Silvicultural Alternatives for

Pacific Silver Fir Stands on the Yakama Reservation

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ABSTRACT

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The Yakama Nation's (YN) upper-elevation forestlands dominated by *Abies amabilis* (Pacific silver fir) and *Tsuga mertensiana* (Mountain hemlock) have tremendous natural and cultural resources that are valued by the YN. Unfortunately, these forest stands are experiencing high mortality rates due to insects and disease following extreme drought events. Increasing tree mortality rates in these upper-elevation forests have been predicted by climate models but field research to document the extent of tree mortality and changes in species composition has not been conducted in upper-elevation forests in eastern Washington State. The lack of research in these upper-elevation forests is not unexpected considering that low-to-mid elevation forests are actively managed because

of their high economic importance. The upper-elevation forests need greater research and management attention because of the high mortality they are experiencing. These forests need to be managed to sustain the multiple resources for future generations.

The objectives of this research were to: 1) Use the Continuous Forest Inventory (CFI) data and technology to verify the related forest health issues that are causative to the high mortality rates within the Pacific silver fir habitat type in the upper elevations of the Yakama Reservation; 2) Estimate the growth rates of all tree species found growing in the upper-elevation Pacific silver fir habitat type using the Yakama CFI database; 3) Assess the mortality rates of tree species in the upper-elevation Pacific silver fir habitat type using the CFI database; and 4) Assess which of three silvicultural treatments would re-establish healthy and productive forests at these upper elevations by using the CFI data in the Forest Vegetation Simulator (FVS) to project growth and yield.

This research showed that the Pacific silver fir habitat type is experiencing higher rates of mortality compared to growth, i.e., a net loss of silver fir habitat. The 2005 mortality rate in these forests was 1.4% of stocking compared to a typical annual mortality rate of ~1% for these forests. Some tree species were more vulnerable to these changes in climate and secondary insect/pathogen attacks which have the potential to change the distribution of these tree species in these upper-elevation forests, *i.e.*, whitebark pine (13.6% in 2005), lodgepole pine (5.2%), western white pine (3.8%), subalpine fir (3.5%), and Engelmann spruce (1.1%).

Silvicultural alternatives are needed to improve the growth and health of the upper-elevation forestlands on the Yakama Reservation. This research suggests that it is not a viable option to not manage these forests. Simulations conducted during this study suggest that the diversity and wood quality would decrease if silvicultural practices were not implemented to restore these high-diversity forests. Furthermore, the YN cannot afford to lose the cultural resources and wildlife habitats that these forest stands provide.

Acknowledgements

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I want to thank my friends and relatives for their kind support, and prayers for my educational goals.

Dedication

I want to dedicate this to my remarkable wife Tavie and our beautiful daughters Charnelle, Mayu, and Nizhoni and our son Sicha for all their love and support. I dedicate this to my mother Marie Olney. Furthermore, I dedicate this to my late step-father Allan Olney whom I travelled and worked with for many years on the Yakama Reservation. Also, I want to dedicate this to my late brother Benjamin his Yakama Indian name is "Pena". In addition, I want to dedicate this to my late grandmother Lily Whitefoot for her strength, wisdom and many lessons. Finally, I want to respect and honor the Yakama Nation ancestors, elders, present generation, and the future generations to come.

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Introduction

The Yakama Nation is one of 29 federally recognized tribes in Washington State. The 1.37 million-acre-Yakama Reservation includes 650,000 acres of forest and woodlands. Yakama tribal people have lived intimately on the land and have depended on the forests for millennia. Their wise stewardship of these forests has been acknowledged in the 2013 Indian Forest Management Assessment Team (IFMAT) Report (Gordon *et al*. 2013). The Bureau of Indian Affairs (BIA) manages the forest resource in trust for the Yakama Nation. Yakamas rely on the forest resource as a dependable source of spiritual renewal, clean water, food and medicinal plants, revenue, and employment. The Yakama Nation manages their significant forest resources to achieve multiple benefits including timber. The Yakama Nation manages their forests *"in accordance with tribal visions; management priorities are shifting towards protection and commodity production receiving less emphasis."* (Gordon *et al*. 2013)

Tribal management of forests is complicated by the multiple products and benefits that tribes want from their forestlands and now they face climate change impacts on their forests. This means that it is more difficult to make choices on how to manage lands so these multiple objectives can be met as the forest health declines in unmanaged areas of the forest. The IFMAT III Report (Gordon *et al*. 2013) summarized well the economic and cultural benefits tribes obtain from their forests and what they would like to continue to obtain from forest:

> ***"Diverse forest types provide irreplaceable economic and cultural benefits.*** *Forests encompass about a third of the total Indian trust lands, and sustain tribal economies, cultures, religions, and spiritual practices. Forests are closely linked to community and cultural vitality in Indian Country. Forests store and filter the water and purify the air. They sustain habitats for the fish and wildlife that provide sustenance for the people. They produce foods, medicines, fuel, and materials for shelter, transportation, and artistic expression. Forests provide revenues for many tribal governments, sometimes the*

principal source of revenue, and sorely-needed employment for Indian people and rural communities."

Tribal forest management is very challenging because forests need to provide economic, environmental and cultural benefits simultaneously (Morishima 1998; Rigdon 2007). It is not just getting the silvicultural practices correct but other resource issues have to be balanced with the need to generate revenue for the tribe and employment opportunities for tribal members. Tribes have been active forest managers before the arrival of European colonizers and there is ample evidence that they deliberately managed their ecosystems (Bonnicksen *et al*. 1999). For example, there are many types of medicinal remedies that indigenous people use in the Pacific Northwest that are collected from forests. Red alder (*Alnus rubra*) contains salicylic acid in the leaves and bark that is used as a medicinal for pain. Extracts from Douglas-fir (*Pseudotsuga menziesii*) and western redcedar (*Thuja plicata*) are used for cold remedies (Moerman 2009).

Maintaining tribal forests and the multiple resources they provide is challenging today due to past land-uses and the occurrence of extreme climatic events that have altered forests and their health. Extreme drought events are decreasing forest health as forests are impacted by more frequent wildfires, disease and insects (Gordon *et al.* 2013). Extreme climatic events will not only increase the frequency of disturbances but will have significant impacts on tribal resources.

In response to these increasing disturbance events and their impacts, tribes have been actively planning their response to these problems even though they have contributed little to causing them. For example, the Yakama Nation is developing their climate adaptation plan and specifically the "Climate Adaptation Plan for the Territories of the Yakama Nation" summarizes the tribe's approach to addressing climate change impacts. A few following excerpts from this report address some of the issues that are relevant to this research:

> *"..we expect that both summer and winter temperatures will continue to increase and snowpack in the mountains will diminish. We have observed that many of these changes are already being realized today.*
>
> *"Climate change is real and, unfortunately, the effects appear to be in motion. We are witnessing changes in the seasons. Our roots and berries must be gathered sooner, and salmon returns are less predictable. Our people notice less snow in the mountains now, and there is less cool water during the summer when it was once abundant. The changes we see may not bode well for our future. Over the years to come, we may lose natural resources that are important to our culture and our heritage. Some of these losses may be irreversible."*
>
> *"Changes in climate can affect forest pest and disease responses in two fundamental ways: first, by lengthening or shortening the seasons when pests reproduce and complete their life cycles, and second, by weakening the host trees and leaving them more susceptible to insect attacks and plant disease. Specific effects in our region are difficult to predict at this time. For example, in some places in the Pacific Northwest, mountain pine beetles are projected to decline, and in other places they are expected to become more prevalent."*

Tribes need to make their forests climate adaptive while managing their resources, which is difficult since our knowledge base on climate change impacts are still emerging. The Yakama Nation is taking a holistic approach to their forest management that includes multiple values from forests as follows (Climate Adaptation Plan for the Territories of the Yakama Nation 2016):

> *"The Yakama Nation has taken an active role in managing and improving its forested lands, using an ecosystem approach, by implementing a complex and comprehensive Forest Management Plan (FMP). Implementation of the FMP is intended to enhance and maintain a diversity of forest conditions, maintain sustainable production of commercial and noncommercial resources, and thereby maintain the forest resource as a dependable source of spiritual renewal, food and medicinal plants, revenue, and employment for the Yakama people. The FMP is a collaborative effort of the Yakama Nation and BIA natural resources programs, including Archaeology and Cultural Resources, Environmental Quality, Fisheries, Forestry, Range, Roads, Soil, Vegetation, Water Code, Water Resources, and Wildlife. The main topics within the FMP include, but are not limited to,*

big-game habitat, forest health, old growth, revenue and employment, threatened and endangered species, and water quality."

What is especially problematic for the Yakama Nation is that forests located on the Yakama Reservation are already unhealthy and experiencing mortality events. This means that the YN needs to determine what options exist today to manage their forests and not sometime in the future. Much of the unhealthy forests are due to drought conditions which is increasing tree stress and the prevalence of insect pest outbreaks such as the mountain pine beetle, western pine beetle, Douglas-fir beetle, and western spruce budworm (WA DNR Forest Health Program 2017). This is something that is being observed in the upper-elevation forests on the Yakama Reservation. The other challenge is that climate models are predicting decadal time periods in which climate change will play out so a solution cannot just address today's problems but has to be long term.

Changes in Upper-elevation Forests

Currently, some of the commercial timberlands of the Yakama Reservation are declining in health due to their increasing age, insects, disease, and climate change. Especially important are the forest stands within the upper-elevation Pacific silver fir habitat type. *Abies* is an important coniferous genus of the Pacific Northwest. There are several true fir species that play important ecological roles.

Therefore, it is important to research how the higher mortality rates will impact the persistence of the Pacific silver fir forest stands that occur at these upper elevations. Considerable research attention has been given to low- and mid-elevation forests but not to the upper-elevation forests even though they hold many economic, environmental and cultural resources and values for the

YN. This research evolved from the importance of these upper-elevation forests and the lack of knowledge for how to manage them in the face of extreme and potentially extended changes in climate. The following points are relevant for explaining the initiation of this research:

- Upper-elevation Pacific silver fir (*Abies amabilis*) stands have received little attention because the focus of research and management has been on low- to mid-elevation forests. This means that tools and frameworks need to be developed to mitigate climate change impacts on species that grow at the upper elevations.
- Pacific silver fir stands have high tree species diversity (Franklin and Dyrness 1973).
- On the Yakama Reservation, the apparently poor health of the upper-elevation forests needs to be determined since the increased amount of disease and insect infestations may cause the loss of several tree species from these forests as the climate changes.
- On the Yakama Reservation, upper-elevation forests contain many cultural resources. Medicinals and foods such as huckleberries may no longer be available if their habitats are altered by climate change and secondary disturbances.
- Silvicultural alternatives have been developed for low- to mid-elevation forests but not for the upper-elevation forests. Therefore, the role of silvicultural practices for achieving economic, environmental and cultural values from these forests is not well known.
- Several models have predicted major changes in forest distribution and composition as a result of climate variability which has resulted in extreme drought events resulting soil water deficits (Littell *et al*. 2009; WA DNR Forest Health Program 2017). This is predicted to especially impact fir and pine species as well as increase the area that burns and result in increased outbreaks of mountain pine beetles and other insect pests/pathogen (WA DNR Forest Health Program 2017).

Research Questions

The research questions being explored in this study are:

- Within the upper-elevation Pacific silver fir habitat type, what are the growth and mortality rates of the different tree species?
- Should forests be left alone to recover without management following any disturbance that causes extensive tree mortality?
- What combination of silvicultural options can be used to manage upper-elevation forests to restore the composition and diversity of the stands?

To address these research questions, this study had several objectives. These objectives are presented below.

Study Objectives

1. Use the Continuous Forest Inventory (CFI) data and technology to verify the related forest health issues that are causative to the high mortality rates in the Pacific silver fir habitat type in the upper elevations of Yakama Reservation.

2. Estimate the growth rates of all tree species found growing in the upper-elevation Pacific silver fir habitat type using the Yakama CFI database.

3. Assess the mortality rates of all tree species in the upper-elevation Pacific silver fir habitat type using the Yakama CFI database.

4. Assess which of two silvicultural treatments (precommercial thinning, and precommercial thinning and commercial thinning) would re-establish healthy and productive forests at these upper elevations by using the CFI data in the Forest Vegetation Simulator (FVS) to predict growth rates and yields.

Study Area Characteristics

The Yakama Reservation is located in south-central Washington State (Figure 1). The Reservation includes agricultural and range lands in the east and forest and woodlands in the west (Figure 2). This scientific study was conducted within the Pacific silver fir habitat type on the Yakama Reservation. The forest stands within this habitat type range from 4000 ft [1,219 m] to 5500 ft [1,676 m] in elevation and receive 40 to 80 inches [1.02 to 2.03 m] of annual precipitation, mostly as snow from November to April. The common tree species include Pacific silver fir (*Abies amabilis* Dougl. ex Forbes), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), mountain hemlock (*Tsuga mertensiana* (Bong.) Carr.), Engelmann spruce (*Picea engelmanii* Parry ex Engelm.), western white pine (*Pinus monticola* Dougl. ex D. Don), western larch (*Larix occidentalis* Nutt.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). Forest stands within the Pacific silver fir habitat type containing these species were used in this study because they are experiencing high tree mortality rates.

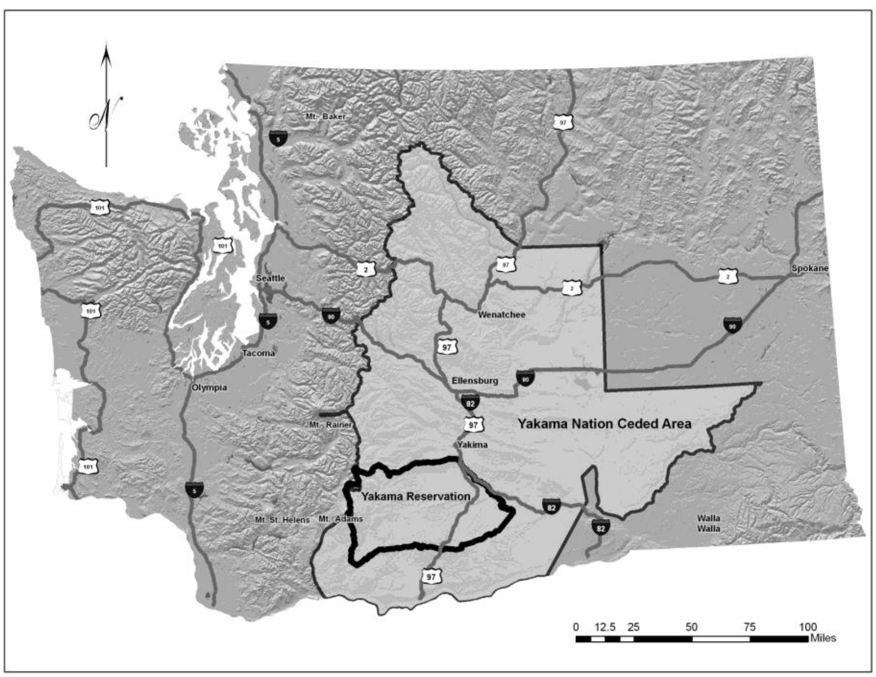

Figure 1. The location of the Yakama Nation Indian Reservation where this study was conducted.

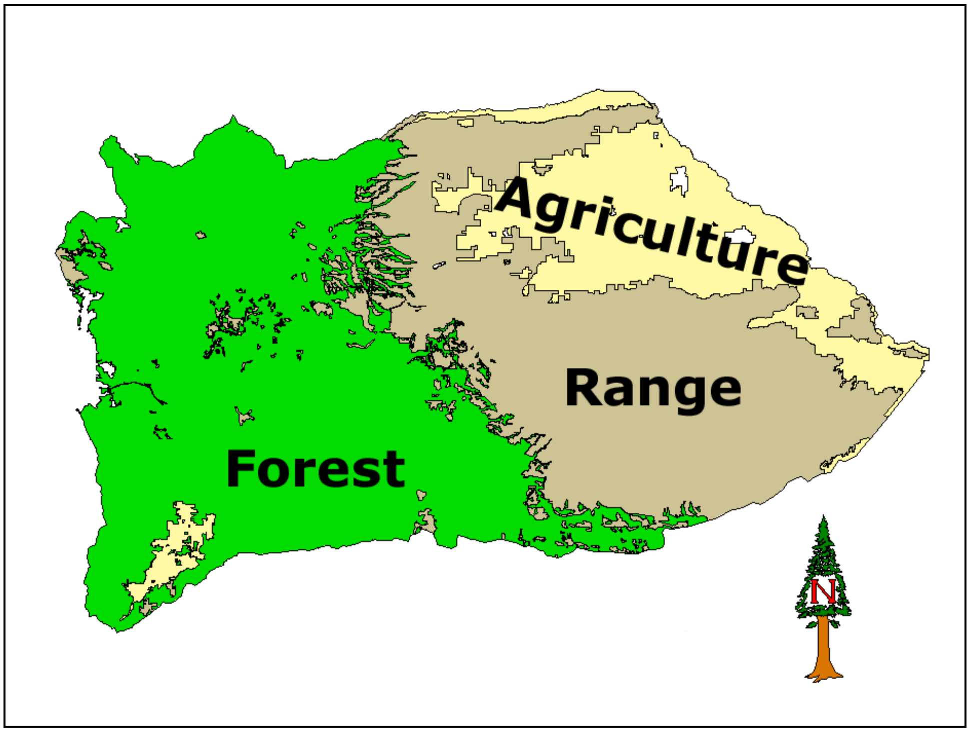

Figure 2. The location of forests, agricultural lands and range lands in the Yakama Nation Indian Reservation.

The forest habitat types on the Yakama Reservation are shown in Figure 3. The Pacific silver fir habitat is dominated by upper-elevation *Abies amabilis* forest stands. The Pacific silver fir habitat type comprises 85,000 acres (34,398 hectares) of forestland. These forests are located on highly-productive, nutrient-rich soils and have an abundance of precipitation, which produces large mature old-growth trees. However, over the centuries these forest stands have been deteriorating due to age, diseases and insects.

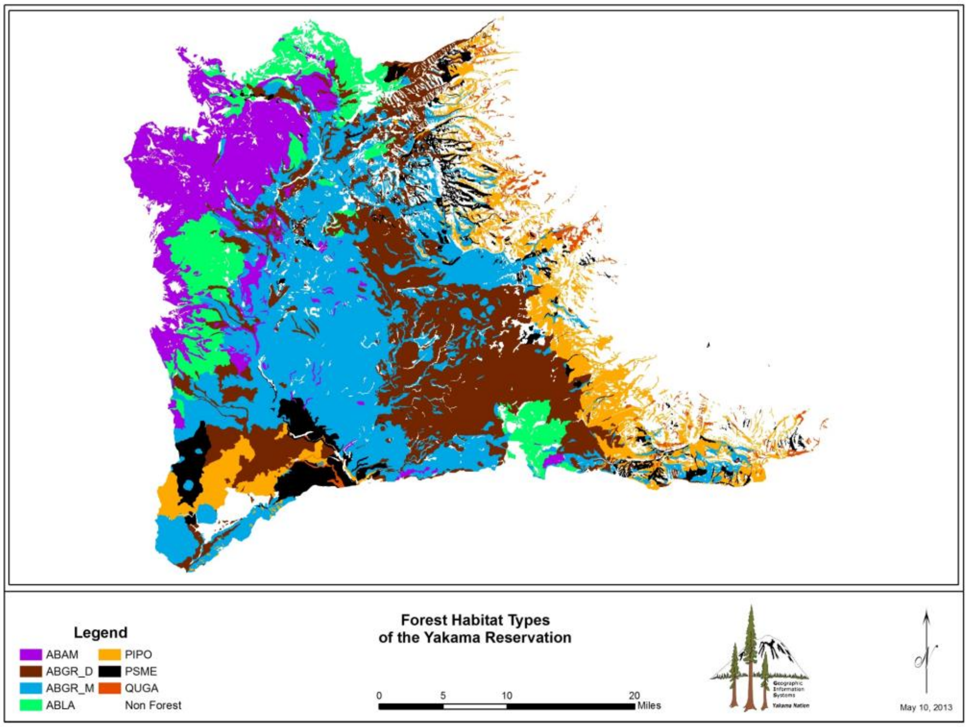

Figure 3. Distribution of the forest habitat types on the Yakama Reservation. The Pacific silver fir habitat type (ABAM) (purple color) occurs in the northwest portion of the Reservation between Mount Adams and the Goat Rocks.

Recently, several large fires burned large areas of forest on the Yakama Reservation (Figure 4A and 4B). Two of the large fires were 'Cougar Creek' fire that burned 53,498 acres [21,650 ha] of forestland and the 'MM 28' fire that burned 26,773 acres [10,835 ha] of forestland. Another wildfire, the 'Cold Springs Incident', occurred in 2008 and burned 7,729 acres [3,128 ha] of forestland.

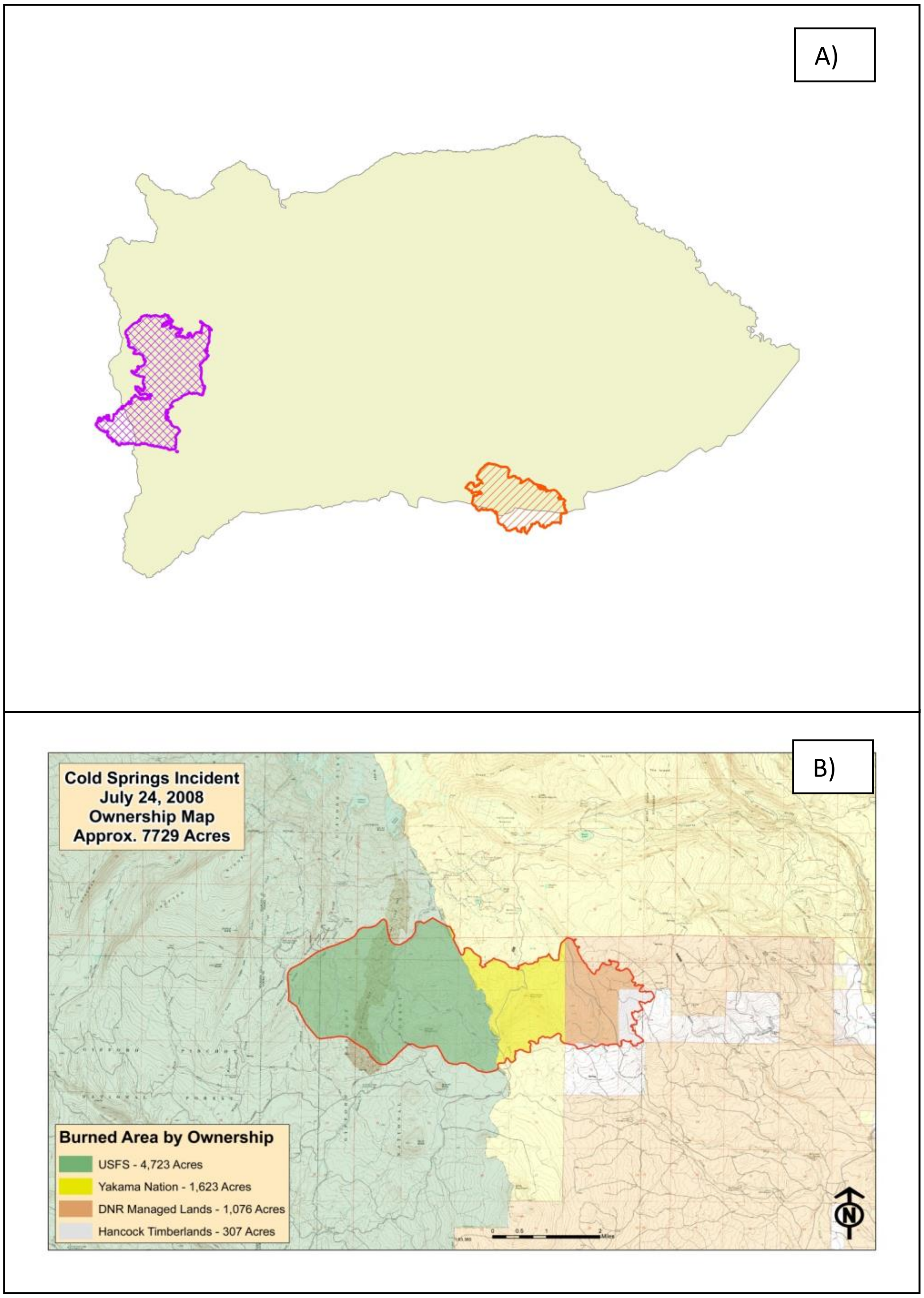

Figure 4. (A) Location of two large scale wildfires that burned sizable areas of forests. The one colored in purple is the Cougar Creek fire (purple, cross-hatched area) that burned 53,498 acres [21,650 hectares] and the MM 28 fire (red, slashed area) that burned 26,773 acres [10,835 hectares] of forest. (B) The location of the Cold Spring Incident fire (outlined in red) that burned forests in the Yakama Nation Indian Reservation as well as US Forest Service (USFS), WA Dept. of Natural Resources (DNR) managed lands and forests of Hancock Timberlands.

Methods

Mortality and Growth Measurements

The Yakama Continuous Forest Inventory (CFI) includes 1,286 1/5-acre (0.08 ha) plots systematically distributed across the Yakama Forest. This study focuses on the Pacific silver fir stands, which are represented by 163 CFI plots. These forest stands are characterized by mature Pacific silver fir, mountain hemlock, western hemlock, subalpine fir, and lodgepole pine.

Stand data were obtained from the CFI plots that were measured from 1970 to 2005. Data collected in all CFI plots included elevation, aspect, tree species, tree diameter, tree height, tree health condition, and regeneration (https://www.bia.gov/cs/groups/xraca/documents/text/idc009150.pdf). CFI data are collected by the Forest Management Inventory and Planning Unit. The CFI data were analyzed using the BIA CFI program developed by the Branch of Forest Resources Planning, and the Forest Vegetation Simulator (FVS) which was developed by the USDA Forest Service (Dixon 2017). The FVS is used to predict the current and future forest stand conditions under different management options (Dixon 2017). It is very useful when comparisons are being made between different management options (Dr. Eric Turnblom, personal communication).

Silvicultural Treatments

Analysis of the CFI data provided stem volume, growth and mortality trends from 1970 to 2005. The CFI data were used with the Forest Vegetation Simulator (FVS) to simulate silvicultural treatments and project the growth and yield to the year 2137. Three simulated treatments were analyzed as shown in Table 1.

Table 1. Summary table of the treatments included in each of the three simulations.

	Year and Treatments				
Simulation	2017	2018	2037	2087	2137
NT					CC
PCT	CC	Plant	PCT		CC
PCT+CT	CC	Plant	PCT	CT	CC

The simulations are described in further detail below and the species acronyms are found explained below:

NT: No treatment (Control). The mature stand was grown and then clearcut (CC) harvested in 2137. Mortality rates were adjusted in the simulation to match the 2005 CFI data.

PCT: The mature stand was clearcut harvested in 2017. Tree seedlings were planted in 2018 at the following densities: DF 100 Trees Per Acre (TPA); WL 100 TPA; WP 100 TPA; and ES 50 TPA. In addition, 100 TPA of LP were added as natural regeneration. Precommercial thinning (PCT) was simulated in 2037, at age 19, where the target residual stand density was 170 TPA. Lodgepole pine mortality was simulated from 2077 to 2097. The stand was clearcut harvested in 2137, at age 119.

PCT+CT: Same treatment as PCT with the addition of a commercial thinning (CT) in 2087, at age 69, where the target residual stand density was 70 TPA. The CT was simulated to harvest the lodgepole pine before the anticipated mortality at age 80. The stand was clearcut harvested in 2137, at age 119.

Results

Growth and Mortality Data

Out of the 163 Pacific silver fir CFI plots within the commercial forest, 59 plots were selected to represent Pacific silver fir stands within the commercial forest that had stem volume ≥ 25,000 BF/AC where BF/AC is 'Board Feet per Acre' and one board foot is the volume of a board that is one-foot long and one-foot wide and one-inch thick. The average stem volume of these plots was 52,927 BF/AC; average gross growth volume was 615 BF/AC/YR; and average mortality by volume was 420 BF/AC/YR. Distributions by tree species of stem volume and mortality by volume are shown in Figures 5 and 6.

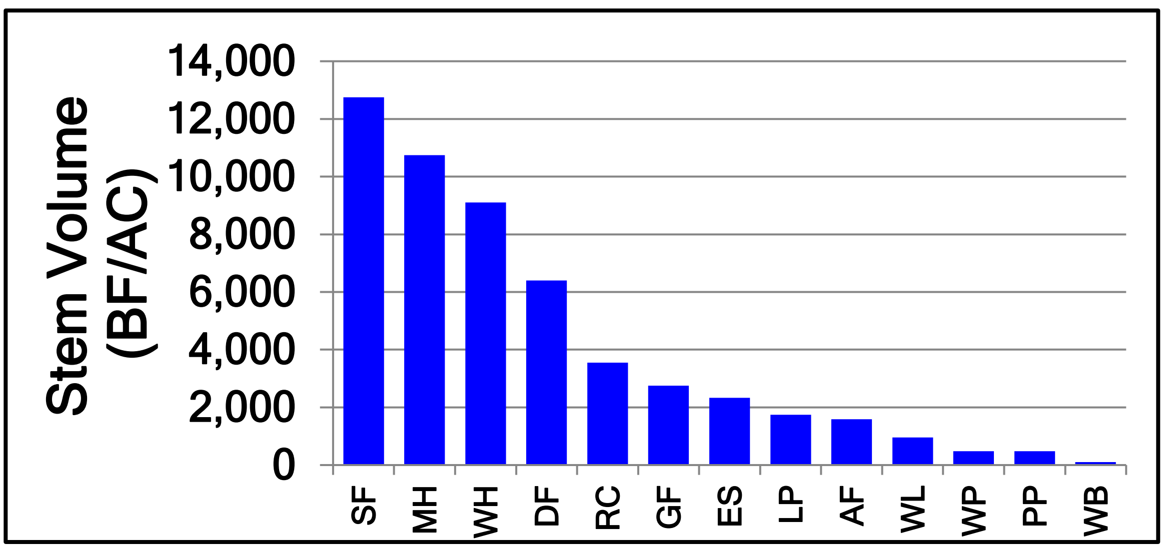

Figure 5. Distribution by tree species of stem volume (BF/AC) in the selected 59 CFI plots.
SF = Pacific silver fir; MH = mountain hemlock; WH = western hemlock;
DF = Douglas-fir; RC = western red cedar; GF = grand fir; ES = Engelmann spruce;
LP = lodgepole pine; AF = subalpine fir; WL = western larch; WP = western white pine;
PP = ponderosa pine; and WB = whitebark pine.

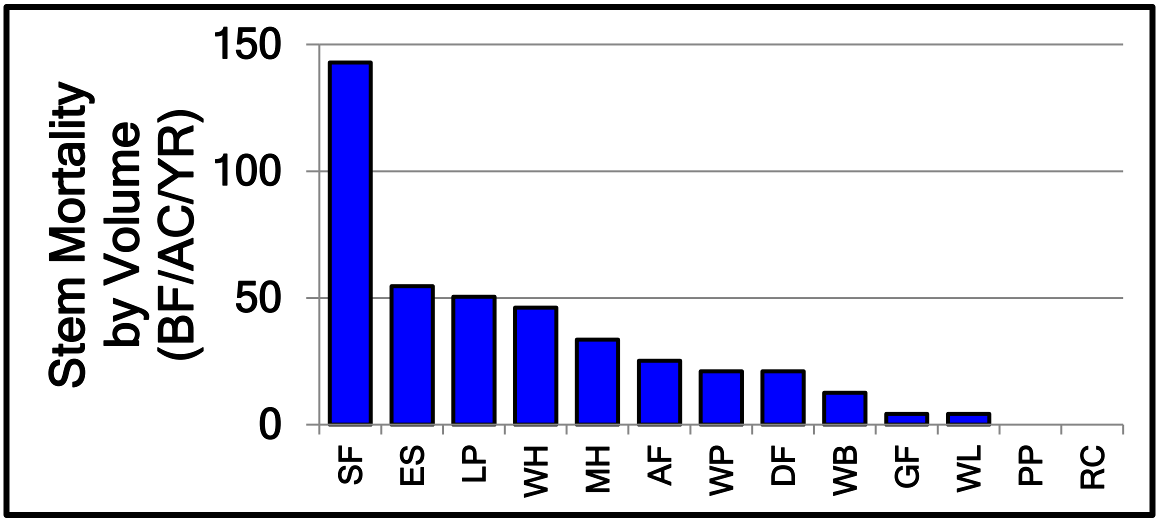

Figure 6. Distribution by tree species of mortality by volume in the selected 59 CFI plots. SF = Pacific silver fir; MH = mountain hemlock; WH = western hemlock; DF = Douglas-fir; RC = western red cedar; GF = grand fir; ES = Engelmann spruce; LP = lodgepole pine; AF = subalpine fir; WL = western larch; WP = western white pine; PP = ponderosa pine; and WB = whitebark pine.

In 2005, the 163 CFI plots had an average stem volume of 31,171 BF/AC. Average gross growth volume was 398 BF/AC/YR while average mortality by volume was 422 BF/AC/YR. The 2010 Yakama Forest Inventory Analysis showed similar results for the true fir-mountain hemlock timber type (Figure 7). The mature trees have a lot of stem defect caused by decay fungi and most of the mortality is caused by balsam wooly adelgid, white pine blister rust, bark beetles, and wind. These data show high mortality for Pacific silver fir, Engelmann spruce, lodgepole pine, and hemlock species. In fact two of the forest types (true fir/mountain hemlock (FM) and lodgepole pine (LP) stands) had negative growth rates because of the high mortality from the mountain pine beetle that increased the tree mortality rate for these forests. This contrasts with the other tree species which were not being impacted by the mountain pine beetle. When considering growth as well as mortality the true fir/mountain hemlock and lodgepole pine stands' mortality exceeds growth creating a negative gross growth rate (Figure 7).

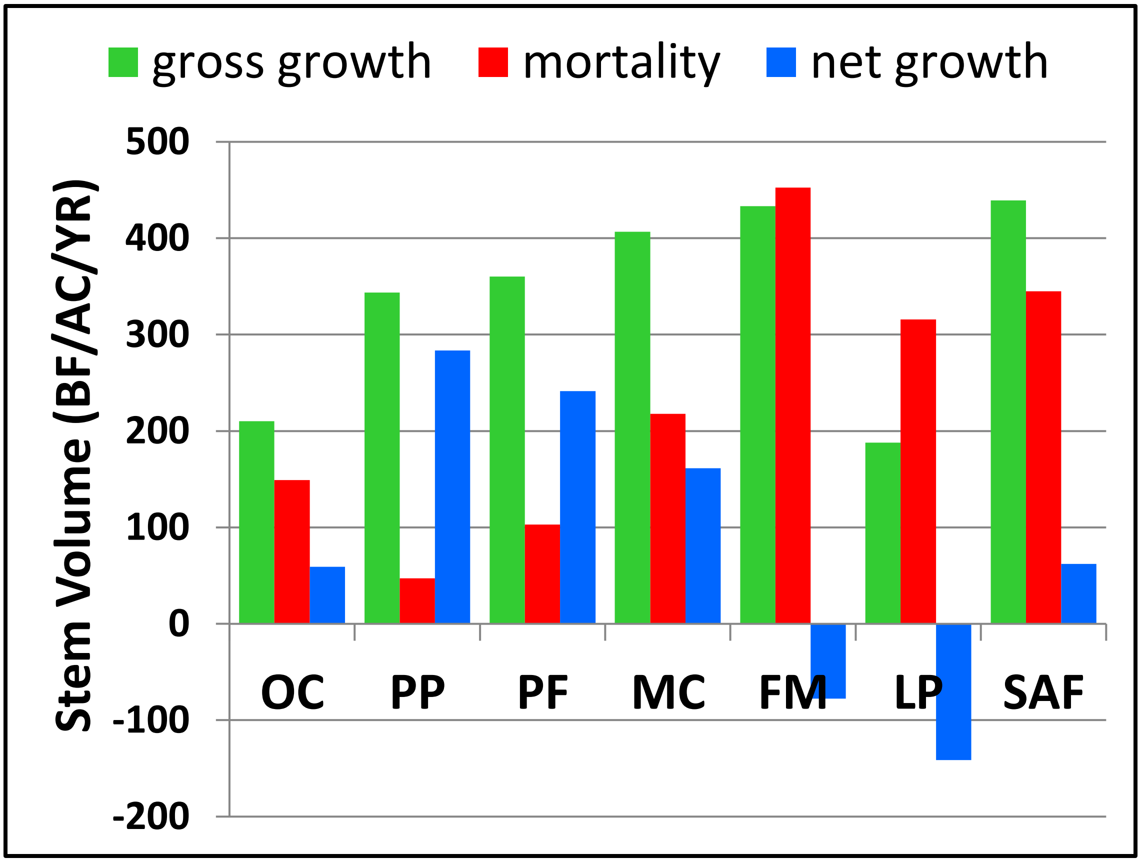

Figure 7. Tree stem volumes per year of gross (green) and net growth (blue) and mortality (red) by volume for the following forest types: Oak-Conifer (OC); *Pinus ponderosa* - Ponderosa pine (PP); Pine-Fir (PF); Mixed Conifer (MC); *Pinus contorta* – Lodgepole pine (LP); *Abies amabilis-Tsuga mertensiana* – True fir-Mountain hemlock (FM); *Abies lasiocarpa* - Subalpine fir (SAF).

The true fir/mountain hemlock (FM) forest type had significant negative growth rates compared to most other forest types (Figure 7 and 8). Forests with higher mortality compared to growth volumes as found in this study would translate in this FM forest type to an annual timber volume loss of 35,820,574 BF on the 79,144 acres occurring in this FM forest type.

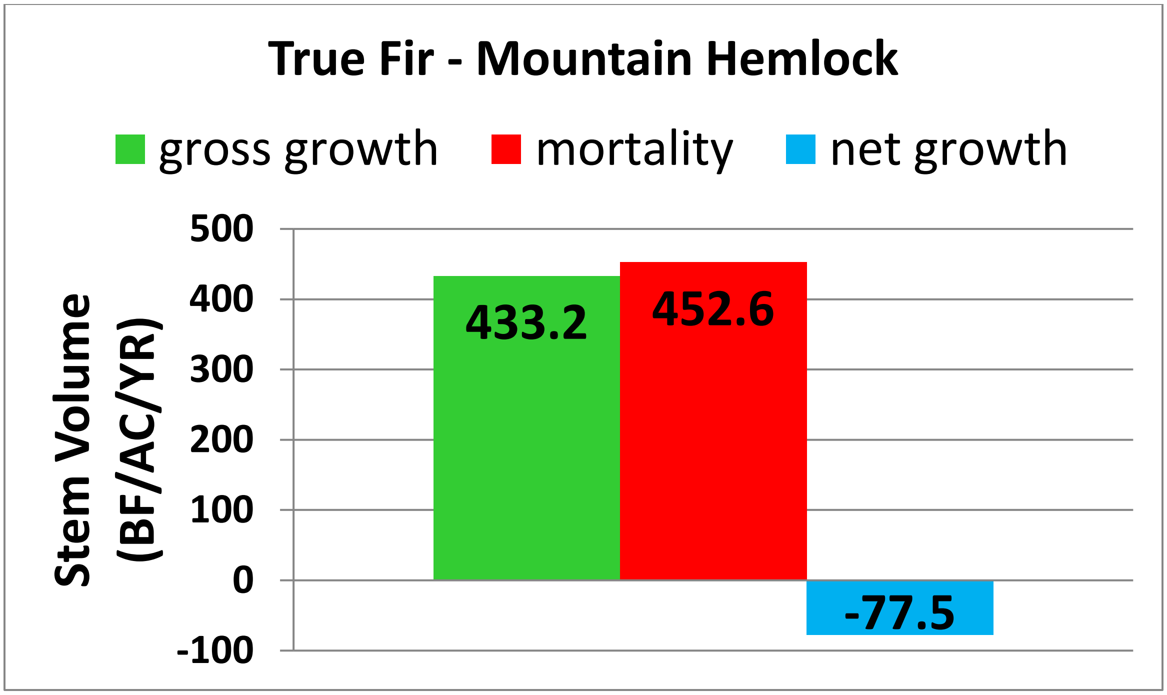

Figure 8. Tree stem volumes per year of gross growth (green) and mortality (red) by volume in the true fir/mountain hemlock forest type resulting in a net negative growth rate (blue).

Silvicultural Treatments Simulations

The following results were obtained from the CFI data and FVS simulations. Stem volumes over time are shown in Figure 9. All three treatment simulations (PCT, PCT+CT, NT) began with the same volume per acre in 2017. All volumes were then harvested in 2017 in the PCT and PCT+CT simulations. Volume reductions then occurred in 2087 and 2097 in the PCT simulation as a result of lodgepole pine mortality. This simulation action is supported by Amman et al. (1977) as they found that lodgepole pine becomes susceptible to attack by mountain pine beetle at age 80 (Amman et al. 1977). Volume reduction also occurred in 2097 in the PCT+CT simulation as a result of the commercial thinning in 2087 that was intended to harvest the lodgepole pine and other suppressed trees before they died. At the end of the simulations in 2137 there was no significant difference in volumes between PCT and PCT+CT. Volume steadily decreased over time in the NT simulation as a result of mortality.

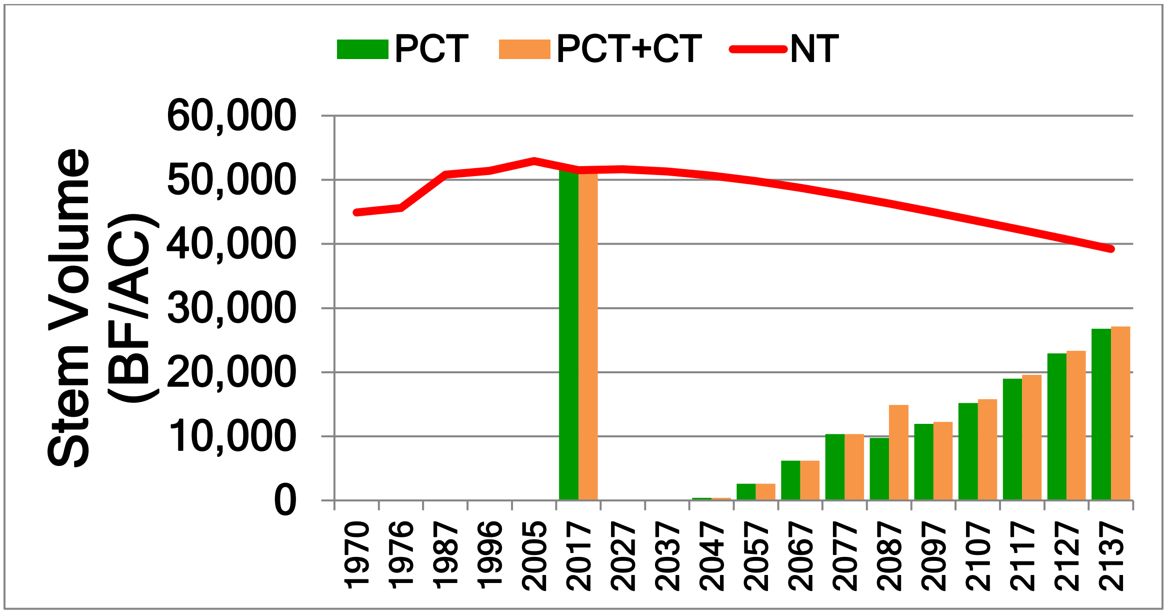

Figure 9. Stem volume (BF/AC) over time for three treatments: PCT (green), PCT+CT (orange), and NT (red line).

Stem growth volume (BF/AC/YR) are shown in Figure 10. Growth steadily increased following regeneration in the PCT and PCT+CT simulations. Growth decreased in the PCT simulation in 2087 as a result of the decreased stocking following lodgepole pine mortality. Growth decreased in the PCT+CT simulation in 2097 as a result of the decreased stocking following commercial thinning in 2087. There was no significant difference in growth between the PCT and PCT+CT simulations in 2137. Growth steadily decreased over time in the NT simulation as a result of decreased stocking caused by mortality.

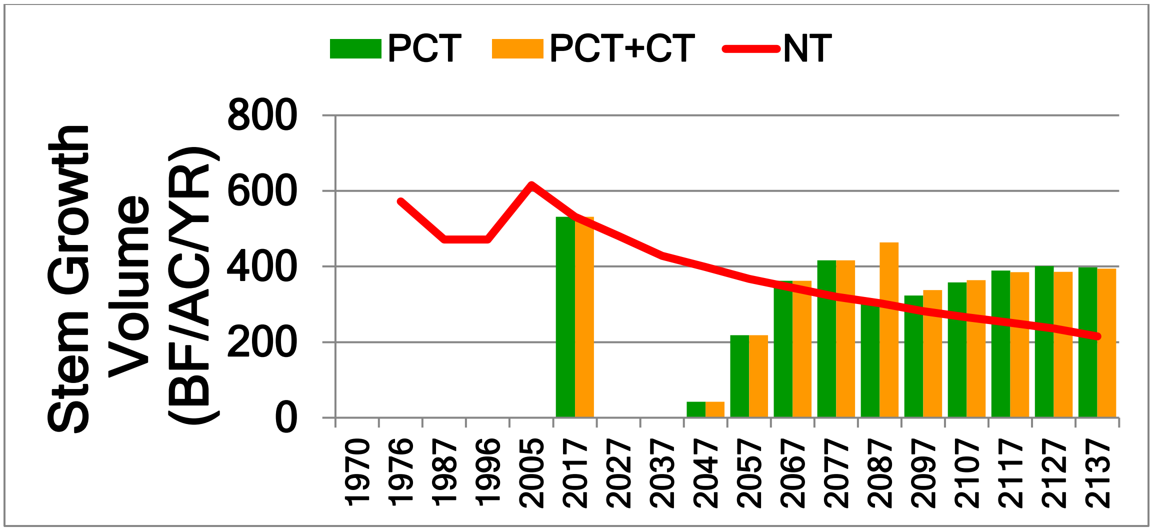

Figure 10. Volume of stem growth (BF/AC/YR) over time for three treatments: PCT (green), PCT+CT (orange), and NT (red line).

Mortality over time is shown in Figure 11. Mortality was insignificant following regeneration in the PCT and PCT+CT simulations. Lodgepole pine mortality spiked in the PCT simulation in 2087. By 2137 there was no significant difference in mortality between the PCT and PCT+CT simulations. Mortality remained high over time in the NT simulation.

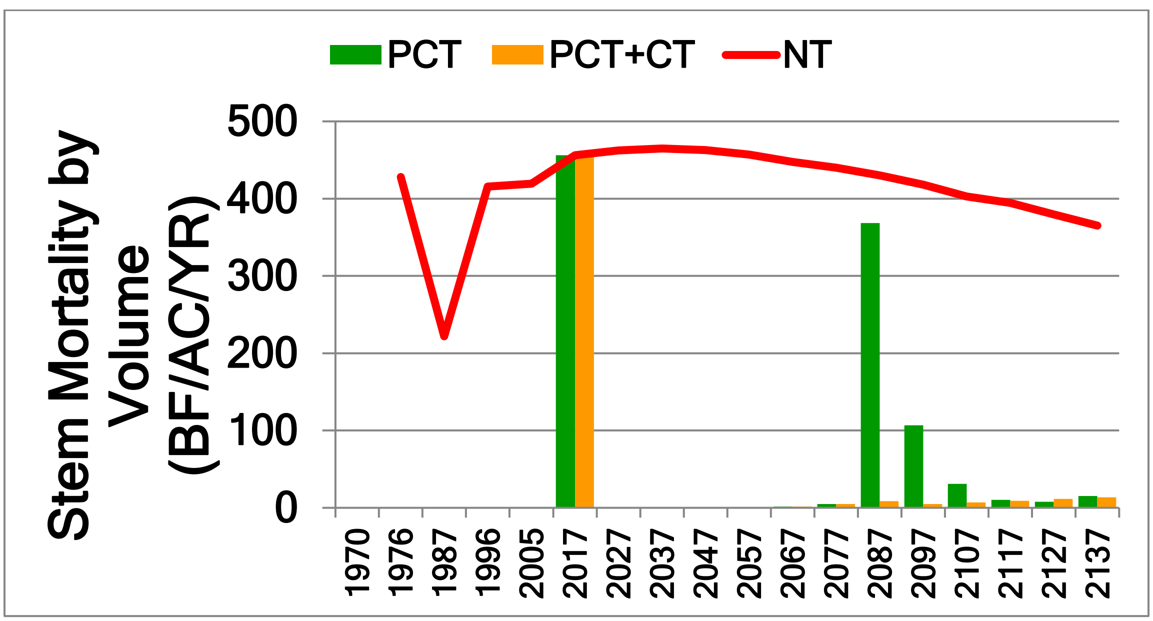

Figure 11. Volume of stem mortality (BF/AC/YR) over time for three treatments: PCT (green), PCT+CT (orange), and NT (red line).

Harvest volume over time is shown in Figure 12 and total harvest volume is shown in Figure 13. Harvest occurred in 2017 and 2137 in the PCT simulation. Harvest occurred in 2017, 2087, and 2137 in the PCT+CT simulation. Harvest only occurred in 2137 in the NT simulation.

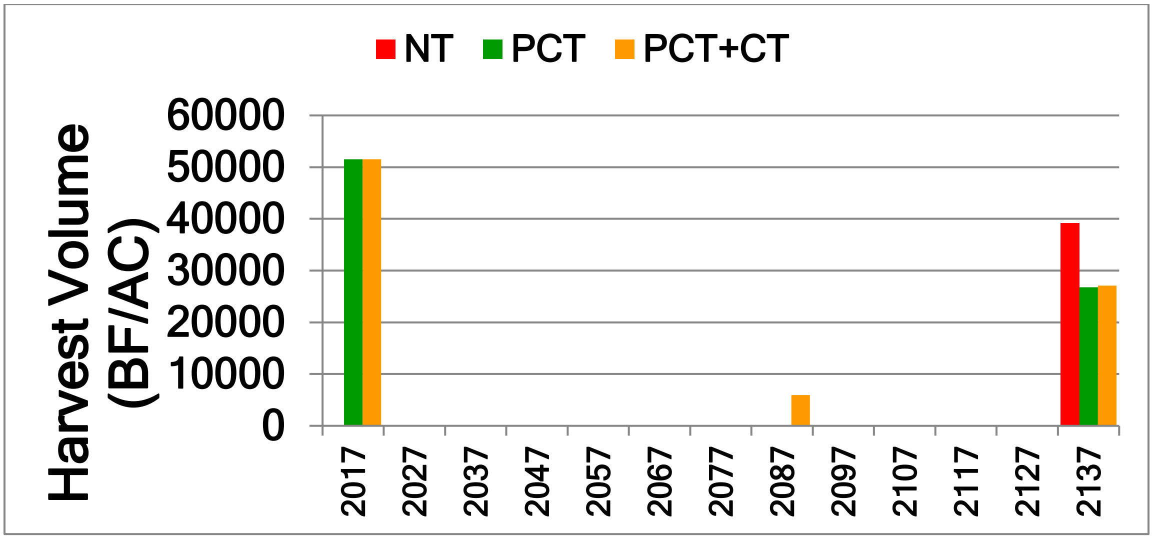

Figure 12. Tree harvest volume (BF/AC) over time for three treatments: PCT (green), PCT+CT (orange), and NT (red).

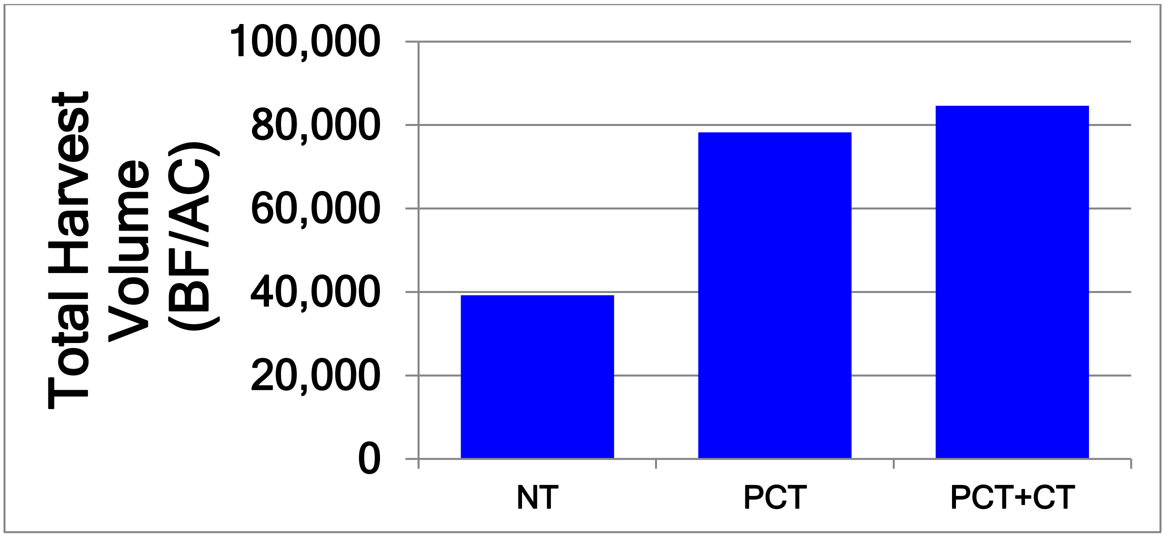

Figure 13. Total tree harvest volume (BF/AC) for three treatments between 2017-2137: PCT, PCT+CT, and NT.

The greatest total harvest volume occurred in the PCT+CT simulation. The extra 6,000 BF/AC harvested in the 2087 CT would make the CT an economically viable operation.

The steady rate of mortality in the NT simulation would result in increasing amounts of fuel accumulation in the stands, which would, therefore, greatly increase the wildfire hazard. These stands burn infrequently but when they do burn they burn at very high intensity and the likelihood of environmental damage, *e.g.*, soil erosion and stream siltation, is greater.

Discussion

Tree Mortality in Upper-elevation *Abies amabilis* Habitat Type

Yakama tribal people have lived intimately on the land of Washington State for millennia. For thousands of years the Yakamas lived upon diverse landscapes across the Pacific Northwest that ranged from the low-elevation grasslands, oak woodlands, pine forest, and further into higher elevation mixed conifer forests (Agee 1993). For the Yakama tribal people, upper-elevation forests provide clean water, foods, and medicines. Access to these resources is being challenged by the forest health issues on the Yakama Reservation. The WA DNR Forest Health Program report (2017) was a state-level assessment that reported model results for which tree species would experience higher mortality rates and their causal factors. It was not designed nor can it be used to assess placed-based forests in a region of Washington State. This research study expands on this report by providing detailed assessment of tree growth and mortality for individual tree species found growing in the upper-elevation forests on the Yakama Reservation.

To address Question 1 [*Within the upper-elevation Abies amabilis habitat type, what are the growth and mortality rates of the different tree species?*], stand data was obtained from 59 Continuous Forest Inventory (CFI) plots that were measured from 1970 to 2005. The diversity of trees founds in the Pacific silver fir habitat type is very clear from the distribution of stem volumes of the 13 dominant and codominant trees found in these inventory plots. The Yakama Nation has managed these forests to maintain a diversity of tree species on their lands since they all contribute to the wood markets and the collection of medicinal plants and cultural foods. The climate change impacts on the mortality of most of these trees species was apparent from the summarization of the mortality data by species in these 59 CFI plots. These mortality data are annual so this does not show the cumulative impact of continuing mortality of tree species.

The Pacific silver fir habitat type includes coniferous shade-tolerant species with a highly structured arrangement of connected canopies of subalpine fir (*Abies lasiocarpa*), Pacific silver fir (*Abies amabilis*), grand fir (*Abies grandis*), and noble fir (*Abies procera*), and mountain hemlock (*Tsuga mertensiana*) (Franklin, 1964). It is the diversity of tree species found in these upper-elevation forests that are important for the wood markets and being able to collect cultural foods and medicines in the Yakama Nation. This diversity is threatened by climate change as some trees are more vulnerable to be lost as part of the forest. This study recorded that a stand level 2005 mortality rate was 1.4%. Also, a large proportion of the mortality was found with whitebark pine (13.6%), followed by lodgepole pine (5.2%), western white pine (3.8%), subalpine fir (3.5%), and Engelmann spruce (1.1%). The mortality rate for Pacific silver fir was similar to what are recorded annual mortality rates for natural forests globally but subalpine fir had mortality rates that were increasing from the baseline rates.

The baseline mortality rates of 1% or less are commonly found for naturally growing forests in temperate and tropical regions of the world. In the U.S., FIA data reported 1.16% mortality rate of natural forests between the years 1952-2012 (USDA FS-1035 2014). Studies conducted in the Pacific Northwest U.S. and western Canada report similar baseline mortality rates during non-disturbance periods. They are useful comparisons to make with the Yakama Reservation CFI plots since it suggests how much the recorded mortality rates deviate from normal rates. In the western U.S., van Mantgem et al. (2009) reported how changes in tree mortality rates were directly and positively correlated to water deficits resulting from climate change. In the latter study, upper-slope forests had annual mortality rates of 0.5% per year with no water deficits (measured in 1960) that increased to twice the levels with water deficits (2000); *Pinus* mortality rates had increased to 2% by 2000. In western Canada, aspen mortality rate annually increased after the 2001-2002 drought from 1.24% to 3.08% in 2006 (Natural Resources Canada 2017). The latter study shows how forests continue to experience high mortality rates when rainfall levels have not returned to normal levels, *i.e.*, the effects of the droughts are chronic and not acute.

The higher mortality rates of some species such as whitebark pine, western white pine, lodgepole pine, and Engelmann spruce suggest that these species have a lower tolerance to water deficits and the increased outbreaks of secondary disturbance agents. These tree species will continue to be highly vulnerable to drought and/or high temperatures so climate change will impact management's ability to retain them as part of a managed forest. For example, lodgepole pine is less tolerant of higher temperatures but grows well even when water deficits limit the growth of other species (Moir 1969; Stephens 1966). In contrast, Engelmann spruce has a low tolerance to drought and also higher temperatures (Hellmers et al. 1970) which make them more susceptible to the spruce beetle attack (Schmid and Frye 1977).

Tree species that had higher mortality rates appear more vulnerable to climate change and will significantly reduce the ability of the tribal members to collect resources from their forests. These forests will provide less wood to be sold to markets and there may be a reduction in the collection and access to medicinal plants and cultural foods. If Engelmann spruce mortality rates increase, the several medicinal plants and cultural foods this species provides would be lost (*e.g.*, bud tips are edible; bud tips boiled into a tea that is incredibly high in Vitamin C; needles can be used as a seasoning much like rosemary; and spruce can be used in construction).

Some tree species appear to be better adapted to climate change and its secondary impacts since mortality rates did not increase during droughts for mountain hemlock, western hemlock, Douglas-fir, red cedar, grand fir, western larch, ponderosa pine. These trees appear to have a higher threshold to climate change impacts before becoming vulnerable to experiencing lower growth rates. However, this study also suggests that even tree species shown to have normal mortality rates in 2005 may still be vulnerable to future extreme climatic events. All of the tree species that did not experience high mortality rates are vulnerable to changes in seasonal precipitation levels and snowpack levels because of their impact on soil moisture levels. For example, droughts are linked to lower precipitation inputs during particular times of the year, *i.e.,* spring and summer, and if the melting of the snowpack occurs more quickly so soil moisture levels will not be maintained (WA DNR Forest Health Program 2017). For example, despite Pacific silver fir having a low mortality rate in 2005, it needs adequate moisture in the soil during the summer months and the growing season to grow. Therefore, reduced snowpack levels have the potential to negatively impact Pacific silver fir growth (Franklin and Dyrness 1973). Similarly mountain hemlock grows where there is adequate moisture (Brooke et al. 1970; Parson 1972) but such conditions may not exist if the drought data published by WA DNR Forest Health Program (2017) is realistic; mountain hemlock should be vulnerable to the extreme droughts that occurred on the Yakama Reservation in 2015.

Some of the species appeared to be less vulnerable to drought, *e.g.,* western hemlock, but are susceptible to the increased frequency of fire. Western hemlock commonly experiences die back when growing on drier sites (Krajina 1969; Pfister et al. 1977) which would contribute fuel for wildfires. So even though western hemlock did not experience higher mortality rates in 2005, it is particularly impacted by the changes in the disturbance cycles such as fire. Western hemlock is very susceptible to fire in a landscape where the frequency of wildfires has increased. In contrast some of the tree species need fire to grow in these upper-elevation forest areas and would expand their range and be more competitive growing in mixed conifer stands, *e.g.*, lodgepole pine and western larch. Western larch is limited to cool climatic zones and soil moisture deficits limits it range but needs fire to remain part of a forest stand (USDA FS 1965; Davis 1980).

In summary, the research results from this study suggest that it will be difficult to maintain a diverse forest composition and distribution in the upper elevations of the Yakama Reservation. The large number of species that grow at these elevations are especially vulnerable to drought and are already experiencing higher mortality rates. These mortality rates are two to ten times higher for these species compared to the natural rates of mortality. Van Mantgem *et al.* (2009) suggested that "..widespread hydrologic changes..declining fraction of precipitation falling as snow..declining snowpack water content .. earlier spring snowmelt and runoff .. consequent lengthening of the summer drought." The key point of the latter study was that temperature and water deficits were directly correlated to tree mortality.

The implications of this study and others are that the forest composition will change and the ecosystem services that forests provide may be lower or no longer available. It also suggests that forests will be less diverse and therefore less resilient to future climate change impacts. Therefore the next discussion needs to address what, if any, silvicultural practices can be used to mitigate and restore forests structure and function so forests continue to provide multiple resources to the Yakama Nation. This addresses the fundamental question of what role management can have in restoring a diverse composition of trees and a healthy forest. It is critical to know whether management practices can be used to mitigate the differential impacts of climate change on tree species.

Silvicultural Treatments or No Management to Restore a Diverse and Healthy Forest

Good forest management practices have been implemented for centuries to develop forest ecosystems and to enhance a forest's ability to deliver environmental, socio-cultural and economic functions. Today, climate change makes it more challenging for silvicultural practices to achieve their goals and to develop the tools to restore unhealthy forests. It is important for forest managers to be able to implement management practices capable of producing the desired range of conditions in a forest that results in healthy forests. When there is selective mortality of some tree species in a mixed and diverse forest stand, it becomes important to determine what options are realistic to address changes in forests due to climate change. This discussion will address the 2nd and 3rd questions driving this research:

- Should forests be left alone to recover without management following any disturbance that causes extensive tree mortality?
- What combination of silvicultural options can be used to manage upper-elevation forests to restore the composition and diversity of the stands?

It was critical to predict whether no treatment or silvicultural treatments would result in restoring forest health and re-establishing the diversity of these upper-elevation forests following large scale mortality due to drought and the secondary disturbances, *e.g.,* pests and pathogens. Since the future desired condition is what is important to assess, simulations were used to compare a 'No Treatment' (NT) simulation where mortality rates matched the 2005 CFI results, and two silvicultural treatments designed to re-establish the diversity of species in these forests. The silvicultural treatments were clearcut harvest in 2017, and then planted with 100 trees per acre each of Douglas-fir, western larch, western white pine and 50 trees per acre of Engelmann spruce. In the silvicultural simulations, lodgepole pine was naturally regenerated at 100 trees per acres in these stands. One of silvicultural treatments included a harvest of lodgepole pine before large scale mortality is commonly found with this species.

Based on this research, the 'No Treatment' option is predicted to continue the significant levels of tree mortality at the upper elevations. Therefore, implementing 'No Treatment' in forests would accelerate the loss of the highly diverse forests that has been common in this region. The NT simulation predicted a continued decrease in volume growth rates and higher mortality rates. Some of this can be explained by the predicted climatic conditions of lower precipitation levels and less snowpack that will occur in Washington. Under the 'No Treatment' simulation, species range shifts are likely to occur and the composition of trees in YN forests will decrease in upper-elevation forests. The changing climatic conditions are further altering the disturbance cycles by increasing the fire frequency and increasing insect outbreaks such as the mountain pine beetle (Littell et al. 2009). Climate model predictions for the Pacific Northwest U.S. "… that more than two million acres will burn in a given year is projected to increase from 5% (observed) to 33% by the 2080s." (US Fish & Wildlife Service 2017). Most of these tree species are not adapted to fire (except for lodgepole pine) and are very susceptible to multiple pests and pathogens – all factors that will contribute to further reduce the diversity of trees growing in these upper-elevation forests on the Yakama Reservation. A NT scenario will likely result in a decrease in diversity of tree species in the upper elevations for YN forests and loss of medicinal plants and cultural foods.

The simulations conducted for this study suggest that there is a need for implementing silvicultural treatments to mitigate and restore the health of upper-elevation forests. The continued impact of climate change on the growth of these forests also suggests that these forests cannot be allowed to ‘recover’ without management intervention. The option of ‘No Treatment’ being applied in upper-elevation forests would result in a continued decrease in growth rates of the stand due to decreased stocking density of trees. The high mortality rates are due to drought and pests/pathogens continuing to cause tree mortality. The simulations suggested that there would be a 30% reduction in the growth of these upper elevation forests if no silvicultural treatments were practiced in these forests over a 40-year time span. Further, the simulations suggest that mortality rates for both silvicultural treatments would return to natural levels after the clearcutting and planting appropriate tree species for the sites. The only significant increase in mortality occurs when lodgepole pine experiences natural mortality after about 80 years of growth (Amman et al. 1977).

Not only do the silvicultural treatments provide the best long-term economic option but they would enable forest managers to maintain a diversity of tree species and healthy forests. Not only do forest managers need to address the decreases in the stocking density of these upper-elevation forests but also the quality of the wood decreases as stem decay becomes more prevalent. Pacific silver fir is very susceptible to the balsam woolly adelgid, which has been reported to “reduced growth for many years; attacks on the stem usually cause a tree to die within 3 years.” Mountain hemlock and western hemlock are very susceptible to heart rot by the

Indian paint fungus (Fowells 1965). Therefore these forests would need to be managed to reduce these negative impacts on tree growth. Further, the poor quality of this wood would mean that its future uses would be mainly pulp instead of more diverse types of wood products.

This study's simulations suggest multiple benefits of implementing silvicultural treatments in these upper-elevation forests. For example, the volume growth of the planted trees would steadily increase as the trees grow and reach relatively similar volume growth following a precommercial thinning - an effect that appeared to last for over 100 years. The main difference between the two silvicultural simulations are related to lodgepole pine which naturally dies after about 80 years of growth. However, sites where lodgepole pine are managed, produce similar volumes just 10 years after treatment. The simulation also suggests that the total harvest volume 120 years after the regeneration harvest would be higher in both of the silviculturally-treated stands compared to the non-treated stands. This result is important for the YN and its ability to provide employment and generate revenue from its forests. The simulation with the combination of planting, precommercial thinning, and commercial thinning produced the highest volume growth and therefore would provide the most economically viable operation in these forests.

This study suggests that whitebark pine, western white pine, lodgepole pine and Engelmann spruce already are experiencing high mortality rates in the upper-elevation forests today. They will continue to be especially vulnerable to continuing changes in Washington's climate conditions. At the same time, some co-dominant tree species growing in these same stands appear to be better adapted to climate change since their annual mortality rates did not increase in 2005 (*e.g.*, mountain hemlock, western hemlock, Douglas-fir, redcedar, grand fir, western larch, ponderosa pine). But these tree species may be vulnerable to extended periods of climate change because they are susceptible to the long-term reductions in snowpack levels and the timing of precipitation (Franklin and Dyrness 1973; van Mantgem et al. 2009). This is another reason why the ‘No Treatment’ should not be pursued. The continuing changes in climates will be briefly discussed to suggest the importance of implementing silvicultural treatments if the Yakama Nation will continue to supply wood markets and collect medicinal plants and cultural foods from their forests.

Silvicultural Treatments Essential to Address Long-term Climate Impacts for Healthy Forests

There is strong evidence from climate models that extreme climatic changes in temperatures and precipitation [especially drought, less precipitation in the spring and summer months] will continue to decrease the health of Washington’s forests. The models predict climate change will directly cause tree mortality in Washington State and increase the outbreaks of secondarily pests and pathogens on already stressed trees. Several models have predicted the continuing impact of climate change on forests in Washington State and the occurrence of extreme weather events. According to the WA DNR Forest Health Program. 2017, “Drought conditions and warm, dry spring weather tend to increase tree stress and insect success, driving acres of damage up in both the current and following year… According to the US Drought Monitor, all of Washington was in an abnormally dry condition during summer 2016, with the southwest and southeast areas of the state experiencing moderate drought at times… Approximately 2.4 million trees were recorded as recently killed in 2016.” This study provided evidence that the high mortality rates are occurring in the upper-elevation forests and growth is not balancing the tree volume losses due to tree mortality. The high tree mortality rates are supported by the much lower precipitation levels in Washington State, and also on the Yakama Reservation, between 1981 and 2010.

Based on the data provided in the WA DNR Forest Health Program (2017), in 2016 the Yakama Reservation experienced from 110 to 200% departure or lower precipitation levels from the 1981 – 2010 normal precipitation levels in 2016.

According to the WA DNR Forest Health Program 2017, drought conditions were not as serious in 2016 as in 2015 (Figure 14). Despite 2016 not being as bad of a drought year, the low spring rainfall during the spring of 2016 caused "*the entire state being abnormally dry with moderate drought conditions*". They further reported "*A severe drought in 2015 resulted in wide-spread damage evident by late summer. Many affected conifers remained green for months as the weather cooled over winter. Then with record-breaking heat in spring 2016, delayed symptoms became more noticeable and widespread…These trees likely had a delayed response to the previous year's drought conditions. The 2016 aerial survey showed increases in ponderosa pine killed by western pine beetle and grand fir killed by fir engraver. Attacks by these bark beetle species often increase following drought events.*" (WA DNR Forest Health Program. 2017). This report by the 2017 WA DNR Forest Health Program supports the idea that these mortality events are not just a one-time occurrence as stressed trees are attacked by secondary disturbance agents. This further supports the idea that these unhealthy forests will not recover if no management is implemented on the stands. Since the forests provide many things to the Yakama Nation, *e.g.*, commercial wood products, medicinal plants, and cultural foods, a 'No Treatment' option would have a significant impact on the YN.

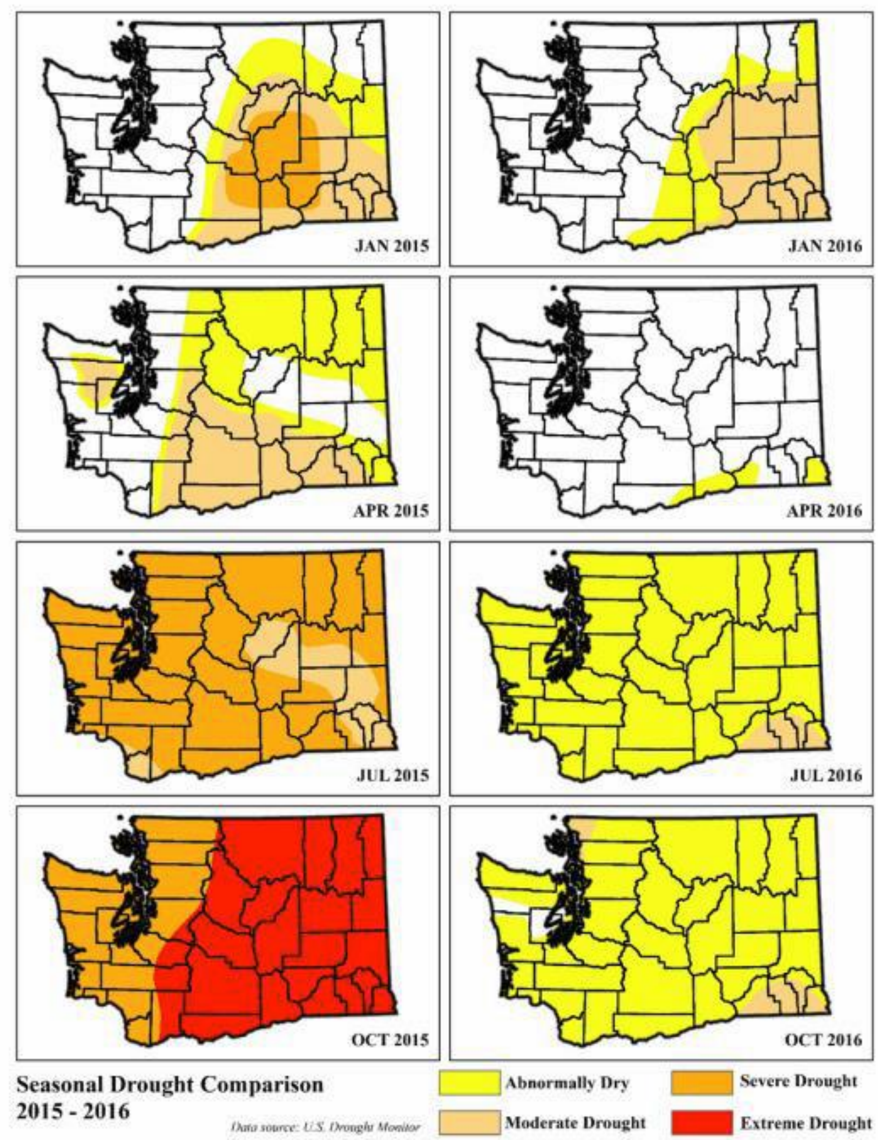

Figure 14. Drought severity in Washington State in 2015 and 2016. Figure Key: Yellow = Abnormally Dry; Light Orange = Moderate Drought; Darker Orange = Severe Drought; Red = Extreme Drought. SOURCE: WA DNR Forest Health Program. 2017

The results of this research support the recommendations made by the UW Climate Impacts Group that silvicultural treatments are needed to restore or mitigate climate impacts on forests, especially the upper-elevation forests. The UW Climate Impacts Group has predicted many tree species will have very reduced ranges and suggested areas climatically suitable for Douglas-fir, pine species and subalpine forests will all decline (http://cses.washington.edu/db/pdf/snoveretalsok2013sec7.pdf). The Climate Impacts Group at UW have also predicted "*Warmer temperatures will result in more winter precipitation falling as rain rather than snow throughout much of the Pacific Northwest, particularly in mid-elevation basins where average winter temperatures are near freezing*." (US Fish & Wildlife Service 2017). This means that it is not an option to allow forests to recover on their own without the intervention of silvicultural practices. If forests are allowed to recover on their own, the diversity of the forests will be lower, the quality of the wood will be poorer, and the many medicinal plants and cultural foods that the forests provide will be less available.

Another cultural food – salmon – can also be impacted by not managing forests to restore their volume growth and diversity. The presence of forests and water flow/temperatures in rivers are linked so maintaining healthy forests is essential for salmon survival. According to NRC (2008), two-thirds of U.S. fresh drinking water originates from forestlands. This fresh water is also important for salmon since the waters originating in healthy forests are cooler. The UW Climate Impacts Group used models to predict by the 2040s that the rise in river temperature may become fatal for salmon (Figure 15). A decrease in density of trees and a potentially lower snowpack would also further exacerbate the flow of the water from forests to the lowlands and further impact the viability of salmon populations. Therefore, not only are forests impacted by climate change but cultural foods such as salmon are also impacted by what happens in forests and, therefore, forest management needs tools to mitigate climate change impacts. The physiological characteristics of true fir species provide an assemblage of overlapping cover for high-elevation watersheds essential to conservation of water quality (Franklin *et al.* 1981).

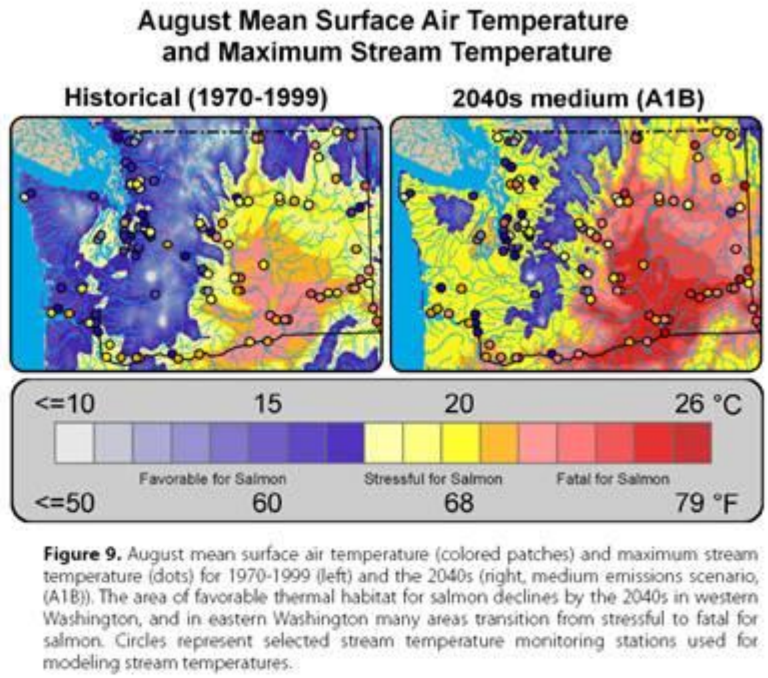

Figure 15. Predicted changes in air and stream temperatures compared to historical levels (UW Climate Impacts Group 2017).

The context of the changes in temperature and precipitation levels in Washington State and the recorded widespread mortality of trees provides explanations for the increased mortality that was measured during this research. The climate change discussion supports the need for active management of the forests to maintain their health and diversity of tree species. This research did not focus on measuring the links between climate change and the secondary impacts of diseases and pests but aimed to document the changes in the growth and mortality of a diversity of tree species that comprise the upper-elevation forests on the Yakama Reservation. This study also highlights the need to recognize that past land-use activities or decisions affect the current conditions. It also calls for the need to protect or enhance cultural resources in upper-elevation forests and provides evidence that management is compatible with protecting/restoring cultural resources important for the Yakama Nation. The unprecedented changes in climates make this even more challenging and create the need to consider all cultural resources and try to find a balance that will enhance cultural resources including clean water, plant species and wildlife. It also hopefully provides information about Yakama Nation's forest management options that can be used to make decisions on forests and how to increase certain tree species in unhealthy forests.

Conclusions

GROWTH/MORTALITY BY TREE SPECIES:

- Higher mortality of whitebark pine (13.6%), lodgepole pine (5.2%), western white pine (3.8%), subalpine fir (3.5%), and Engelmann spruce (1.1%) suggest these species have a lower tolerance for changes in climatic variables
- Stand-level 2005 mortality rate was 1.4% compared to ~1% during non-disturbance years
- Normal mortality rates for mountain hemlock, western hemlock, Douglas fir, redcedar, grand fir, western larch, ponderosa pine suggest these species are better adapted to climate change. But they are vulnerable to future extreme climatic events that change moisture conditions during the growing season. These tree species currently grow in areas where the melting of the snowpack maintains soil moisture levels.

SILVICULTURAL TREATMENTS SIMULATIONS:

- Option 'No Treatment' = continued decrease in growth rates of the stand due to decreased stocking density of trees. High mortality rates due to drought, pests/pathogens will continue to cause tree mortality.
- Option 'No Treatment' = a 30% reduction in the growth of these upper-elevation forests if no silvicultural treatments were practiced in these forests in a 40-year time span.
- Option 'No Treatment' = Steady rate of mortality would increase amounts of fuel building up in the stand, which would greatly increase wildfire hazard. These stands burn at very high intensity and the likelihood of environmental damage, *e.g.*, soil erosion and stream siltation, is greater.
- Converting the over-mature stands to young, vigorous stands would provide jobs, revenue and maintain forest habitat on a sustainable basis.

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