AN ABSTRACT OF THE THESIS OF

Kayla M. Johnston for the degree of Master of Science in Sustainable Forest Management presented on June 11, 2018.

Title: The Past, Present, and Future of Fire and Ponderosa Pine Stand Dynamics in the Metolius Research Natural Area, Central Oregon.

Abstract approved:

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John D. Bailey

The Metolius Research Natural Area (RNA), located 29 km northwest of Sisters, Oregon, was originally established in 1931 to maintain a ponderosa pine (*Pinus ponderosa* Dougl. Ex Laws) and dry, mixed-conifer forest with the aim to meet objectives of preserving natural conditions, providing for research opportunities, and preserving gene pools of certain plants and animals via intact natural disturbance processes. Historically, frequent fire was a keystone natural disturbance in central Oregon and the Metolius RNA. However, with European settlement in the late 1800s and the creation of the US Forest Service in the early 1900s came organized wildland fire suppression efforts. These efforts have been highly effective at excluding fire from the landscape for over a century. Fire-deficit has been shown to cause a variety of stand alterations for actively managed forests including shifts in density, structure, composition, and fuel loading that can be detrimental to the resistance, resilience, and overall function of the stand. Since the Metolius RNA is part of a landscape where fires historically were expansive and returned frequently we assumed that the Metolius RNA also burned frequently and that fire was a keystone disturbance process here prior to European settlement. Further, we questioned if stand conditions were truly natural despite a fire deficit of more than a century. We sought to validate our assumption and quantify current versus historical stand conditions via reconstructing historical fire frequency and historical stand conditions using dendrochronology methods for a 4.5ha permanent research plot. We also discuss the future of the Metolius RNA with population growth rates from 1981-2016 and modeled fire behavior and tree mortality and compare the fuel loading and modeled fire behavior and mortality to a representative, established fuel model, Scott & Burgan TL8 (2005). We found that fire returned to the plot on average every 9.5 years from 1613-1898, and that stand characteristics have greatly deviated from estimated 1898 conditions. Further, with the population growth rates from 1981-2016 and the model fire behavior and mortality, we suggest that the stand is in decline and at risk of high-severity disturbance. If meeting the objectives of the Metolius RNA and minimizing risk to high-severity disturbances is desired, we suggest one-time mechanical treatment followed by repeated prescribed fire to restore natural conditions and intact natural disturbance processes.

The Past, Present, and Future of Fire and Ponderosa Pine Stand Dynamics in the Metolius Research Natural Area, Central Oregon

by
Kayla M. Johnston

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Kayla M. Johnston, Author

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CHAPTER 1 – BACKGROUND

Fire History

East of the Cascade Crest, Oregon receives an abundance of dry lightning storms annually resulting in numerous wildfire ignitions. Human activity also creates a considerable number of wildfire ignitions in any given year. Through fire suppression efforts, most of these ignitions are contained small, between single tree and stand sized. When modern wildfires do burn large expanses, they tend to burn with large patches of high-severity (Reilly et al. 2017). Contrasting, historical wildfire ignitions (lightning or Native American activity) were more likely to burn large expanses when there were few natural barriers to stifle fire spread and primarily burned at low-moderate severity across the landscape and forest types (Merschel et al. 2018, Johnston et al. 2016).

Of eastern Oregon forest types, pure ponderosa pine (Pinus ponderosa) stands historically tended to have had the smallest fire return intervals. In the southern Blue Mountains of the Malheur National Forest, Johnston et al. (2016) found intervals of 10.6 – 14.9 years on average for their pure ponderosa pine stands. In a 30,000-ha study area in the Deschutes National Forest, Merschel et al. (2018) found intervals of 15-25 years. In dry-to-moist ponderosa pine stands in the Deschutes, Bork (1984) found intervals of 4 – 24 years on average.

Historical frequent fire in persistent ponderosa pine forests maintained and required adequate fuel loading to carry fire but low enough loading not to cause high-severity in mature trees. Fuels primarily would have consisted of grasses, pine needle litter, bark slough, and a minor component of shrubs. Grasses would have been dominant in the understory, much more so than is commonly seen today, as frequent fire favors grass systems. Grasses burn hot and quick and so would have been unlikely to contribute to mortality of mature trees but would have been sufficient to cull seedlings and possibly saplings. Grasses also tend to recover very quickly post-wildfire and so would have been able to consistently provide fuel for frequent fire.

The contribution of pine needle litter and bark slough was also likely to be critically important to fire spread, and especially to creating the scars in trees necessary for dendrochronological fire history reconstructions. Pine litter and bark slough tend to build up at the base of ponderosa pine trees, creating a thick layer of surface and ground fuels that would support a long flaming and smoldering residence time necessary to scar a mature tree with thick bark. However, too much accumulation at the base of a tree would likely contribute to mortality of even a mature tree.

Historical frequent fire also maintained ponderosa pine stands with generally lower-density and wider spacing between trees (Merschel et al. 2018, Johnston et al. 2017, Youngblood et al. 2004, Morrow 1985). Frequent fire would have killed most small trees and left most large trees, partially because of the fuel loading mentioned previously but also because of how the stand structure contributes to fire behavior. With low stand density, wide spacing, and few small trees it would be difficult for a fire to transition into the canopy, especially since ponderosa pine self-prunes its lower branches.

Eastern Oregon continues to receive an abundance of both lightning and human ignited wildfires annually. In 2017, Oregon and Washington had 3,404 wildfires (1,254 lightning, 2,150 human) (NIFC, 2018). Though there are still an abundance of ignitions that would support landscape-scale fire, organized fire suppression has been highly effective at containing most fires small throughout its tenure. Fire has effectively been reduced from a landscape-scale process to a much smaller scale process, commonly forest stand or smaller. Therefore, much of the forest lands have a fire-deficit – missing all or several fire events over the past century compared to historical regimes. Such a fire-deficit can wreak havoc for fire-dependent forests such as ponderosa pine.

Ponderosa Pine Forest Fire Ecology

Ponderosa pine trees are fairly fire-resistant and ponderosa pine stands are arguably fire-dependent. Ponderosa pine develop thick, cambium-insolating bark at a small size and so are generally able to resist fire-induced mortality from a small size. This typically means only the smallest trees would be culled off by frequent mild fire. Ponderosa pine is also moderately drought, insect, and disease-resistant, however, the species is not a great competitor. Its poor ability to compete and strong fire-resistance are essentially why a ponderosa pine stand is dependent on frequent fire return intervals. Other tree species that would survive where ponderosa pine tend to establish are generally significantly less fire-tolerant. Because of the fire-intolerance of the alternative species, the frequent fire maintains ponderosa pine stands as predominantly ponderosa pine by eliminating the competing tree species. However, in the absence of fire, other tree species tend to invade ponderosa pine stands and out compete ponderosa pine.

Though, despite the absence of fire, some ponderosa pine stands have stayed predominantly ponderosa pine. However, the absence of fire has created other issues (that the invaded stands also have) like increased stand density, increased fuel loading, and stand conditions favorable to insect and disease outbreaks. These stand conditions also likely contribute to increased drought- and fire-induced mortality.

A high-severity fire event would be devastating to a ponderosa pine stand as ponderosa pine is a climax species and thus is poor at fire-resilience. Ponderosa pine regeneration happens typically through seed rain from parent trees large enough to produce a good cone crop. The best cone crops come from trees >50 cm DBH and seedling density essentially disappears after 250 m distance from the parent tree. So if a ponderosa pine stand experiences a high-severity fire, it may be unlikely to recover very quickly, or at all, back to a ponderosa pine forest type. So ponderosa pine forests also need frequent mild fire to reduce fuel loads and maintain lower stand density to mitigate risk of a high severity fire which they would poorly respond to.

Restoring Fire Processes and Creating Stand Conditions for the Future

Managers often attempt to mitigate against the effects of fire-deficit and provide a surrogate for wildfire via mechanical thinning and prescribed fire implementation. These restoration efforts are being utilized across the western US (Hessburg et al. 2016). However, these efforts primarily take place in forests that have been logged or extensively grazed before, which is also where nearly all of the research on these issues takes place. Yet, since fire has been removed as a landscape scale process then the whole landscape must be experiencing fire-deficit and should be evaluated and considered for restoration, including places like research natural areas.

Research natural areas are managed for intact natural processes and minimizing human impacts in order to meet the objectives of having intact natural conditions, preserving gene pools, and providing for research opportunities. However, following the logic of my previous statements, it is unlikely that a research natural area within a fire-prone landscape would have intact natural processes or conditions. Yet, research natural areas are considered intact and natural unless proven otherwise in regards to priority or need for restoration. Therefore, studies should be conducted examining fire history and effects of fire-deficit for research natural areas in fire prone landscapes, if evaluating and meeting objectives is desired.

This study examined fire history and effects of fire-deficit for a ponderosa pine stand in the Metolius Research Natural Area, located 29 km northwest of Sisters, Oregon in a fire prone landscape. In order to evaluate if the study site had intact natural processes, I used dendrochronological methods to estimate historical fire frequency. In order to evaluate if the study site was in natural condition, I reconstructed historical stand dynamics using a subset of tree cores and a stem map and monitoring data from 1981 – 2016. In order to evaluate future resistance to wildfire, I estimated how the stand would handle a wildfire using computer modeling programs.

CHAPTER 2 – FIRE HISTORY AND THE EFFECTS OF FIRE EXCLUSION IN THE METOLIUS RESEARCH NATURAL AREA, CENTRAL OREGON

Introduction

Central Oregon historically experienced frequent, large fires primarily burning with low-severity and maintaining forest stand density, structure, and function (Johnston 2017, Rodman et al. 2017, Johnston et al. 2016, Abella et al. 2015, Merschel et al. 2014, Hagmann et al. 2013, Taylor 2010). These fires often ignited and spread to ultimately burn large expanses (Merschel et al. 2018, Rorig and Ferguson 1999), as there would have been few natural impediments to fire spread and likely limited anthropogenic fire suppression efforts. These historic fires would have only gone out when they either ran out of fuel or when unfavorable weather conditions occurred. This basic concept of fire spread partially explains how large-extents of fire-prone landscapes historically burned frequently, likely in few large fires not many small fires. This historical frequent fire regime allowed central Oregon's ponderosa pine (*Pinus ponderosa* Dougl. Ex Laws) and mixed-conifer forests to be functionally resistant to fire by limiting the build-up and continuity of vertical and horizontal fuels (regeneration, understory vegetation, and litter fall) (Rodman et al. 2017, Hagmann et al. 2013, Taylor 2010, Everett et al. 2008, Perry et al. 2004, Hessburg and Agee 2003, Covington and Moore 1994).

However, organized fire suppression efforts began in the early 1900s and have been highly efficient at containing most fires small. This has changed fire from a landscape-scale process in central Oregon to a small-scale process, most often occurring at the single tree-to-stand-scales. This shift in process scale for wildfires has created a fire-deficit for many forests, causing them to miss most or all fire intervals over the past century. Such a fire-deficit can cause destructive shifts in stand density, structure, composition, and function. It would also be a violation of management plan for forests such as those in Research Natural Areas (RNA) that require intact natural disturbance processes.

RNAs are parcels managed for natural conditions via allowing natural physical and biological processes to dominate without human intervention (Federal Committee on Ecological Reserves 1977). These parcels aim to meet objectives to preserve natural ecosystems, provide for research opportunities, and preserve gene pools of certain plants and animals (Greene et al. 1986). However, meeting objectives without human intervention can become complicated when the RNA is set within a fire-prone landscape where, historically, fires grew very large and modern fire suppression activities virtually exclude fire from the RNA. Luckily, human intervention via prescribed fire is allowed by RNA guidelines in instances where an ecosystem was historically maintained by fire. However, due to constraints such as budget, weather, smoke intrusions, and personnel, it can be difficult for a management district to adequately provide for an RNA in need of fire when wildland-urban-interface and other fuel reduction treatments are prioritized.

As part of the central Oregon fire-prone landscape, the Metolius RNA, 29km northwest of Sisters, Oregon (Figure 1), was theoretically groomed by frequent fire prior to European settlement. This assumption would lead us to believe that management of the Metolius RNA, which does not currently include regularly implemented prescribed fire, is not supporting intact natural disturbance processes. We evaluate that assumption for a permanent research plot dominated by ponderosa pine (*Pinus ponderosa* Dougl. Ex Laws) by quantifying the historical fire frequency using dendrochronology methods. We also estimate current fuel loading, and model wildfire behavior and associated mortality for the same permanent research plot in the Metolius RNA to examine how a “natural condition” forest would handle a future wildfire disturbance after missing several natural, low-severity fire disturbances. Further, we compare fuel loading, fire behavior, and mortality with Scott & Burgan fuel model TL8 (2005) to assess inconsistencies in modeling fire behavior and mortality because of fire exclusion effects.

If the Metolius RNA truly has a fire-deficit, we also would expect to observe the effects of fire exclusion. Prescribed fire has been implemented on three, approximately 5-ha, permanent study plots but a majority of the RNA has never been treated with prescribed fire. This raises the question of if the Metolius RNA is truly in natural condition despite over a century of fire-deficit. Specifically, we investigate changes in stand structure, composition and spatial pattern from 1898 to 1981 to 2016 in a ponderosa pine (*Pinus ponderosa* Dougl. Ex Laws) dominated permanent research plot. Characteristics of the stand in 1898 were reconstructed using a subset of live tree cores and dendrochronology methods. We use these findings to discuss what the future of the permanent plot may entail and suggest thinning and frequent implementation of prescribed fire to restore natural conditions to improve potential response to climate change and a future of erratic disturbance events.

Excluding fire from fire-maintained forests alters stand structure via densification, mesophication, and fuel abundance and fuel continuity (Johnston 2017, Rodman et al. 2017, Johnston et al. 2016, Brown et al. 2015, Stephens et al. 2015, Hagmann et al. 2014, Merschel et al. 2014, Hagmann et al. 2013, Taylor 2010, Spies et al. 2006, Moore et al. 2004, Hessburg et al.

1999, Camp 1999). Those effects impact ecosystem functions such as water cycling, nutrient cycling, wildlife habitat value, and recreation and aesthetic value (DeLuca et al. 2006, Reich et al. 2001, Tilman et al. 2000, Neary et al. 1999). Ultimately, all those repercussions decrease resistance and resilience to disturbances such as drought, insects, diseases, and wildfire (McDowell et al. 2016, Vose et al. 2016, Taylor et al. 2014, Reynolds et al. 2013, Williams et al. 2013, Kitzberger et al. 2012, Allen et al. 2010, Miller et al. 2009, Savage and Mast 2005, Kolb et al. 1998, Larsson et al. 1983, Sartwell and Stevens 1975). It is logical that these effects must also be occurring in RNAs despite being “managed to reflect natural condition” as they are still experiencing fire exclusion. If an RNA is experiencing the effects of fire exclusion, we expect that it will eventually reach the same fate as other forests lost to fire, drought, insects, and disease (McDowell et al. 2016, Vose et al. 2016, Taylor et al. 2014, Williams et al. 2013, Kitzberger et al. 2012, Allen et al. 2010, Miller et al. 2009, Spies et al. 2006, Savage and Mast 2005, Kolb et al. 1998, Larsson et al. 1983, Sartwell and Stevens 1975).

Decreased resistance and resilience to fire may be the most notable change as dead trees accumulate on the landscape, forests covert to shrub dominated ecosystems, and managers and researchers struggle to understand and quantify the impacts of compound disturbances (McDowell et al. 2016, Vose et al. 2016, Keane et al. 2015, Taylor et al. 2014, Reynolds et al. 2013, Williams et al. 2013, Kitzberger et al. 2012, Allen et al. 2010, McHugh et al. 2003). This phenomenon should be of particular concern in forests managed for minimal human impacts and intact structure and function, such as RNAs, as they theoretically contribute disproportional value to the landscape by being in a natural, and theoretically high functioning, condition.

Management efforts for fire-prone and fire-dependent natural condition forests should aim to mitigate effects of fire exclusion and maximize resistance and resilience to fire if it is desired to maintain natural condition forests on the landscape. Specific strategies for these efforts would likely include prescribed fire since it would be the least invasive, cheapest, and most ecologically based method to reduce fuels and restore structure to a fire resistant or resilient state. However, it would be important to understand the historical role and frequency of fire in a defined area before implementing a prescribed fire regime, as we do below for the Metolius RNA.

The Metolius RNA was originally established in 1931 with the primary objectives to support an example of ponderosa pine and mixed conifer forest in natural condition while providing research opportunities and preserving a gene pool for certain plant and animal species. The primary management strategy for accomplishing these objectives is intact natural disturbance processes (Greene et al. 1986). However, as explained above, the Metolius RNA has over a century of fire deficit – a conflict with the management plan that potentially places the area in a precarious position when inevitably confronted by a wildfire. Mechanical fuel reduction treatments are heavily restricted in the Metolius RNA, limiting manager's abilities to minimize the effects of fire suppression. A new management plan could be drafted for the restoration of the Metolius RNA to maximize resistance and resilience to wildfire, which would ideally have a major component of prescribed fire and require a solid database of the historical role of fire in the Metolius RNA.

Understanding changes or reactions to fire exclusion from an area managed to reflect natural conditions is critical to managers so that they can adapt their management to reflect best available science and protect and serve their forest. This information may also be useful in application to areas historically managed for other objectives that managers seek to restore to reflect natural conditions. In a somewhat broader scope, having a better understanding of the effects of fire exclusion for a forest otherwise unaltered may help us to understand mechanisms affecting wildlife populations, particularly those in decline. Foremost, this information is critical if meeting current RNA objectives is desired as restoration objectives would require an understanding of what “natural conditions” meant for any particular stand or forest.

Restoring to historical, natural conditions would likely be beneficial to mitigating against climate change and associated erratic disturbances (Reynolds et al. 2013). Historically, natural conditions in a frequent fire-prone forest typically meant relatively low stand density and more proportional distribution of trees by DBH class (Johnston 2017, Rodman et al. 2017, Johnston et al. 2016, Abella et al. 2015, Brown et al. 2015, Stephens et al. 2015, Hagmann et al. 2014, Merschel et al. 2014, Hagmann et al. 2013, Taylor 2010, Moore et al. 2004, Camp 1999, Hessburg et al. 1999). Lower stand densities have been associated with increased resistance to insect and disease outbreaks (Reynolds et al. 2013, Kolb et al. 1998, Larsson et al. 1983, Sartwell and Stevens 1975). Lower stand density also means less competition stress, and, thus, healthier individuals with theoretically greater ability to stave off insects, disease, and to resist succumbing to drought (McDowell et al. 2016, Vose et al. 2016, Reynolds et al. 2013, Williams et al. 2013, Allen et al. 2010, Kolb et al. 1998, Larsson et al. 1983, Sartwell and Stevens 1975).

Lower density forests with less vertical canopy continuity are also more resistant to wildfire (Taylor et al. 2014, Kitzberger et al. 2012, Miller et al. 2009, Savage and Mast 2005).

Restoring to historical, natural conditions would likely increase stand resistance and resilience to disturbances compared to fire exclusion caused stand conditions. However, since projected future climate conditions may be more adverse than historical climate, historical stand conditions may not be sufficient in dealing with future climate change and disturbances. Therefore, species and associated life strategies should be considered when resistance and resilience to future climate and disturbances is a main objective. We conclude this chapter with management suggestions for restoring to historical, natural conditions on par with the RNA management objectives that would likely improve stand resistance and resilience to climate change and disturbances, but more research should be done if it is desired to maximize resistance and resilience to climate change and disturbances.

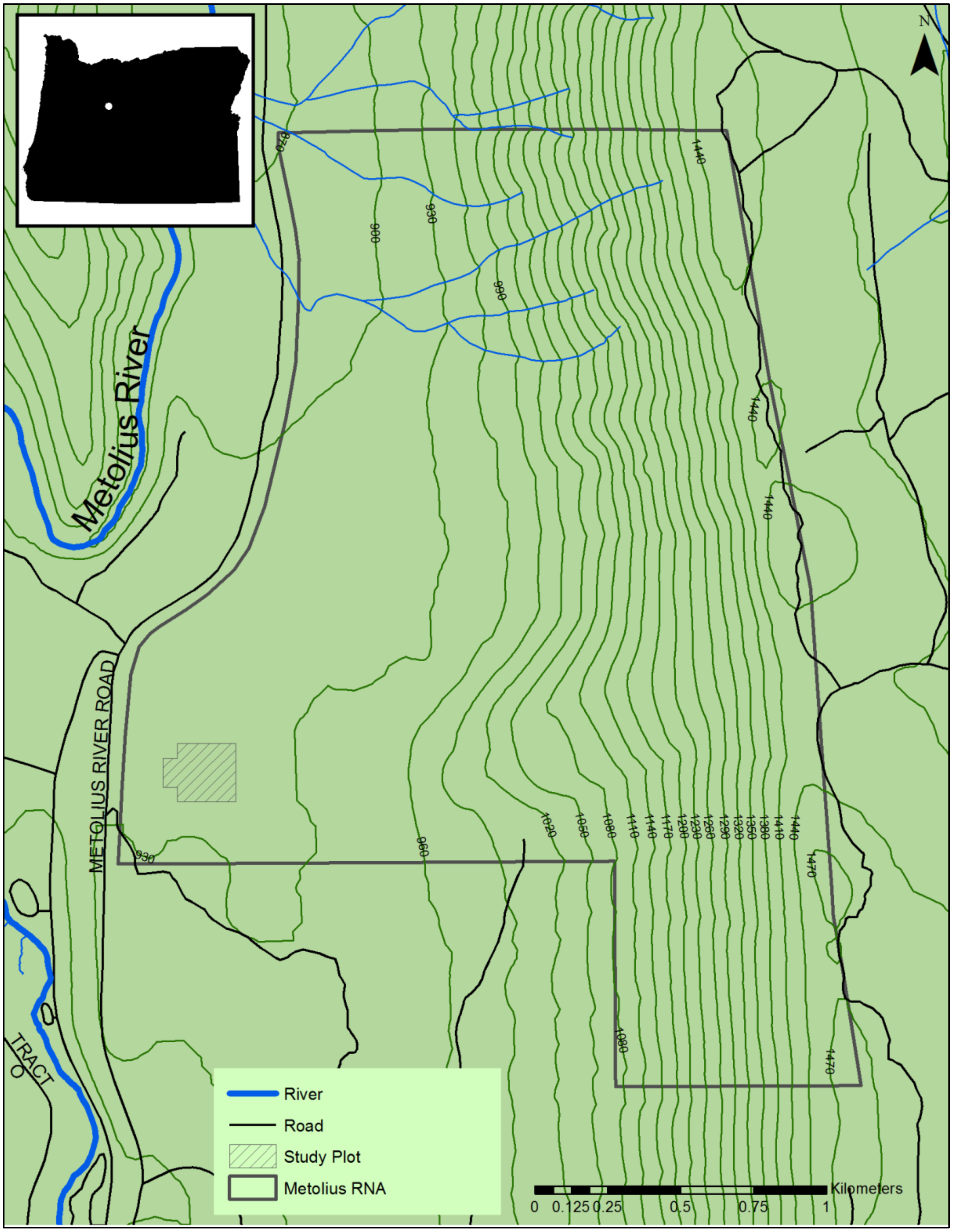

Figure 1. Map of the Metolius Research Natural Area (581 ha) with location of study plot (4.5 ha), inset location in Oregon.

Methods

Metolius Research Natural Area

The Metolius RNA is managed by the US Forest Service Sisters Ranger District as part of the Deschutes National Forest. It covers 581 ha, the western half being a relatively flat bench and the eastern half being the steep, west slope of Green Ridge (Figure 1). The flat bench is dominated by ponderosa pine, while the Green Ridge slope is primarily mixed-conifer with ponderosa pine, Douglas-fir (*Psuedotsuga menziesii*), grand fir (*Abies grandis*), incense cedar (*Calocedrus decurrens*), and western larch (*Larix occidentalis*). The shrub and herbaceous components are primarily comprised of bitterbrush (*Purshia tridentata*), western needle grass (*Achnatherum occidentale*), bottlebrush squirreltail (*Elymus elymoides*), and Ross' sedge (*Carex rossii*). The soils are of basalt and basaltic andesite parent material and the entire area is covered by a 2-5 cm layer of dacite pumice, and up to 7 cm of basaltic ash (Hall 1972). The area experiences a modified continental climate with most precipitation (mean annual ~ 41-66 cm) falling as snow during a cool winter with warm, generally dry summers (Hall 1972).

The only major land use change the Metolius RNA has experienced since European settlement is fire exclusion. The RNA has never been logged or otherwise mechanically altered. It was potentially grazed prior to its establishment date in 1931, but we expect this would have had little impact on fire spread and return intervals as there would have still been plenty of pine litter to support frequent fire.

The specific study site for this research is a 4.5-ha permanent plot on the flat bench of the Metolius RNA at an elevation of 920 m (Figure 1). This plot is primarily composed of ponderosa pine with few Douglas-fir, grand fir, incense cedar, and western larch, and an understory dominated by bitterbrush (*Purshia tridentata*). It is the unburned control plot in another study examining variable fire return intervals, and, as-such, we suggest it as representative of much of the rest of the Metolius RNA and other dry ponderosa pine stands in the region that have experienced a century of fire exclusion with no mitigation efforts.

Historical Fire Frequency

We surveyed the study plot for fire-scarred cross-sections to estimate historical fire frequency. Fire-scarred partial and whole cross-sections were removed from logs, snags, and stumps all around the outside of the plot but within 500m of the plot perimeter (Figure 2). Cross sections had to be taken from outside the plot to comply with restrictions of cutting within the plot and to not disrupt the other research projects taking place within the plot. Fire-scarred cross-section sampling was allowed to extend away from the plot by up to 500m as the local terrain is monotonous and pine litter creates continuous fuels allowing for the ease of fire spread (likely from any point across the plot). Fire-scarred cross-sections were analyzed visually and with a master tree ring chronology.

A master tree ring chronology is a collection of multi-century, tree-ring records derived from increment cores from live trees. Our increment cores came from 24 of the largest trees within the plot (n=20) and within 50m outside the plot (n=4). The cores were cross-dated and accuracy was verified with the computer program COFECHA (Grissino-Mayer 2001). This chronology was used to cross-date the fire scar cross sections in the same computer program. Once dated, the fire scarred cross-sections were visually analyzed to record fire years. All fire years were compiled to create a multi-century record of fire frequency. Our final historical fire frequency was reduced to the time period when we had multiple cross sections recording fires and contained only fires recorded on at least two cross sections.

Fuel Loading, Fire Behavior & Tree Mortality

Fuel loading was estimated via sixteen 15.24m transects (Brown 1974) in a systematic grid across the study plot. Fire behavior under August 2017 weather conditions was modeled using fuel loading data and Metolius Arm RAWS weather data for the computer model 'BehavePlus5' (Andrews, Bevins, and Seli 2008). Tree mortality was estimated with the computer model 'FOFEM 6.3.1' (Lutes & Keane 2016). Fuel loading for Scott & Burgan (2005) TL8 was also used in modeling fire behavior and tree mortality under the same weather conditions for comparison to a system with more desired fuel characteristics. Fuel loading, fire behavior, and tree mortality for TL8 was compared to those for the Metolius RNA data.

2016 Stand Data

The study site was originally stem mapped in 1981. All live and dead stems >10cm were geospatially mapped, species and DBH were recorded, and each tree was tagged with a specific ID number. A mortality check was done for the plot every year from 1981 – 1997 then again in 2001, 2006, 2011, and 2016. DBH was updated and ingrown trees were added to the database every five years from 1981-2016. We derived annual population growth rates by DBH class from this database of ingrowth and mortality records for 1981-2016. We also estimated seedling, sapling, and pole densities with nested transects in 2017. Seedlings were counted in 2-1 m x 200 m transects, and 2-1m x 250 m transects. Saplings were counted in 2-5 m x 200 m transects, and 2-5 m x 250 m transects. Poles were counted in 2-10 m x 200 m transects, and 2-10 m x 250 m transects. Transects were systematically spaced across the study plot.

Tree Core Sampling and Analysis

Increment cores were taken from 141 ponderosa pine individuals for estimating 1898 stand dynamics of the remaining trees in the study site. The year 1898 was used as a cut-off year because it was the last recorded fire in a fire history study done for this study site. The entire population of live trees (2167) within the study plot >10cm DBH were available to be selected for coring. Choosing trees for coring was done by randomly selecting individuals by DBH class, with efforts focused on trees <70 cm DBH. DBH of sampled trees ranged from 10-105.5 cm (Figure 3). Each tree was cored at a maximum height of 0.40 m above the litter layer (minimum = 0.04 m, average = 0.17 m). Height and canopy base height was measured with a standard clinometer. DBH was measured using standard methods.

Tree cores were mounted and sanded until rings could be clearly analyzed under a binocular microscope to assign years. Years were assigned to each ring via visual counts when possible and cross-correlation of measured ring-width series when necessary. Cross-correlation was done using a master tree ring chronology; a dense network of site specific, multi-century, tree-ring records developed from live-tree samples (Holmes 1983). Cores were measured using a manual 2-axis Acu-Gage video system and MeasureJ2X computer program and dates were verified with the computer program COFECHA (Grissino-Mayer 2001). The suggested dates that occurred multiple times and were associated with strong correlation coefficients (>0.40) were applied to the cores.

Reconstructing the Stand for the Year 1898

To determine ponderosa pine trees >10cm DBH present in 1898, a simple linear regression was used to estimate individual 1898 basal area (BA) from individual 1981 BA. The

1981 BA was calculated using standard methods. Growth from 1898-1981 was measured on tree cores with those rings (n = 77) using a manual 2-axis Acu-Gage video system and MeasureJ2X computer program. That growth was subtracted from 1981 DBH to estimate 1898 DBH and 1898 BA was calculated using standard methods. The 1981 BA predicted 1898 BA with adjusted R^2 = 0.89 (BA1898 = 0.708256(BA1981) – 0.080255). This equation was used to estimate 1898 BA, and sequentially calculate 1898 DBH, for the uncored trees that were present in the plot in 1981. Trees estimated to have DBH >10cm in 1898 were retained for comparison analysis with current stand density, structure, BA, and spatial pattern.

Spatial Statistics

Spatial pattern was analyzed with Ripley's K(r) function (Ripley 1976) in R 3.4.4 (R Core Team 2017) with the "spatstat" package (Baddeley et al. 2015). Ripley's K(r) is a reduced second moment function that compares expected points within a certain distance of a center point to the actual points within a certain distance of a center point. We created a 95% confidence envelope for the function with 99 Monte Carlo simulations. If the test statistic was beyond the upper envelope limit, the spatial pattern was judged to be clustered. If the test statistic was beyond the lower envelope limit, the spatial pattern was judged to be dispersed. If the test statistic was within the envelope, the spatial pattern was judged to be random.

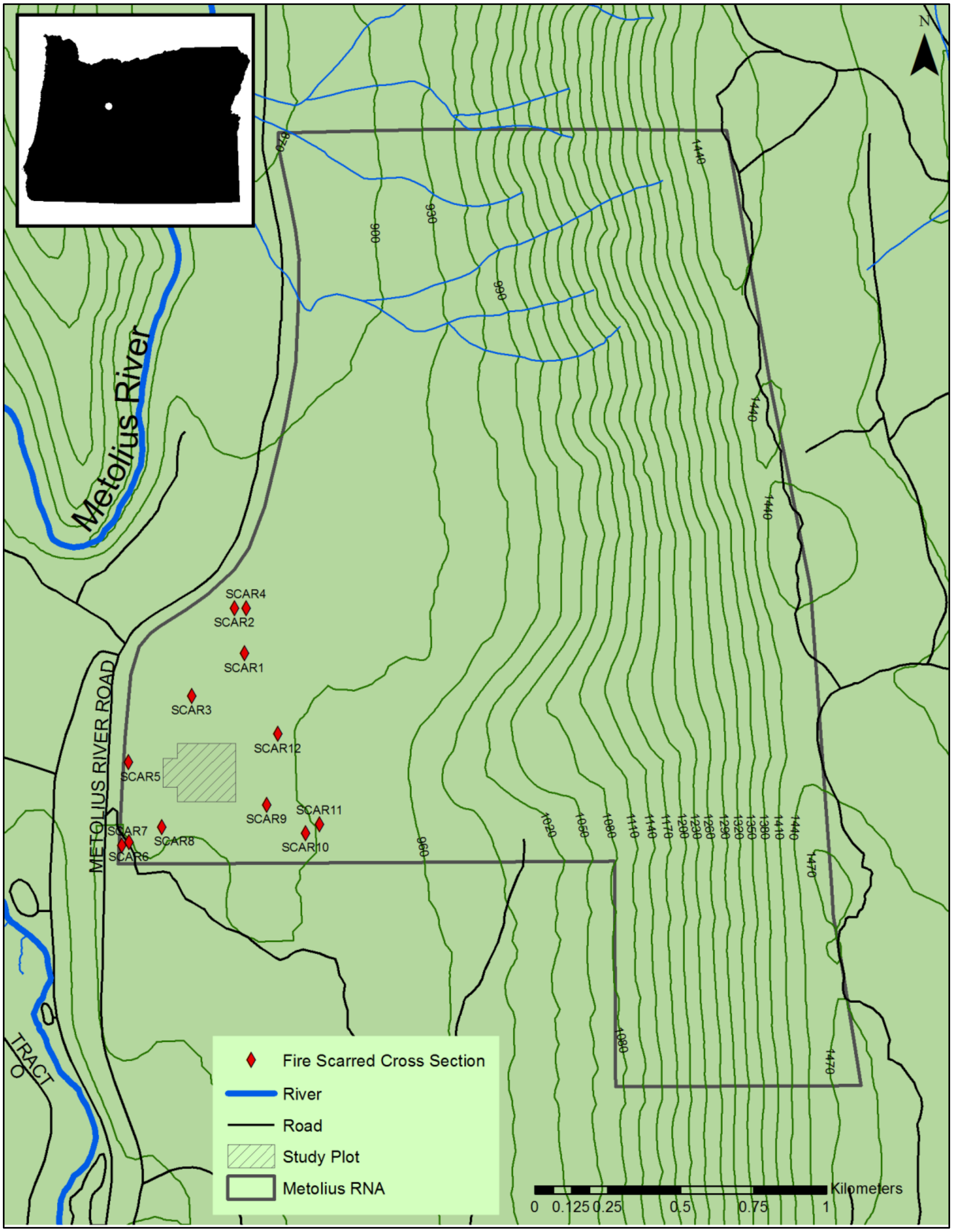

Figure 2. Map of the Metolius Research Natural Area with location of study plot and fire scarred cross sections, inset location in Oregon.

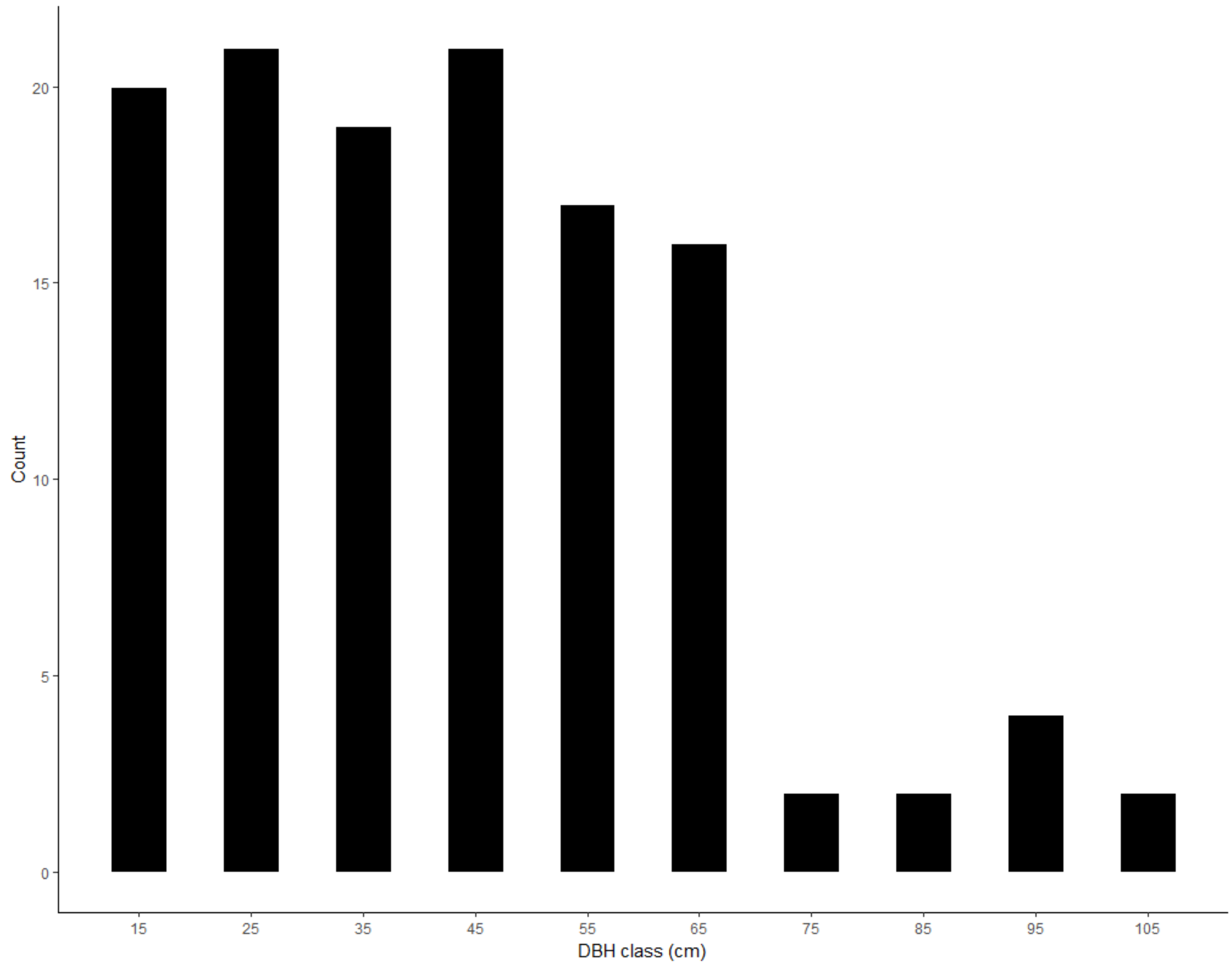

Figure 3. Histogram of cored trees by DBH class.

Results

Historical Fire Frequency

We found evidence of 56 fires from 1365-1898 CE (Figure 4). The final historical fire frequency record covered 1613-1898 CE during which there were 30 recorded fires with an average fire return interval of 9.5 years, standard deviation 3.96 (Figure 5). The minimum fire return interval was 3 years and the maximum fire return interval was 19 years.

Fuel Loading, Fire Behavior & Tree Mortality

Total estimated fuel loading was 116.63 tons per hectare. Excluding the 1000-HR fuels, fuel loading was 29.91 tons per hectare compared to 20.51 tons per hectare for TL8 (Table 1). Modeled rate of spread ranged from 0.11 – 7.71 km/hr for the Metolius RNA and 0.03 – 1.97 km/hr for TL8 (Table 2). Modeled flame length ranged from 1.6 – 12.8 m for the Metolius RNA and 0.5 – 4.0 m for TL8 (Table 2). Modeled total tree mortality was 50.21-79.46% for the Metolius RNA and 4.43-79.46% for TL8 (Table 3).

Stand Density, Basal Area, and Growth Rates

Density of trees >10cm DBH in 2016 (Figure 6) was 483 stems per hectare, a 52.4% increase from 1981 (Figure 7) and a 906.3% increase from the 1898 estimate (Table 4, Figure 8). Basal area of trees >10cm DBH in 2016 was 31.87 m^2h^{-1}, a 34.1% increase from 1981 and a 235.1% increase from the 1898 estimate (Table 4).

From 1981-2016, the study plot had a net population growth of 1.22% per year (Table 4). The population growth of small trees (<30cm DBH) was 1.28% per year. The population growth of large trees (>50cm DBH) was -0.06% per year. In 2016, there was also a large quantity of regeneration (seedlings, saplings, and poles; Table 5).

Stand Structure & Spatial Patterns

Stand structure in 2016 and 1981 was skewed toward small diameter trees with median DBH of 17.2cm and 13.5cm respectively, contrasting with the 1898 estimate where 58% of trees were 30-60cm DBH and median DBH was 47.1cm (Figure 9).

According to the Ripley's K(r) function, spatial patterns in 2016, 1981, and 1898 were clustered at nearly all spatial scales (Figure 10). However, departure from a complete random pattern was relatively much greater for 2016 and 1981 than for the 1898 reconstruction.

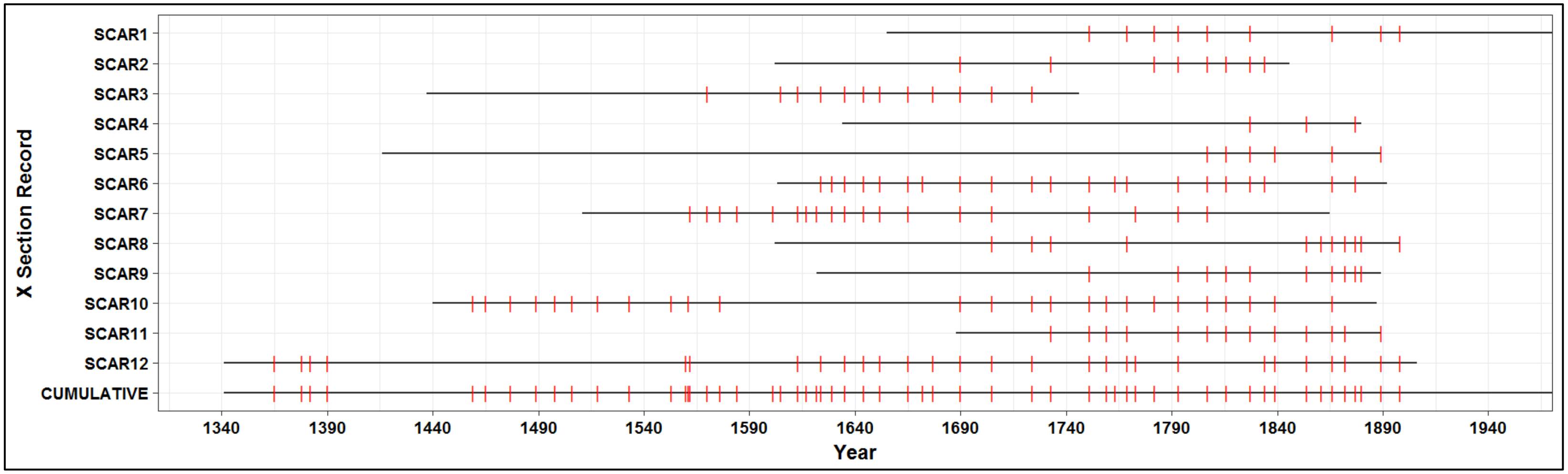

Figure 4. Complete fire history by sample for the study plot in the Metolius Research Natural Area, Oregon. Horizontal lines represent the measured lifespan of each sample. Vertical dashes represent a recorded fire. Samples recorded 56 fires from 1365-1898 CE.

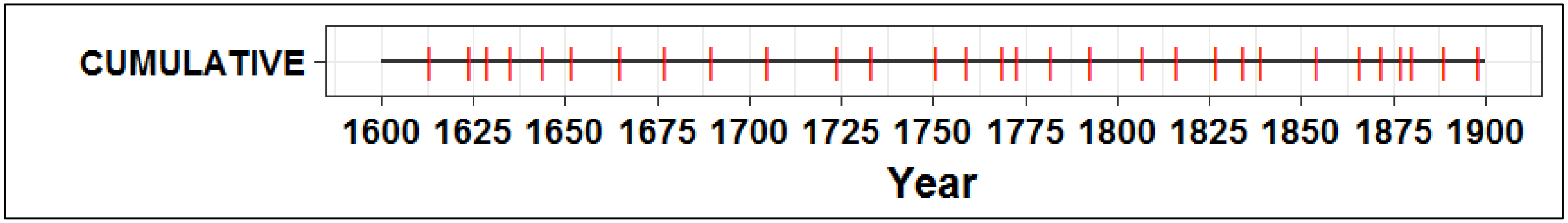

Figure 5. Final fire history (1613-1898 CE) recorded by two or more samples for the study plot in the Metolius Research Natural Area, Oregon. Vertical dashes represent a recorded fire. Average fire return interval was 9.5 years (SD = 3.95).

Table 1. Estimated fuel loading for the study plot, Metolius Research Natural Area, Oregon; compared to fuel loading for Scott & Burgan (2005) fuel model TL8. Fuel loading for the plot is similar to the "representative" fuel model, with the exception of 1-hr and live fuels.

Fuel Class	Metolius RNA (Tons/Ha)	Fuel Model TL8 (Tons/Ha)
1-HR	20.92	14.33
10-HR	2.13	3.46
100-HR	5.14	2.72
1000-HR	87.72	--
Live	1.72	0.00
Total (without 1000-HR)	29.91	20.51
Total (with 1000-HR)	116.63	--

Table 2. Expected fire behavior under extreme, average, and mild August weather conditions for the study plot, Metolius Research Natural Area, Oregon; and Scott & Burgan (2005) TL8 from the computer model BehavePlus 5.

Weather Conditions	Fuel Model	Rate of Spread (km/hr)	Flame length (m)
Extreme	Metolius RNA	0.78 – 7.71	4.5 – 12.8
	TL8	0.21 – 1.97	1.4 – 4.0
Average	Metolius RNA	0.21 – 1.54	2.2 – 5.4
	TL8	0.05 – 0.37	0.7 – 1.6
Mild	Metolius RNA	0.11 – 0.61	1.6 – 3.4
	TL8	0.03 – 0.14	0.5 – 1.0

Table 3. Estimated tree mortality from FOFEM under extreme, average, and mild August 2017 weather conditions for the study plot, Metolius Research Natural Area, Oregon.

DBH Class (cm)	2016 Density / BA	Fuel Model	Extreme Mortality (%)	Average Mortality (%)	Mild Mortality (%)
15	297 / 4.93	Metolius RNA	80	80	78.33 – 80
		TL8	37.5 – 80	5.83 – 78.33	5.83
25	107 / 4.82	Metolius RNA	79.07	79.07	6.98 – 79.07
		TL8	6.98 – 79.07	6.98	6.98
35	29 / 2.76	Metolius RNA	83.33	16.67 – 83.33	8.33 – 83.33
		TL8	8.33 – 83.33	8.33	8.33
45	9 / 1.36	Metolius RNA	75	0 – 75	0 – 75
		TL8	0 – 75	0	0
55	8 / 1.96	Metolius RNA	66.67	0 – 66.67	0 – 66.67
		TL8	0-66.67	0	0
65	9 / 3.01	Metolius RNA	75	0 – 75	0 – 75
		TL8	0 – 75	0	0
75	9 / 4.02	Metolius RNA	75	0 – 75	0 – 75
		TL8	0-75	0	0
85	7 / 3.7	Metolius RNA	66.67	0 – 66.67	0 – 66.67
		TL8	0 – 66.67	0	0
>95	7 / 5.29	Metolius RNA	66.67	0 – 66.67	0 – 66.67
		TL8	0 – 66.67	0	0
Total	482 / 31.85	Metolius RNA	79.46	63.07 – 79.46	50.21 – 79.46
		TL8	25.10 – 79.46	5.39 – 50.21	4.43

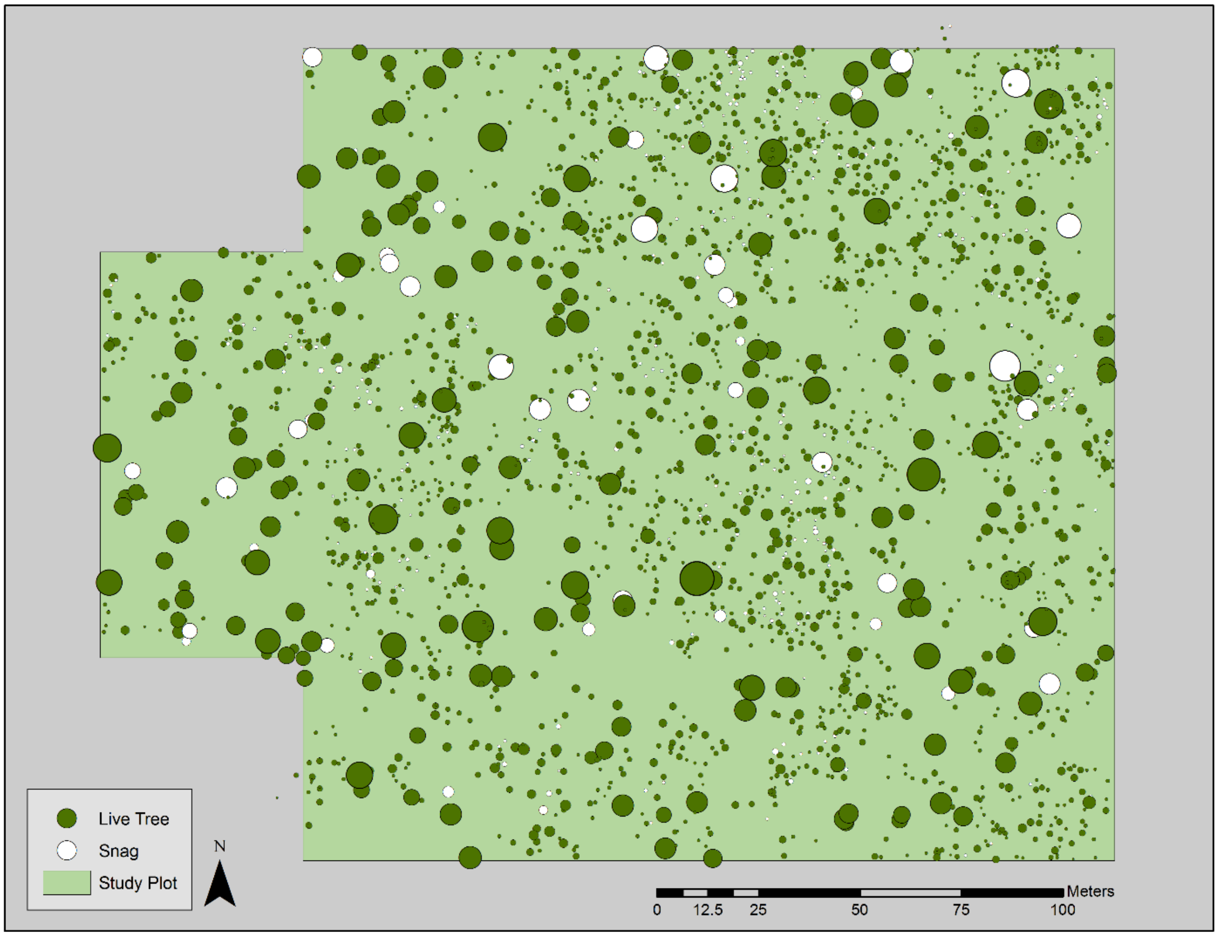

Figure 6. Stem map of all trees >10 cm DBH in the study site in 2016. Symbol size correlates to DBH (minimum = 9.8 cm, maximum = 125.7 cm). Density = 483 trees per hectare. Basal area = 31.87 sq. meters per hectare.

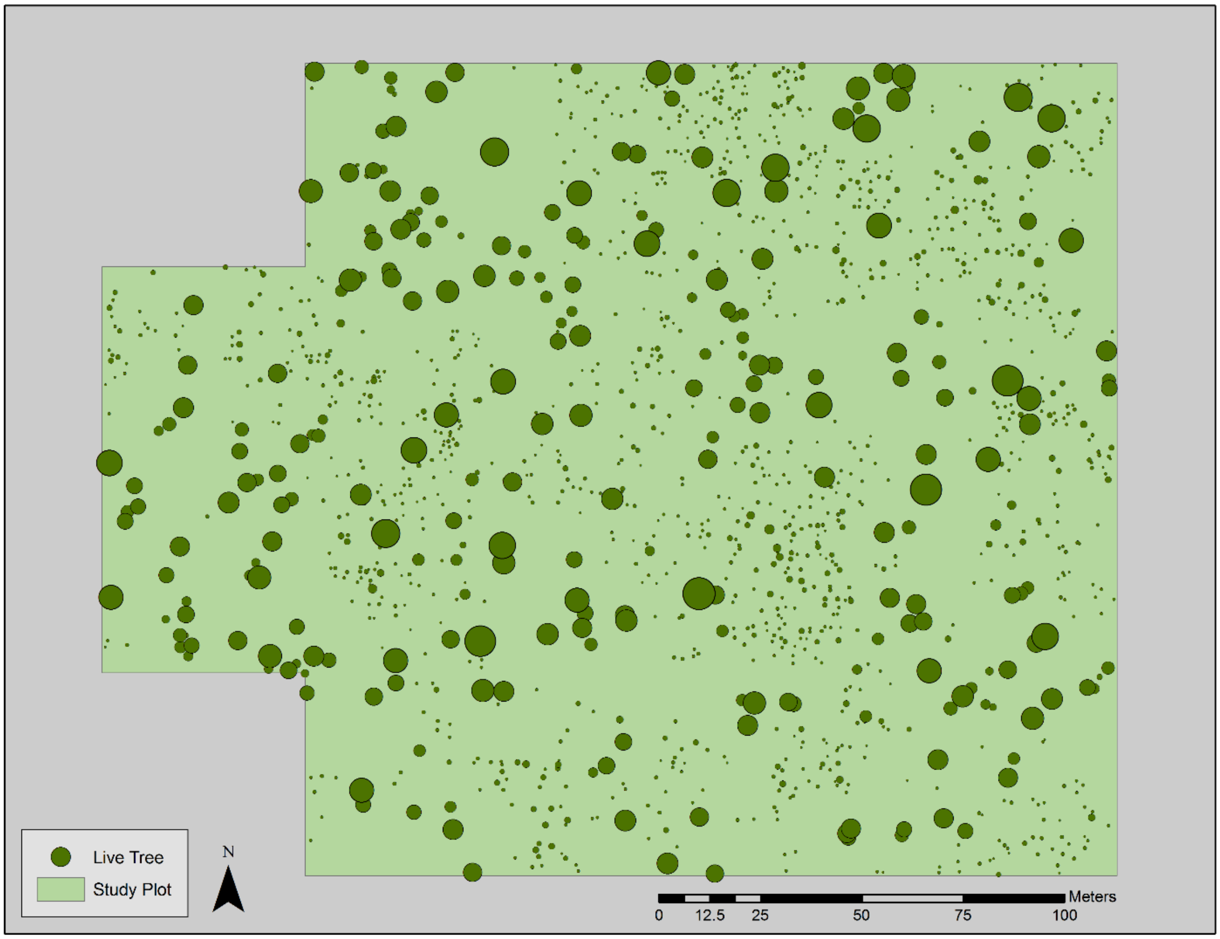

Figure 7. Stem map of all trees >10 cm DBH in the study site in 1981. Symbol size correlates to DBH (minimum = 9.8 cm, maximum = 120.5 cm). Density = 317 trees per hectare. Basal area = 23.77 sq. meters per hectare.

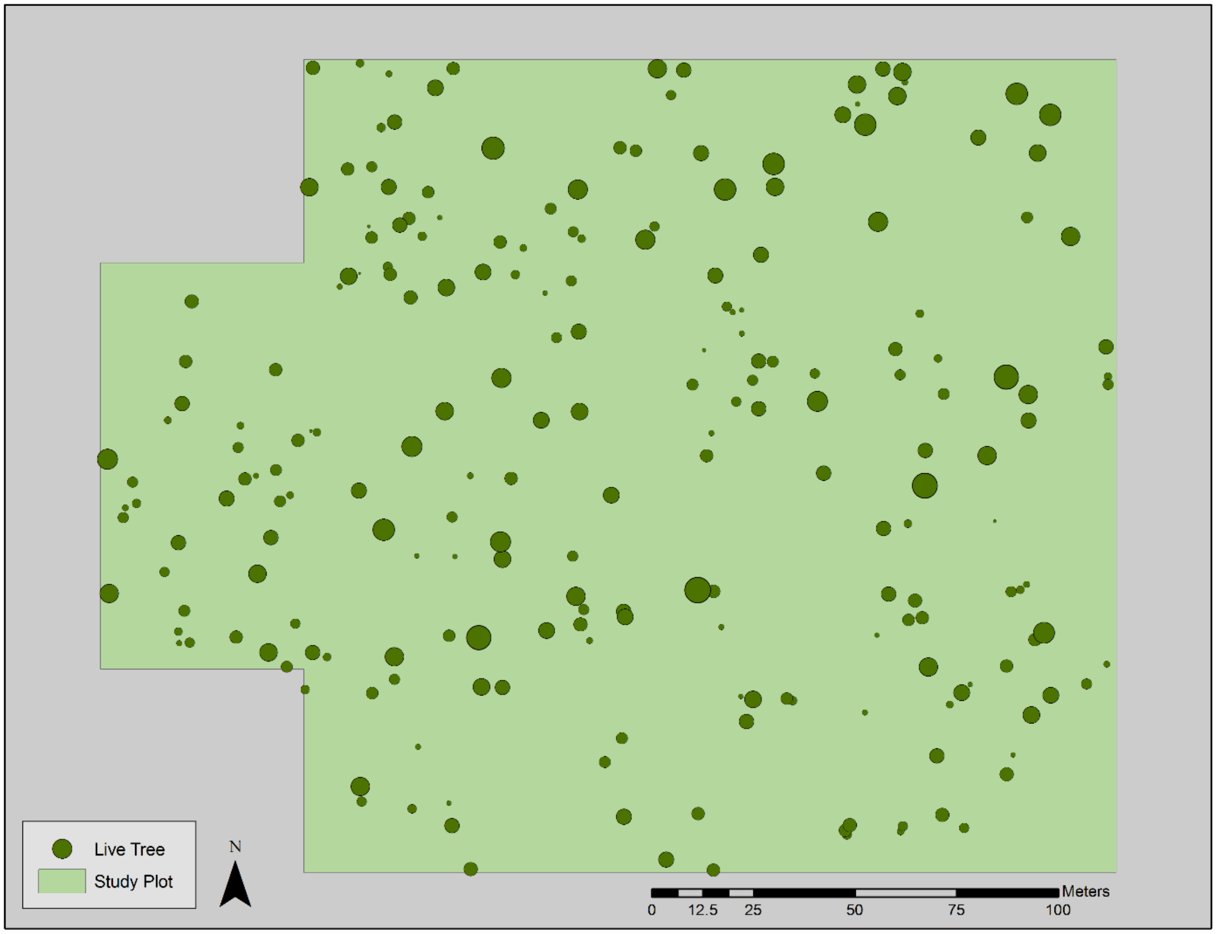

Figure 8. Estimated stem map of all trees >10 cm DBH in the study site in 1898. Symbol size correlates to DBH (minimum = 10.3 cm, maximum = 96.2 cm). Density = 48 trees per hectare. Basal area = 9.51 sq. m^2h^{-1}.

Table 4. Stand density and basal area for the study plot in 2016, 1981, and 1898; Metolius Research Natural Area, Oregon. Growth rate is given by DBH class for the population growth from 1981-2016.

	2016			1981		1898	
DBH class	Stems/h	BA (m^2h^{-1})	Growth Rate (%)	Stems/h	BA (m^2h^{-1})	Stems/h	BA (m^2h^{-1})
15cm	298	4.95	0.69	240	3.25	4	0.09
25cm	107	4.82	12.31	20	0.88	6	0.29
35cm	29	2.76	7.92	8	0.77	9	0.87
45cm	9	1.36	0.42	8	1.20	9	1.53
55cm	8	1.96	-0.45	10	2.37	10	2.43
65cm	9	3.01	-0.19	10	3.29	6	2.04
75cm	9	4.02	-0.25	10	4.42	2	1.08
85cm	7	3.70	0.87	5	2.88	1	0.58
>90cm	7	5.29	0.32	6	4.71	1	0.6
TOTAL	483	31.87	1.51	317	23.77	48	9.51

Table 5. Estimated stems per hectare for seedlings, saplings, and poles in the study plot, Metolius Research Natural Area, Oregon.

DBH Class	Stems per hectare
Seedlings	3417
Saplings	97
Poles	94

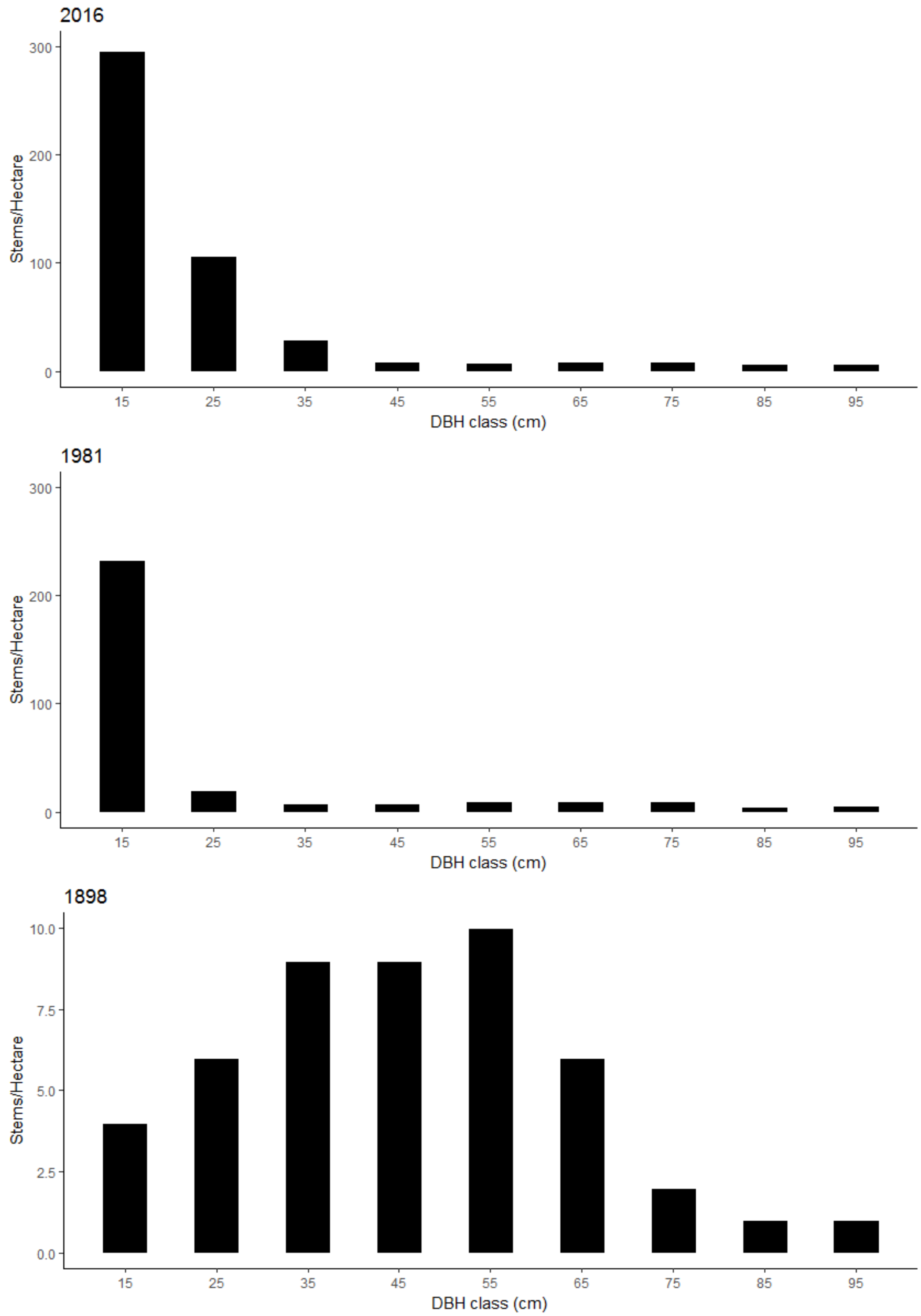

Figure 9. Histograms showing stand structure for the study plot in 2016, 1981, and estimated 1898, Metolius Research Natural Area, Oregon.

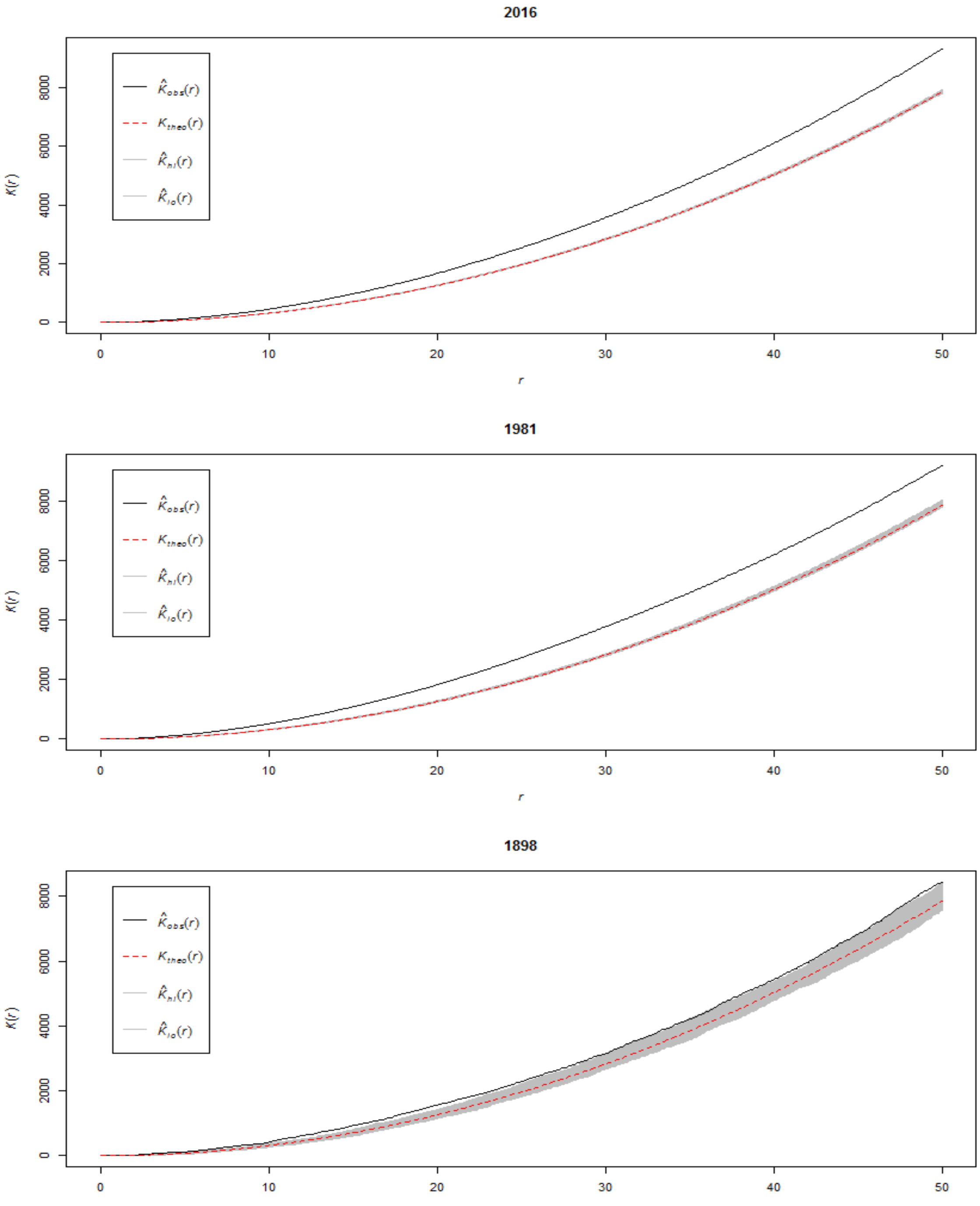

Figure 10. Ripley's K(r) function plotted for 2016, 1981, and estimated 1898 spatial pattern. When K_{obs} escapes above the theoretical envelope, the spatial pattern is judged to be clustered. When it is within the envelope, the spatial pattern is judged to be random. The x-axis (r) is essentially the spatial extent, in meters, at which the spatial pattern exists. Here we see a much larger deviation from random in 2016 and 1981 compared to in 1898.

Discussion

Unsurprisingly, the Metolius RNA historically experienced frequent fire like much of the surrounding landscape (Merschel et al. 2018, Johnston et al. 2016). This frequent fire likely maintained low stand density similar to reconstructed historical stand density from other studies (Johnston 2017, Rodman et al. 2017, Johnston et al. 2016, Abella et al. 2015, Brown et al 2015, Stephens et al. 2015, Hagmann et al. 2014, Merschel et al. 2014, Hagmann et al. 2013, Taylor 2010, Moore et al. 2004, Camp 1999) and lower fuel loading. With low stand density and fuel loading, a frequent fire system would have likely experienced primarily low-severity fires creating a positive feedback loop for the low stand density and fuel loading.

The high fuel loading we observed for the Metolius RNA is reflective of the century-long fire-deficit and congruent with other studies (Brown et al. 2015, Stephens et al. 2015, Moore et al. 2004). Fuel loading and structure was also empirically and visually different from fuel model TL8 (Table 6). This difference was the sole contributor to the differences in fire behavior and tree mortality we observed between Metolius RNA and fuel model TL8. These differences are important because it implies that established fuel models may not be reliable to represent fuel loading or model fire behavior and effects in forests effected by fire exclusion.

Over the past 120 years, the study plot experienced a 10-fold increase in stem density, a tripling of basal area, a sharp shift to small tree dominance, and increased deviation from random spatial pattern. From 1981 to 2016, the study plot also had a large positive growth rate for the small tree population, and a negative growth rate for the large tree population growth. Our results are congruent with other research done in dry ponderosa pine forests across the west (Rodman et al. 2017, Johnston et al. 2016, Abella et al. 2015, Brown et al. 2015, Stephens et al. 2015, Merschel et al. 2014, Hagmann et al. 2013, Taylor 2010, Spies et al. 2006, Moore et al. 2004, Camp 1999, Hessburg et al. 1999). The novelty of our findings is that they are from a forest managed to be in a natural condition, and theoretically shouldn't be experiencing these repercussions. The study plot is clearly not in a natural condition, as defined by the historical reconstruction, since it has significantly changed due to fire exclusion. We presume much of the Metolius RNA to be in a similar state and can postulate that other "natural condition" forests in fire-prone landscapes likely also have experienced effects of fire exclusion.

The modern stand conditions created by fire-exclusion pose an eminent threat to the longevity of the Metolius RNA since denser, more clustered forests are more at risk to high-mortality effects from disturbances such as fire, insects, disease, and drought. In fact, two RNAs dominated by ponderosa pine in fire-prone eastern Oregon have recently succumbed to such disturbances. The Dugout RNA, Malheur NF, is currently inundated with an outbreak of western pine beetle (*Dendroctonus brevicomis*) (James Johnston, personal communications). Whereas the Canyon Creek RNA, also in the Malheur NF, was wiped out (100% mortality) by the Canyon Creek Complex of 2015 (James Johnston, unpublished data). While these disturbances may provide unique research opportunities, meeting one objective of RNAs, it negates the other primary objectives of maintaining nature condition ecosystems and preserving gene pools.

Another concern for the Metolius RNA is the decline of trees in the 50-80cm DBH range while the population of trees <50cm and >80cm DBH both increase. That indicates that trees are growing out of the 50-80cm DBH range but not being replaced by smaller trees growing into the 50-80cm DBH range. This is alarming since as the trees >80cm DBH senesce and die there will be few trees in the 50-80cm range to grow up to replace them and the stand will eventually become dominated by young, small trees – effectively converting the stand to a second growth ponderosa pine stand simply through the process of succession. Conversion to second growth is typically done via clear-cut harvesting or high-severity disturbance and would have been unlikely to have occurred under a historical frequent fire regime. Clear-cut harvesting theoretically did not exist pre-European settlement and so likely would not have impacted forests the way they do today. A high-severity disturbance also would have historically been much less likely than today since frequent fire would have maintained low fuel loading, stand density, and open stand structure conducive to resistance and resilience to fire, insects, disease, and drought.

A major limitation to dendrochronological reconstructions of historical stand structure is that small trees were potentially present but have decomposed and are no longer available for sampling (Harmon et al. 2008, Fritts and Swetnam 1989). We argue that frequent fire would have culled most regeneration that established between fires and thus, small tree density and basal area could have been as low as we estimated for 1898. However, to entertain doubt we estimated 1898 density and basal area of the 15cm DBH class using the population growth rate from 1981-2016. Using this method, we estimate density at 143 stems per hectare and $2.53m^2h^{-1}$ of basal area for the 15cm DBH class. This would increase total 1898 density to 191 stems per hectare and $12.04m^2h^{-1}$ of basal area, which is still considerably lower than the density and basal area in 1981 or 2016.

Adjustments to the management of the Metolius RNA are needed if it is desired to meet the original objectives outlined in the establishment record and USDA directory (Federal

Committee on Ecological Reserves, 1977). Management strategies should be altered to include periodic prescribed fire as a surrogate for historically frequent wildfire. Restoring the natural fire regime is critical to meeting the primary objective of the Metolius RNA having intact natural disturbance processes and would likely support meeting the other objectives of maintain natural conditions, providing research opportunities, and preserving a gene pool of certain plants and animals. Further, considering the effects of fire exclusion documented in this study, and the way dense forests typically respond to fire, insects, disease, and drought: we suggest mechanically thinning the stand, and potentially the whole RNA, prior to implementing repeated frequent fire. However, fire alone may not be the desirable or effective method to restore and maintain the area.

Attempting to use fire only to restore structure and density would likely be unsuccessful and strategically very difficult. Successfully thinning ponderosa pine requires intense fire behavior because ponderosa pine trees develop resistance to fire at a relatively small diameter, making it difficult to kill with fire (Agee 1996). The fire would have to be intense enough to either mortally wound the tree's cambium or torch away the tree's canopy, either scenario would likely be supported by fire behavior also capable of killing larger diameter trees via crown scorch, cambium girdling, and fine root damage. This would also strategically complicate fire implementation as intense fire is difficult to manage in terms of holding the fire within the unit and meeting objectives (not killing large trees). Additionally, thinning by fire typically produces an unappealing aesthetic of a thicket of black stick "trees" much like that used in a persuasive fire prevention ad (Figure 11). The aesthetic post-restoration is potentially of great importance for the Metolius RNA as it sets just down river of Camp Sherman, Oregon, a heavily visited camp ground and recreation area. Prior to implementing fire, mechanically thinning the stand from below to restore a more natural stand structure and density would be advised. A mechanical fuel reduction or other protection of large diameter trees prior to implementing prescribed fire may also be useful to minimize risk of intense fire behavior and tree mortality related to smoldering.

The Metolius RNA is at considerable risk of being lost to catastrophic disturbance due to a century-long fire-deficit. Surface fuels have built-up and the stand is densely stocked with small- and medium-sized trees creating substantial horizontal and vertical fuel continuity that could attribute to a high severity wildfire under typical August weather conditions. Higher stand density also correlates to increased risk of insect and disease outbreaks (Reynolds et al. 2013, Kolb et al. 1998, Larsson et al. 1983, Sartwell and Stevens 1975). Further, the current state of the Metolius RNA and lack of fire violates the management plan and prevents the area from meeting the objective of providing an example of ponderosa pine and mixed-conifer forests in natural condition with intact natural processes. If restoring the Metolius RNA to a state more resistant and resilient to disturbances and more in line with the management objective is desired, steps should be taken to restore a more natural forest structure and natural fire regime.

In conclusion, fire-prone forests should be managed to mitigate effects of fire exclusion and maximize resistance and resilience to wildfire. This should especially apply to fire-prone forests managed to be in natural conditions. Preservation of natural condition ecosystems is invalidated by the exclusion of fire as it is a keystone natural process. The treatments and maintenance efforts described above would be minimally invasive, allow the Metolius RNA to meet its primary objectives, and create conditions likely to sustain it through an uncertain future of climate change and erratic disturbances. We also extend our suggestion to managers of any fire-prone landscapes, particularly those meant to be natural condition ecosystems, to consider the effects fire exclusion and develop management plans that more adequately foster healthy and resistant ecosystems. Fire-prone landscapes are often dependent on fire to maintain structure, function, and therefore resistance and resilience to disturbances. If we wish to have forests that can deal well with the erratic and unpredictable conditions of the future considering global climate change, we must prepare them for it.

Table 6. Example photos of fuel loading for the study plot, Metolius Research Natural Area, Oregon (2017); and Scott & Burgan (2005) TL8.

Metolius Research Natural Area		
Scott & Burgan TL8		

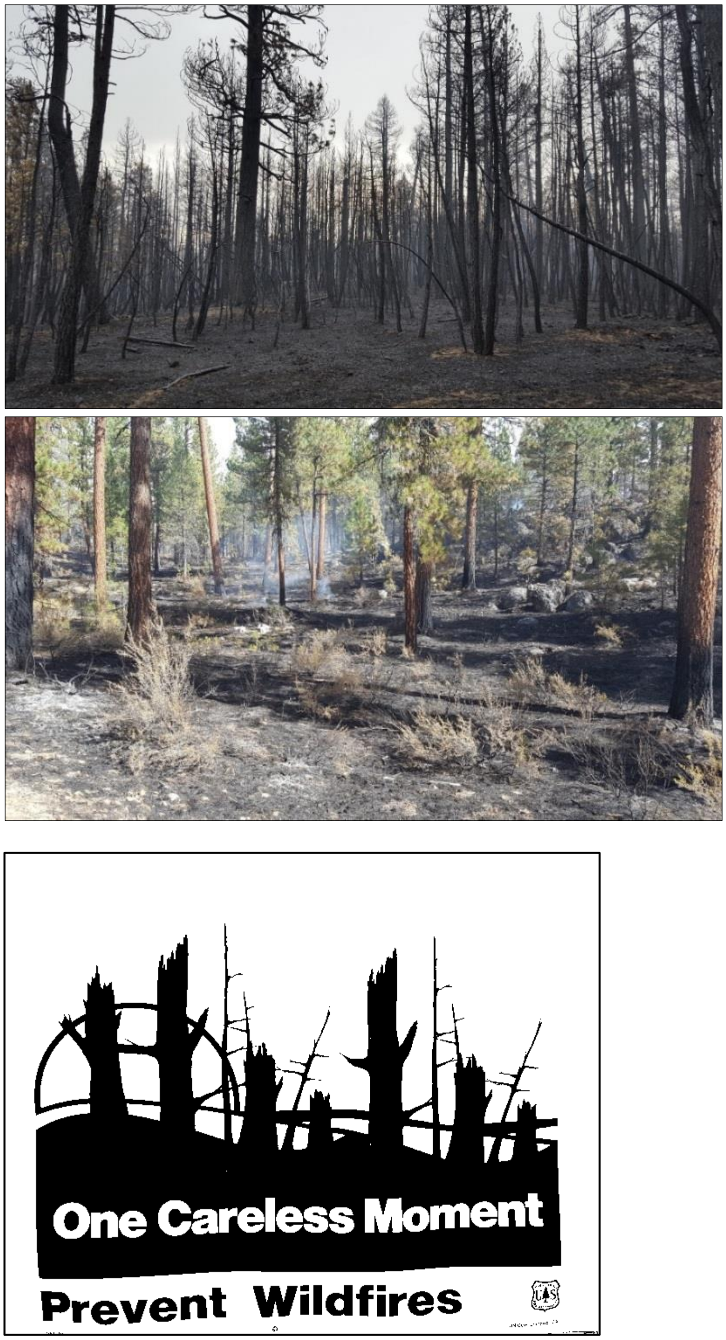

Figure 11. Top) The result when fire lowers small tree density compared to Middle) the result when mechanically thinned prior to prescribed fire. The top result is very similar in appearance to a fire prevention ad used by the US Forest Service (bottom graphic) that essentially uses the idea of an undesirable aesthetic to persuade the public to do their part to prevent wildfires.

CHAPTER 3 – CONCLUSION

First, the Metolius RNA study plot does not have intact natural processes, nor is it in natural condition. Both violate the management strategy (intact natural processes) and one objective (natural conditions) of an RNA. Second, the current condition of the study plot predisposes it to high-severity disturbances. This means the stand is set-up to violate another objective (preserve gene pools). Third, the stand is on a trajectory to convert to a second growth ponderosa pine stand through simple succession mechanisms. This would violate the 'natural conditions' objective by losing the pre-settlement old-growth forest that was once maintained by frequent fire. This would also create a curious scenario as it never would have occurred historically without some large, uncharacteristic disturbance. Finally, the established fuel model chosen to represent the stand was not representative of observed fuel loading or modeled fire behavior and mortality, proposing established fuel models may not be accurate when used to model fire behavior and mortality for other forests affected by fire exclusion.

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