


FINAL REPORT

Fire Regime Dynamics of the Southwestern Alberta Foothills

Final Report
fRI Research, Landscapes in Motion,
part of Healthy Landscapes Program

June 1, 2020

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INDIGENOUS PEOPLES ACKNOWLEDGEMENTS

We respectfully acknowledge that the land on which we have conducted our research is the traditional territory of the *Piikáni* Nation, the *Siksika* Nation, the *Kainai* Tribe, the *Tsuut'ina* Nation, and the *Iyarhe Nakoda* First Nation of the Treaty 7 region in southern Alberta[1].

[1] Spelling follows the websites of each Nation and Tribe.

https://www.stoneynation.com/
http://siksikanation.com/wp/
https://bloodtribe.org/
https://tsuutinanation.com/
http://piikanination.wixsite.com/piikanination

REPORT SUMMARY

The concurrent impacts of past land management and recent and projected increases in wildfire activity have driven concerns about near future forest resilience and transitions to non-forest alternative states in montane forests of western North America. Fire-climate models developed for forests in the Interior Rocky Mountains suggest that fire-driven tipping points may be surpassed by the mid-21st century. However, despite their importance, key vegetation feedbacks on fire-climate relationships have not been incorporated into these previous modeling efforts. Evidence of mixed-severity fire regimes in Foothills forests has raised questions about the fire regime dynamics, ecological outcomes, and implications of this finding for forest resilience and management strategies. To address these questions, the Fire Regime component of LIM conducted a landscape-scale assessment of fire frequency, severity and age structures for six study areas distributed throughout the montane and lower subalpine zone of the Foothills. This effort required compilation of a large synthesis dataset of dendroecological fire severity records to calibrate a fire severity metric that was then used to evaluate fire severity patterns in the Foothills. We document contrasting fire regimes and ecological outcomes for the lodgepole pine and Douglas-fir zones, despite similar fire frequencies. Our analyses detail the geographic variability, spatio-temporal dynamics, and resilience mechanisms that characterized forests of each zone and allowed forests to persist under frequent fire.

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1. Introduction

1.1 Background

The forests of southwestern Alberta are valued in many ways. They are the headwaters of our rivers; providing opportunities for recreation; diverse habitats for wildlife and fish; and jobs in forestry, ranching, tourism and oil and gas. Like all forest types in Canada, these forests are "disturbance dependent". They constantly change as natural disturbances such as fire and insect outbreaks reshape the landscape, resulting in a shifting pattern of old and younger forests, habitat types, nutrient availability, and even water flow and sedimentation. In Alberta, our approach to caring for our forests is to learn from these natural patterns and to try to maintain them with the idea that the forest ecosystem will continue to provide the range of services and habitats we value. To do so, we need to understand not only how, where, when, and in what form disturbances occur (i.e. a "disturbance regime"), but how disturbances influence other landscape values over time and space.

Appling this concept to southwestern Alberta has proven to be a challenge for several reasons. First, we are discovering that the pattern of fires is more complex in this area than we previously assumed. Rather than seeing only intense forest fires that kill all the trees, which are then replaced by a completely new, young forest, it appears that lower intensity fires also occur that kill only a portion of the trees. Therefore, rather than having even-aged forests covering the landscape, historic landscapes may have had a mixture of even and multi-aged stands resulting from a "mixed severity fire regime" (MSRF). A second challenge is that many human disturbance activities in our forests are very different from natural disturbances. For example long linear features like trails and roads through the forests are not seen in the patterns created by fires and insects. These human disturbances can create unforeseen, and often negative impacts on forest ecosystems, including altering predator-prey interactions, and increasing sedimentation in streams and rivers. Both challenges have potential implications for forest managers who are trying to be informed by natural patterns in how they can better manage the forests.

Towards addressing this knowledge gap, a larger project proposal for Alberta Innovates called *"Science-based management tools to support Ecosystem-Based Management of forests in Southwestern Alberta"* was developed and approved in 2016 that included four elements with four goals:

1) Provide the details of what the historic fire regime in southwestern Alberta was through dendrochronological field sampling, lab processing, cross-dating, and spatial analyses.
2) Understand better what the historic landscape condition was, and how they have changed over the last century through the use of historical oblique aerial photos, and
3) Create computer models that will integrate knowledge gained from the first two elements to simulate these patterns over time and space.
4) Understand the differences between the sedimentation caused by both natural and human caused disturbances.

This report describes the findings and outcomes from the first element from above on historic fire regimes.

1.2 Landscapes in Motion

The intimate and logical relationship between the first three of these elements from the original SW Alberta AI proposal quickly teamed up under the lead of Dr. Andison to enable a) greater integration, communications, and efficiencies, and b) apply for additional funding (as per the AI proposal). This team became known as ***Landscapes in Motion***, or LIM.

The subsequent funding application to the Forest Resource Improvement Association of Alberta (FRIAA) not only allowed for the completion of the original objectives from the Alberta Innovates proposal, but expanded on it. The following is a list from the FRIAA proposal. Items 1-4 were the promised deliverables to Alberta Innovates (conditional on finding supporting funding). Items 5-7 (in italics) were the additional items as part of the FRIAA proposal.

1) Develop and refine two interrelated analytic tools for assessing vegetation pattern changes in historical and repeat oblique photographs. The first tool extends from an adaptation of a mono-plotting tool that transforms digital oblique images to an overhead projection suitable for spatial analysis. The second tool uses web-based visualization tools to segment, classify and calculate statistical changes in images over time.
2) Develop a first approximation landscape-scale 'model' of mixed-severity fire regime dynamics in southwestern Alberta using available related studies, knowledge of mixed-severity fire regimes in related ecosystems, and knowledge gained from objective #1.
3) Document the patterns of historical fire severity (including the incidence of partial severity burning), frequency, and size in the SW Alberta foothills.
4) Develop a first approximation of a fire spread module capable of dealing with partial mortality.
5) *Evaluate the external drivers (i.e. topography, climate) and key self-regulating fire feedbacks (fire severity-frequency interactions) of the historical fire regimes in the SW Alberta foothills.*
6) *Integrate the new knowledge from objectives #1, #2, #3, and #5, and the new module from #4, into an existing modular spatial simulation modelling framework called SpaDES. Included in this objective will be the calibration of all modules, and other fire regime parameters (as available) to the SW Alberta study area.*
7) *Share the process of the exploration of historical landscape dynamics and model development with stakeholders and the public via a dedicated outreach program.*

This report describes the findings and outcomes from the original first Alberta Innovates LIM element on computer modelling, and item #2 above. Work on item #5 above continues under the FRIAA funding.

1.3 Study Area

The study area for the larger SW Rockies project covers about 950,000 ha bordered by the US border to the south, Bow Valley to the north, the treeline to the west, and a mix of parkland and fescue to the east. It is a long, narrow zone in which elevation, physiography, soils, and climate change over very short distances from east to west. It includes parts of the Montane (55%) and Subalpine (45%) natural subregions. The climate ranges from mild summers and warm winters at lower elevations to cool wet summers and long cold winters at higher elevations, and conditions can change dramatically over very short distances in response to topography. Tree species range from Douglas fir, aspen, lodgepole pine and white spruce to englemann spruce and subalpine fir at higher elevations to the west. Soils are similarly variable, from chernozems to the east to luvisols and brunisols to the west.

1.4 Indigenous Peoples

The Landscapes in Motion study area is strongly associated with the traditional territory of the *Piikáni* Nation (Reeves and Peacock 2001, McMillan and Yellowhorn 2004) and is encompassed by *Kitaowahsinnoon*, the broader territory of the Blackfoot Confederacy (Blackfoot Confederacy 2020). As well, the traditional territory of the *K'tunaxa* Nation, who live west of the Rocky Mountains, overlapped the southern Alberta Foothills where they travelled annually to hunt (Brink 1986, Reeves and Peacock 1995, 2001, McMillan and Yellowhorn 2004, ?*aq'am* 2020).

Since time immemorial, the southern Alberta Foothills have been home to the *Piikáni* (Peigan), *Iyarhe Nakoda* (Stoney Nakoda), and *Tsuut'ina* (Sarcee) Nations, as well as the *Siksika* (Blackfoot) and *Kainai* (Blood) Nations who live on the Great Plains to the east (McMillan and Yellowhorn 2004). Today, the *Siksika*, *Kainai* and *Piikáni* (*Apatohsipiikani* in Alberta and *Amsskaapipiikani* in Montana) are collectively known as *Siksikaitsitapi* or the Blackfoot Confederacy (Yellowhorn and Plain Eagle undated, McMillan and Yellowhorn 2004, Oetelaar and Oetelaar 2006).

The member Nations of the Blackfoot Confederacy travelled seasonally within their territories to hunt game and collect plants, moving onto the grasslands in summer and returning to the valleys of the foothills during winter (Reeves and Peacock 2001, McMillan and Yellowhorn 2004, Oetelaar and Oetelaar 2006). The foothills environments also provided year-round habitat for bison (*iini*), a coveted resource that provided food, clothing, shelter, and was the foundation of many cultural and spiritual customs (Yellowhorn and Plain Eagle undated, McMillan and Yellowhorn 2004). A rich archaeological record within our study area (Brink 1986, Reeves and Peacock 1995, 2001, Hannis 2012, Zedeño et al 2014), including important sites such as Heads-Smashed-In Buffalo Jump (Reeves 1978, Brink 2008) and Napi's Playground (Yanicki 2014), attest to the enduring and intimate use of this landscape by the *Siksikaitsitapi* and other First Nations.

The name "Blackfoot" comes from a legend of walking across burned prairie (McMillan and Yellowhorn 2004). Oral histories and physical evidence indicate controlled burning was practiced to cultivate plants for harvesting and maintain productive meadows for bison and horses, especially near seasonal encampments and bison jumps (MacMillan and Yellowhorn 2004, Brink 2008, Oetelaar and Oetelaar 2008, Zedeño et al. 2014, Roos et al. 2018). As well, burning the perimeter of camps, especially near tree groves near springs and river crossings along travel corridors, reduced surface fuels and the chance of crown fire ignited by uncontrolled grassfires (Oetelaar and Oetelaar 2008). Journal entries by Peter Fidler of the Hudson Bay Company, who lived with the *Piikáni* in 1792-3, documented these practices (Fidler 1991). He recorded numerous controlled burns over large areas in the grasslands along the Foothills between November and March and noted they were ignited by people (Fidler 1991), rather than lightning (Oetelaar and Oetelaar 2008). Although Fidler did not report burning in mountain valleys, others have attributed the establishment and persistence of grasslands in river valleys of the Foothills, including the Old Man River, to Indigenous fire management (Pickard 1981; Stockdale et al. 2019).

The arrival of Europeans disrupted the Blackfoot way of live, with direct and indirect impacts on cultural fire practices (Stockdale et al. 2019). Epidemics of smallpox and other diseases were introduced by Europeans in 1730s, 1830s and 1860s (Reeves and Peacock 1995, 2001, McMillan and Yellowhorn 2004, Hannis 2012). The rapid destruction of bison herds to near-extinction during the 1860-80s undermined the lifeblood of the Blackfoot traditional land and cultural practices (McMillan and Yellowhorn 2004, Brink 2008, Oetelaar and Oetelaar 2006). In 1877, the Blackfoot Treaty (Treaty #7) was signed by the five Indigenous Nations of southern Alberta, yielding 129,500 square kilometers of land in return for reserves, the promise of livestock, farming implements and other considerations (Government of Canada 2009). Ultimately, the Treaties and Indian Act largely removed the Blackfoot from their traditional territories and cultural practices by confining people to reserves where farming and ranching were controlled by federal Indian Agents and by requiring children to attend residential schools (McMillan and Yellowhorn 2004, Appendix 1 in Yanicki 2014). Nevertheless, many Blackfoot traditions remain strong and Elders hold knowledge of their traditions associated with the land, plants, and animals (Reeves and Peacock 1995, McMillan and Yellowhorn 2004), which is critical for understanding, managing and restoring the Foothills landscape (Oetelaar and Oetelaar 2006, 2008).

1.5 Partners

The Southern Rockies project began as an Alberta Innovates project on behalf of the Government of Alberta. The delivery of the four project elements was the responsibility of fRI Research, who managed that administration and budget. The fRI Programs involved includes the Healthy Landscapes Programs (elements 1-3, or LIM) and the Water Program (element 4). The LIM component was further supported by a FRIAA application, as well as two successful Mitacs Accelerates grants, and two more Mitacs Elevates grants.

2. Foothills Fire Regimes

2.1 Background

Increasing global temperature and potential climate-forcing of fire frequency (Westerling et al. 2006, Moritz et al. 2012) has heightened interest in future fire impacts to ecosystem dynamics, function and resilience. The directional climatic shifts towards warmer, drier conditions predicted for much of western North America(Flannigan et al. 2009, Barbero et al. 2015) may not only increase fire frequency, but may also increase its severity (van Mantgem et al. 2013) and reduce vegetation recovery rates (Enright et al. 2015, Stevens-Rumann et al. 2018), creating potential for abrupt climate-driven, fire-induced ecosystem change. Motivated by this context, key questions have emerged about the role of feedback mechanisms, which may limit fire activity or severity even under increasing drought conditions, and ecosystem resilience, especially to high-severity fire. Both theory (Peterson 2002, Miquelajauregui et al. 2016) and some empirical evidence (Parks et al. 2014, 2015, Héon et al. 2014, Harvey et al. 2016) show that fire-vegetation feedbacks can regulate fire occurrence and severity, even where climatic conditions conducive to fire exist. However, this finding has been challenged by studies in other systems (Bessie and Johnson 1995, Moritz 2003) where fire-vegetation feedbacks are weak or are overridden by climatic conditions during fire years. Similarly, there is considerable debate about the resilience of western forest ecosystems to potential increases in fire severity (Williams and Baker 2012, Stephens et al. 2013, Odion et al. 2014, Schoennagel et al. 2017, Guiterman et al. 2017). These discrepancies likely reflect biogeographic differences and the importance of local context, but they may also result, in part, from limitations imposed by characteristics of modern fire regimes, including: 1) modern fire data are constrained to short time periods (often < 25 years), which may limit the range of events captured in the record and the ability to monitor recovery trajectories over necessary timescales and 2) they cannot control for the influence of historical fire exclusion and changes in vegetation characteristics on the observed fire-vegetation-climate interactions.

In contrast to many modern fire records, historical fire records represent a rich data source for analysis of fire dynamics, feedback mechanisms, landscape conditions and resiliency over long timescales and under active fire regimes. Informed by historical fire studies, the fire regime concept (Agee 1993) provides a useful framework for understanding ecosystem response to changes in fire activity because it identifies key stabilizing/destabilizing feedback mechanisms that influence resilience and it makes testable predictions about how these mechanisms change along the fire regime gradient. For example, in systems that historically experienced frequent low-severity fire, fire-resistant vegetation structures characterized by heterogeneous trees sizes, fire-tolerant tree species, and patchy understory fuels created a negative feedback on subsequent fire severity (Hessburg and Agee 2003, Schoennagel et al. 2004). In systems with high-severity fire regimes, slow vegetation recovery and cooler, moister climates created a negative feedback on subsequent fire that lasted for many decades (Schoennagel et al. 2004, Héon et al. 2014). Based on these feedbacks, climate-driven increases in fire frequency might be predicted to reinforce the negative frequency-severity feedback in low-severity systems (if historical vegetation characteristics had not been altered by fire exclusion), while it might drive high-severity systems closer to a tipping point, if fire frequency surpasses vegetation recovery rates (Westerling et al. 2011, Stephens et al. 2014). In between these endpoints of the fire regime gradient, mixed-severity fire regimes (MSFRs) were historically characterized by diverse spatio-temporal patterns of fire frequency and severity (Hessburg et al. 2007, Margolis and Balmat 2009, Amoroso et al. 2011, Marcoux et al. 2013, Sherriff et al. 2014, Heyerdahl et al. 2014). Due to the complexity and diversity of MSFRs, however, there is great uncertainty about their fundamental ecology, spatio-temporal dynamics, feedback mechanisms, resiliency, and potential responses to climate change. Motivated by the growing recognition that MSFRs are broadly distributed within western North America, (Schoennagel et al. 2004, Halofsky et al. 2011, Perry et al. 2011, Hessburg et al. 2016), greater understanding of fire severity (Hessl 2011, Dillon et al. 2011, Keyser and Westerling 2017) and MSFRs (Baker et al. 2007, Odion et al. 2014, Stockdale et al. 2016), in particular, has been identified as a key need in fire ecology and forest management research. This information is fundamental to effective ecosystem-based forest management approaches, because the implications of a MSFR model are considerable and may differ significantly from alternative fire regime models (Agee 2005, Marcoux et al. 2013, 2015, Stephens et al. 2013, Stockdale et al. 2016, Hessburg et al. 2016).

In western Canada, the management model associated with montane and boreal forest ecozones has been based on the long-standing assumption that the historical fire regime was dominated by low-frequency, high-severity wildfire (Johnson 1992). Over centuries, this stand-replacing fire regime creates a “shifting mosaic” of even-aged forest polygons with simple forest structures (Turner et al. 1993). This is in contrast with recent research in montane forests of BC and Alberta, which indicate a combination of stand-maintaining fires and periodic stand-replacing fires that create heterogeneous landscapes including multi-cohort stands with greater levels of structural and compositional diversity (Amoroso et al. 2011, Marcoux et al. 2015, Chavardès and Daniels 2016, Rogeau et al. 2016, Greene and Daniels 2017). Although evidence of MSFRs in western Canada is accumulating, many of these studies have been local, and/or addressed select attributes of the fire regime. As a result, the distribution and fundamental ecology of MSFRs in western Canada is poorly understood.

In the Alberta Foothills broader ecological questions about the resilience of fire-sensitive forests to climate-driven increases in fire frequency and the dynamics of mixed-severity fire regimes form an interesting confluence. Projections of high rates of forest to non-forest conversion and forest ecosystem collapse made for lodgepole pine forests of the northern U.S. Rockies are based on climate-fire models (Westerling et al. 2011) which predict fire return intervals to decline below ~20-30 years by mid-century. These models, however, do not account for vegetation feedbacks on climate-fire relationships that are likely to constrain the range of possible outcomes (Grabinski et al. 2017, Marchal et al. 2017). Yet, with more frequent fire, fuels are expected to be limited and vegetation structure and composition may shift to a more fire resilient state, creating a negative feedback on subsequent fire even under continued drought. These changes could result in a shift from high- to more mixed severity fire regimes. In the lodgepole pine forests of the Alberta Foothills, recent studies have documented historical median fire return intervals of 25-40 years (Rogeau et al. 2016). Such frequent fire coincides with the critical thresholds of ecosystem collapse predicted for these forests (Westerling et al. 2011), yet forests persisted under this regime for centuries (Davis et al. 2016). One component of resilience that has been suggested in recent studies (Amoroso et al. 2011, Chavardes & Daniels 2016) is the existence of a mixed-severity fire regime in Foothills forests that have previously been considered to be an exclusively stand-replacing regime (Johnson and Larsen 1991). The unique spatio-temporal dynamics and fire-mediated feedbacks of mixed-severity regimes could help explain the resilience of Foothills forests to frequent fire and may provide insights to lodgepole pine dynamics more broadly under similar regimes. These studies, however, have been limited, smaller-scale case studies, leaving many questions about the extent and dynamics of mixed severity fire regime forests in the Foothills yet unanswered. As such, the Foothills forests represents a unique opportunity to examine the dynamics, feedbacks and ecological outcomes of frequent fire in a fire-sensitive forest. To take advantage of this opportunity, the Fire Regime component of LIM seeks to examine these questions using a combination of muti-proxy dendroecological and photogrammetric techniques.

2.2 Dendroecological Reconstructions of Mixed-Severity Fire Regimes

Given the complexities of mixed-severity fire regimes, they are particularly challenging to characterize and reconstruct. Multiple types of dendroecological evidence is required to infer the timing and severity of each fire and the spatio-temporal variation within and among sites (Daniels et al. 2017). In concert with fire scars crossdated to yield precise years or seasons, living and dead trees are sampled to represent site-level age structures and to identify cohorts, remnant survivors of past fires, and tree mortality synchronous with fire scars (Ehle and Baker 2003, Baker et al. 2007). Within remnant trees, fire dates may be corroborated by the presence of resin ducts, micro-rings and radial-growth suppressions or releases (Brown and Swetnam 1994, Sherriff and Veblen 2006, Smith et al. 2016).

Determining the severity of historical fires has proven most challenging because pre-fire forest densities and mortality rates of overstory trees are unknown (Agee 1993, Schoennagel et al. 2011). Traditionally, the classification of historical fire severity works best for recent fires(Yocom-Kent et al. 2015), as evidence becomes less reliable through time due to losses during subsequent fires, non-fire mortality and decay of older trees (Sherriff and Veblen 2006). This fading record problem in dendroecology has been a particular barrier to evaluation of historical fire severity. Although numerous studies have made important methodological advancements and ecological contributions to the study of historical fire severity patterns (Taylor and Skinner 1998, Sherriff and Veblen 2007, Schoennagel et al. 2011, Amoroso et al. 2011, Heyerdahl et al. 2012, Marcoux et al. 2015), this barrier has limited comprehensive understanding of fire regime dynamics and mechanistic understanding of fire feedbacks from historical records. The principal shortcomings of existing methods include: (i) failure to address the fading record problem, which results in a shifting baseline over time that is difficult to interpret , (ii) many fire severity methods are qualitative or depend on tailored rulesets that differ between studies, (iii) lack of consistent criteria, definitions, and analytical approaches limits comparison of results between studies, and (iv) some methods do not account for fundamental scale differences between multi-proxy dendroecological records (age structure and fire scars).

Tepley & Veblen (2015) developed a dendroecological density decay function that is based on changes in the density of surviving trees with each fire event through time that is unique in its ability to account for the fading record problem. Theoretically, this permits reconstruction of fire severity for all fires in the fire history record of each sample location for which sufficient establishment exists. Thus, fire history records are often longer than fire severity records. Two metrics are generated using this method to represent different components of fire severity. The first metric, λ, is a measure of the cumulative severity of all fires at a patch integrated over time, calculated as the absolute value of the slope of a linear model fit to the density decay curve (Naficy et al. in review). The second metric, ΔS_n, is a relative event-level severity metric specific to each fire event recorded at each patch (Tepley and Veblen 2015). This method has several key advantages over current alternatives. Both metrics are quantitative, not based on rulesets, and provide continuous measures of severity that can be classified to produce easily interpretable severity classes. The metrics do not rely on identification of cohorts, a common method for classifying severity in some studies, which can itself be challenging and often relies on ruleset approaches. The metrics are directly comparable across studies as long as a set of basic design criteria are followed. This should permit cross-study comparison and synthesis of datasets that is ultimately desirable if dendroecological records are to. The method requires few assumptions and is therefore implementable in a wide range of systems. However, it does have at least one important potential drawback, which is that ΔS_n is standardized by the mean severity of the input dataset. As a result of this relative nature, ΔS_n values may be sensitive to the characteristics of the input dataset, which could make interpretation challenging and limit cross-study comparisons. ΔS_n has only been used in two other studies previously (Tepley & Veblen 2015, Naficy et al. in review) and has always been standardized to individual datasets. Theoretically, study-level standardization of ΔS_n may not result in strong bias if the input dataset is from a system with a wide range of severities. This is the argument that has been made in studies to date. But no study has yet explicitly tested the sensitivity of the metric to the characteristics of the input data, provided a framework for understanding sources of bias in relation to ecosystem characteristics and research, or attempted to calibrate or validate the ΔS_n metric.

2.3 Objectives

Objectives for the Fire Regime component of LIM were to:

1. Calibrate a dendroecological fire severity metric for use in the Southern Foothills.
2. Document the extent, geographic variability and characteristics of mixed-severity fire regimes in the montane and lower subalpine forest zones of the southern Foothills.
3. Describe the dynamics and ecological consequences of the fire regime for the lodgepole pine and Douglas-fir zones of the Alberta Foothills.

3. Methods

3.1 Study Area

Our study was situated in the southwestern Alberta Foothills, Canada, encompassing the majority of the headwaters of the South Saskatchewan River watershed (Fig. 1). The forested area (1,996,695 ha) of this region (bounding box lower left: 49° 00' N -115° 40' W, upper right: 51° 05' N, -113° 35' W) extends from the Continental Divide on the west to the forest-grassland ecotone of the northern Great Plains on the east and from Waterton National Park near the international border in the south to the boundary of Banff National Park in the north. Climate of the region is continental, with annual average temperature of 4° C, 366 mm of summer-dominated rainfall, and 193 cm of winter-dominated snowfall (Environment Canada 2020; Kananaskis & Calgary International stations). Moisture regimes and vegetation are closely linked to the strong west to east elevational gradient (943-3098 m) driven by the steep transition from mountains to prairies (Fig. 1).

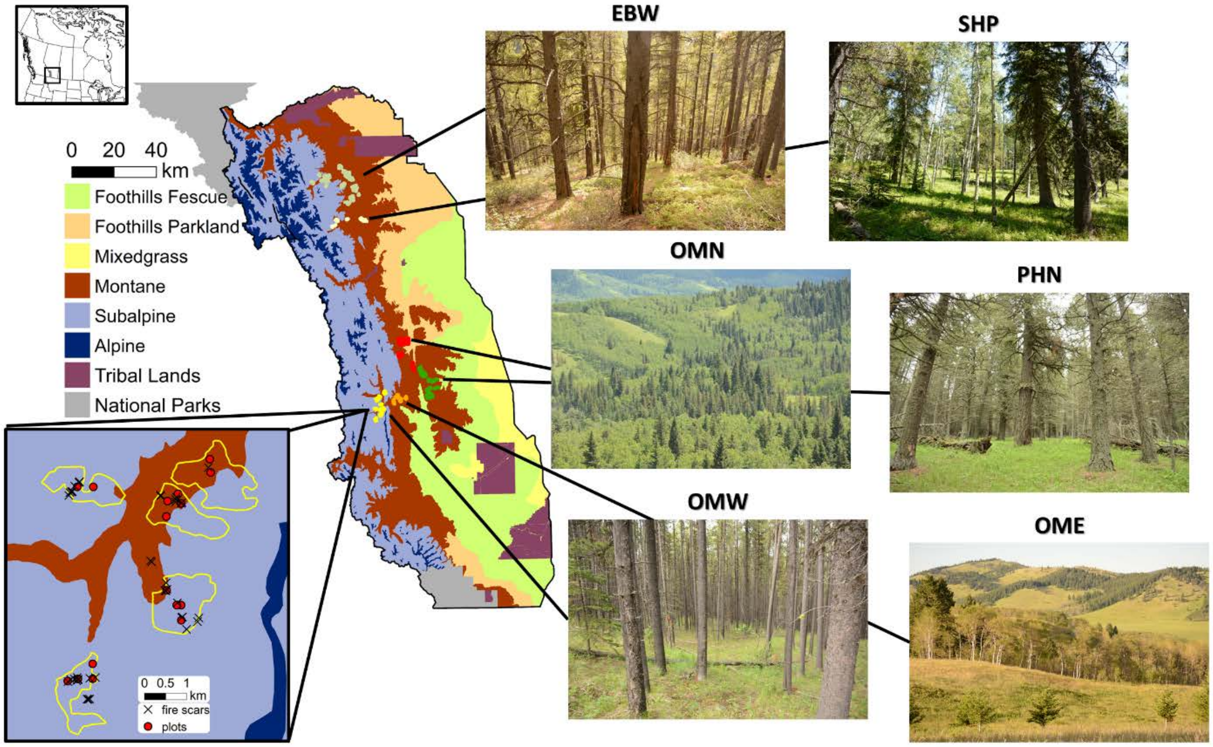

Figure 1. Map of the study area in southwestern Alberta, showing the distribution of natural subregions, tribal lands, National Parks, and the six sample landscapes, including Elbow River (EBW), Sheep River (SHP), Old Man River north (OMN), Old Man River west (OMW), Old Man River east (OME), and the Porcupine Hills north (PHN).

Forests of the upper subalpine zone largely consist of subalpine fir (*Abies lasiocarpa*) and hybrid Engelmann/white spruce (*Picea engelmannii* x *glauca*). Pure and mixed stands of lodgepole pine (*Pinus contorta* var. *latifolia*) comprise the majority of forest area in the region, occupying much of the lower subalpine and montane zones. In the lower subalpine and montane zones, trembling aspen (*Populus tremuloides*) forms mixed stands with lodgepole pine and extensive pure stands (aspen parklands). Douglas-fir (*Pseudotsuga menziesii*) approaches its northern limit, on the eastside of the Rockies, within our study area. In the montane zone of the southern portion of our study area it forms pure and mixed stands with lodgepole pine, aspen and limber pine (*Pinus flexilis*). It is absent from the montane zone in the northern portion of our study region. Fescue-dominated (*Festuca* sp.) grasslands and shrublands comprised of *Symphoricarpos* sp., *Amelanchier alnifolia*, *Rosa* sp., *Prunus virginiana*, *Elaeagnus argentea*, *Shepherdia* sp., and *Arctostaphylos uva-ursi* abut and intermix with the montane forest zone (Moss 1955).

3.2 Research Design

Our research design was shaped around the principal goal of documenting the dynamics and variability of fire regime attributes, ecological outcomes, and landscape conditions across a gradient of relatively frequent fire documented in the region. We employed a multi-scale, multivariate random stratification procedure (Naficy et al. in review) based on analysis of historical aerial photos and a suite of geospatial biophysical datasets to distribute our sample sites across key geographic, biophysical and ecological gradients. This procedure involved first creating an orthomosaic from historical imagery that was used to evaluate the broad-scale variation and geographic variation of forest structural and compositional features. Second, we constrained our analysis to the montane zone and a 2 km buffer of the lower subalpine. This constrained analysis zone encompassed 100%, > 90% and 71% of the areas dominated by Douglas-fir, aspen, and lodgepole pine, respectively. Third, we used coarse-scale photointerpretation of the orthomosaic and gridded climatic data to qualitatively assess broad-scale geographic patterns of forest structural and compositional features and to delineate six study areas that captured this biophysical and geographic variation. Fourth, within each of the six study areas, we used fine-scale photogrammetric analysis (see *Photogrammetric analysis and landscape stratification*) to delineate individual patches with distinct photointerpreted structural and compositional features that we used to stratify our sample sites.

3.3 Image Pre-Processing

We procured a set of 1,908 panchromatic aerial images (1:40,000 scale) from the Canadian National Air Photo Library archives. This collection represented the earliest available imagery with full coverage for our study region acquired in multiple flights from 1949-52. The available imagery had been scanned from contact prints at 20 microns, resulting in a moderate quality digital product. Because wildland fires in the region were quite active through approximately the 1930s (Murphy 1985, Fryer and Johnson 1988, Rogeau et al. 2016), including several well-known large fire years in the early 20th century (e.g. 1910 and 1919), landscape conditions captured in this imagery should reflect this fire history more than the effects of fire exclusion resulting from Euro-American colonization and land management practices.

We created an image mosaic from the individual scenes using automatically generated tie points using Agisoft Photoscan v. 1.4.5. To orthorectify the mosaic we co-registered it to high resolution RGB aerial imagery (30-50 cm resolution) acquired by Alberta Environment and Parks in 2012-2013 using a Lidar-generated 1-m digital terrain model and 437 manually placed ground control points (GCPs). Features used as GCPs included historical roads, bridges or buildings, individual trees in open meadows or distinct remnant trees in forested stands, and geological features such as rocky outcrops, large boulders, and scree fields. Final average geometric error of the orthomosaic was < 15 m.

Table 1. Description of the six study areas sampled in this study with summaries of biophysical, fire regime, and age structural attributes stratified by cover type.

Study area	zone	size[#]	elevation (m)	Slope (◦)	(years)[□]	(ΔSn)[□, !]	SRE (years)[□]	SRE (events)[□]	(years)[□]	simple	intermediate	complex
EBW	PICO	18 (56)										
lodgepole pine		12 (35)	1,634	18	26 (23.5, 38.5)	0.85 (0.44, 0.99)	17	2	23	39	28	0
mixedwood		2 (6)	1516	11	25 (24, 26)	0.91 (0.87, 0.95)	11.5	1.5	20	0	11	0
MMC		3 (13)	1551	12	35.5 (26.75, 41.25)	0.74 (0.47, 0.87)	14	2	20	6	11	0
spruce-fir		1 (2)	1526	15	27	-0.56	96	5	113	0	0	6
SHP	PICO	7 (21)										
lodgepole pine		5 (15)	1556	11	28 (24.5, 49)	0.67 (0.22, 0.85)	17 (0, 49)	3 (1, 3)	14 (5, 37)	43	14	14
mixedwood		1 (4)	1520	14	17	0.26	40	4	31	0	14	0
MMC		1 (2)	1590	6	29.5	0.80	10	2	4	0	14	0
PHN	PSME	9 (32)										
Douglas-fir		4 (18)	1588	13	15 (13.25, 15.88)	-0.23 (-0.26, -0.19)	152.5 (132.25, 216.5)	10.5 (10, 12.5)	111 (43, 194)	0	22	22
DMC		2 (6)	1559	11	41.25 (33.88, 48.63)	0.51 (0.26, 0.75)	81 (40.5, 121.5)	4 (2.5, 5.5)	92 (52, 133)	11	0	11
lodgepole pine		1 (2)	1639	9	202	0.97	0	1	15	11	0	0
MMC		2 (6)	1560	11.5	26.5 (19.25, 33.75)	0.50 (0.26, 0.74)	25 (12.5, 37.5)	2 (1.5, 2.5)	22 (16, 29)	11	11	0
OMN	PSME	3 (10)										
Douglas-fir		1 (4)	1474	18	19.5	-0.26	174	9	195	0	0	33
DMC		1 (2)	1433	17	42	-0.02	45	2	46	0	33	0
MMC		1 (4)	1460	7.5	27	-0.07	54	3	41	0	0	33
OME	PSME	4 (14)										
Douglas-fir		3 (12)	1519	16	18 (17.5, 20.5)	-0.32 (-0.37, -0.15)	146 (120.5, 154)	7 (6, 8)	159 (101, 166)	0	50	25
aspen		1 (2)	1445	5	14	0.07	14	2	73	0	25	0
OMW	PICO	10 (33)										
lodgepole pine		10 (33)	1607	19	40 (37.88, 42)	0.91 (0.01, 0.99)	28 (0, 41)	2 (1, 2)	23 (16, 61)	60	20	20

- values are the number of sample patches (plots).

□ - values represent medians (interquartile range). The IQR is not provided for rows with a sample size of one.

! - For reference, note that low/moderate and moderate/high thresholds of ΔS_n are -0.37 and 0.53, respectively.

* - values are percent of patches of each age structural category within each study area.

3.4 Coarse-Scale Photogrammetric Analysis & Selection of Study Areas

In the coarse-scale photogrammetric analysis, we incorporated gridded climate data and an assessment of the geographic variation in forest structural and compositional attributes to select target study areas, each ranging from 10,000-40,000 ha. Our goals in this analysis were to reduce spatial autocorrelation resulting from replicated sampling over small scales (Wei & Larsen 2018) and to capture a broad range of the variation in fire regimes and biophysical settings that exists within our study area. A clear latitudinal moisture gradient exists within our broad study region (Table 1), which we represented using a gridded climatic moisture deficit dataset (Wang et al. 2011). To capture this variation, we split our study region (c. 50° 15′ N) into northern (wetter) and southern (drier) units that approximate the northern range limits of Douglas-fir. Within these units, we assessed the geographic variability of vegetation conditions by qualitatively evaluating the relative patch sizes, degree of intermixing and diversity of different structural (even-sized vs. multi-sized) and compositional types (grassland, deciduous, lodgepole pine, Douglas-fir). Vegetation conditions in the northern unit consisted of large areas with a coarse patch mosaic of short-stature, even-sized stands, smaller patches of short-stature, multi-sized lodgepole pine, and some areas of short-stature, complexly patterned stands of pure aspen parklands and mixed stands of aspen, lodgepole pine and spruce. In the southern unit, lodgepole pine stands were dominated by coarse-scale short- and medium-stature even-sized stands and some smaller scale, multi-sized stands. The Douglas-fir zone in the southern unit exhibited much higher diversity of landscape conditions, including highly fragmented multi-sized stands within a grassland dominated matrix, more extensive open-canopy multi-sized stands, small stature open canopy woodlands, and closed canopy even-sized stands. Due to this additional complexity in the Douglas-fir zone in the southern unit, we determined that a greater number of study areas was merited.

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From this analysis, we defined six study areas, two in the northern unit and four in the southern unit (Fig.1, Table 1). In the northern unit, the Elbow River (EBW) study area consisted of extensive lodgepole pine in rugged terrain within the main river corridor and mixed lodgepole pine/aspen stands along the rolling topography of the outer Foothills. The Sheep River (SHP) study area was located within the Sheep River Provincial Park in mild terrain and was characterized by abundant aspen, often mixed with lodgepole pine, and pure lodgepole pine, sometimes mixed with spruce forests at higher elevations. In the southern unit, the three study areas were located along different portions of the Old Man River. The Old Man River is has great cultural importance for the Blackfoot Nation, featuring a number of well-documented archaeological sites such as Napi's Playground (Yanicki 2014). Old Man West (OMW) was located on the middle reaches of the Old Man River watershed in rugged terrain dominated by lodgepole pine. Further downstream, Old Man East (OME) was situated at the forest-grassland ecotone and consisted of open canopy and often semi-isolated patches of Douglas-fir, limber pine and aspen nested within grasslands. Old Man North (OMN) was situated within a zone heavily dominated by aspen and some mixed conifer forest with rolling terrain. Our easternmost study area was located in the northern Porcupine Hills (PHN) and was characterized by a mix of montane meadows, open and closed canopy Douglas-fir/aspen forest, and closed canopy mixed conifer forest. The Porcupine Hills are also an area of historical and contemporary cultural value to the Blackfoot Nation, as evidenced by the presence of important archaeological sites such as Heads-Smashed-In Buffalo Jump (Reeves 1978, Brink 2008), the location of the Piikani Timber Limit B (Hannis 2012) in the southern portion of the range, and the Piikani reservation lands that lie in the adjacent prairies.

3.5 Fine-Scale Photogrammetric Analysis & Stratification of the Dendroecological Sample Units

Our objective in the fine-scale photogrammetric analysis was to collect dendroecological data that were representative of the fire regime and ecological dynamics within each of the six target study areas. To achieve this, we manually delineated patches and visually interpreted forest structural and compositional attributes in the orthomosaic using established methods (Avery and Berlin 1992, Hessburg et al. 1999) to determine (1) the canopy cover of the overstory and understory tree layers, and their total cover (sum of over and understory strata), (2) the size class of trees in the overstory and understory strata, and (3) the dominant cover type (lodgepole pine, aspen, or Douglas-fir) of each patch (Table 2a). Based on these raw attributes, a ruleset (Table 2b) was applied to derive seven multi-variate structural types, including: stand initiation, young open and closed canopy single-strata, young open and closed canopy multi-strata, and old open and closed canopy multi-strata stands. These structural type classes represent potentially unique disturbance-mediated successional pathways (Oliver and Larson 1996, O'Hara et al. 1996) that formed the basis for a stratified random selection of dendroecological sample sites. To capture the variability in structural types, and the potentially unique disturbance histories associated with them, we selected a random subset of patches for sampling in proportion to the area weighted distribution of the distinct structural types in each study area.

Table 2. Description of (a) the raw photointerpreted structural attributes in the historical orthomosaic and (b) the multivariate structural types derived from the raw attributes, their physiognomic description, and hypothesized inferences they provide about disturbance history.

a)

Attribute	Abbreviation	Range	Attribute levels
Canopy cover	$Total_{CC}$, OS_{CC}, US_{CC}	0-100%	10% canopy cover deciles (e.g. 0-10%, 10-20%, etc.)
Mean size of tree strata	OS_{size}, US_{size}	1-5	1 – seedling/sapling 2 – pole-sized trees 3 – small trees 4 – medium trees 5 – large trees

b)

Structural type	Structural attributes	Description and potential disturbance regime inference	# sample plots	# sample cores
Stand initiation	$OS_{size} = 1$ $US_{size} = 0$	Recently disturbed; dominated by seedlings/saplings.	2	20-30
Young, single strata, closed canopy	$Total_{CC} \geq 70\%$ $US_{CC} < 20\%$ $OS_{size} = 2\text{-}3$	Dense forest of small trees recovering from high severity fire.	2	20-30
Young, single strata, open canopy	$Total_{CC} < 70\%$ $US_{CC} < 20\%$ $OS_{size} = 2\text{-}3$	Open woodland with small trees of similar size. Slow recovery from high severity fire or possible underburn.	3	30-45
young, multi-strata, closed canopy	$Total_{CC} \geq 70\%$ $OS_{CC} \geq 20\%$ $US_{CC} \geq 20\%$ $OS_{size} = 2\text{-}3$ $US_{size} = 1\text{-}2$	Relatively closed canopy forest comprised of patches with different size classes. Likely represents at least one non stand replacing fire.	4	40-60
young, multi-strata, open canopy	$Total_{CC} < 70\%$ $OS_{CC} \geq 20\%$ $US_{CC} \geq 20\%$ $OS_{size} = 2\text{-}3$ $US_{size} = 1\text{-}2$	Low density forest dominated by small and medium sized trees. May represent multiple mixed severity fires.	4	40-60
old, multi-strata, closed canopy	$Total_{CC} \geq 70\%$ $OS_{CC} \geq 20\%$ $US_{CC} \geq 20\%$ $OS_{size} > 4$ $US_{size} > 4$	Closed canopy forest comprised by patches with different size classes, including large, old trees. May represent long time since fire or a low frequency underburn.	4	40-60
old, multi-strata, open canopy	$Total_{CC} < 70\%$ $OS_{CC} \geq 20\%$ $US_{CC} \geq 20\%$ $OS_{size} > 4$ $US_{size} > 4$	Open forest with multiple size classes, including a component of large, old trees. May indicate long term fire history of repeated underburns.	4	40-60

3.6 Field Data Collection and Laboratory Methods

Within each patch identified for sampling, we collected a combination of fire scar samples and increment cores from age structure plots. The combination of both data types allowed us to reconstruct the patch-level history of fires, including annually-resolved fire dates, their severity, and the resulting age structures. Age structure plots were located in each patch by selecting a random subset of points from a computer generated 350 m grid. To sample as efficiently as possible, we scaled the within-patch sample intensity (e.g. # of plots) by the inferred complexity of disturbance history associated with each structural type class (Table 2b). This flexible approach (sensu Naficy et al. in review) allowed us to avoid inefficiencies resulting from oversampling patches with simple disturbance histories, while still obtaining sufficient sample size to characterize patches with more complex disturbance regimes.

We used an n-tree sample design (Lessard et al. 2002) with two nested variable-radius plots at each sample point. In the outer plot, one increment core from each of ten large trees (defined as trees with DBH > 30 cm for Douglas-fir and > 20 cm for lodgepole or aspen plots) nearest to plot center was sampled. In the inner plot, increment cores were sampled from the closest 5 small trees to plot center. Increment cores were collected from as close to ground level as possible (usually around 15cm). If a core was estimated in the field to be further than 5 years from true pith, another core was collected. For trees with rotted piths or other anomalies that prevented adequate sampling, we collected a sample from the nearest tree of similar size, apparent age and species. The distance to the distal tree was measured for each subplot to allow calculation of plot area and tree densities. We also recorded the diameter at breast height (1.37 m), species, live/dead status, and coring height of all sampled trees.

To reconstruct the history of fires at each site, we conducted extensive surveys of fire-scarred trees in a 400 m search radius around each plot. Where fire-scarred trees were rare within this search radius, we conducted supplementary surveys over a larger area within the patch and in targeted portions of the landscape where fire scarred trees are more likely to occur (e.g. ridgetops, rocky outcrops, old fire boundaries). Depending on the apparent complexity of fire history in a patch and the abundance of fire-scarred trees near a plot, we sampled up to a maximum of 12 partial cross sections from fire-scarred trees(Arno and Sneck 1977) in each plot. Cross sections were preferentially collected from recently dead trees, although samples from live trees were also taken. Where present, full cross sections from old dead wood (e.g. stumps, downed logs) were collected to extend our dendroecological records of old establishment and death dates, fire scars or growth anomalies that might help date fire events.

Dendroecological samples were processed using standard methods (Speer 2010). All samples were sanded with increasingly fine grit until the cellular wood structure was visible, then scanned in color (2400 dpi for cross sections, 1200 dpi for cores) for subsequent measurement and archiving. Ring width measurements were made to a precision of 0.001mm using Coorecorder (Cybis Elektronik & Data AB). To develop region- and species-specific of master chronologies for sample crossdating, we acquired previously published, regionally-specific ring width chronologies for Douglas-fir (Axelson et al. 2009, Sauchyn et al. 2011; available from the ITRDB at https://www.ncdc.noaa.gov/paleo-search) and combined lodgepole pine samples collected by D. Goldblum (unpublished) with our dataset. Evaluation of the master ring width chronologies was carried out using COFECHA (Holmes 1983). All samples were statistically crossdated against these master chronologies using CDendro (Cybis Elektronik & Data AB). In the absence of species-specific chronologies, aspen and spruce samples were crossdated with the lodgepole pine master chronology, while limber pine was crossdated with the Douglas-fir master chronology. For all increment cores, we recorded the pith date to determine the age, early growth rates (sensu Sibold et al. 2006) to infer conditions in which trees established, and outer-ring dates to determine the year of death from dead wood samples. We accounted for missing rings in samples without pith using a geometric estimation method (Duncan 1989). For fire-scarred sections, we recorded the calendar year and intra- or inter-ring position of each scar, as well as the dates of any indirect forms of fire evidence, such as abrupt growth anomalies and resin rings. These indirect forms of fire evidence were only used when they were corroborated by nearby fire scars (sensu Naficy et al. in review).

In many portions of the central and northern Rocky Mountains, inter-ring scars (i.e. those that are located between two rings and span the dormant season of two calendar years) are generally interpreted as evidence of a late summer or fall fire (Heyerdahl et al. 2008b, Chavardès and Daniels 2016). This interpretation is supported by records of burn seasonality for recent fires, a pattern which is mostly driven by lightning or escaped human ignitions. However, in our study region where indigenous fire practices included regular spring burning (Oetelaar and Oetelaar 2007, 2008) that contributed substantially to the fire regime (White 1985, Rogeau et al. 2016), this assumption may be incorrect. In our study region, inter-ring scars may indicate either late summer to early winter fires during the calendar year of the ring predating the scar or late winter to early summer fires of the calendar year of the ring post-dating the scar. To account for this complexity when interpreting inter-ring scars, we initially assigned calendar years to inter-ring scars and compared them to fire scar dates on samples from the same site or from adjacent sites to critically assess if fires burned in the same or consecutive years. In many cases, intra-ring scars that were clearly interpretable as early- or late-summer fires occurred in other samples from the same or adjacent sites and were used to infer the most-likely calendar year on inter-ring scars. Further corroborating these inferences, we found that the evidence within patches and between adjacent patches was more consistent when inter-ring scars were assumed to be fires from different seasons within the same calendar year (*versus* consecutive fire years), so we applied this method to the whole dataset. In cases where no intra-ring scars occurred, we assumed the fire was a late summer fire and assigned the calendar year of the ring that pre-dated the scar. Examination of well-documented fires in our study areas and the region more broadly (Chavardès and Daniels 2016) also corroborate this inference of single fire years that burned in multiple seasons as a likely scenario. For instance, the well-known 1910 fire was marked by substantial fire activity in both early and late summer (Arthur 2014) that is captured in our reconstruction if this assumption is made.

3.7 Dendroecological Classification of Cover Types

To evaluate patterns and variability in fire regimes and ecological dynamics between well-recognized forest cover types (MacKenzie and Meidinger 2018), we developed a compositional classification system from our age plot data to assign patch-level cover types. The ruleset (Table 3) was based on species basal area composition and the proportion of dry- and moist-site indicator species. The ruleset produced seven classes that occurred within our study region, including: pure Douglas-fir forests (PSME), dry mixed-conifer forests dominated by Douglas-fir but with a mix of aspen or lodgepole pine (DMC-PSME), lodgepole pine-dominated stands (PICO), pure aspen stands (POTR), mixedwood stands of aspen and conifers (MXWD), moist mixed-conifer forest comprised of a diverse mix of lodgepole pine, spruce or aspen (MMC), and spruce-fir stands (PIEN).

Table 3. Description of the rulesets and composition of the forest cover type classes used in this study.

Cover type	Ruleset□	Description
Douglas-fir (PSME)	BA_{PSME} >= 80% & $BA_{moist\ sp}$ < 10%	stands comprised of pure Douglas-fir or almost pure Douglas-fir with minor components of lodgepole, aspen, spruce or juniper.
dry mixed-conifer Douglas-fir (DMC-PSME)	BA_{PSME} < 80% & BA_{PSME} + $BA_{dry\ sp}$ > 50% & $BA_{moist\ sp}$ < 10%	mixed stands dominated by PSME, but with a component of POTR or PICO.
lodgepole pine (PICO)	BA_{PICO} >= 50%	pure stands of pure lodgepole pine or dominated by lodgepole pine with minor components of aspen, spruce, or subalpine fir.
broadleaf (POTR)	BA_{POTR} + BA_{POBA} >= 80%	stand of pure or near pure aspen.
mixedwood (MXWD)	BA_{POTR} + BA_{POBA} < 80% & BA_{POTR} + BA_{POBA} >= 50%	stands dominated by aspen, and occassional balsalm poplar, with a component of lodgepole pine or spruce.
moist mixed-conifer (MMC)	if not PSME, DMC-PSME, PICO, POTR, MXWD, PIEN	highly mixed stands of PICO and PIEN, sometimes with significant component of aspen.
spruce-fir (PIEN)	BA_{PIEN} + BA_{PIGL} + BA_{ABLA} + BA_{ABBA} >= 50%	stands heavily dominated by hybrid white x Engelmann spruce, with minor components of aspen or lodgepole pine.

□ - dry species include: Rocky Mountain juniper and limber pine. moist species include: cottonwood, spruce, subalpine fir.

3.8 Fire History Reconstruction

The abundance of fire scar evidence in this landscape is highly variable; in some places it is quite abundant and in others it can be lacking over large areas (> 10^3 ha), including entire patches. We addressed the challenges this posed in two ways. First, we composited all fire scar data from plots within the same patch to produce a more comprehensive patch-level composite fire history that was subsequently used for all fire history analyses. We found this necessary to minimize gaps in the fire history record. Although compositing can result in exaggerated fire frequency estimates (Baker and Ehle 2001), compositing of plots within patches using a similar design in more heterogeneous fire regime systems than the Foothills found no inflationary effect (Naficy et al. in review), suggesting a low likelihood of introduced bias using this method in this study. This assertion is corroborated qualitatively by the large fire sizes documented in this study region (Murphy 1985, Johnson and Larsen 1991, Van Wagner et al. 2006, this study). Second, for patches with limited or no fire scar samples, we were able to extend fire histories in some cases using age structure data combined with fire scar evidence from neighboring sites. We did so by identifying abrupt peaks in tree establishment for each patch using a running median filter with an 80-year moving filter and a gaussian mixture model fit to the residuals to identify significant peaks (defined as the 90th percentile of outliers) from background establishment (Higuera et al. 2009, Tepley and Veblen 2015, Andrus et al. 2018). For plots with fire history gaps, the identified cohorts were used to assign a fire date to the patch if the initiation date of a cohort (e.g. the first 10-year establishment bin of the cohort) occurred within 20 years of a fire date recorded on an adjacent patch. Patch composite fire demography charts depicting fire scars, indirect fire evidence, and age cohorts were created for graphical display of the multi-proxy fire histories and creation of .fhx files for archiving using BurnR (Malevich et al. 2018). Fire dates composited at the scale of individual patches were used to calculate fire frequency statistics from uncensored, scar-to-scar intervals.

3.9 Calibration of the Dendroecological Fire Severity Metric

To quantify the severity of fires recorded at each patch, we employed a dendroecological density decay function (Tepley and Veblen 2015) that is based on changes in the density of surviving trees with each fire event through time. This method is unique in its ability to account for the fading record problem of age structure data, which permits reconstruction of fire severity for all fires in the fire history record of each sample patch for which sufficient establishment exists (set at a minimum threshold density of 10 trees/ha). Thus, fire history records are often longer than fire severity records. We used two metrics generated by the method to represent different components of fire severity. The first metric, λ, is a measure of the cumulative severity of all fires at a patch integrated over time, calculated as the absolute value of the slope of a linear model fit to the density decay curve (Naficy et al. in review). Lower values (shallower slopes) of λ represent lower average severity and higher values (steeper slopes) represent higher average severity. The second metric, ΔS_n, is a relative event-level severity metric specific to each fire event recorded at each patch (Tepley and Veblen 2015).

An important objective of this work was to evaluate the potential bias in ΔS_n when calibrated for individual studies with a limited mix of fire severities and to test the possibility of improved cross-study calibration using pooled datasets that span a range of cover types and study regions. In order to do so, we assembled a calibration dataset from ten previously published (or in press) studies that were compatible with the density decay metrics. This calibration dataset (Table 4) represents the largest dendroecological database compiled to date, spanning a broad geographic region across western North America (Fig. 2a) with diverse forest types and fire regimes (Table 4). We used this dataset to test for potential bias in ΔS_n resulting from standardization within individual studies versus the pooled calibration dataset by comparing correlation coefficients and quantifying the magnitude and direction of shifts in ΔS_n values between the two standardization methods.

Table 4. Summary of the number of sample plots, increment cores sampled, and fire events observed for each study included in the dendroecological severity metric calibration dataset.

Study name	# plots	# cores	# fire events	Forest types	Inferred fire regime
Brookes & Daniels 2020	31	620	23	Douglas-fir	low to mixed
Chavardes & Daniels 2016	26	503	14	lodgepole pine, spruce	mixed to high
Heyerdahl et al. 2006	15	407	17	Douglas-fir	low
Heyerdahl et al. 2011	84	3,015	213	ponderosa pine, juniper, mixed conifer, spruce	low, mixed and high
Heyerdahl et al. 2012	14	522	47	ponderosa pine, Douglas-fir	low
Heyerdahl et al. 2014	12	365	7	ponderosa pine, lodgepole pine	mixed to high
Heyerdahl et al. 2019	45	2,673	130	ponderosa pine, dry mixed conifer	low to mixed
Naficy et al. (this study)	51	2,472	60	lodgepole pine, aspen, Douglas-fir, spruce	mixed to high
Naficy 2017 (GYE)	43	1,379	29	Douglas-fir	mixed
Naficy 2017 (NCDE)	70	2,572	38	ponderosa pine, dry mixed conifer, moist mixed conifer	mixed
Tepley & Veblen 2015	80	4,335	36	ponderosa pine, dry mixed conifer, moist mixed conifer	mixed
Total	471	18,863	614		

To test the hypothesis that the diversity of fire severities in a dataset is an important determinant of the magnitude and direction of bias in study-level calibration of ΔS_n, we evaluated the magnitude and direction of change in pooled versus individual standardization values of ΔS_n as a function of the mean λ values (an absolute, time-integrated measure of fire severity across all fires) for each study. Finally, we directly compared the mean calibrated ΔS_n across all events in each patch with λ for data binned at the individual plot scale, by study, and by forest cover type. If calibration effectively reduces bias in ΔS_n, then mean ΔS_n and λ should be closely related across all binning schemes.

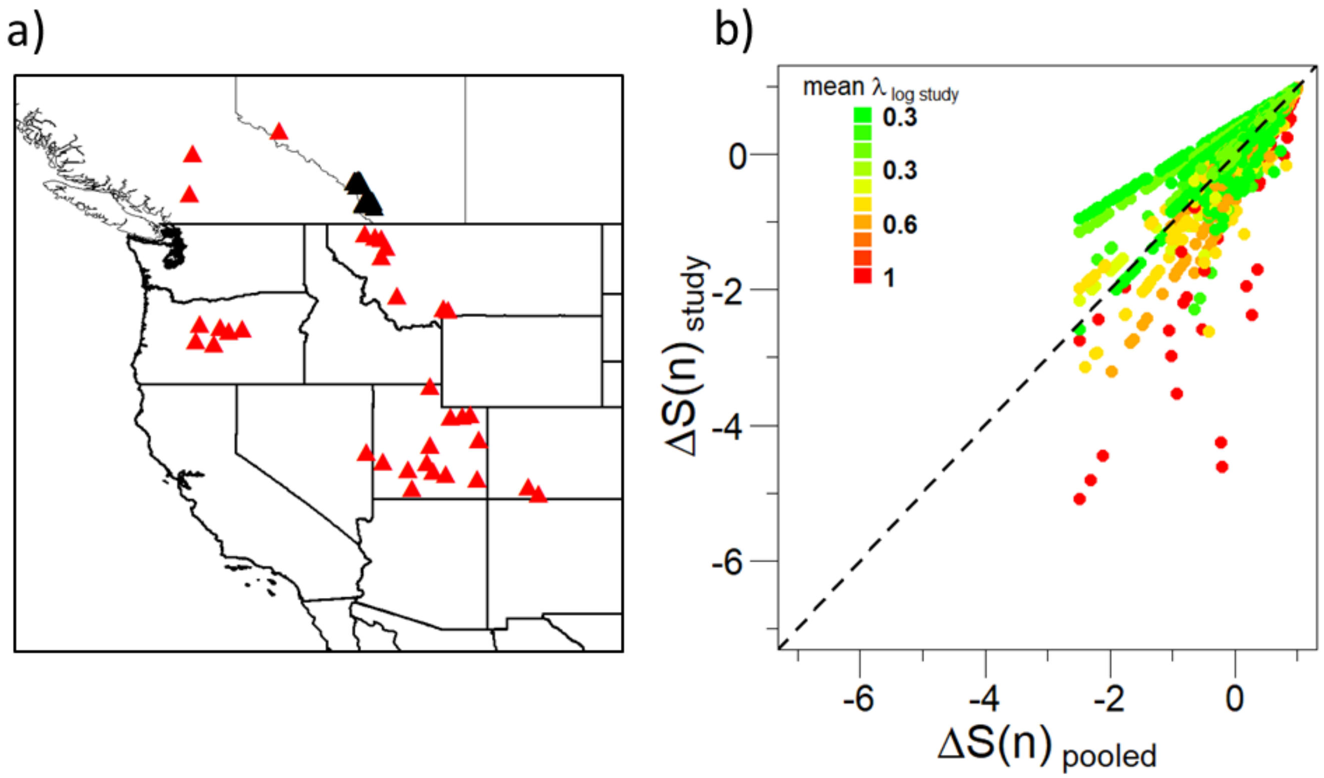

Figure 2. The dendroecological dataset used to calibrate the severity metric for this study, showing (a) a map of the datasets used for calibration (red triangles) and this study (black triangles) and (b) a comparison of changes in the event-level fire severity metric, ΔS_n, when calculated using individual studies (y-axis) versus the pooled calibration dataset (x-axis). In panel (c), the dashed line plots a 1:1 relationship for visual reference. Colors represent the cumulative severity (λ) of each study, with green representing studies with predominantly low-severity regimes, red representing predominantly high-severity regimes and yellow to orange colors representing studies with more mixed-severity regimes.

3.10 Characterization of Fire Severity and the Fire Regime

Multiple aspects of fire severity were examined to reveal both the aggregate trends and variability of fire severity as well as the time-integrated fire severity dynamics for different cover types and study areas. Similar to Thode et al. (2011) who used remote sensing data of fire severity to characterize the modern fire severity regime of vegetation types in California, we used probability density and boxplots to evaluate the distribution of calibrated ΔS_n values for each cover type. To aid with interpretation, we also classified ΔS_n values into low, moderate and high severity classes using the 30th and 80th percentiles as thresholds. Similar thresholds have been used to classify fire severity in multiple other studies (Hessburg et al. 2007, Schoennagel et al. 2011). Binning the distribution of ΔS_n values by forest cover type permits characterization of forest-specific severity regimes. Because this aggregate view of fire severity, may obscure temporal or spatial variability in fire severity dynamics, we defined the time-integrated fire severity for each patch using qualitative and quantitative approaches. Time-integrated severity was qualitatively described using a ruleset approach (Naficy et al. 2020) by classifying each patch as non-stand-replacing if all fires were categorized as low or moderate, mixed severity if at least one high severity fire and one low or moderate severity fire occurred, and high severity if all fires were of high severity. We used λ as a quantitative measure of time-integrated fire severity. Shallow slopes of lambda would indicate a lower severity fire regime over most events, even if infrequent high severity fire occurred at a site. Whereas the ruleset is quite sensitive to the choice of definitions, integration of results from the aggregate and two time-integrated severity characterizations provides a comprehensive view of different aspects of fire severity.

While fire regimes can be described according to multiple criteria (Agee 1993, Sugihara et al. 2006) two key components of many fire regime classification systems are fire frequency and severity. To provide a holistic view of the fire regime we therefore used the median and standard deviations of fire frequency and time-integrated severity (λ) from all plots in each class to define the principal axes of the fire regime space for the distinct cover types and study areas in our region.

3.11 Characterization of Age Structural Attributes

Age structure is an important ecological feature that emerges from interactions between disturbance regimes, plant traits, and biophysical gradients. We used multiple aspects of patch age structure to reveal key ecological outcomes of the fire regime for the cover types and our study areas. First, we calculated the historical stand age for each patch as the median age of trees in the oldest cohort at the time of fire exclusion, which we defined as 1940 for this study. To quantify the complexity of age structures resulting from the fire regime for each cover type and study area, we used hierarchical agglomerative clustering and principal components analysis on a suite of summary statistics describing the distribution and composition of the age structure data from each patch. First, we grouped tree species into three functional groups including shade-intolerant conifer (lodgepole pine, Douglas-fir, limber pine), shade-tolerant conifer (spruce, true firs), and deciduous (aspen, balsam poplar). We then assigned functional compositional groups to each cohort identified by the peak detection algorithm in each patch based on the dominance (by density) of trees within each of these functional groups. We used a threshold of 70% of the cohort density to distinguish between pure aspen cohorts and mixedwood cohorts with a significant conifer component. For each patch, we summarized age structure by calculating the number of cohorts for all species pooled and by functional group, the median, standard deviation, and trimmed range (5^{th} to 95^{th}) of ages for all species pooled and by functional group, and the mean number of years between cohorts. Bray-Curtis distances calculated from the scaled and centered matrix of these variables and Ward's linkage method was used in the cluster analysis. The final number of clusters was determined by examination of the dendrograms and the within-cluster sum of squares (Everitt and Hothorn 2010) and was tested for significance using multi-response permutation procedure. The vegan and pvclust R packages were used for this analysis. To visualize group differences and characterize the variables that distinguish groups, we performed a principal components analysis on the outputs from the cluster analysis.

Understanding the net ecological outcome of variations in fire severity over recurrent events through time can be challenging. Different sites with a mixed or moderate severity regime may result in fairly different age structures across a landscape, depending on their spatial and temporal properties (Pennanen 2002, Wimberly and Kennedy 2008). A useful approach to distilling these net outcomes is to examine the rate of fire-driven turnover (e.g. loss of survivors) in a stand. We approximated this by calculating the stand-replacing equivalent (SRE), defined as the number of fire events or years required to cause a cumulative loss in stand density that is equivalent to stand-replacement (i.e. high severity fire). Because sparse remnant trees occurred in several sites and prevent density from reaching zero, we used a density threshold, calculated as the 10th percentile of all 10-year density bins (53 trees/ha) across all patches, to represent the stand replacement equivalent. We then calculated the number of years (SRE_{years}) and fire events (SRE_{events}) required for each patch to reach the SRE.

4. Results

4.1 Fire Frequency Dynamics

Fires were quite frequent (Fig. 4) and showed surprisingly little variation between cover types or study areas (Fig. 5a, Table 1), except in Douglas-fir forests, which experienced notably more frequent fires (median=17 years) than all other cover types (median=28 years). Maximum fire free intervals recorded for lodgepole pine and other non Douglas-fir cover types were relatively short (median=49, $lower_{IQR}$=31, $upper_{IQR}$=80) compared to fire free intervals in these forest types in other regions and even to Douglas-fir forests in our study region (median=63, $lower_{IQR}$=46, $upper_{IQR}$=72). Although the abundance of fire-scarred lodgepole pine trees was patchy, they were relatively widespread (Fig. 1), and included trees with multiple scars (median=1, 75th percentile=2, maximum=4 scars), despite its thin bark and high fire-caused mortality rates in modern fires (Hood et al. 2007). Tree age at first scarring (Fig. 5b), which is considered to be an inflated fire free interval due to low scarring rates in non-recording trees (Stephens et al. 2010), was nonetheless quite low for lodgepole pine (median=33 years). Interestingly, it was slightly higher and more variable for limber pine and Douglas-fir, which generally experienced more frequent fire. Regional fire frequency declined in the 1920s-30s.

Regional fire years (≥ 20% of patches recording) documented in our region include 1919, 1910, 1896, 1869, 1863, 1800, 1748 and 1717 (Fig. 3a). The 1863 and 1910 fires were recorded in over 50% of the 950,000+ ha study area that encompassed our sample patches, suggesting very large total fire sizes in these years that have been well-documented locally (Arthur 2014, Rogeau et al. 2016) and regionally (Heyerdahl et al. 2008a, Diaz and Swetnam 2013). Widespread fire years (≥ 10% of patches recording) include 1853, 1845, 1831, 1823, 1792, 1784, 1751, and 1688. Most fire events in our record were recorded only in a small proportion of our sample patches (74% and 51% of events were recorded in < 10% and <5% of patches, respectively). For the lodgepole pine zone, this mix of large and small fire years resulted in a bimodal spatial pattern of age structure consisting of widespread pulses of shared tree establishment between many patches in the landscape, juxtaposed with more heterogeneous portions of the landscape where stand ages were quite variable and recorded on only a few patches (inset, Fig. 3b). In the Douglas-fir zone, a contrasting pattern emerged in which diverse older cohorts initiated by different fires were scattered throughout the landscape (the peak centered at the 0-10% bin), fire-initiated cohorts were spread more evenly across a greater number of patches in the landscape and no single event created the same magnitude of age cohort synchrony as in the lodgepole pine zone (inset, Fig. 3c).

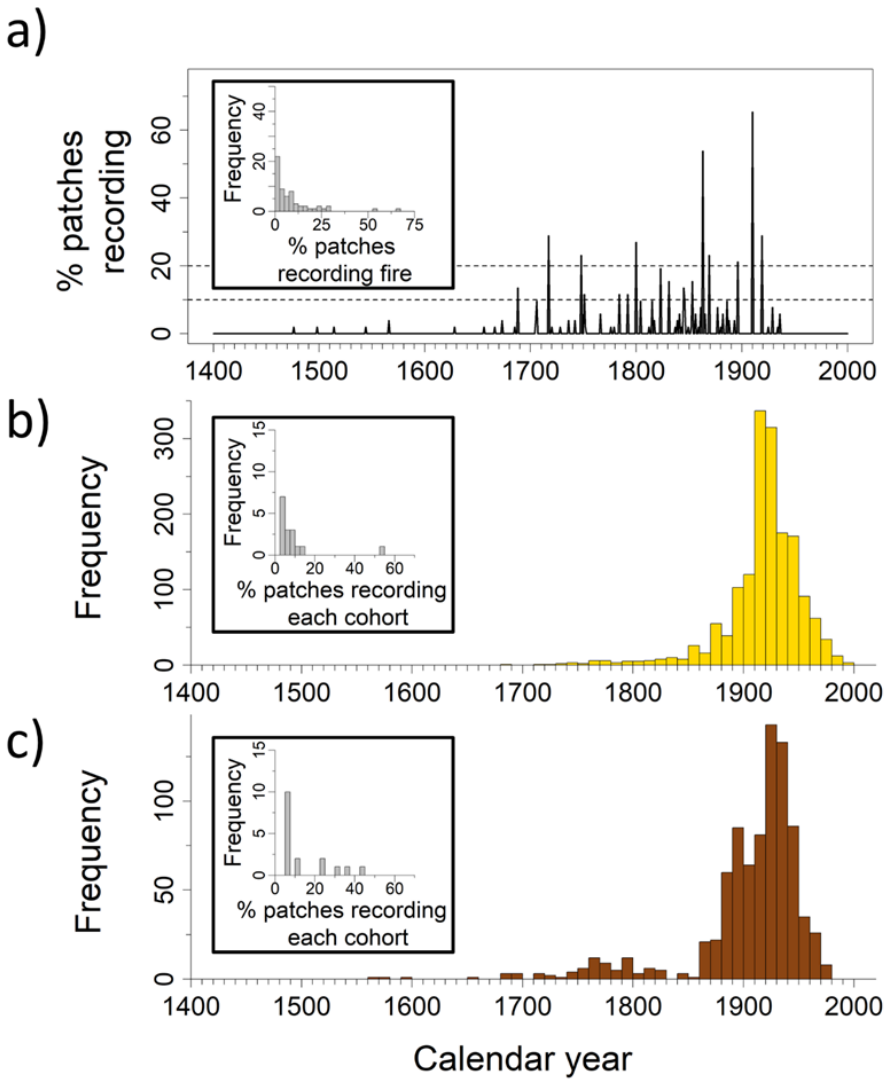

Figure 3. Summary of (a) percent of patches recording fire (dashed horizontal lines show the 10% an 20% thresholds used to define widespread and regional fire years, respectively) with inset showing the frequency distribution of percent recording values, (b) establishment dates for all trees in the lodgepole pine zone and (inset) the distribution of the % of patches recording each fire-initiated cohort, and (c) establishment dates for all trees in the Douglas-fir zone and (inset) the distribution of the % of patches recording each fire-initiated cohort.

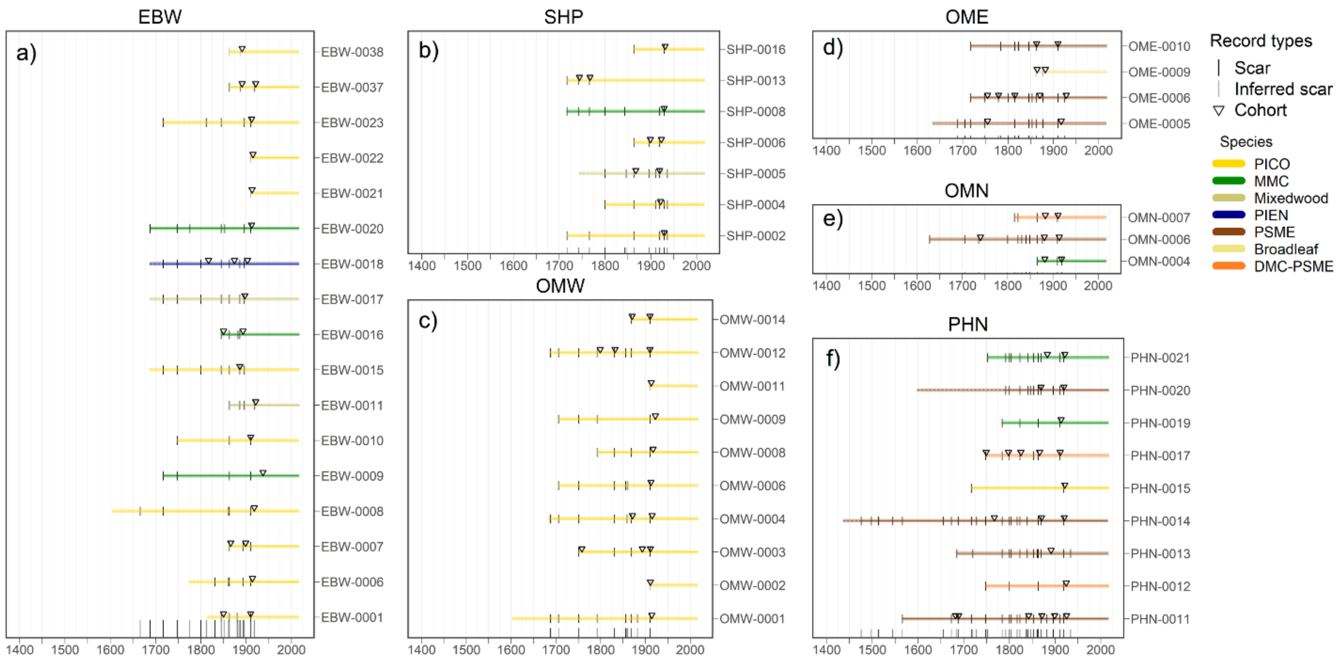

Figure 4. Fire history charts for each sampled area. Each line represents the patch-scale composite of fire scar and age structure data. Patches are color coded by forest cover type. The solid (dashed) portion of each line represents the recording (not recording) period. Vertical hatches represent fire events documented by fire scars (black) or inference from indirect evidence (grey) such as age cohorts, death dates and growth anomalies. The unfiltered composite record of all patches within each study area is shown at the bottom of each plot. Inverted triangles represent the initiation date of age cohorts identified by CharAnalysis.

4.2 Calibration of the Fire Severity Metric

As hypothesized, calculation of ΔS_n was sensitive to the data and this effect was conditional on the diversity of fire severity in each dataset. Fire regimes with predominantly low or high severity (Fig. 2b) showed the largest differences between calibrated and uncalibrated ΔS_n values. Spearman rank correlations between the mean or median difference in ΔS_n between the calibrated and uncalibrated ΔS_n values were strongly and negatively related (r = -0.76 to -0.94) to all measures of variability (e.g. standard deviation, interquartile range, range) of ΔS_n of λ in each study. In other words, studies with greater diversity of fire severity did not suffer from as much bias in the uncalibrated ΔS_n values as those with less diversity, e.g. predominantly low- or high-severity fire regimes. As an example, the difference between the calibrated and uncalibrated ΔS_n values for this study ranked third highest (an 8% underestimation compared to the range of calibrated ΔS_n values). Trends in bias of the metric as a function of event-level severity were also apparent for lower severity events (Fig. 2b). Examination of the relationship between the mean calibrated ΔS_n and λ values showed good correlation for individual plots or when data were binned by study or cover types (Fig. 6a-c). Applying thresholds to the calibrated ΔS_n and λ values at the 30th and 80th percentile values to create severity classes resulted in break points at -0.37/0.52 and 0.18/1.3, respectively.

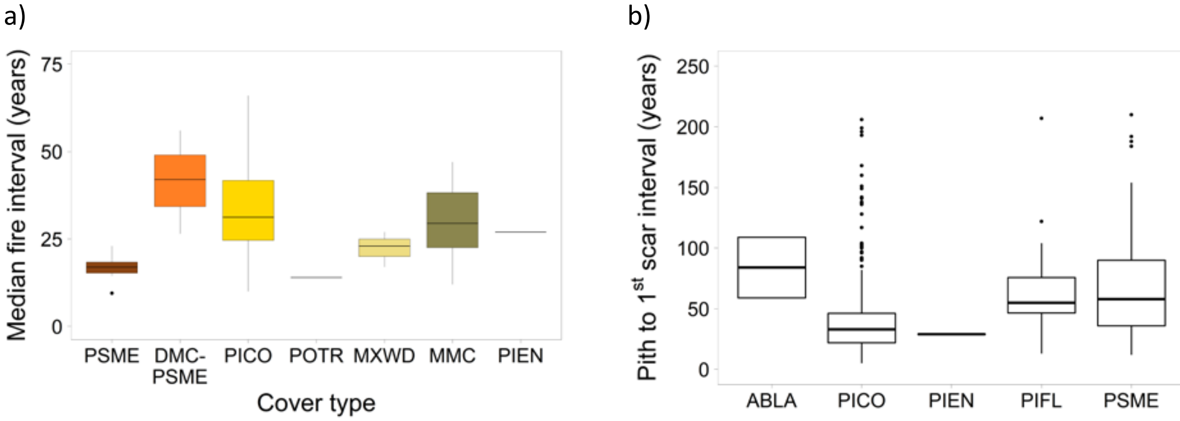

Figure 5. Boxplots showing the distribution of median scar-to-scar intervals for forest cover types and (b) years between the pith date and first scar for fire-scarred cross section of different tree species.

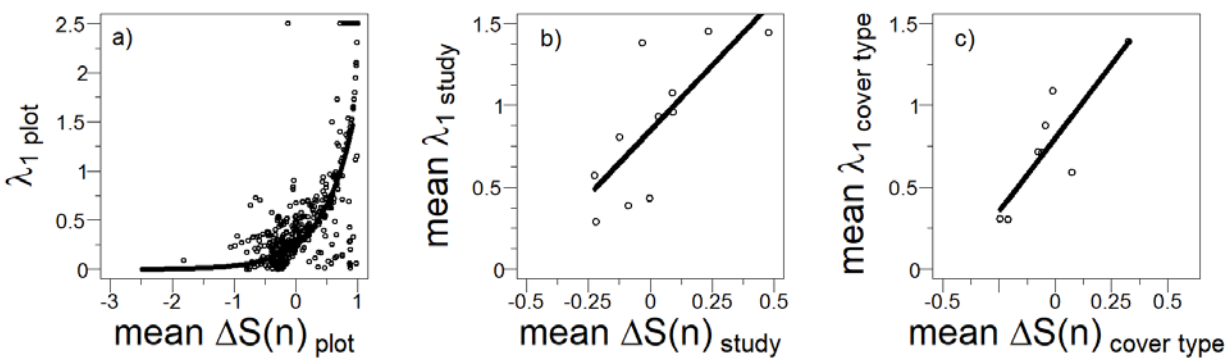

Figure 6. Comparison of cumulative fire severity (λ) and the mean calibrated event-level severity (ΔS_n) for data grouped at (a) the individual plot-scale, (b) by study, and (c) by cover types. Note that cumulative fire severity (λ) is not a relative metric and does not vary as a function of the data used, so it is useful as point of comparison with the event-level severity metric. Black, solid lines show non linear, for panel (a), and linear, for (b-c), models fit to the data. All models were significant ($p < 0.01$), exhibited good fit (R2 = 0.82, 0.75, and 0.75) and metrics are highly correlated ($r = 0.75$-0.91), suggesting little bias in the calibrated event-level metric.

4.3 Fire Severity & Fire Regime

Although fire frequency did not vary strongly among study regions or most forest types, fire severity exhibited significant variability (Fig. 7, Table 1). Douglas-fir forests were characterized by a mix of moderate- and low-severity fires, with few high-severity events. Lodgepole pine forests were dominated by high-severity fire (> 70 % of the sampled fire events), but experienced a significant component of low- and moderate-severity fires. The remaining forest cover types had a highly variable severity regime. Quantitative (Fig. 8) and qualitative (Fig. 9a) time-integrated fire severity analyses confirm these patterns and provided similar insights, with the exception of Douglas-fir. λ did not characterize rare high-severity events well, where residual low-density remnant trees or small clusters survived. In these cases, classifications based on λ indicated a low-severity regime because even very low-density establishment clusters caused the slope of the density decay function (λ) to remain shallow long after the event-level metric indicated a high severity fire. The event-level and qualitative characterizations, in contrast, were sensitive to these high-severity fires and classified all Douglas-fir stands as mixed-severity.

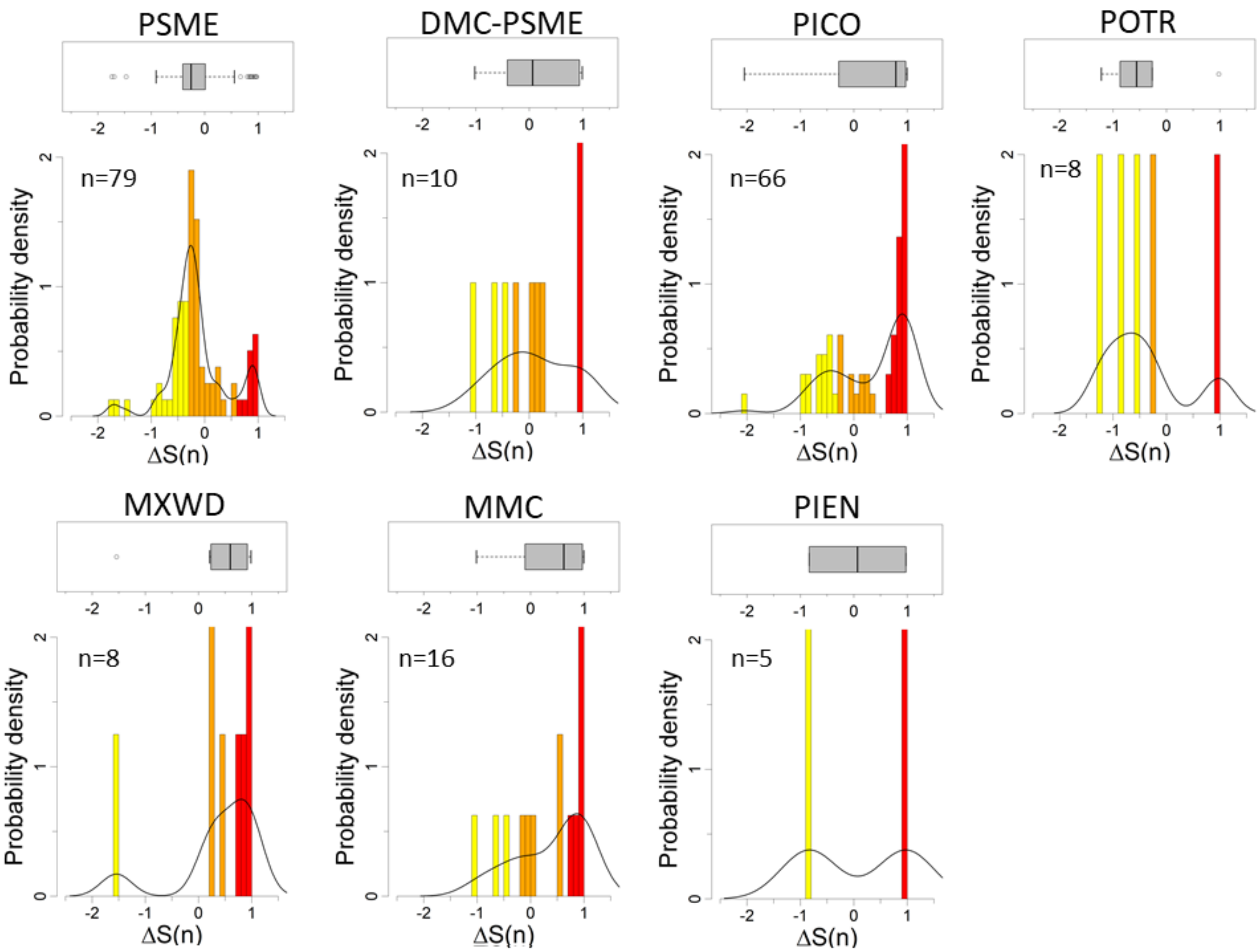

*Figure 7. Distribution of event-level severity values (ΔS_n) for each forest cover type. Boxplots show the median (black vertical bar), interquartile range (gray box), 1.5*IQR (whiskers), and outliers (points). Histograms and fitted curves show the probability density distribution of ΔS_n values. Negative ΔS_n values indicate lower severity and positive values indicate higher severity. Colors represent low (yellow), moderate (orange) and high (red) severity classes based on 30th and 80th percentile rank thresholds for the entire calibration dataset.*

Plotting cover types in fire regime space reveals several notable patterns of the aggregate fire regime of each cover type and its geographic variability. First, cover types clearly sort out in fire regime space (Fig. 9b), visually highlighting many of the key differences in the central tendency and variability of fire frequency and severity noted above.

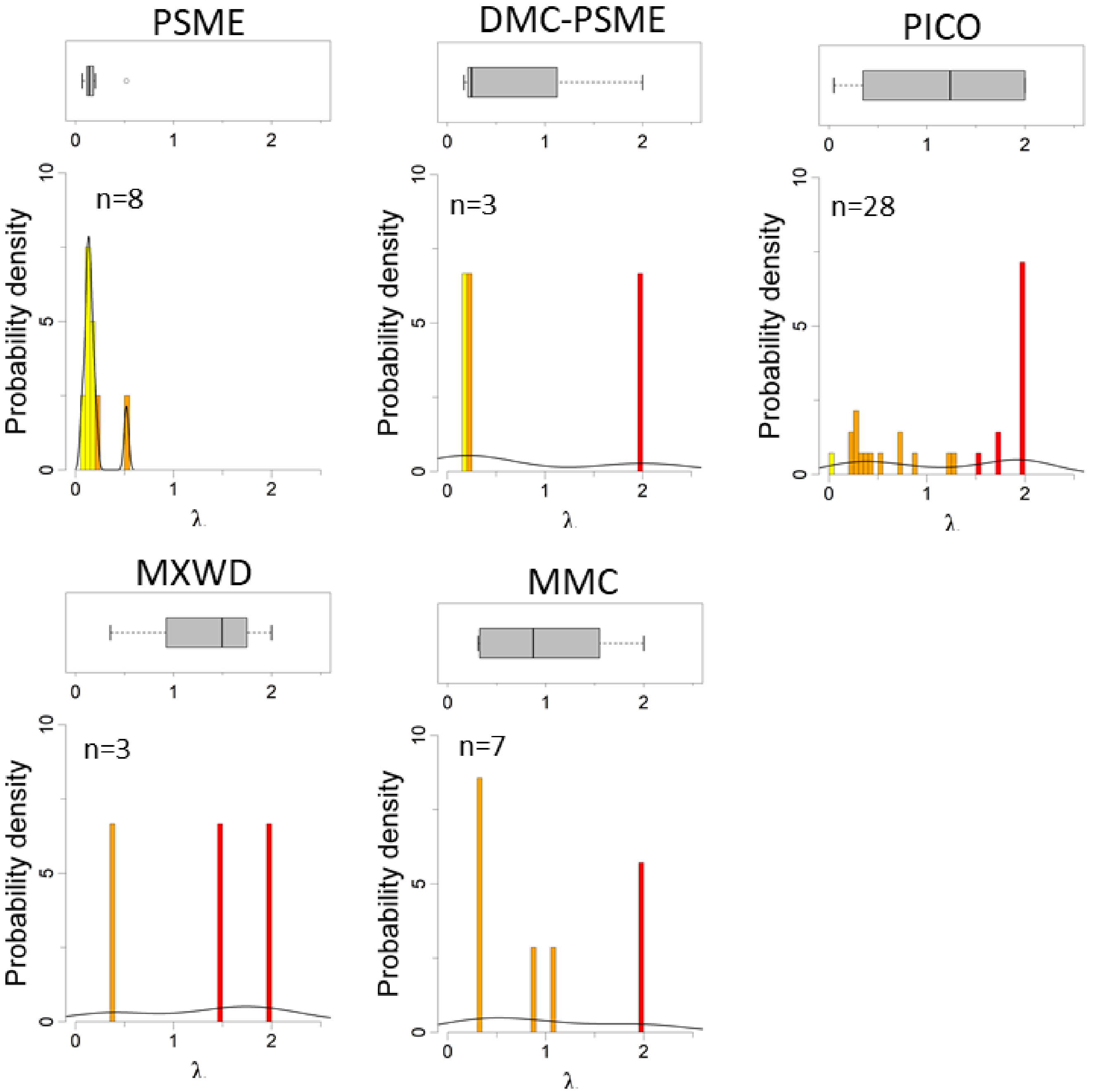

*Figure 8. Distribution of time-integrated severity (λ) values for each forest cover type. Boxplots show the median (black vertical bar), interquartile range (gray box), 1.5*IQR (whiskers), and outliers (points). Histograms and fitted curves show the probability density distribution of λ values. Smaller λ values indicate lower severity over time and positive values indicate higher severity over time. Colors represent low (yellow), moderate (orange) and high (red) severity classes based on 30th and 80th percentile rank thresholds for the full dataset.*

Second, a general positive relationship between fire interval length and severity is apparent (Fig. 9b). Third, geographic variation in fire severity is evident in the degree of inter-regional variability for some forest types and intra-regional variability between intermingled cover types. Fire severity of pure Douglas-fir forests varied less between study areas than it did for lodgepole pine (Table 1). However, when considering the intra-regional variability of fire severity between adjacent cover types an important contrast emerges. Independent of cover type, fire severity in OME and OMN tended to be lower (Fig. 9c). In contrast, PHN was characterized by a greater diversity of intermixed cover types that generally experienced much higher severity than the pure Douglas-fir patches (Table 1). Although all study areas in the lodgepole pine zone were characterized by predominantly high-severity fire and some degree of mixed-severity over time (Fig. 8, 9a), OMW had significantly longer fire intervals and higher severity, while SHP experienced more frequent non-destructive fires (Fig. 9c).

a) *b)* *c)*

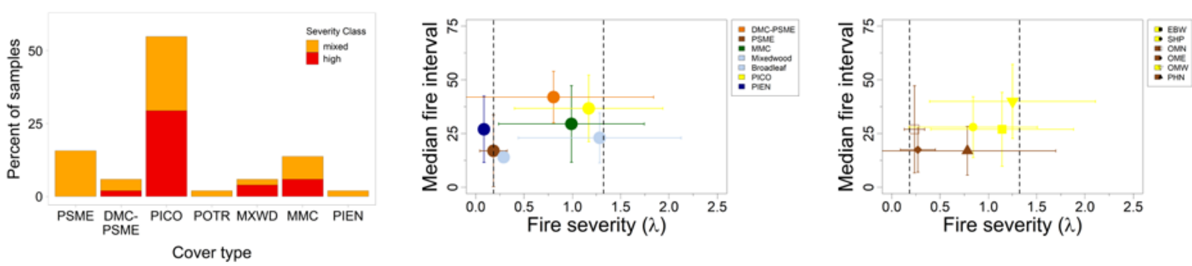

Figure 9. Characterization of the (a) time-integrated fire severity regime and (b) fire regime space, defined by median fire interval and median cumulative fire severity, by forest cover types, and (c) fire regime space aggregated by study areas and corresponding forest zones. In (a), the mixed-severity class is defined as sites with a mix of stand-replacing and non stand-replacing fire effects over time, whereas sites with the high severity class only recorded high severity effects. In (b, c), points represent the median values for each axis for each forest type; whiskers represent the standard deviations. Smaller values of fire severity (λ) represent lower cumulative fire severity. The vertical dashed lines represent the 30th and 80th percentile values of cumulative fire severity, representing breakpoints between low, moderate and high severity regimes, based on data from all plots in the pooled calibration dataset.

Fire severity patterns for the eight regional fire years we document reveal key differences in the spatio-temporal severity dynamics of the mixed-severity fire regimes for the dominant forest types of the region (Fig. 10). In Douglas-fir forests, low and moderate severity fire predominated even in these large fire events that occurred during significant drought years. Both a spatial and temporal component of variability are apparent in the Douglas-fir fire regime, as evidence by variability in the median, range, and frequency of outlier ΔS_n values. In contrast, the pattern for lodgepole pine forests is of predominantly high severity fire across most events, with some events exhibiting greater variability. Rather than a strongly temporally varying severity pattern, this suggests that a spatial component of fire severity characterized the mixed-severity fire regime of this forest type.

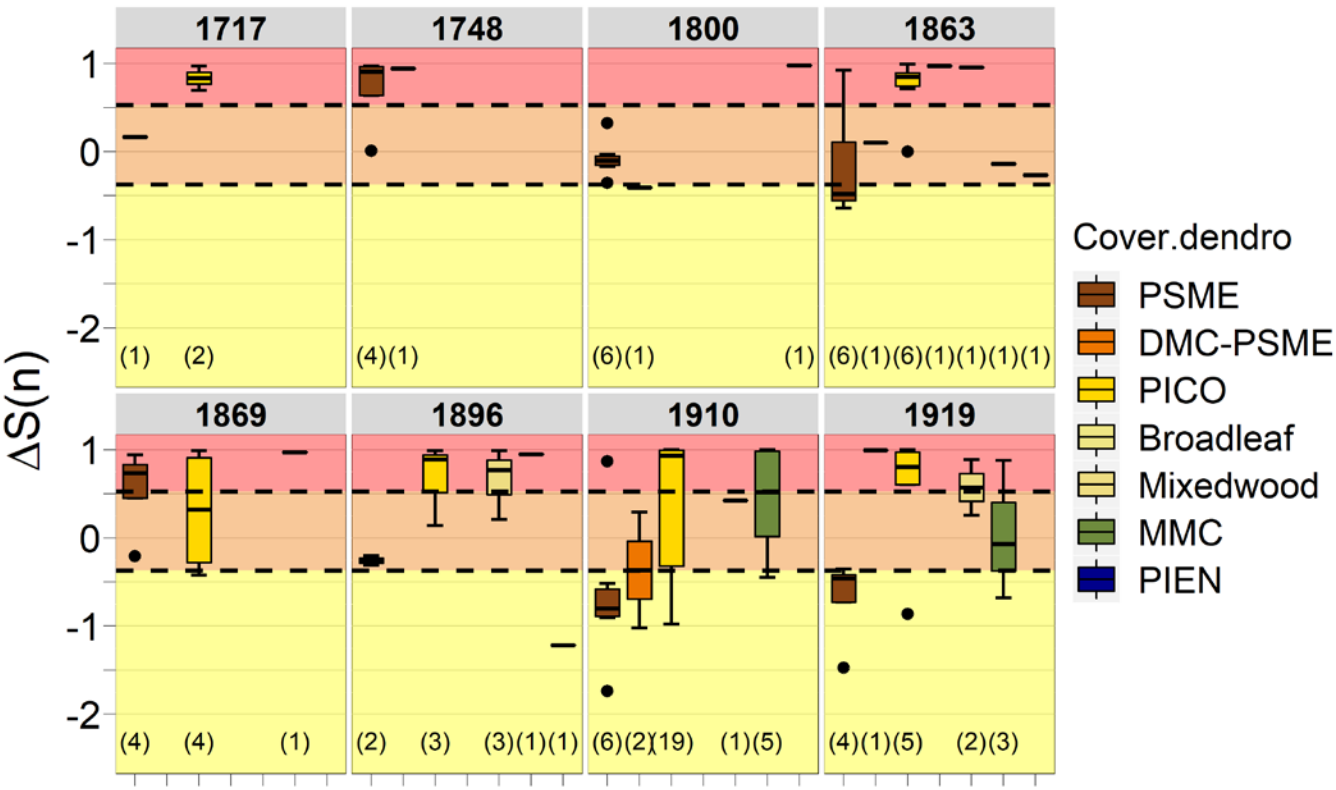

Figure 10. Distribution of the observed fire severity (ΔS_n) values stratified by cover type for each of the eight regional fire years documented in this study. Sample sizes for each fire year and cover type are listed in parentheses at the bottom of each panel.

4.4 Age Structure Complexity

The cluster analysis resulted in three age structure complexity groups (Fig. 11a), which we label as simple, intermediate, and complex (Fig. 11c-e). Principal components analysis showed relatively good separation of the three groups in feature space (Fig. 11b) and a multi-response permutation procedure test confirmed that significant differences ($p < 0.001$) existed among the three complexity groups. Examination of a scree plot showed that the first two principal components accounted for the majority of the variance (73%) in the data. Both structural complexity and functional composition were important variables in the (Fig. 11b). The first principal component is negatively correlated (r = -0.23 to -0.36) with the number of cohorts, number of years between cohorts, the median, standard deviation and range of ages of shade intolerant conifer species. The second principal component is positively correlated with the number cohorts and the median, standard deviation and range of ages of deciduous species (r = 0.25 to 0.44) and negatively correlated (r = -0.21 to -0.28) with the median, standard deviation and range of shade tolerant conifers and the median age of shade intolerant conifers. Simple patches were generally lodgepole pine dominated, even-aged stands resulting from a single fire (Fig. 11c, 12d). Patches with intermediate complexity patches usually had 2 cohorts resulting from two or a few fires (Fig. 11d, 12d), sometimes with scattered background establishment that wasn't identified as a cohort by the peak detection algorithm, they were young and had short time between cohorts. This class was common across all cover types. Complex patches contained multiple cohorts, including an older cohort and long gaps between cohorts, resulting from multiple, often frequent, non-stand-replacing fires (Fig. 11e, 12d). Complex patches were most prevalent in Douglas-fir forests, and often had a prominent aspen component, although complex patches occurred in low proportions for all conifer dominated cover types (Fig. 12d).

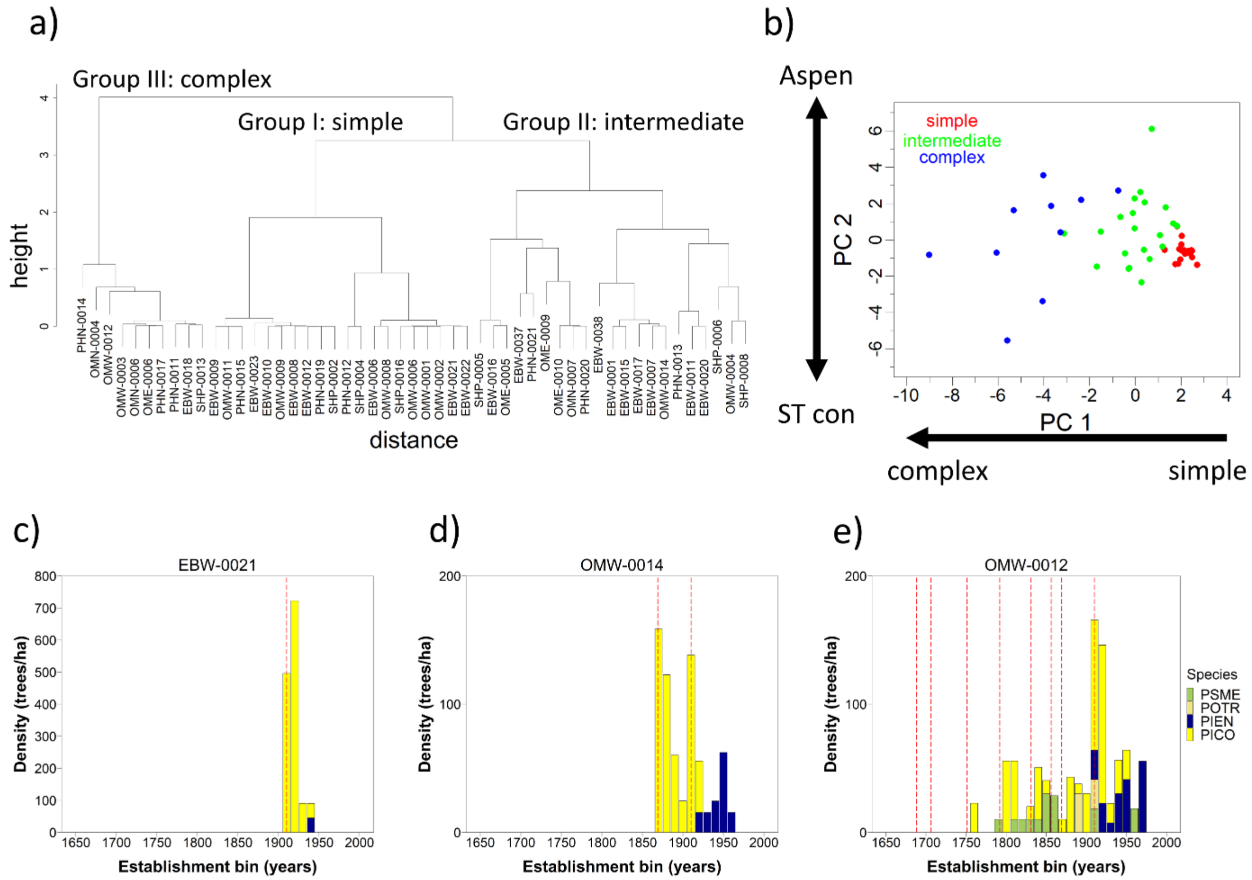

Figure 10.

Figure 11. Definition and characterization of age structural complexity, showing (a) dendrogram produced by the hierarchical cluster analysis with the groupings of the simple, intermediate and complex classes, (b) a principal components analysis of age structure attributes, showing the three complexity classes, and (c-e) examples of the age structure and fire history of patches classified as (c) simple, (d) intermediate, and (e) complex. In (b), PC 1 is negatively correlated (r = -0.23 to -0.36) with the # of cohorts, # years between cohorts, the median, standard deviation and range of ages of shade intolerant conifer species. PC 2 is positively correlated with the # cohorts and the median, standard deviation and range of deciduous species (r = 0.25 to 0.44) and negatively correlated (r = -0.21 to -0.28) with the median, standard deviation and range of shade tolerant conifers and the median age of shade intolerant conifers. In (c-e) bars represent binned establishment dates colored by species and red dashed vertical lines indicate fire events.

At the time of fire exclusion, around 1940 C. E., the landscape of the montane and lower subalpine zone, excluding Douglas-fir stands, was dominated by very young forest recovering from recent fire. The median age of lodgepole pine stands was 22 years and exhibited limited variation (Fig. 12a), although a few patches of older forest remained within this matrix of young forest. The mean SRE for lodgepole pine was 35 years or two fire events (Table 1, Fig. 12bc), suggesting that the mixed-severity fire regime of lodgepole pine and other cover types lacking a Douglas-fir component produced transient, non-equilibrium dynamics. These dynamics resulted in a heterogeneous landscape of young even-aged and uneven-aged lodgepole pine stands (Fig. 12d). Douglas-fir stands, and to a lesser extent DMC-PSME stands, were significantly older, with median ages of 166 and 46 years, respectively, and exhibited large variability in ages (Table 1, Fig. 12a). The mean SRE_{years} was 156 and 69 and SRE_{events} was 9 and 3, for Douglas-fir and DMC-PSME forests respectively (Table 1, Fig. 12b-c). Douglas-fir forests were comprised of intermediate and complex age structures, while DMC-PSME were evenly mixed between all three classes.

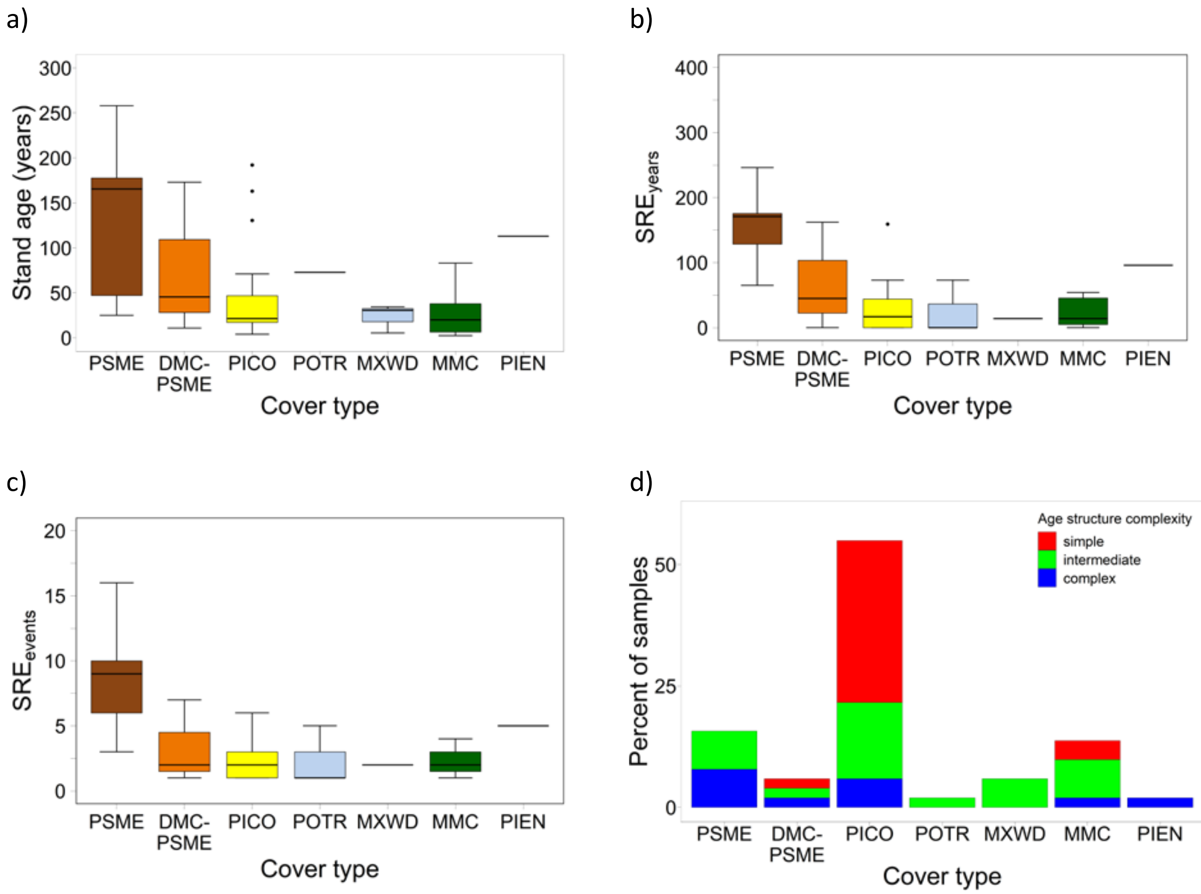

Figure 12. Distribution of (a) stand ages at the time of fire exclusion, the stand replacing equivalent, expressed in terms of (b) number of years and (c) number of fire events required to reach cumulative stand replacement, and (d) age structural complexity classes for each forest cover type. In (d) total bar height represents the percent of sample patches in each cover type out of the total dendroecological sample.

5. Discussion

5.1 Novel Insights From the Use of a Calibration Dataset and Multiple Severity Metrics

In this study we make the first broad-scale assessment of the sensitivity of the relative, event-level severity metric (ΔS_n) developed by Tepley & Veblen (2015) to the data inputs, the factors that influence bias and variability in the uncalibrated values, and the potential for cross-study calibration to limit this bias and improve interpretations of historical fire severity. We demonstrate the benefits of working with a large-scale calibration dataset that incorporates data from diverse fire regimes and provide a framework for understanding bias in the metric that can help inform the design and analysis of dendroecological data in future studies. The magnitude of bias in ΔS_n was inversely related to the variability of fire severity in the input dataset, whereas the direction of bias depended on mean severity of the input data, with underestimation errors for high-severity and overestimation errors for low-severity regimes, respectively. For the Alberta dataset, which exhibits a narrower range of fire severities than other mixed-severity fire regime systems, this calibration process was critical to our ability to make robust interpretations. Although it is difficult to evaluate the extent to which the calibrated ΔS_n metric approaches an absolute severity metric, relativizing it over a broader range of fire regimes and forest types at least provides important context for evaluation of a particular dataset or landscape. But more importantly, the close positive relationship between the calibrated ΔS_n metric and the λ suggests that it is a relatively unbiased approximation of absolute severity. This is an important finding because it highlights the potential of this approach for cross-study data synthesis and broad-scale, quantitative analysis of historical fire severity patterns that has not been previously feasible but is a major research need (Daniels et al. 2017).

5.2 Fire Regime of the Lodgepole Pine Zone: A Frequent Fire, Fire-Sensitive Ecosystem

Our research design and data analyses make a unique contribution to the existing body of fire history work in the Foothills. Despite the patchiness of fire scar evidence and the prevalence of lodgepole pine and aspen, species considered to be poor fire recorders, we demonstrate the potential to combine crossdated fire scars from live and long dead trees with age structure data to produce robust, annual resolution, multi-century fire records, at least for the montane to lower subalpine zone. This approach has clear advantages to time since fire methods based on age structure (Johnson and Van Wagner 1985), especially for forests with species (e.g. spruce-fir) whose establishment dynamics are weakly related to coarse scale disturbances such as fire or those with plastic regeneration strategies and multi-decadal regeneration windows (e.g. Douglas-fir). However, for the lodgepole pine forests that represent the principal forest cover of the region and whose regeneration dynamics are closely linked to fire disturbance, our fire frequency estimates are generally consistent with previous studies in lodgepole pine forests of the montane and lower subalpine zone of the region (Rogeau et al. 2016). Our data build upon this previous work to show the scale and extent of frequent fire in the lodgepole pine zone. Not only was fire frequent for this forest type, but it was consistently frequent, with low variation in median or maximum values, over the last several hundred years, and this appears to be true across the montane to lower subalpine zone of this broad region (spanning 2° latitude, c. 950,000+ ha). Investigation of historical fire dynamics in the lodgepole pine forests of the Foothills therefore provide a unique empirical opportunity to contribute to broader ecological debates about the resilience of ecosystems dominated by fire-sensitive species to climate driven increases in fire frequency (Westerling et al. 2011, McWethy et al. 2013, Turner et al. 2019).

5.3 Ecological Dynamics of a Fire-Sensitive Forest Under a Frequent Fire Regime

The lodgepole pine zone of the montane and lower subalpine portions of the southwestern Alberta Foothills was a heavily fire-impacted landscape, comprised of young even-aged and uneven-aged patches in different states of recovery (Fig. 13). The historical fire regime of this landscape was a mixed-severity regime dominated by severe fire effects, but with a significant component of non-stand-replacing fire effects that occurred for many fires. These dynamics are similar to those described in studies from neighboring areas (Amoroso et al. 2011, Chavardès and Daniels 2016), which suggests a coherent collective regional regime for montane forests of the eastern slopes of the Rocky Mountains. But these dynamics contrast strongly with the mixed-severity fire regimes described in many other systems (Schoennagel et al. 2011, Heyerdahl et al. 2012, 2019, Flower et al. 2014, Marcoux et al. 2015, Tepley and Veblen 2015, Naficy et al. in review), where low- or moderate-severity effects were interspersed with less frequent or smaller scale high severity effects. The diversity of fire dynamics for systems collectively referred to as mixed-severity fire regimes illustrates the need for clear description and definition and the benefits of quantitative treatment of fire regime space, as we have done here.

We present multiple lines of evidence of a complex fire regime and landscape condition, despite the prevalence of very young stand ages and transient dynamics of Foothills forests in the lodgepole pine zone. Young forest is often equated with simple, even-aged conditions, but we document that almost a third of the landscape of young forest in the Foothills was instead of intermediate or higher complexity. Portions of this landscape (SHP and portions of EBW) consisted of a highly heterogeneous mix of grassland, aspen and conifer patches with multi-cohort and even-aged cohorts from initiated in distinct fire events (Fig. 13a). In other portions of the landscape (OMW, and portions of EBW) single large, severe fire events, such as the 1910 fire, created a coarser-scale mosaic (Fig. 13b) through the maintenance and expansion of grasslands, creation of multi-structured patches in areas burned with low- and moderate-severity effects, and development of a patchwork of burned and unburned forests. As in crown fire systems elsewhere, heterogeneity of the template was further developed through interactions between initial fire effects and biophysical factors (e.g. topography, serotiny) that result in spatial diversity of post-fire successional trajectories (Turner and Romme 1994, Turner et al. 1998). The high turnover rates (e.g. low SRE values) we document for forests in the lodgepole pine zone suggest that forest conditions were transient, with substantial shifts in the relative abundance and spatial pattern of age structures over time. This may indicate weak self-regulating fire regime behaviors and an important role of local or stochastic factors in disturbance outcomes that is generally consistent with interpretations from other studies in the region (Bessie and Johnson 1995); however, we have not yet quantitatively addressed this for the montane zone (see *Next Steps*). Notwithstanding some uncertainty about the role of this spatial patterning on subsequent fire behavior and effects, the presence of a bimodal landscape states, greater abundance of multi-cohort age structures, and spatial variation in stand ages is relevant for wildlife habitat, carbon storage and other ecological functions that are key considerations in forest management (Christensen et al. 1996, Spies 1998, Landres et al. 1999).

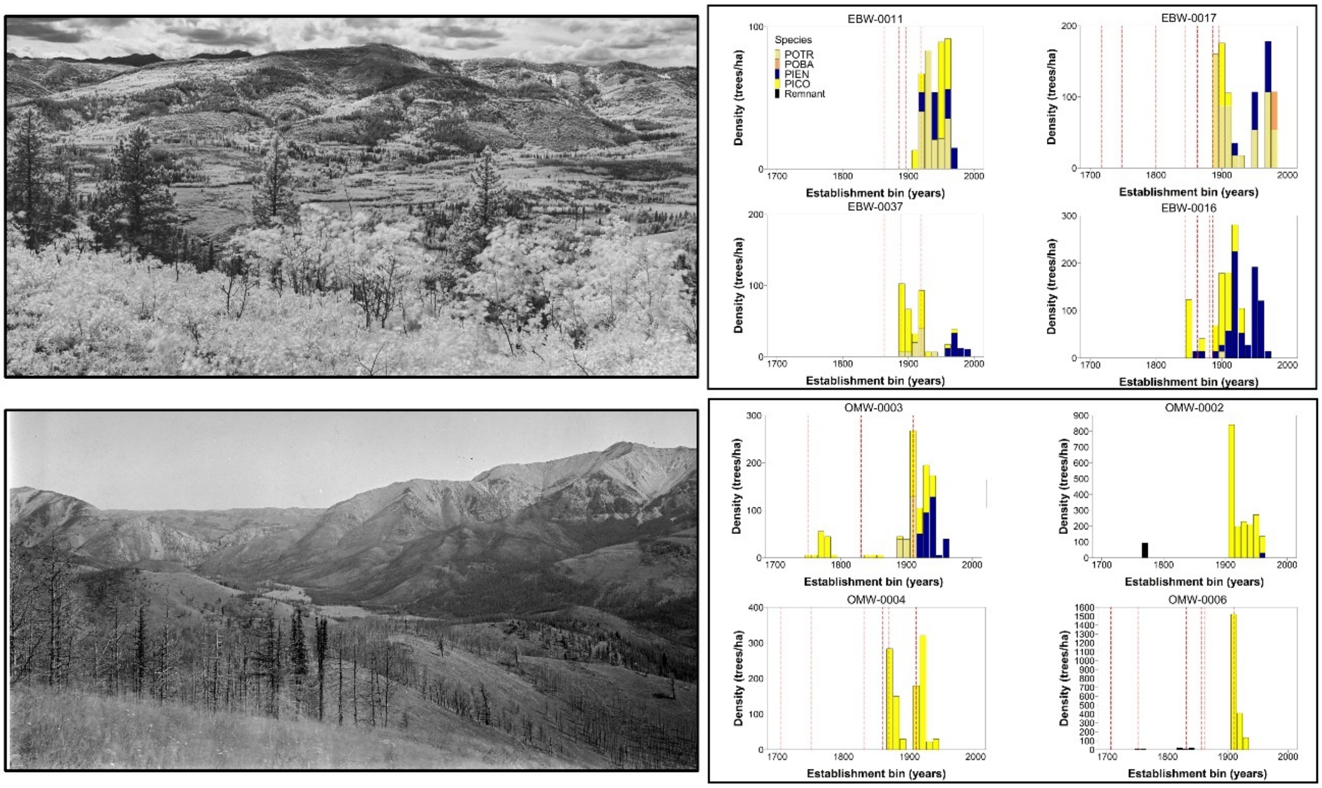

Figure 13. Historic images, courtesy of the Mountain Legacy Project (http://mountainlegacy.ca/), showing contrasting landscape conditions of the lodgepole pine zone. (upper left) Image taken by R. J. Parlee in 1940 in EBW, located in the northern unit, showing a heterogeneous landscape of aspen- and conifer-dominated, multi-cohort and even-aged patches of different ages. Note the open canopy lodgepole "woodland" in the left foreground resulting from partial mortality and the burned aspen in the foreground showing the boundary between two very young cohorts of aspen initiated by two shortly-spaced fire events. (upper right) Age structure and fire history graphs from the same portion of EBW showing the heterogeneity of fire history, composition, and age structure of neighboring sites. (bottom left) A view of the OMW study area in the southern unit of our study region, taken by M. P. Bridgland in 1913, less than three years after the 1910 fire. Scattered individual trees and small clusters remain in the burn footprint amidst large severely burned areas. Unburned forest patches and perennial grasslands (evident by the lack of snags and developed prairie vegetation) are scattered around and within the burn perimeter. Note also the small stature of standing snags left by the fire that indicate young age of the forest prior to being burned. This young snag forest will result in less fine- to coarse-fuel shed in the post-fire environment. (bottom right) Age structure and fire history graphs from the area of OMW depicted at left. Note the less frequent, more synchronous fire history and less variable age structures of OMW compared to EBW.

Another key consideration that emerges from these findings is the striking context that a landscape of young, mixed-age lodgepole pine presents for questions about fire behavior, the use of prescribed fire and fire suppression decisions. Fire behavior modeling originated, and has largely continued to be applied, in mature forests (Van Wagner

1977, Rothermel 1983). A small number of recent studies (Nelson et al. 2016, 2017) conclude that fuels and fire behavior in young, post-fire lodgepole pine stands recovering from high-severity fire are likely to support a crown fire-dominated regime. Some empirical evidence supports this (Turner et al. 2019), but from a very limited sample of events that constrain extrapolation to long-term frequent fire regimes. A key discrepancy between these studies, which document consecutive fires at short intervals preceded by a long fire-free interval, and the dynamics we document in the Foothills is the consistently frequent fire with closer parallels to projected future fire regimes (Westerling et al. 2011, Barbero et al. 2015). Ground, understory, and standing fuel complexes will certainly differ in these two scenarios (Larson et al. 2013, Stevens-Rumann and Morgan 2016, Turner et al. 2019), with important consequences for fire behavior and fire-related ecological outcomes. In the first case, and irrespective of whether long-fire free intervals are caused by natural or human causes, post-fire fuel complexes will be characterized by patchy ground fuel consumption, much higher levels of coarse woody fuels, and more homogeneity across the landscape. In the latter scenario, much less ground fuel is likely to accumulate as a result of repeated burns, fine to coarse fuels from dead trees are likely to be greatly reduced as a result of the small diameter and crown size of young, regenerating trees, and spatial heterogeneity of fuels is likely to be higher. Repeated fire may also promote the abundance and extent of aspen forest within the landscape (Kulakowski et al. 2013, Shinneman et al. 2013), which can have an important regulating influence on fire spread and severity (Cumming 2001, Stockdale et al. 2019). The relative abundance of fire-scarred lodgepole pine and the short pith to first scar intervals indicate that sufficient heterogeneity in fuel complexes and fire behavior existed in historical fire regimes to allow survival of a fire-sensitive species at its most fire sensitive stage. These dynamics suggest that understanding fire behavior in young, repeatedly burned lodgepole pine forests is an important area of future research that will contribute critical insights to land management agency approaches to fire suppression, post-fire recovery, and silvicultural design.

5.4 Resilience Mechanisms to Frequent Fire

Previous literature has not comprehensively described the ecological dynamics and resilience mechanisms of a frequent, high-severity regime. Existing models for montane forests (B.C. Ministry of Forests 1995, Schmidt et al. 2002, Schoennagel et al. 2004) tend to assume an inverse relationship between frequency and severity that restricts the range of potential dynamics to a gradient between frequent, low-severity and infrequent, high-severity regimes. Within this framework, the critical resilience mechanisms identified for high-severity regimes are long fire intervals that allow slow recovery or slow fuel accumulation that creates strong age-related effects that limit subsequent fire for decades (Halofsky et al. 2018). But in frequent, severe fire regimes like those of the montane zone of the Foothills, long fire-free intervals are essentially non-existent and the strength or duration of negative feedbacks between fire frequency and severity may be weak. Boreal forests are one of the few forest types where frequent, severe fire regimes have been documented (Bergeron et al. 1998, Johnson et al. 1998). Resilience mechanisms in these forests are thought to emerge from the presence of resprouting tree species, serotiny, and self-regulating spatial interactions between fires that limit large distances to seed source and can result in forest loss (Héon et al. 2014, Hart et al. 2019). The montane forests of the Foothills share some of these traits (e.g. serotinous and resprouting trees) that are likely part of the resilience response in the Foothills. Despite previous characterizations of the area as dominated by large, severe fires (Hawkes 1980, White 1985, Johnson and Larsen 1991), we show that in the montane zone, this dynamic was complemented by a finer-grained mosaic of intermixed patches of different ages likely resulting from variable fire severity and heterogeneity of fire perimeters. The spatial patterning of fires in lodgepole pine forests of the Foothills have not received sufficient attention so the strength of these spatio-temporal interactions is not currently known. This is an area of needed future research.

Given the bimodal landscape pattern of forest conditions in the Foothills it is likely that resilience to frequent fire was an outcome of some blending of the above-described fine scale spatial patterning and those that have been identified for large-scale crown fire ecosystems more broadly (Turner and Romme 1994). A key component of this resilience is the low reproductive age (< 20 years) of lodgepole pine (Crossley 1956, Brown 1975) that would allow cone production to occur even under the 20- to 40-year median fire return intervals documented in the Foothills. An interesting component of resilience in frequent fire systems that has not been well-examined is the potential adaptive significance of low levels of serotiny in young lodgepole pine (< 30 years) that has been documented locally and more broadly for lodgepole pine (Crossley 1956, Schoennagel et al. 2003). The open-cone habit of young trees would seem to be especially adaptive in this ecosystem by permitting faster rates of recolonization into the interiors of the small and large meadows intermixed with lodgepole pine forests that were created by repeated burns.

5.5 Fire Regime of the Douglas-Fir Zone

Few studies have investigated the fire regimes and ecological dynamics of the interior pure Douglas-fir forests ecosystems like those of our study area. Yet these pure Douglas-fir forests are the dominant lower montane forest cover over broad areas throughout central BC, portions of southwestern Alberta, and the interior mountains of Washington, Oregon, Idaho, Montana and Wyoming in the United States. Most studies of Douglas-fir forests outside of coastal system have been conducted in mixed-conifer forests of ponderosa pine, western larch and lodgepole pine, where pure Douglas-fir is often limited to small patches, narrow elevational bands, or specific topographic positions (Hadley and Veblen 1993, Margolis and Malevich 2016). The dynamics of Douglas-fir forests in this setting are a product of interactions between their autoecology and that of the landscape in which they are embedded (Hessburg et al. 2015), which has created uncertainty about the ecology of pure Douglas-fir forests. Insights from the pure Douglas-fir forests of the Foothills, therefore represent an important contribution to the small number of previous studies (Houston 1973, Arno and Gruell 1983, Barrett 1994, Heyerdahl et al. 2006, Harvey et al. 2017, Brookes et al. in review, Naficy et al. in review) in this ecosystem type. Most of these studies have been conducted at the grassland-forest ecotone, similar to our study areas, but have documented longer fire intervals (30-55 years). Fire severity dynamics have only been examined in a few of these cases, mostly in a qualitative fashion, with interpretations varying between a mixed-severity regime predominantly of non stand-replacing fires similar to those of ponderosa pine (Barrett 1994, Harvey et al. 2017, Brookes et al. in review) to a more evenly mixed regime of stand-replacing and non stand-replacing fires (Naficy et al in review). Compared to these studies, fire frequency in the Douglas-fir forests of the Foothills stands out as amongst the highest.

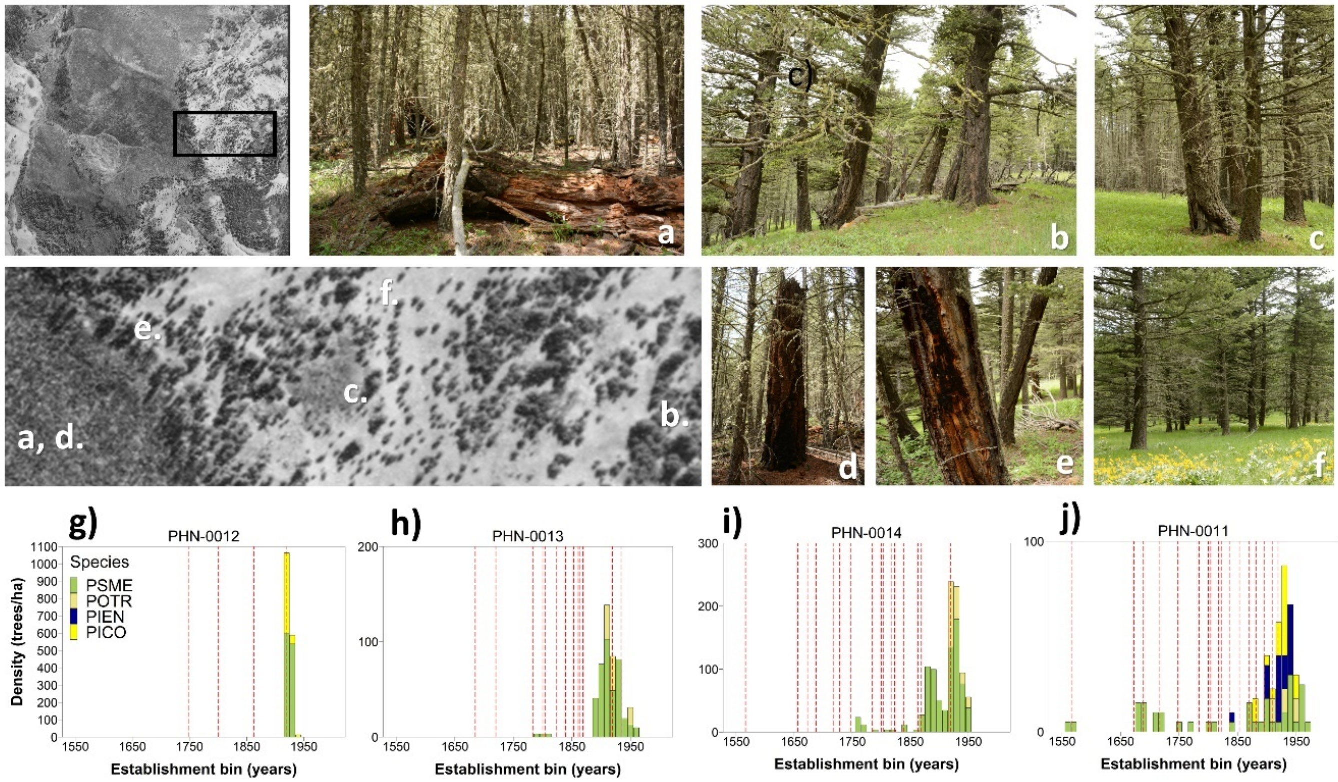

Figure 14. Example of landscape conditions and disturbance legacies of the Douglas-fir zone. A panchromatic aerial image from 1920 (upper left and inset) shows the diversity of stand conditions including (a, d) area burned at high-severity in 1919 where evidence of type conversion from open canopy, old Douglas-fir forest (downed and stand dead) to dense regenerating stand was encountered in the field, (b) small clusters of very old remnant trees, (c) individual old, repeatedly fire-scarred tree with adjacent younger trees, (e) medium-aged trees with multiple fire scars, and (f) young, open canopy woodlands. (g-j) Graphs showing the diversity of age structures and disturbance histories of adjacent patches within PHN. Note that the scale of the y-axis in (g-j) varies. Panel (g) is the same patch depicted in (a, d), showing the even-aged age structure and mixed-species composition resulting from high-severity effects in the 1919 fire. Panel (h) shows the patch circumscribing (b-c, e-f) that was dominated by young woodlands with isolated individuals and small clusters of medium-aged to old, often fire-scarred trees. Panel (i) is a case where SREyears (171 years) and time-since-high-severity-fire (71 years) diverge as a result of the old remnant trees established following the 1748 fire that survived until present day, despite the high-severity event that occurred in the site in 1869. Panel (j) is an example patch that experienced frequent, mostly moderate- and some low-severity fire effects.

The mixed-severity dynamics that emerge from this high fire frequency can be understood at two scales; that of pure Douglas-fir or Douglas-fir/aspen patches and that of the broader landscape in which these patches are co-mingled with mixed conifer and pure aspen patches. Despite very frequent fire, Douglas-fir patches did not experience a predominantly low-severity regime; rather it was relatively evenly influenced by low- and moderate-severity fires, with a much less frequent component of high-severity fire. Despite the relative infrequency of high-severity fire, it was an important part of the dynamics of this forest type. Median time since high-severity fire at the onset of fire exclusion in 1940 was 71 years ($lower_{IQR}$=69, $upper_{IQR}$=106), with only two patches (out of eight) not recording high-severity fire for more than the previous century. The cumulative mortality resulting from these intermediate-frequency high-severity fires and frequent moderate-severity fires, resulted in the high variability of stand ages and complexities, as opposed to the more consistently open canopied, multi-cohort, uneven-aged, stands with an old age component that is expected to result from frequent, but predominantly low-severity fires (Abella et al. 2007). It is also apparent that two types of forest conversion resulted from this fire regime. First, the extent of aggressive tree encroachment that has occurred in some open woodland Douglas-fir patches and intermingled grasslands suggests that a substantial portion of the landscape that could support forest had been converted to perennial grassland as a result of this fire-driven cumulative mortality. Second, within several post-high-severity even-aged sample patches of DMC-PSME and MMC, we encountered large, thick-barked, charred, heavily rotted, Douglas-fir logs and standing dead trees that resembled the clusters and scattered old individuals of intact stands (Fig. 14) in terms of their apparent ages and spatial distribution. We interpret these cases as indirect, but convincing, evidence of a second type of fire-driven forest conversion from older, previously fire-maintained Douglas-fir-dominated stands to dense regenerating stands of mixed-species composition.

Considering the larger landscape setting of the Foothills (Fig. 14), Douglas-fir patches were intermixed with less fire-resistant cover types of lodgepole pine and dry- and mixed-moist conifer forests that experienced much higher average severity (Table 1), a more even mix of structural complexities, and younger stand ages (Fig. 12). This intermixing appears to be at least partially driven by the rolling topography and, in particular, subtle changes in aspect between cooler and drier expositions and potentially also the influence of previous high severity fire, as discussed above. The effect and importance of this spatial arrangement of cover types is evidenced by the greater mean and variation of fire severity in PHN compared to the other two study areas (OME, OMN) in the Douglas-fir zone (Fig. 9c), despite the similarity of the fire regime and age structural features of Douglas-fir patches within them (Table 1). Viewing the fire regime of the Douglas-fir zone at both of these scales reveals important temporal and spatial mixed-severity components that jointly shaped the landscape.

6. Next Steps

6.1 Fire-Fire Interactions: Self-Regulating Feedbacks Between Fire Frequency, Severity and Biophysical Factors

A unique opportunity afforded by the multi-proxy fire regime dataset we have compiled is to quantitatively evaluate the strength, duration, and conditionality of feedbacks between fire severity and frequency to other influences on fire (e.g. climate, topography). Modeling of fire regime feedbacks provide a fundamental mechanistic framework that can inform predictive capacity under future climate-driven and management-related scenarios and has led to important insights in studies of modern fire regimes (Parks et al. 2014, 2018, Harvey et al. 2016). This type of analysis has not been possible previously due to time constraints. We are developing a statistical framework to evaluate these feedbacks using nested marked Poisson point process models (Illian et al. 2008) to determine the duration and strength of self-regulating feedbacks between fire occurrence and severity, in relation to conditioning topographic and climate variables. One planned outcome of this work is to utilize the models of these feedbacks as a primary calibration tool for the partial mortality simulation model. Model calibration of these fundamental mechanistic fire regime relationships using our empirical data is a novel approach that can complement pattern-matching calibration (e.g. similarity of fire frequency, age structure). This work is one of the fundamental linkages under development between the Fire Regime and Modeling portions of the LIM project.

6.2 Gradient Modeling Threshold Behaviors to Frequent Fire

An emerging literature (Westerling et al. 2011, Turner et al. 2019) has begun to question the resilience of lodgepole pine forests and other forests dominated by fire-sensitive species to climate-driven increases in fire frequency. The Foothills provide a unique opportunity to address these questions with empirical data. A gradient analysis of how fire severity, the fire regime more broadly, and landscape vegetation (structural and compositional) conditions respond to changes in fire frequency is planned using multiple datasets generated by this project. This work seeks to characterize multiple ecosystem responses to gradients in fire frequency and to identify critical fire frequency thresholds that can help predict future outcomes of different climate and management scenarios. Dendroecological data from this study will be combined with an already compiled and crossdated regional fire scar network (see below *Regional spatial model of fire frequency*) and maps of vegetation condition derived from historical photos (see below *Mapping historical vegetation conditions and spatial properties*) to evaluate gradient responses, identify tipping points, and quantify changes in the spatial patterning of fire severity, fire regimes, age structure complexity and vegetation conditions.

6.3 Mapping Historical Vegetation Conditions and Spatial Properties

Linkages between pattern and process are fundamental in ecology (Turner 1989) and serve as an important foundation for ecosystem-based management. Dendroecological analyses provide robust information on fire-driven ecological processes, but they afford more limited spatial inferences. To fill this gap and better understand the landscape conditions that emerged from the fire regime documented in this study, the objective of this work is to (1) produce a fine-scale map of vegetation composition and structural complexity using the orthomosaic of 1949-52 imagery and (2) quantify the spatial patterning (e.g. patch sizes, interspersion, diversity) of vegetation along geographic and biophysical gradients (e.g. elevation). Vector-based vegetation maps of canopy cover, structural complexity, and compositional types similar to those used in this study (e.g. lodgepole pine, aspen, Douglas-fir, spruce-fir), will be generated using an object-based analysis (Blaschke et al. 2014) framework and supervised machine learning. Results from this analysis will provide spatially and geographically specific information on historical vegetation characteristics, spatial patterns and changes along key biophysical gradients.

6.4 Regional Spatial Model of Fire Frequency

The collective body of fire history work that has been accomplished in the Foothills to date (van Wagner et al 2006, Johnson & Larsen 1991, Rogeau et al. 2016, White 1985) has documented significant spatial variation and gradients in fire frequency. However, because many of these studies were relatively small-scale and used different methods, there is still limited understanding of the geographic and spatial patterns of fire frequency for the Foothills and its key drivers. A spatially explicit regional fire frequency model would help to address this knowledge gap and would facilitate larger landscape analyses, where dendroecological data are lacking, but that require fire frequency estimates. There is a prime opportunity to conduct a synthesis of fire history data produced in multiple recent, published and unpublished, studies, and develop a spatially explicit regional fire frequency model for the Foothills. As part of the Fire Regime component of LIM, we compiled, processed, measured and crossdated fire scars from two other researchers, M-P Rogeau and S. Jevons (Fire Ecologist, Alberta Environment and Parks) and combined them with fire scars records from this project. The resulting fire scar network consists of over 1,000 crossdated samples that are spatially distributed throughout the Foothills region and cover a wide range of biophysical gradients. Our goal is to use gradient boosted models to quantify the drivers of median fire frequency and its variability that can be used to construct regional predictive maps of fire frequency.

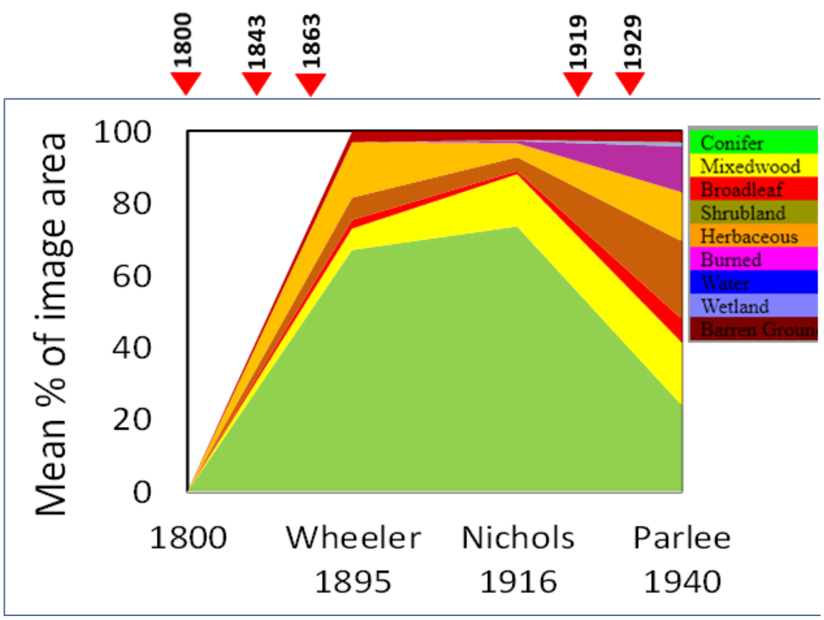

Figure 15. Graph of the landscape vegetation change documented in three surveys conducted in 1895, 1916, and 1940 in relation to fire year perimeters reconstructed using dendroecological methods. A clear successional progression is clear between 1895 and 1916, when no major fire years occurred within the image area, followed by large scale vegetation cover change following the short interval 1919 and 1929 fires.

6.5 Fire-Induced Landscape Vegetation Shifts

Combination of our spatially distributed fire history records and the Mountain Legacy Project images presents a unique opportunity to document fire-caused transitions in landscape vegetation. By definition, high severity fire destroys most evidence of the pre-fire vegetation condition. This is a major limitation to dendroecological reconstructions of fire severity and vegetation conditions. However, for portions of our study region, MLP imagery exists for two or three surveys, often separated by 10-30 years. In many cases, these surveys bracket one or more fire events. By combining reconstructed fire perimeters with vegetation reconstructions in each survey, we can determine the pre- and post-fire landscape condition and, even for high severity fires, evaluate the types and rates of fire-driven vegetation transitions. This is a rare opportunity to document vegetation transitions and their potential drivers (e.g. annual reconstructed drought, fire size, topographic variables). As a proof of concept, we have worked with the MLP program to select 20 image pairs or triplets in the Sheep River Provincial Park from three survey dates (Parlee 1940, Nichols 1916, Wheeler 1897) where fire history reconstructions documented fires in 1800, 1843, 1863, 1919, 1929. Clear relationships in vegetation succession and abrupt change following fires are visible (Fig. 15). Next steps for this work could include scaling up of the analysis shown in Fig. 15 to all 20 image pairs (or more) and development of a statistical framework to estimate the nature and rates of vegetation transitions for different fire events in the study region.

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