353.05	712.10	719.36	24058.59
	100	0.12	10.99	1.37E-03	-351.48	708.96	716.22	23164.27
	120	0.12	10.58	1.67E-03	-349.67	705.33	712.59	22173.59
	140	0.11	9.91	2.30E-03	-347.48	700.95	708.21	21034.35

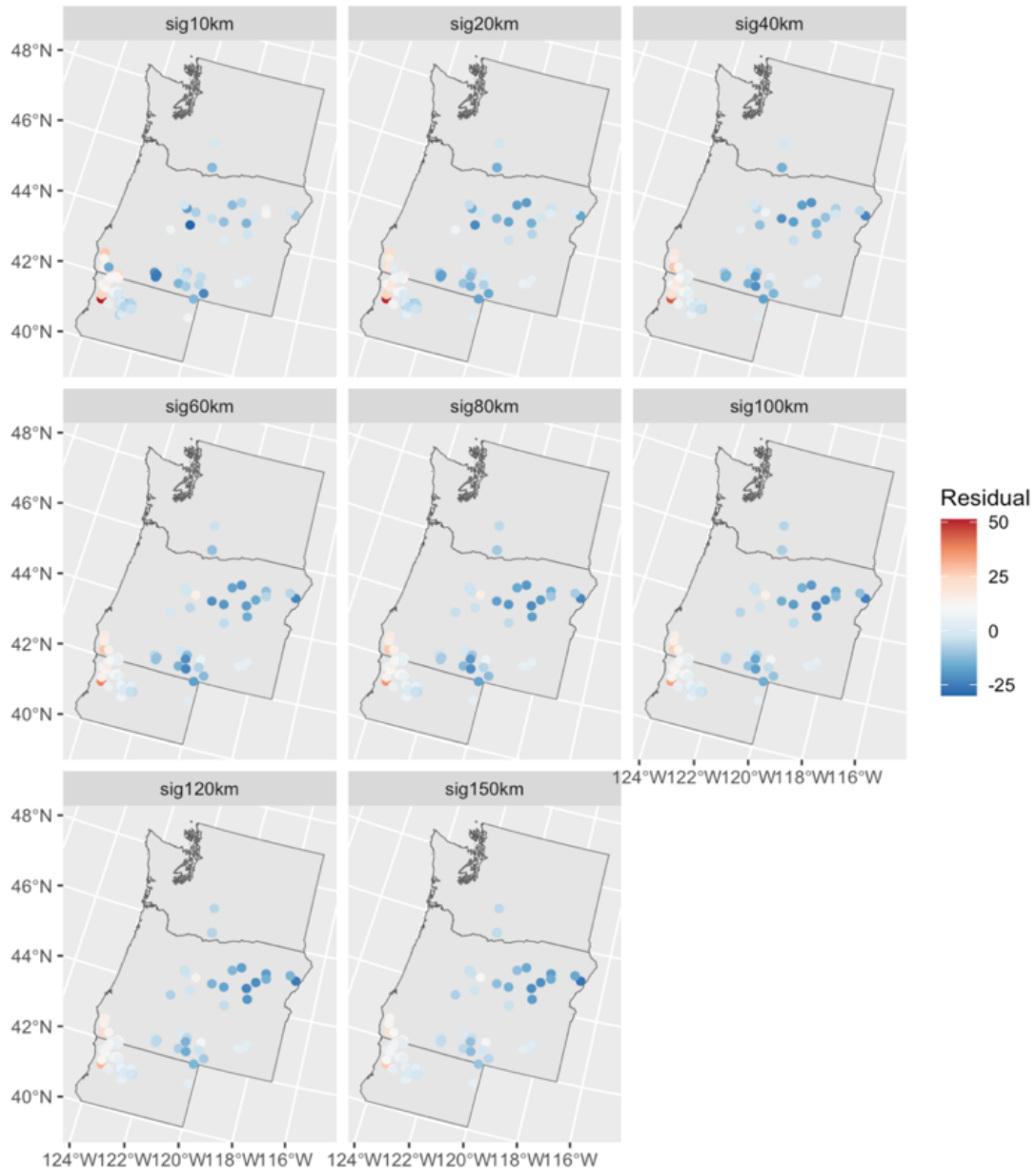


Figure 38 Maps of residuals of linear regressions focal mean canopy cover and O_p .

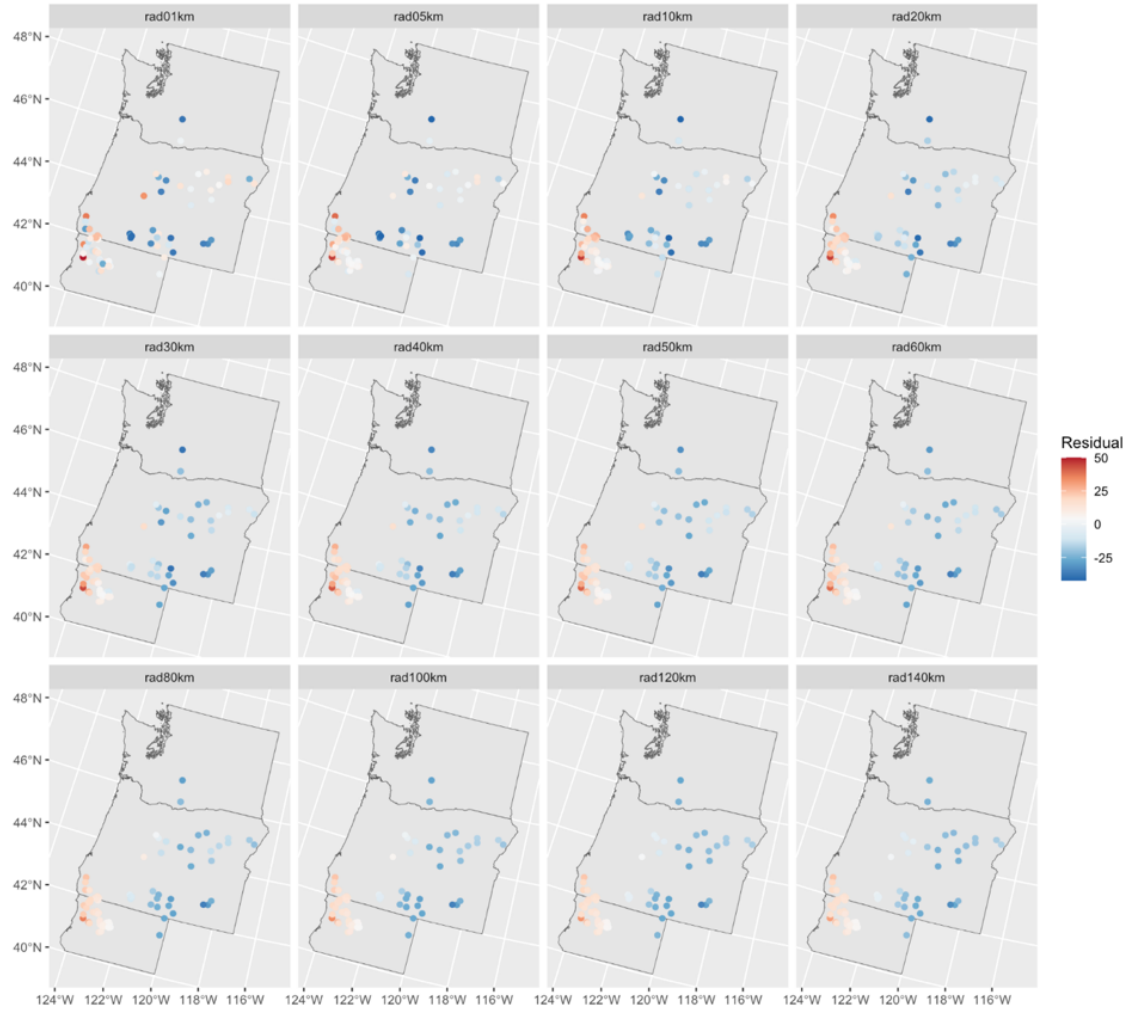


Figure 39 Maps of residuals of linear regressions zonal mean canopy cover and O_p .