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# Modeling the Effects of Climate Change on Western Larch Stands in Idaho

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# TABLE OF CONTENTS

## Abstract

Climate change research has shown irrefutably that global temperatures are rising, and almost all climate-model projections agree that in the coming decades the western US is likely to experience warmer springs and summers. Hotter and drier conditions are a concern for the future of western forests because climate is an important factor in determining plant distributions. The general effects of climate change on forests include a significant increase to the variability in disturbance regimes, shifts in species ranges, or a shift in germination and establishment requirements. Adding to the complexity of challenges faced by western forests are the poor land management practices of the 20th century, such as fire suppression and high-grade logging, which have led to an adverse change in forest structure including a decline in shade intolerant species such as western larch (*Larix occidentalis*). We modeled the growth and yield effects of climate change on western larch stands in two United States Forest Service (USFS) national forests in Idaho. The Idaho Panhandle National Forests (IPNF) in the North contain core western larch habitat, and the Boise National Forest (BNF) in West Central Idaho represent the southernmost edge of its range. By modeling silvicultural actions, we provide resistance and resilience climate change adaptation strategies for sustaining western larch in the BNF and IPNF. Our results showed that by increasing growing space and available light, nutrients, water and managing horizontal and vertical structure we can improve forest resistance and resilience. Without active management western larch growth, vigor, and abundance will likely decline in the BNF and IPNF as the climate continues to change.

# Section I: Introduction

## Section 1.1. Climate Change

Climate change research has shown irrefutably that global temperatures are rising (e.g. Thomas et al. 2001; Walther et al. 2002; Parmesan and Yohe 2003; Root et al. 2003; Rehfeldt et al. 2006). The Intergovernmental Panel on Climate Change (IPCC) estimates that global average temperature has risen 1.5°C over the past 22 years (Figure 1), and that much of the intermountain western United States has received 5-15 percent less precipitation (IPCC 2014). Additionally, almost all climate-model projections agree that in the coming decades the West is likely to experience warmer springs and summers (Westerling et al. 2006).

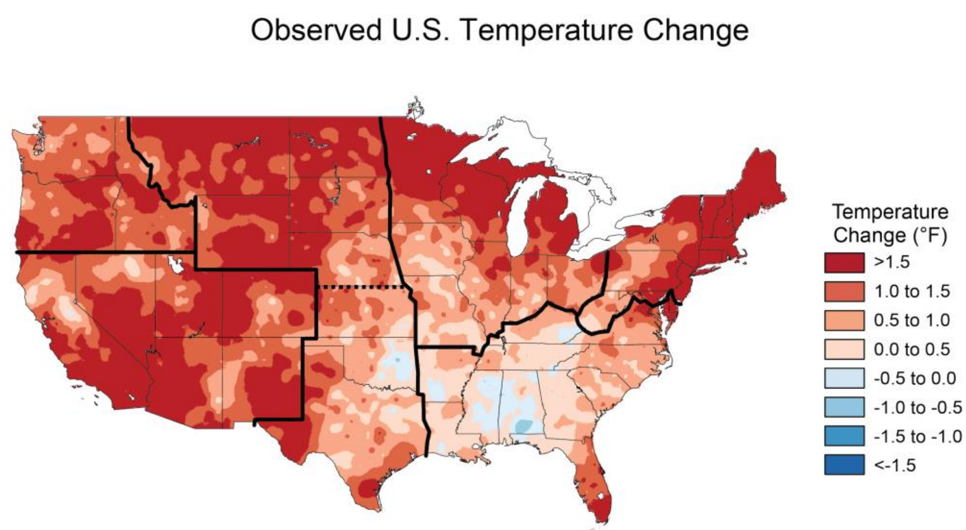



Figure 1. The colors on the map show temperature changes over the past 22 years (1991-2012) compared to the 1901-1960 average. The bars on the graphs show the average temperature changes (relative to the 1901-1960 average) for each region. (Figure source: http://nca2014.globalchange.gov/)

Hotter and drier conditions are a concern for the future of western forests because climate is an important factor in determining plant distributions (e.g., Woodward 1987; Rehfeldt 2010). Given this relationship, it can be expected that as temperatures rise, many tree species may be adversely affected. The general effects of climate change on forests include a significant increase to the variability in disturbance regimes (Miller et al. 2009; DeRose and Long 2014), shifts in species ranges (Rehfeldt et al. 2006, DeRose and Long 2014), or a shift in germination and establishment requirements (McKenney et al. 2009; DeRose and Long 2014). According to the Fourth National Climate Assessment (CSSR 2017) widespread tree die-off has occurred because of the negative effects associated with climate change, such as increasing wildfire, insect outbreaks, and tree diseases.

Adding to the complexity of challenges faced by western forests are the poor land management practices such as fire suppression of the 20th century (Westerling et al. 2006). These management practices have led to a change in forest structure (increased vertical complexity, tree density, crown connectivity, etc.) that have adverse effects on western larch growth, vigor, and abundance, and a shift in forest composition (establishment of shade tolerant/non-fire adapted tree species) throughout the west (Hessburg et al. 2005). Because of this, western forests are less resistant to drought (Westerling et al. 2006). There is a growing need to understand the effects of climate change on forest tree species growth and distribution, to assist land management agencies such as the United States Department of Agriculture Forest Service (hereafter USFS) in sustaining forested land. As of 2013, the USFS managed 193 million acres of land across 154 national forests and 20 grasslands, providing 20 percent of America's clean water supply (USDA.a).

Section 1.2. Land Management and Western Larch

The USFS National Forest land within the range of western larch in Idaho is the region of interest for this study. The National Forests in Idaho contain core western larch habitat in Northern Idaho as well as the edge of its range in West Central Idaho (Figure 2). Comparing the effects of climate change between the core and edge portions of western larch habitat can provide important insight about the future of western larch for land managers in Idaho.

**USFS National Forests**

The USFS Boise National Forest (BNF) and Idaho Panhandle National Forests (IPNF) recognize the threat of climate change and have explicit management objectives to foster more resilient forests, and maintain or increase the composition of long-lived, early successional, drought- and fire-tolerant tree species, such as western larch (*Larix occidentalis*; USDA.b; USDA.c; USDA.d), which occurs across much of the BNF and IPNF.

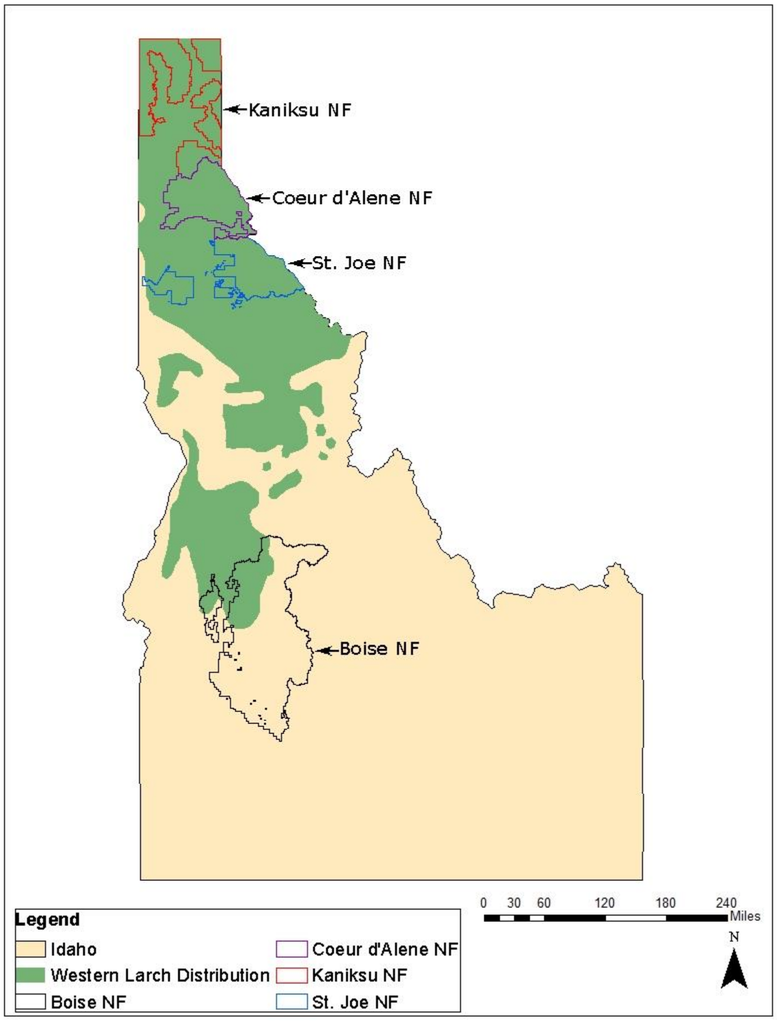



Figure 2. The Boise National Forest, Idaho Panhandle National Forests, and western larch distribution across Idaho.

## Western Larch

Western larch is a valuable timber species that fulfills important forest ecosystem functions (Schmidt and Shearer 1990). It is quick to reforest areas that have experienced a loss in trees due to disturbance (Schmidt and Shearer 1990), such as wildfire or logging. Reforestation provides protection for watersheds, and other important ecosystem services (Schmidt and Shearer 1990). Western larch grows in relatively cool-moist climatic zones, with low temperature limiting its upper elevational range, and deficient moisture limiting its lower elevational range (Schmidt and Shearer 1990). The continental range of western larch includes the Upper Columbia River Basin of northwestern Montana, northern and west central Idaho, northeastern Washington, and southeastern British Columbia; along the east slopes of the Cascade Mountains in Washington and north-central Oregon; and in the Blue and Wallowa Mountains of southeastern Washington and northeastern Oregon (Figure 3; Schmidt and Shearer 1990).

Figure 3. Distribution of western larch (green polygon) across the western US and Canada (Little E.L. 1980).

## Study Approach

Many studies in the last two decades have been conducted to describe the responses of forest trees to warming climate (e.g. Rehfeldt 2006; McKenney et al. 2007; Tchebakova et al. 2005, 2010; Gómez-Mendoza and Arriaga 2007; Iverson et al. 2008; Rehfeldt and Jaquish 2010). This study however, approaches the growth, yield, and distribution responses of western larch to climate change through the lens of a land manager in the USFS. The large task of managing national forests for resilience to climate change falls to USFS land managers. Traditionally, land managers have used highly valuable approaches, such as ecological sustainability, historical variability, and ecological integrity to guide land management decisions (Lackey 1995; Landres et al. 1999; Millar et a. 2007). In addition to these more traditional approaches, climate change is creating a need to develop multiple strategies, both short- and long-term, that consider adverse climate change effects, as historical conditions become less likely in the future (Millar et al. 2007). Silviculture can be used to recruit or sustain western larch on the landscape and provide for climate change adaptation through resistance, resilience, and transition strategies (Millar et al. 2007; Nagel et al. 2017).

A resistance strategy involves manipulating forest stand structure so it can absorb or resist the negative effects of climate change (Parker et al. 2000; Millar et al. 2007). It can be thought of as maintaining the status quo (Parker et al. 2000; Millar et al. 2007). Effective resistance treatments reduce the negative impacts of extreme disturbance events (Agee and Skinner 2005; Millar et al. 2007). Resistance is more short-term than resilience (Millar et al. 2007). Forests are resilient when they undergo change due to a major disturbance event, which alters the forest conditions, but are then able to return to a similar prior condition, either through natural means or with management assistance (Millar et al. 2007). Resilience is most readily achieved through manipulating structure, composition, and function (Millar et al. 2007; Nagel et al. 2017). Resilience is not a panacea (Millar et al. 2007). More extreme management actions, such as a transition strategy, may be necessary to keep trees on the landscape. Rather than seeking to maintain or return to a condition, transition seeks to incorporate change. For example, transition may be achieved by altering forest composition, while maintaining many of the natural forest function, through facilitated species migration (Millar et al. 2007). Transition may involve drastic alterations to disturbance regimes, structure, and composition to prevent sudden and catastrophic events that could be brought on by climate change (Millar et al. 2007).

Managing western larch may become more difficult as climate changes, requiring land managers to have multiple options for sustaining western larch on the landscape. The objective of this study was to model growth and yield of stands dominated by western larch on the BNF and IPNF using different management options (no action, resistance, and resilience) under two climate scenarios (current climate and projected climate change). The results of this study can help inform land manager decision making for maintaining western larch on the BNF and IPNF.

# Section II: Methods

## Section 2.1. Study Areas

The project area is located in Idaho on the Boise National Forest (BNF) and Idaho Panhandle National Forests (IPNF). The BNF is the southernmost part of the western larch range (Figure 2) located in West Central Idaho and is made up of five ranger districts; Mountain Home, Idaho City, Cascade, Lowman and Emmett. The BNF is within the USFS Intermountain Region and is comprised of over 2.5 million acres with elevations ranging from 2,800 feet to almost 10,000 feet (USDA.e). The average annual precipitation ranges from 15 inches at lower elevations to 70 inches at higher elevations (USDA.e). The coarse-textured soils on the BNF readily take in and transmit water (USDA.e). They are primarily made up of granitic rock, with areas comprised of basalt in the west, and volcanic rock in the south (USDA.e). The BNF is approximately 76 percent forested and about 23 percent non-forested or dominated by grass, forb, or shrub species (USDA.e). The forested areas include pure or mixed stands of primarily ponderosa pine (*Pinus ponderosa*), quaking aspen (*Populus tremuloides*), grand fir (*Abies grandis*), Douglas-fir (*Pseudotsuga menziesii var. glauca*), Engelmann spruce (*Picea engelmannii*), lodgepole pine (*Pinus contorta*) and subalpine fir (*Abies lasiocarpa*; USDA.e).

The Idaho Panhandle National Forest (Northern Region) is primarily located in Northern Idaho but stretches into parts of Montana, and Washington. The IPNF is an administrative organization that oversees three national forests including the Coeur d'Alene, Kaniksu, and St. Joe National Forests, which are comprised of five ranger districts; Priest Lake, Bonners Ferry, Sandpoint, Coeur d'Alene, and St. Joe Ranger Districts (USDA.f). The IPNF contains 2.5 million acres which is about 97 percent forested land that includes pure or mixed stands of primarily ponderosa pine, grand fir, Douglas-fir, Engelmann spruce, lodgepole pine and subalpine fir (USDA.f). Elevations range from 2100 to 7600 feet (USDA.f). The IPNF receives about 58 inches of average annual precipitation (NOAA), and up to 80 inches of annual precipitation at the higher elevations (USDA.f). The IPNF features highly productive soils derived from volcanic ash (USDA.f).

Historically in dry mixed conifer forests of the Inner West, fire was the primary disturbance process (Hessburg and Agee 2003). Fire suppression and exclusion, and timber harvesting began in late 1800s which has shifted the forest composition (USDA.g; USDA.h). Long-lived early seral species such as ponderosa pine, and western larch have experienced the most significant negative effects of past management, with high-grade logging practices reducing early seral seed sources and wildfire suppression limiting opportunities for regeneration of shade-intolerant species (USDA.g; USDA.h). Western white pine (*Pinus monticola*) another once prominent long-lived early seral species has experienced an extreme decline primarily due to many recent anthropogenic and natural events (Arno 1986; Kendall 1995; Kendall and Keane 2001; Tomback et al. 2001; Keane et al. 2012; USDA.h) including the introduction of white pine blister rust (*Cronatrium ribicula*) in the 1920s (Harvey et al. 2008). These early successional species, including western larch, have been replaced across the forest by more shade-tolerant climax species such as Douglas-fir, grand fir, western red cedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), and subalpine fir (USDA.h).

The shift in forest composition away from long-lived early seral species and towards shade-tolerant species has resulted in a reduction in the growth and distribution of western larch (USDA.g). Western larch grows on a wide variety of deep and well drained soils derived from limestone, argillite, and quartzite primarily from the taxonomy orders inceptisols and alfisols and occasionally spodosols (Schmidt and Shearer 1990). The tree species most associated with western larch is Douglas-fir (Schmidt and Shearer 1990). Other tree associates include: ponderosa pine on the lower, drier sites; grand fir, western hemlock, western redcedar, and western white pine on moist sites; and Engelmann spruce, subalpine fir, lodgepole pine, and mountain hemlock (*Tsuga mertensiana*) on the more cool-moist sites (Schmidt and Shearer 1990).

## Section 2.2. Data Sources

We used common stand exam (CSE, USDA.i) data along with downscaled climate data specific to each forest stand to model stand growth and yield, and climate change. CSE data were gathered from the FSVeg database. CSE data is collected using nationally consistent protocols for collecting land vegetation information (USDA.i). CSE data are collected to describe vegetation composition, structure, and productivity (USDA.i). The CSE collection dates for this analysis ranged from 1995-2017. The stands used for this analysis were selected based on two criteria; western larch needed to be well represented (basal area ($ft.^2ac^{-1}$) greater than or equal to 30 percent), and the stands needed a known location (latitude and longitude, Figure 4). The most current CSE year associated with each stand was used, since there were multiple data collection years associated with some stands.

Table 1. The number of available common stand exams per forest, and the number of actual stands exams used.

| Total Common Stand Exams | Stands That Meet Criteria |
|---|---|
| BNF = 178,098 | BNF = 32 |
| IPNF = 4,006 | IPNF = 211 |

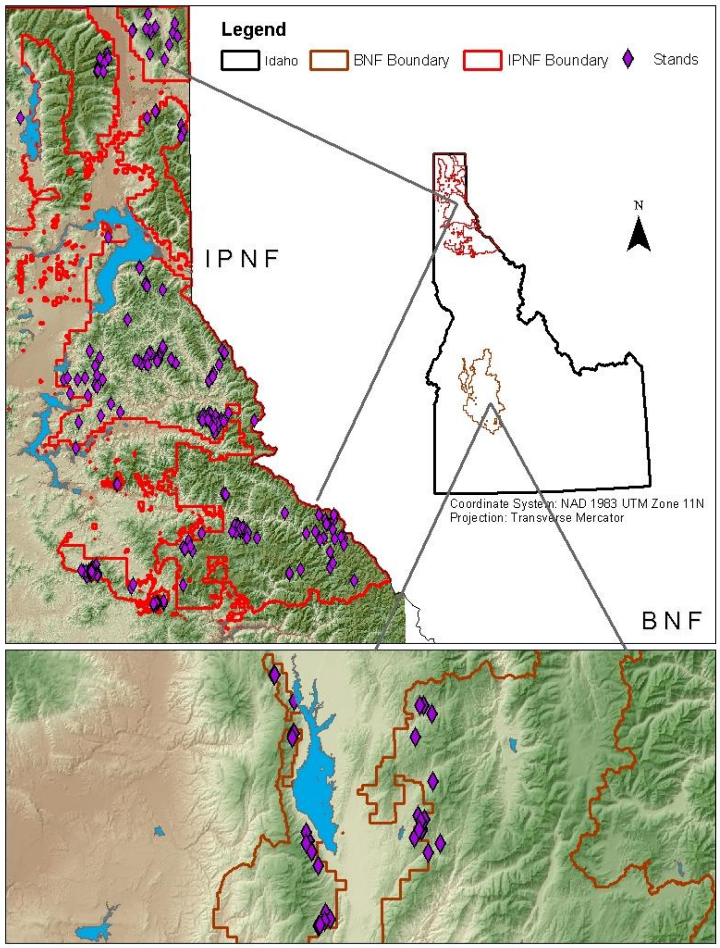



Figure 4. The 243 project stands located on the BNF and IPNF in Idaho.

To provide future global temperature alternatives, the IPCC has developed four Representative Concentration Pathways (RCPs). Each are different future climate scenarios defined by their respective estimated total radiative forcing (or the amount of human emissions of greenhouse gases in Watts per square meter) by 2100 (IPCC 2014). The RCPs are RCP2.6, RCP4.5, RCP6, and RCP8.5 (IPCC 2014). RCPs provide valuable temperature estimates applicable to forest tree growth and yield models (Crookston 2014) and was chosen for this analysis, because it represents a mid-range future scenario between the best case RCP4.5 and worst case RCP8.5.

## Section 2.3. Treatments Defined

Climate scenarios modeled for this analysis include current climate and climate change (RCP6.0). The treatment objectives are defined in Table 2. There were two management options modeled, a resistance and resilience treatment. The resistance option was modeled as a thinning treatment and the resilience option was modeled as a regeneration method.

Table 2. The management objectives for both forests.

| Objectives | | | | |
|---|---|---|---|---|
| Encourage western larch growth and yield | Reduce within stand competition | Increase proportion of shade intolerant species | Recruit large diameter (20"+) shade intolerant trees | Reduce wildfire hazard |

## Section 2.4. Desired Landscape-Scale Conditions

To achieve the treatment objectives, a multiaged silviculture system was modeled through the planned series of treatments in the form of a thin from below and single tree selection. A thin from below reduces competition for the most vigorous trees in a stand by removing trees of lower crown positions, such as overtopped or suppressed trees (Nyland 2007). A single tree selection regenerates a stand by removing individual trees or groups of trees of different sizes (Helms 1998; O'Hara 2014). Trees were divided into four diameter classes; 0-5-inch, 5-12-inch, 12-20-inch, 20-32-inch and above, based on the BNF forest plan (USDA.b). For the resistance and resilience treatments in FVS the preferred order for leave species highest to lowest was western larch, quaking aspen, ponderosa pine, and Douglas-fir.

*Species Composition*

Shade tolerance is an important factor in determining a tree species' architecture and light compensation point, or the point where respiration and photosynthesis are equal (O'Hara 2014). In the context of this study species shade tolerance is used as a proxy for resistance and resilience because shade intolerant species are more drought- and fire-adapted (Westerling et al. 2006). The tree species occurring across both forests were placed into one of three tolerance classes: shade tolerant, moderate shade tolerant, and shade intolerant. To achieve resistance and or resilience, the management objective is to increase the proportion of medium-to-large diameter early-successional tree species such as western larch and ponderosa pine.

*Density*

We have chosen to use the Zeide (2005) method of average Stand Density Index (SDI) as the driving mechanism of our resistance and resilience treatments. The Zeide method (2005) accounts for both trees per unit area, and the accumulation of gaps between tree crowns. Stand density is useful in predicting tree form, growth, and survival (Zeide 2005). SDI is broadly used to measure the ratio of relative stand density to maximum stand occupancy as an index of some measured stand value compared to a standard condition (Helms 1998; Nyland 2007). Ponderosa pine is the management species of interest with the lowest average max SDI (USDA.i) and was therefore chosen as the treatment average max SDI for this analysis. Ponderosa pine has a max SDI of 450 as suggested by (Long and Shaw 2005). This paper considers the general stand development stages and associated percent SDI maximums (Table 3).

Table 3. The stand development stages and associate percent SDI maximums.

| Percent SDI | Stand Development Stage | | |
|---|---|---|---|
| 0% | Stand initiation | Occurs after disturbance has created available growing space for new trees to establish, or smaller existing trees to grow into (Smith et al. 1996) | Not all of the space is occupied at this stage (Smith et al. 1996) |
| 0-24% | Understory reinitiation | Due to gaps created by self-thinning or management new seedlings establish under the existing trees (Smith et al. 1996) | Typically, shade tolerant species, because they can establish and grow under low light conditions (Smith et al. 1996) |
| 25-34% | Crown closure | The point in stand development when space becomes limited and trees begin to compete (Smith et al. 1996) | The transition from open-grown to competing populations (Long 1985) |
| 35-59% | Full Site Occupancy | Relative density creates active competition among trees promotes crown differentiation within cohorts (Long and Shaw 2005) | The upper range of this stage marks the threshold for the onset of density-related mortality (Long and Shaw 2005) |
| ≥60% | Self-thinning | The original cohort begins to die, individuals from subsequent cohorts grow into the upper strata (Smith et al. 1996) | The zone-of-imminent-competition-mortality (Drew and Flewelling 1979; Long and Shaw 2005) |

### *Fire Hazard*

There were two crown fire indices modeled in FVS to calculate fire hazard (torching index and crowning; Rebain et al. 2015). The torching index is the 20-foot wind speed (in miles per hour) that will carry a surface fire into the crown layer, while crowning index is the 20-foot wind speed (in miles per hour) needed to spread a crown fire (Rebain et al. 2015). Torching index variables include surface fuels, surface fuel moisture, canopy base height, slope steepness and wind reduction by the canopy (Rebain et al. 2015). It can take less wind to convert a surface fire to a crown fire as surface fire intensity increases due to increasing fuel loads, drier fuels, steeper slopes, or canopy base height decreases (Rebain et al. 2015). Crowning index is a function of canopy bulk density, slope steepness, and surface fuel moisture content (Rebain et al. 2015). Active crown fire occurs at lower wind speeds in denser stands (Rebain et al. 2015). Lower index numbers indicate a higher fire hazard, in other words, less wind speed is necessary to move a surface fire in and through a canopy (Rebain et al. 2015). Fire hazard was calculated based on the crowning and torching index matrix (Figure 5). For example, a low crowning index and a medium torching index would be given a fire hazard rating of 2 (Figure 5). A multistoried condition with dense and continuous canopy would represent a high fire hazard, or rating of 4 out of 5 (USDA.j).

```
*****************************************************************************
* Fire.kcp -- Fire Model Output Variables (Severe Fire)           01/19/2005 *
*  _CRBD   =Crown Bulk Density                                               *
*  _CRBHT  =Crown Base Height                                                *
*  _FLGTH  =Flame Length                                                     *
*  _TRIDX  =Torching Index                                                   *
*  _CRIDX  =Crowning Index                                                   *
*  _FIRE   =Fire Hazard Rating                                               *
*  _SNAGS  =Number of hard and Soft Snags per Acre                           *
*                                                                            *
*  Fire Hazard Rating: Calculated from Torching and Crowning Index           *
*   - Hazard Matrix developed by Paul Langowski & Eric Twombley (INFORMS)    *
*                                                                            *
*                      Crowning Index                                        *
*                      Low  Med  High                                        *
*                                                                            *
*              Low       L    M    M          L = Low                        *
*                      --------------         M = Moderate                   *
*    Torching  Med       M    H    VH         H = High                       *
*    Index             --------------        VH = Very High                  *
*              High      H    VH   E          E = Extreme                    *
*             =============================                                  *
*                                                                            *
*                Torching        Crowning                                    *
*                 Index           Index                                      *
*                                                                            *
*    High         15 mph-         15 mph-                                    *
*                                                                            *
*    Medium     >=16-39<=       >=16-39<=                                    *
*                                                                            *
*    Low          40 mph+         40 mph+                                    *
*    =====================================                                   *
*                                                                            *
*  Low(1), Moderate(2), High(3), VeryHigh(4), Extreme(5),                    *
*  Undefined(0) = canopy fuels so sparse, canopy base hgt undefined. CI&TI=-1 *
*****************************************************************************
```

Figure 5. The fire hazard rating matrix based on torching and crowning index relationships (USDA.j).

## Section 2.5. Management Options

### *Strategy A - No Action*

The no action contributes important information on how the stands would progress over time in the absence of disturbance. Strategy A provides a baseline against which the proposed resistance and resilience strategies can be measured and compared. Under Strategy A, no new vegetation management activities would occur. Regeneration was scheduled based on conditions explained in Table 4.

Table 4. FVS input for the no action, resistance, and resilience strategies. Note: Regeneration parameters only apply to the current climate scenario, because Climate-FVS automatically schedules regeneration.

| FVS Input | No Action | Resistance | Resilience |
|---|---|---|---|
| Max SDI | N/A | 450 | 450 |
| SDI Target Overall | N/A | 0.35 | 0.2 |
| SDI Target 0-5" Size Class | N/A | 0.07 | 0.07 |
| SDI Target 5-12" Size Class | N/A | 0.11 | 0.11 |
| SDI Target 12-20" Size Class | N/A | 0.22 | 0.22 |
| SDI Target 20-32" Size Class | N/A | 0.6 | 0.6 |
| Species Preference Western Larch | N/A | -500 | -500 |
| Species Preference Ponderosa Pine | N/A | -300 | -300 |
| Species Preference Douglas-fir | N/A | -50 | -50 |
| Species Preference Aspen | N/A | -350 | -350 |
| Western Larch Regeneration | BA<100 plant 38 TPA | BA<100 plant 38 TPA | BA<100 plant 38 TPA |
| | BA>100 plant 0 TPA | BA>100 plant 0 TPA | BA>100 plant 0 TPA |
| Ponderosa Pine Regeneration | BA<50 plant 49 TPA | BA<50 plant 49 TPA | BA<50 plant 49 TPA |
| | BA>50 plant 0 TPA | BA>50 plant 0 TPA | BA>50 plant 0 TPA |
| Lodge Pole Regeneration | BA<150 plant 52 TPA | BA<150 plant 52 TPA | BA<150 plant 52 TPA |
| | BA>150 plant 0 TPA | BA>150 plant 0 TPA | BA>150 plant 0 TPA |
| Douglas-fir Regeneration | BA<200 plant 70 TPA | BA<200 plant 70 TPA | BA<200 plant 70 TPA |
| | BA>200 plant 0 TPA | BA>200 plant 0 TPA | BA>200 plant 0 TPA |
| Grand fir Regeneration | Plant TPA= 39.0189+(0.4575xBBA*) | Plant TPA= 39.0189+(0.4575xBBA*) | Plant TPA= 39.0189+(0.4575xBBA*) |
| Englemann Spruce Regeneration | Plant TPA= 40.9216+(0.2245xBBA*) | Plant TPA= 40.9216+(0.2245xBBA*) | Plant TPA= 40.9216+(0.2245xBBA*) |
| Sub-Alpine FIr Regeneration | Plant TPA= (1.668xBBA*) | Plant TPA= (1.668xBBA*) | Plant TPA= (1.668xBBA*) |
| Fire Condition | Fuel Moisture Content (Percent) | | |
| Severe | 0-0.25" = 4 | 0.25-1" = 4 | 1-3" = 5 |
| | 3"+ = 10 | Duff = 15 | Live Woody = 70, Live Herb = 70 |
| | Wind (MPH) = 20 | Temp (F) = 70 | |
| Moderate | Fuel Moisture Content (Percent) | | |
| | 0-0.25" = 12 | 0.25-1" = 12 | 1-3" = 14 |
| | 3"+ = 25 | Duff = 125 | Live Woody = 150, Live Herb = 150 |
| | Wind (MPH) = 6 | Temp (F) = 70 | |

*BBA= Before thin basal area

*Strategy B - Resistance*

The goal of this strategy was to create a short-term solution for maintaining or increasing the current composition, and growth of early-successional species, while favoring western larch overall. The silvicultural prescription is a thin from below to an average 35 percent SDI based on a max average SDI of 450 (Table 4). Grand fir in the 0-8-inch diameter class was scheduled to be removed one year prior to treatment. Regeneration was scheduled one-year after treatment based on the parameters described in Table 4. The evaluation criteria for this treatment are listed in Table 5.

*Strategy C - Resilience*

The goal of this strategy was to create a long-term solution to allow early-successional species to undergo structural and compositional change from disturbance and return to a similar pre-disturbance condition. Strategy C is a single tree selection based on average SDI. The prescription reduces tree densities to 20 percent SDI max. Grand fir in the 0-8-inch diameter class was scheduled to be removed one year prior to treatment entry. Regeneration was scheduled one-year after treatment based on the parameters described in Table 4. The evaluation criteria for this treatment are listed in Table 5.

Table 5. The resistance and resilience management strategies evaluation criteria.

| Treatments | Evaluation criterion 1 | Evaluation criterion 2 | Evaluation criterion 3 |
|---|---|---|---|
| Resistance and Resilience | Recruitment of shade intolerant species into large tree diameter class (20+” DBH) | Average percent basal area ($ft.^2ac^{-1}$) of western larch or shade intolerant species class maintained or increased when compared to the No Action strategy | Average fire hazard rating maintained or reduced across forests when compared to the No Action strategy |

Section 2.6. Management Strategy Modeling

## Forest Vegetation Simulator

The Forest Vegetation Simulator (FVS Suppose v2.07, Stage 1973; Wykoff et al. 1982; Dixon 2002; Crookston and Dixon 2005) was used to model growth and yield of the 243 BNF and IPNF stands. In the early 1980s FVS was adopted by the USFS as the national standard for forest growth and yield modeling (Dixon 2002). It integrates analytical tools built on natural resource scientific knowledge (Dixon 2002) and consists of a collection of "variants" which are specific to different geographic areas across the country (Dixon 2002). The BNF is classified into the Central Idaho variant, and the IPNF is classified into the Inland Empire variant as defined by the FVS. The FVS is an individual-tree, distance-independent model that uses forest stands as the basic unit (Dixon 2002). Growth and yield simulations are dependent on interactions among trees within stands (Crookston and Dixon 2005). The primary tree growth, mortality, and regeneration components in FVS are computed as functions of site capacity, tree size, and competition (Dixon 2002). The FVS has a valuable tool for visualizing stand structure and composition called the Stand Visualization System (SVS; Dixon 2002). This output renders a drawing of how the stand might look on the ground (Dixon 2002). The FVS models growth and yield in the absence of climate change (Crookston 2014).

### *Regeneration*

Regeneration density was predicted as a function of total overstory basal area ($ft^2$ $ac^{-1}$). To account for regeneration in the current climate scenario, the relationship between current regeneration density and overstory basal area was assessed. Western larch, ponderosa pine, and lodgepole pine were not present below certain threshold values of overstory basal area;

these limits were used to add the average regeneration density found below these thresholds, with no regeneration added for these species at higher overstory basal area levels (Table 4). There was no relationship between Douglas-fir regeneration density and overstory basal area, thus the average regeneration density was added for all stands (with the assumption that few stands contain basal area >200 $ft^2$ $ac^{-1}$). Average regeneration density of the more shade tolerant grand fir, Engelmann spruce, and subalpine fir increased with increasing overstory basal area, and for these species a linear regression was developed to predict regeneration under different densities (Table 4). The regression equations generally did not explain most of the variation ($R^2$ 0.10-0.30) but provided the only guidance based on actual data for approximating regeneration that we had available. For the no action strategy, natural regeneration was set up to be conditional on the species-specific parameters described above and detailed in Table 4. The resistance and resilience strategies had regeneration scheduled one-year post-treatment at the same levels of the no action strategy (Table 4).

*Time scale*

To capture effects for all the timeframes mentioned above, the years 2018, 2078, and 2118 were used for a comparison between alternatives. The year 2018 represents the common starting year for all stands (Table 5). The years 2078 and 2118 represent the forest conditions 20 years post-treatment, with 2118 being the end year of the analysis.

Table 5. FVS entry timeline for both the control and climate scenarios.

| Current Climate (control) | | Scenario RCP6.0 (future climate) |
|---|---|---|
| **Year** | FVS Input | FVS Input |
| **2018** | Treatment 1st entry | Treatment 1st entry |
| **2019** | Regeneration parameter | N/A |
| **2058** | Treatment 2nd entry | Treatment 2nd entry |
| **2059** | Regeneration parameter | N/A |
| **2098** | Treatment 3rd entry | Treatment 3rd entry |
| **2099** | Regeneration parameter | N/A |

## Climate-FVS

To capture the effects of climate change the Climate-FVS extension (Crookston 2014) can be applied to the FVS. The Climate-FVS extension modifies, without replacing, the core FVS components with new climate estimators (Crookston 2014). The FVS model assumes that site capacity is constant, but the Climate-FVS extension uses climate change models to alter site capacity and estimate the effects on tree growth, mortality, and regeneration potential (Crookston 2014). The model is adjusted when site climate conditions change from the optimal climate conditions within a given species range (Crookston 2014). Conditions outside optimal climate envelopes for a given species negatively affect growth and regeneration and increases mortality using a calculated viability score (mortality rates increase when the viability score falls below 0.50; Crookston 2014). Establishment of the most viable species is implemented when stocking is low but does not represent migration (Crookston 2014). If climate conditions become more suitable for a species, the growth and regeneration potential is increased (Crookston 2014).

Climate-FVS needs additional climate and species-viability data to estimate changes in growth rates, mortality, and regeneration establishment in the form of Climate-FVS ready data (Get

Climate-FVS ready data website). The Climate-FVS ready data for this study were obtained from the Climate-FVS web page. By submitting stand level attributes including latitude and longitude coordinates, elevation, and stand identification numbers, the web page server creates a data file which includes derived variables and relevant species-climate profile scores (Figure 6, Get Climate-FVS ready data website). An area specific RCP6.0 climate data file (Get Climate-FVS ready data website) was used to set climate attributes in the Climate-FVS.

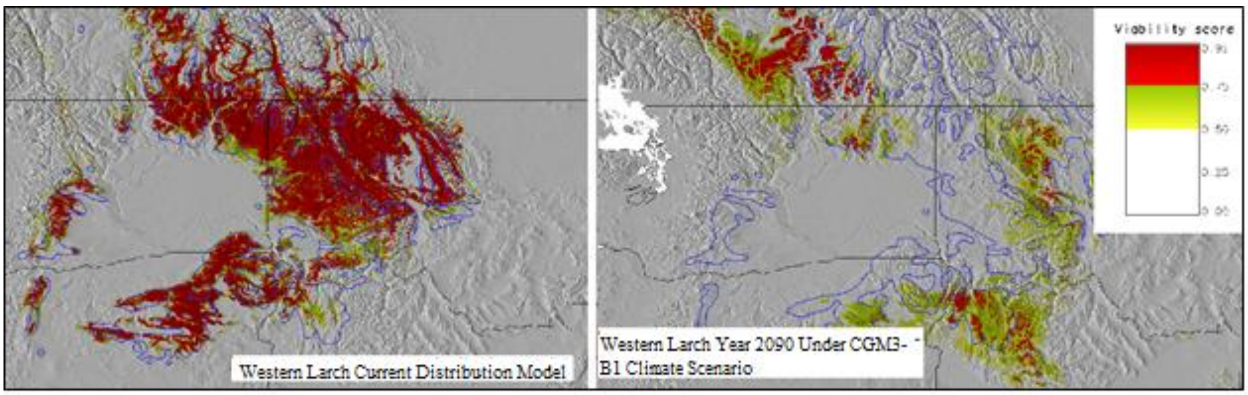



Figure 6. Example of a relevant western larch species-climate profile map, with associated viability score. The map is a comparison of current distribution to predicted distribution under CGM3-B1. CGM3-B1 is an older climate scenario that describes an increased level of environmental and social consciousness combined with an effective approach to more sustainable development (IPCC website; Figure from USDA.k).

### *Climate-FVS Regeneration*

For Climate-FVS regeneration the “AutoEstb” keyword was used to account for stand regeneration (climate scenarios only). Auto establishment is a Climate-FVS feature that allows for the natural establishment of trees when the stand stocking is below the stocking threshold. The “schedule by cycle/year” parameter was set to “0”. The default 40 percent stocking threshold was used. The number of species to regenerate was set to the default amount “4”. The species regenerated is determined by Climate-FVS and depends on the viability data (a default of 500 trees/acre was used).

## Fire and Fuels Extension

The Fire and Fuels Extension (FFE) of FVS was used to simulate the crown fire indices. FFE does not simulate fire spread or the probability of fire (Rebain et al. 2015). FFE contains existing models of fire behavior and fire effects (e.g. crowning approaches developed by Van Wagner 1977; Scott and Reinhardt 2001; Rebain et al. 2015).

# Section III: Results

## Section 3.1. Current Conditions at Project Scale

The average basal area ($ft.^2ac^{-1}$) for the BNF and IPNF was 46 and 61 respectively (Table 6). Both forests are entering the crown closure phase with average SDI's of 129 and 171 (BNF and IPNF respectively), based on a max average SDI of 450 (Table 6). Both forests consisted of primarily shade intolerant and shade tolerant species in year 2018, with moderate shade tolerant species under represented (Figure 7). Most of the trees per acre (TPA) were also contained in the lower diameter size classes in the year 2018 (Figure 7).

Table 6. The current conditions averaged across stands for both forests including trees per acre, basal area ($ft.^2ac^{-1}$), average SDI, and QMD. Also shown are the average percent basal area ($ft.^2ac^{-1}$) by tolerance class, and species by tolerance class.

| | BNF | | | | IPNF | | | |
|---|---|---|---|---|---|---|---|---|
| Year | TPA | BA ($ft.^2ac^{-1}$) | SDI | QMD | TPA | BA ($ft.^2ac^{-1}$) | SDI | QMD |
| 2018 | 1095 | 46 | 129 | 2.7 | 998 | 66 | 171 | 3.6 |

| | %BA () by Shade Tolerance Class | | | | %BA () by Shade Tolerance Class | | | |
|---|---|---|---|---|---|---|---|---|
| | **Western Larch** | **Shade Intolerant** | **Moderate Shade Tolerant** | **Shade Tolerant** | **Western Larch** | **Shade Intolerant** | **Moderate Shade Tolerant** | **Shade Tolerant** |
| 2018 | 43 | 15 | 9 | 33 | 25 | 12 | 13 | 51 |
| 2028 | 40 | 19 | 13 | 28 | 23 | 12 | 15 | 50 |
| 2038 | 37 | 23 | 15 | 25 | 18 | 14 | 18 | 50 |
| 2048 | 34 | 24 | 17 | 25 | 15 | 16 | 20 | 49 |
| 2058 | 32 | 24 | 18 | 26 | 13 | 17 | 21 | 49 |
| 2068 | 30 | 23 | 19 | 28 | 11 | 18 | 21 | 50 |
| 2078 | 28 | 22 | 19 | 31 | 10 | 19 | 20 | 51 |
| 2088 | 27 | 20 | 20 | 33 | 9 | 19 | 20 | 52 |
| 2098 | 25 | 19 | 20 | 35 | 8 | 19 | 20 | 54 |
| 2108 | 24 | 18 | 21 | 37 | 7 | 18 | 20 | 55 |
| 2118 | 23 | 17 | 21 | 39 | 6 | 18 | 20 | 56 |

| Species Tolerant Classes | | |
|---|---|---|
| **Shade Tolerant** | **Moderate Shade Tolerant** | **Shade Intolerant** |
| western redcedar | western white pine | western larch |
| western hemlock | Douglas-fir | lodgepole pine |
| grand fir | | ponderosa pine |
| subalpine fir | | quaking aspen |
| Engelmann spruce | | paper birch |
| mountain hemlock | | whitebark pine |
| Rocky Mountain maple | | |
| Pacific yew | | |

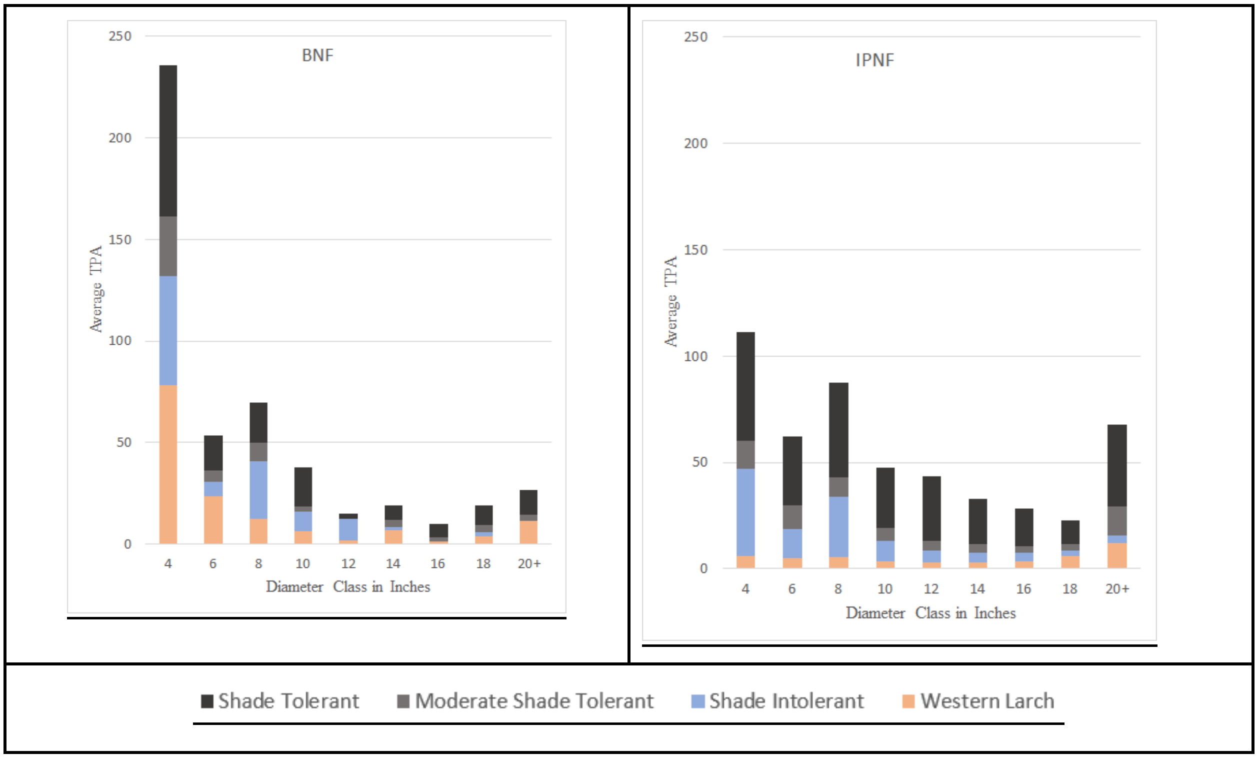


Figure 7. Comparison of the current (year 2018) average trees per acre by diameter class in inches grouped by shade tolerance class for the BNF (left) and IPNF (right).

## Section 2.1. Future Projections

### *BNF*

**No Action**

A representative stand was chosen from the BNF to depict the no action option through time in SVS under both climate scenarios (Figures 8). SVS shows considerable density increases in the representative stand by year 2078 under the current and climate change scenarios (Figure 8). However, the stand density is shown to be lower for both years (2078 and 2118) under the climate change scenario (Figures 9). Under the no action strategy, the effects of climate change on the average TPA metric of forest structure showed an increase in shade tolerant species on the BNF, when compared across analysis years 2018, 2078, and 2118 (Figures 7 and 9). The no action had little effect on average percent basal area ($ft.^2ac^{-1}$) for each shade tolerance class, however, an overall decrease was observed in the average percent basal area ($ft.^2ac^{-1}$) of western larch under both climate scenarios (Figures 10 and 11). In general fire hazard was maintained or increased throughout all years under both climate scenarios (Table 7).

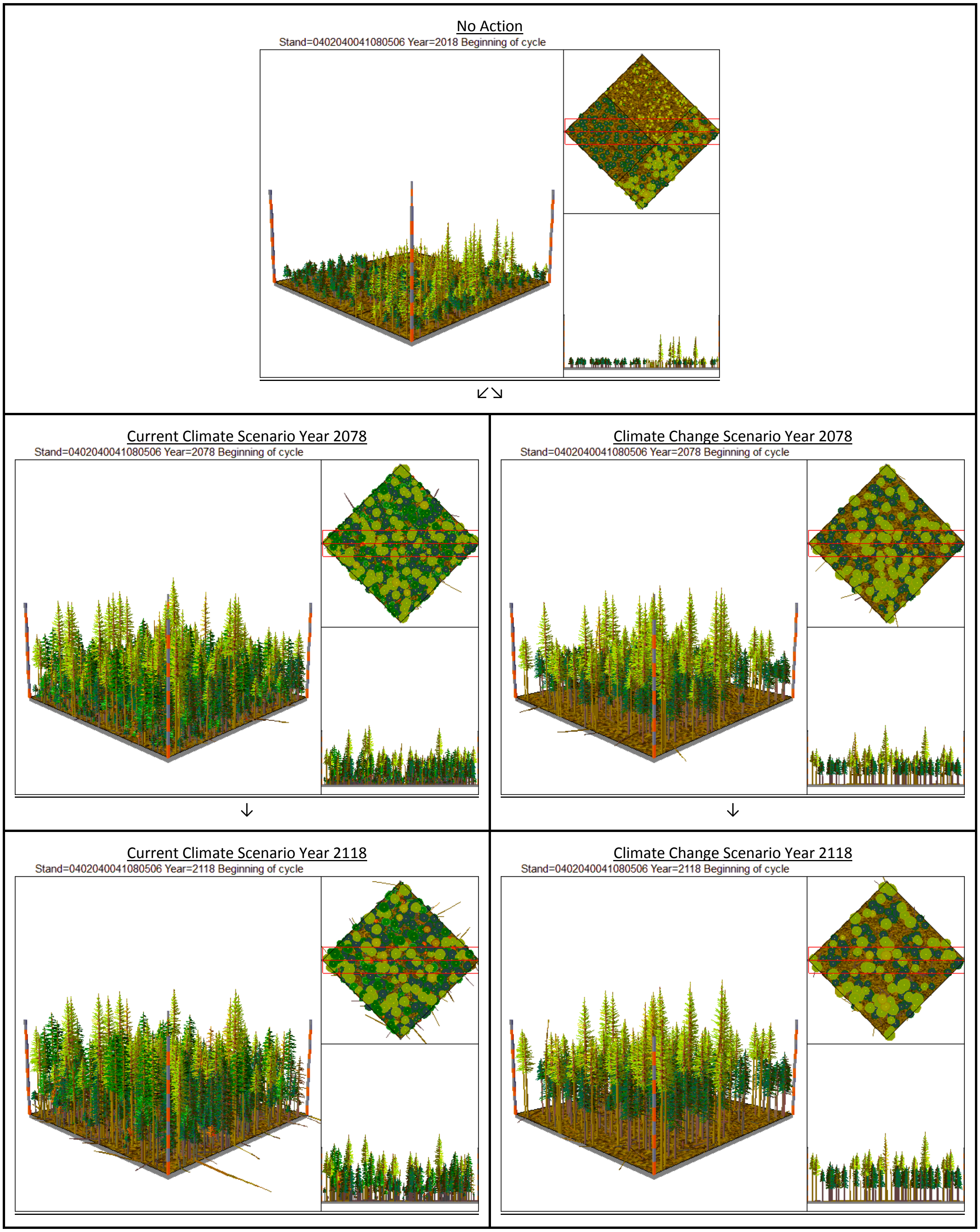
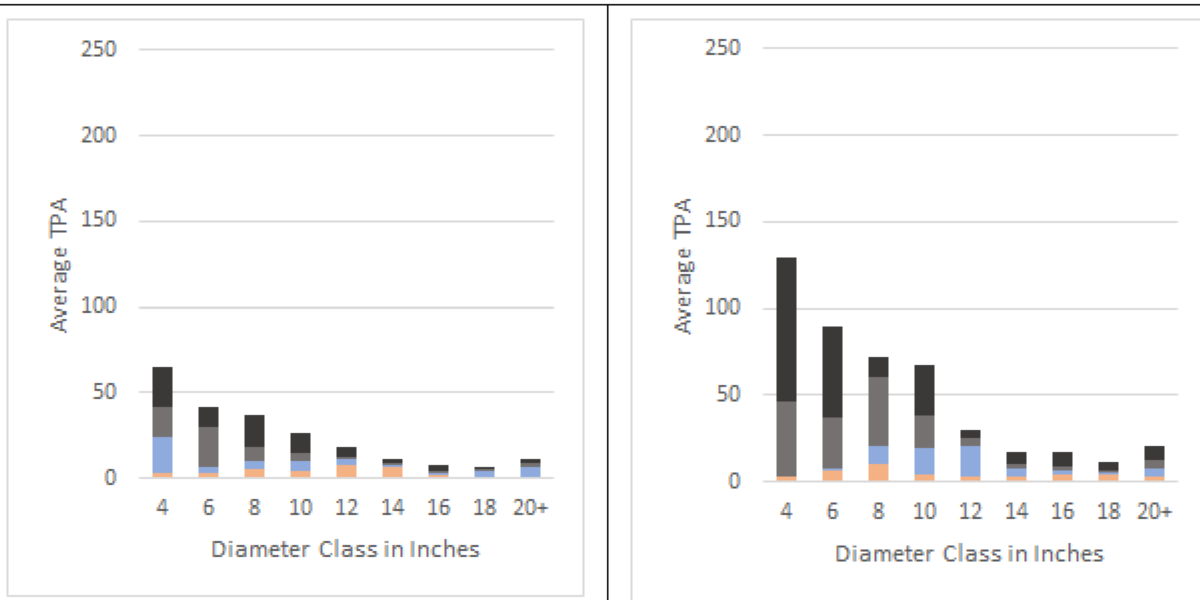



Figure 8. SVS depiction of an example BNF stand with no action under both climate scenarios through time.




BNF: Climate Change - No Action 2078

BNF: Climate Change - No Action 2118

Figure 9. Comparison of the average trees per acre on the BNF by diameter class in inches, grouped by shade tolerance class year 2078 (left) and year 2118 (right) for the No Action strategy.

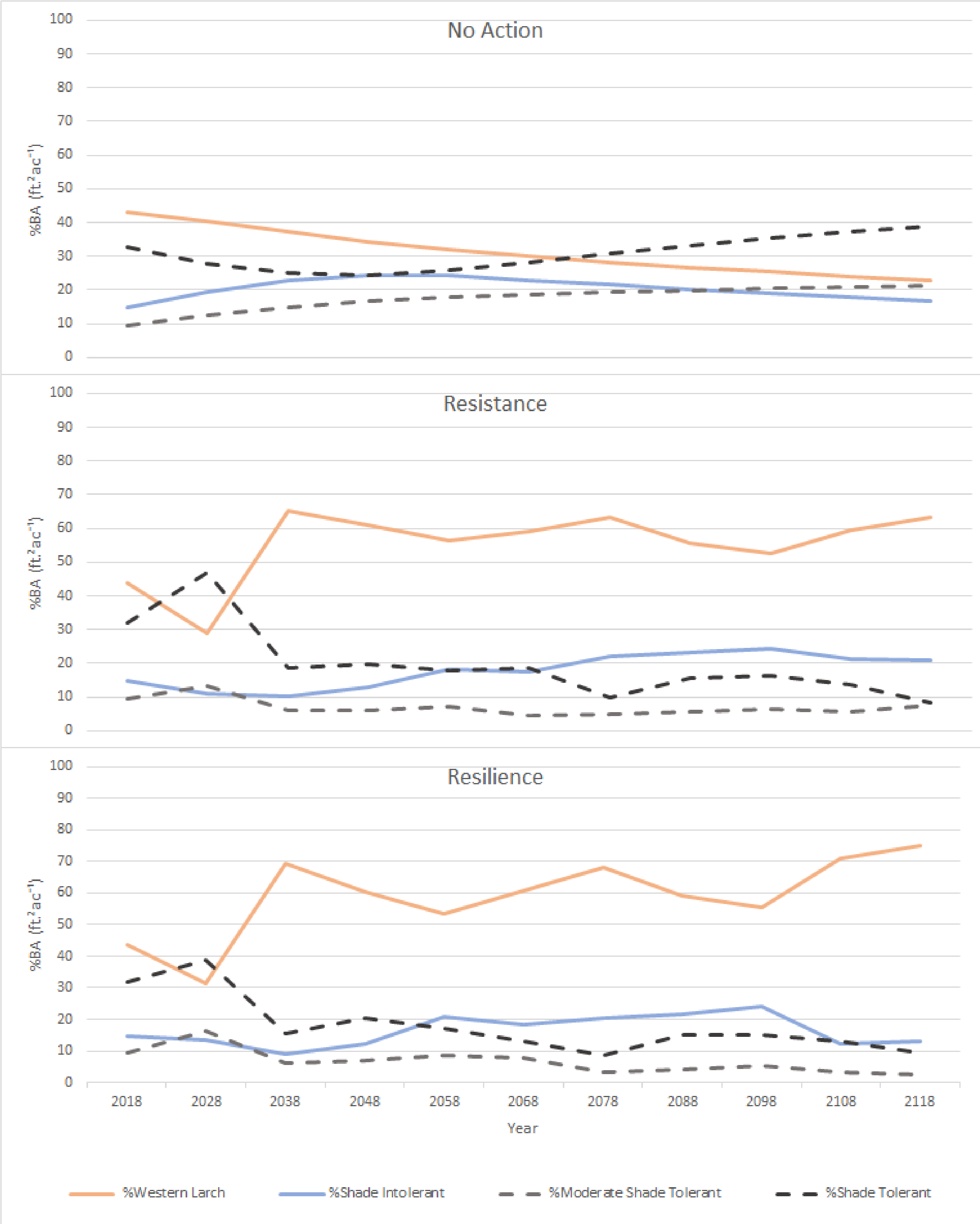



Figure 10. Percent basal area (ft.$^2$ac$^{-1}$) for western larch and the shade intolerant, moderate shade tolerant, and shade tolerant classes on the BNF years 2018-2118 under the current climate (control) scenario.

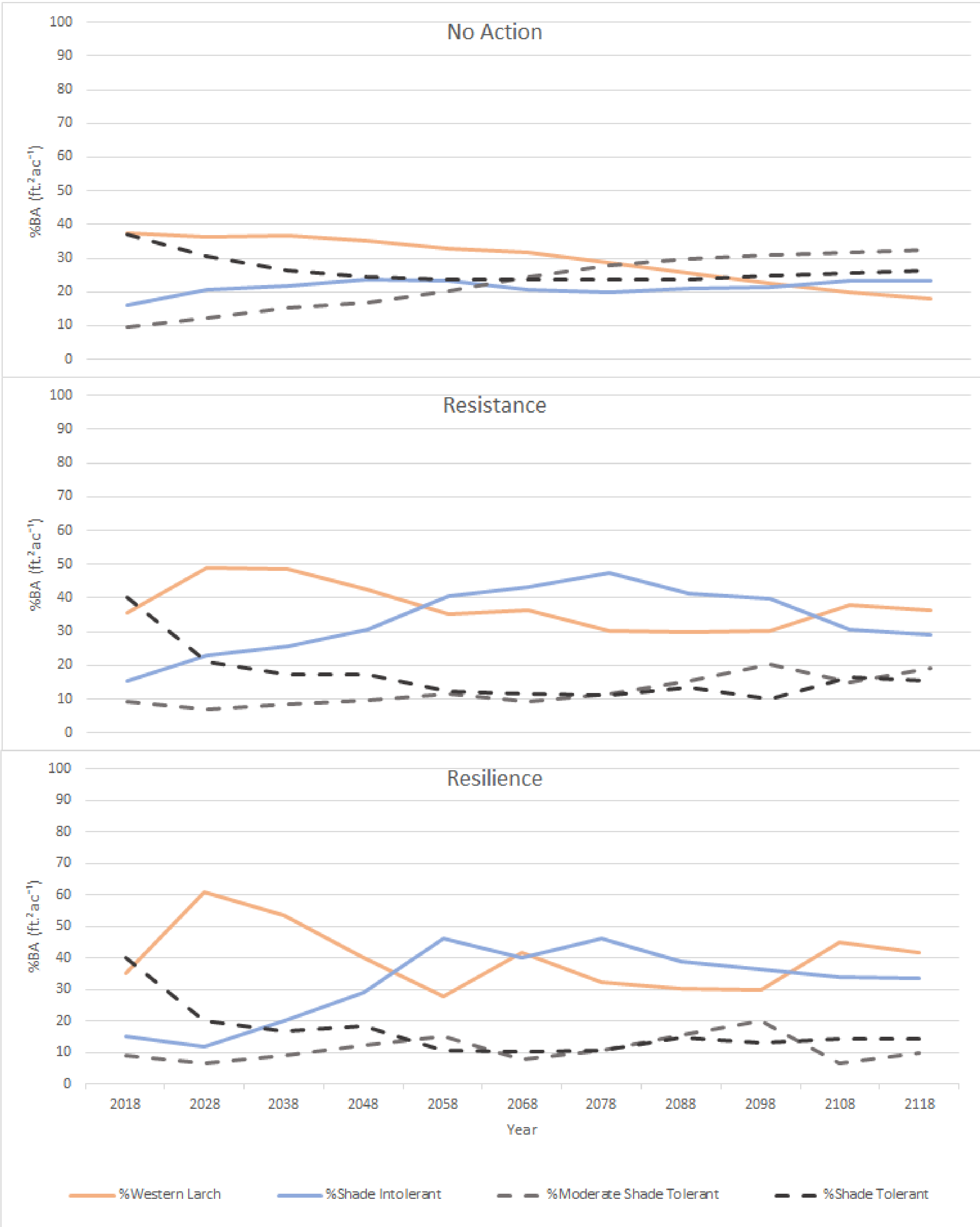


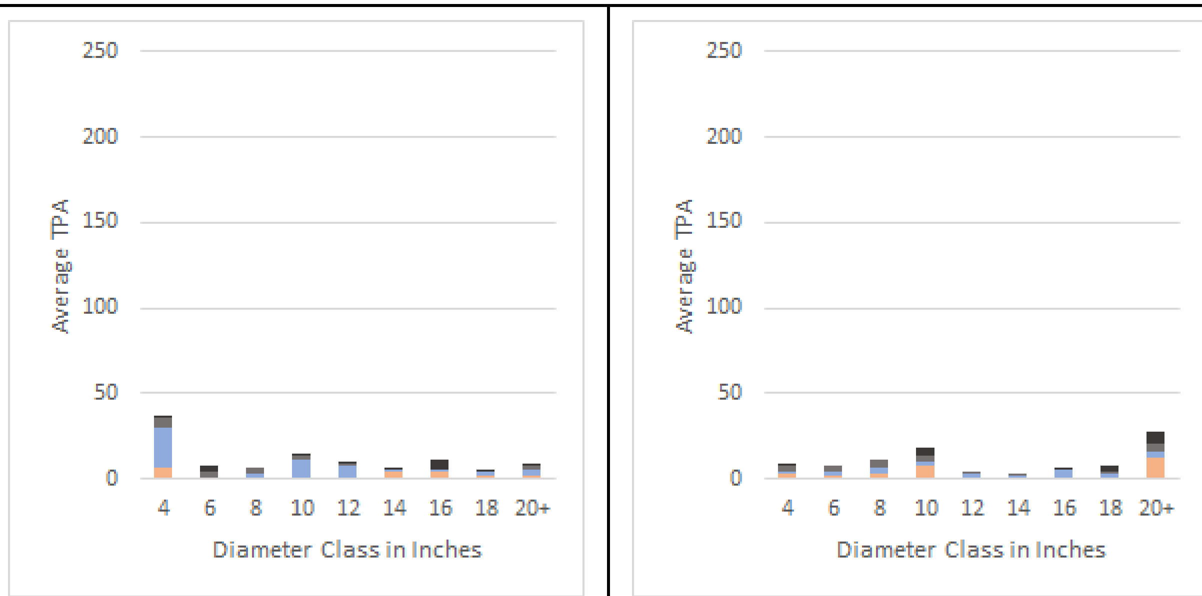

Figure 11. Percent basal area ($ft.^2ac^{-1}$) for western larch and the shade intolerant, moderate shade tolerant, and shade tolerant classes on the BNF years 2018-2118 under the climate change scenario.

Table 7. Fire hazard rating (1-5) for the no action, resistance, and resilience strategies averaged across all stands on the BNF under the current and future climate scenarios.

| | BNF Current Climate Scenario | | | BNF Future Climate Scenario | | |
|---|---|---|---|---|---|---|
| | No Action | Resistance | Resilience | No Action | Resistance | Resilience |
| Year | Fire Hazard Rating | | | Fire Hazard Rating | | |
| 2018 | 3 | 3 | 3 | 3 | 3 | 3 |
| 2028 | 3 | 3 | 3 | 3 | 3 | 3 |
| 2038 | 3 | 3 | 3 | 3 | 3 | 3 |
| 2048 | 3 | 3 | 4 | 3 | 3 | 3 |
| 2058 | 4 | 2 | 2 | 3 | 3 | 2 |
| 2068 | 5 | 2 | 2 | 3 | 3 | 3 |
| 2078 | 5 | 2 | 3 | 3 | 3 | 3 |
| 2088 | 5 | 3 | 3 | 4 | 3 | 3 |
| 2098 | 5 | 2 | 1 | 4 | 2 | 2 |
| 2108 | 4 | 2 | 1 | 3 | 2 | 2 |
| 2118 | 4 | 3 | 3 | 3 | 2 | 3 |

**Resistance**

On the BNF maintenance of the large tree shade intolerant species was successful, especially western larch (Figures 12). There was also substantial recruitment of shade intolerant species into the large tree (20+ inch DBH) diameter class (Figure 12). The resistance treatment showed a shift in the average TPA dominance from shade tolerant species to shade intolerant species including western larch (Figures 12). On the BNF under both climate scenarios the average percent basal area ($ft.^2ac^{-1}$) of shade intolerant species, and especially western larch, responded positively to the resistance treatment. Shade intolerant average percent basal area ($ft.^2ac^{-1}$) was maintained or increased under both climate scenarios (Figures 10 and 11). The fire hazard was maintained or reduced by the resistance option throughout all analysis years under both climate scenarios (Table 7).




BNF: Climate Change - Resistance 2078

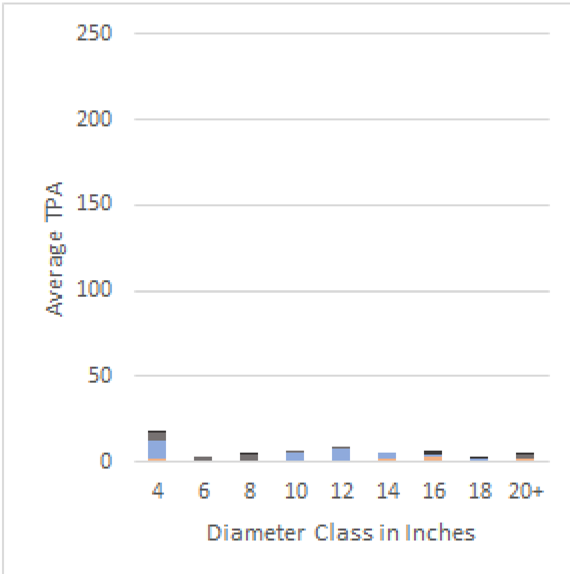
BNF: Climate Change - Resistance 2118

Shade Tolerant   Moderate Shade Tolerant   Shade Intolerant   Western Larch

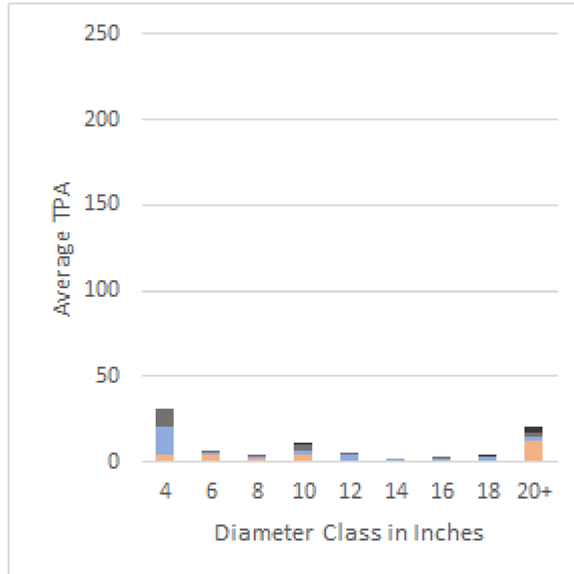
Figure 11. Comparison of the average trees per acre on the BNF by diameter class in inches, grouped by shade tolerance class year 2078 (left) and year 2118 (right) for the Resistance strategy.

**Resilience**

The resilience treatment caused substantial reductions in the average TPA overall on the BNF, but especially with the shade tolerant species under climate change (Figure 13). The maintenance of the large tree shade intolerant species was successful, especially western larch under the climate change scenario (Figure 13). On the BNF under the current climate and climate change scenarios the average percent basal area ($ft.^2ac^{-1}$) of shade intolerant species, and especially western larch, responded positively to the resilience option (Figures 10 and 11). The fire hazard was maintained or reduced by the resilience option throughout all analysis years under both climate scenarios, except for year 2048 under the current climate scenario (Table 7).




BNF: Climate Change - Resilience 2078




BNF: Climate Change - Resilience 2118

■ Shade Tolerant ■ Moderate Shade Tolerant ■ Shade Intolerant ■ Western Larch

Figure 13. Comparison of the average trees per acre on the BNF by diameter class in inches, grouped by shade tolerance class year 2078 (left) and year 2118 (right) for the Resilience strategy.

*IPNF*

**No Action**

A representative stand was chosen from the IPNF to depict the no action option through time in SVS under both climate scenarios (Figures 14). SVS shows considerable density increases in the representative stand by year 2078 under the current and climate change scenarios (Figure 14). However, the stand density is shown to be lower for both years (2078 and 2118) under the climate change scenario (Figures 14). By the end year 2118, SVS shows considerable mortality has occurred under the climate change scenario in the IPNF stand (Figure 14). Figure 15 shows that the average TPA increased between 2018 and 2078 across tolerance classes but decreased across tolerance classes when compared between 2078 and 2118, particularly the shade intolerant species (Figures 7 and 15). On the IPNF average percent western larch basal area ($ft.^2ac^{-1}$) decreased for the no action under both climate scenarios. In general fire hazard was maintained or increased throughout all years under both climate scenarios (Table 8).

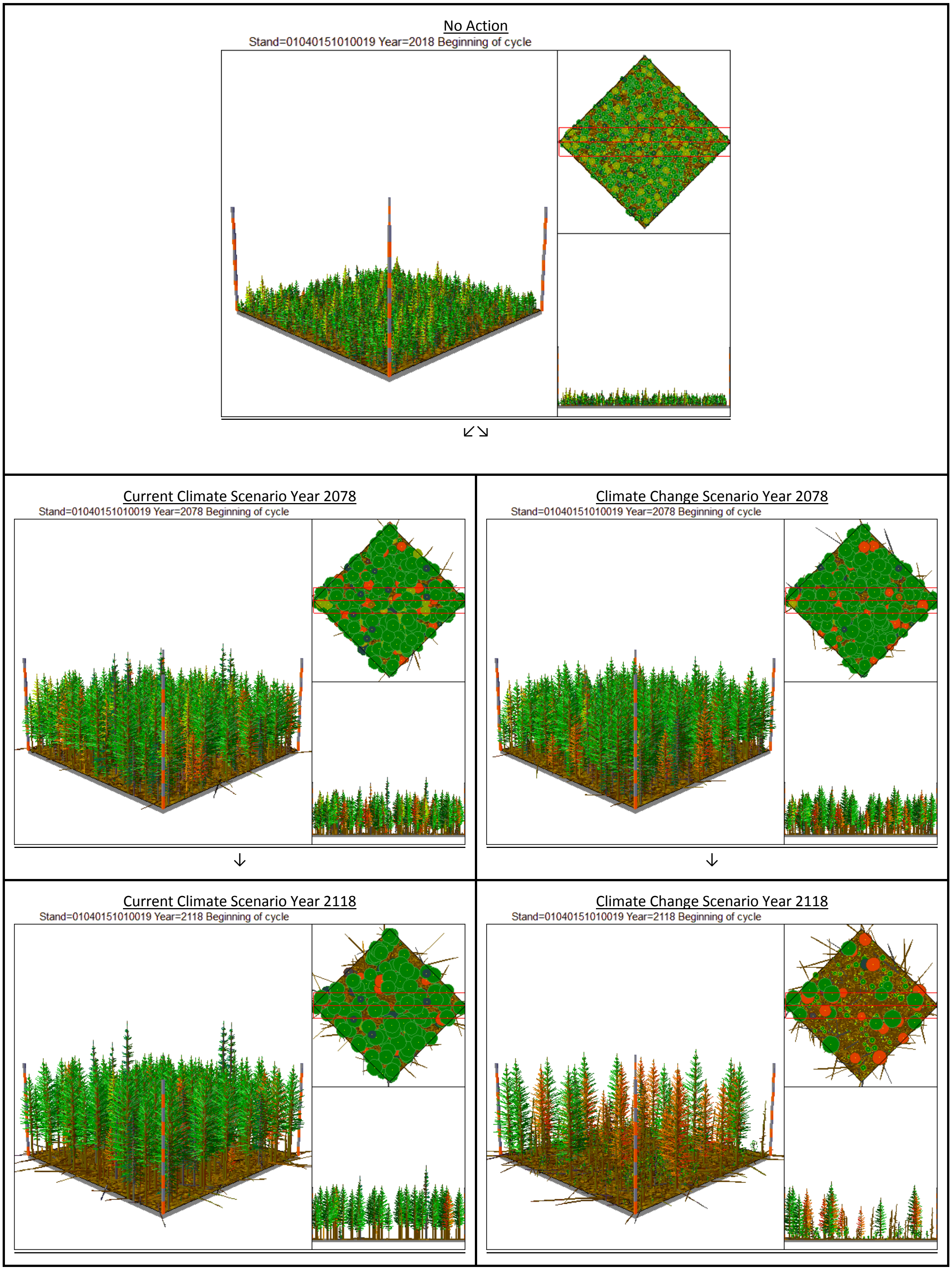

No Action
Stand=01040151010019 Year=2018 Beginning of cycle
Current Climate Scenario Year 2078
Stand=01040151010019 Year=2078 Beginning of cycle
Climate Change Scenario Year 2078
Stand=01040151010019 Year=2078 Beginning of cycle
Current Climate Scenario Year 2118
Stand=01040151010019 Year=2118 Beginning of cycle
Climate Change Scenario Year 2118
Stand=01040151010019 Year=2118 Beginning of cycle

Figure 14. SVS depiction of an example BNF stand with no action under both climate scenarios through time.

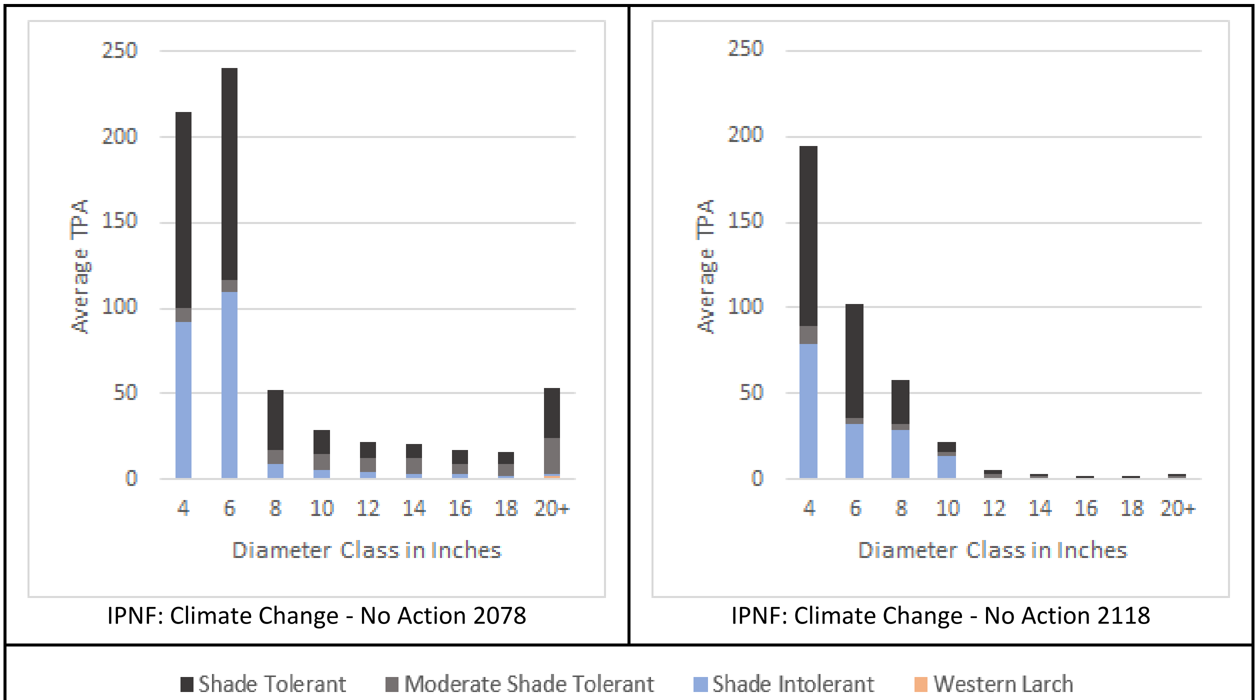


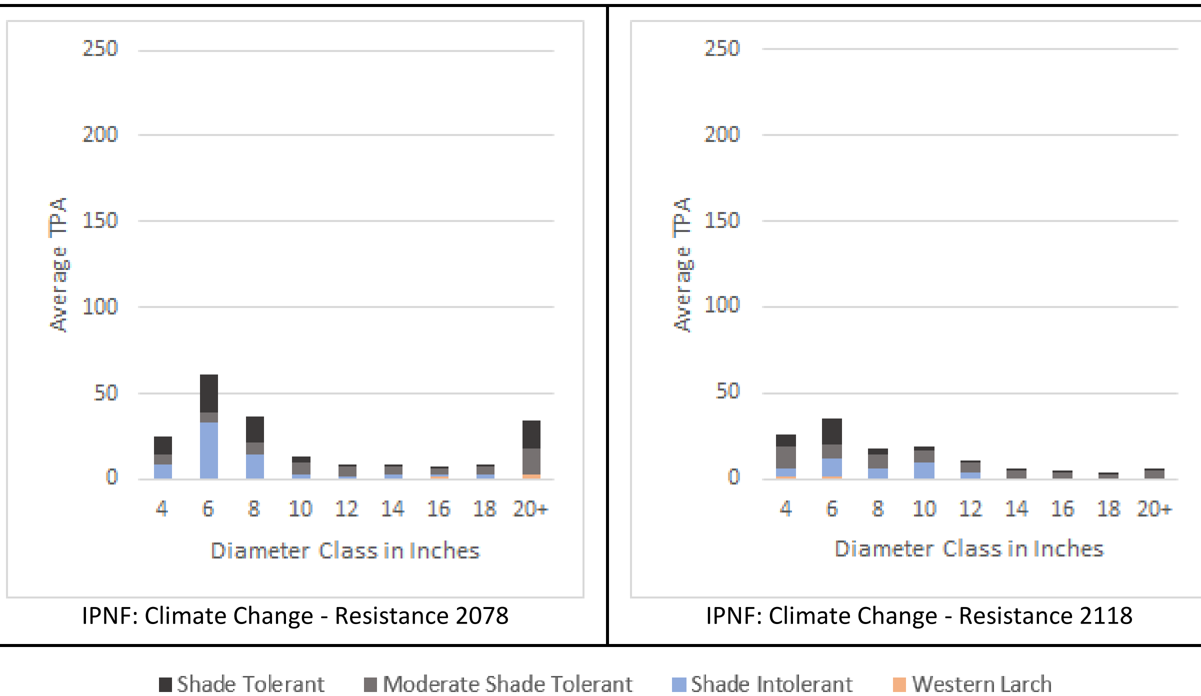

Figure 15. Comparison of the average trees per acre on the IPNF by diameter class in inches, grouped by shade tolerance class year 2078 (left) and year 2118 (right) for the No Action strategy.

Table 8. Fire hazard rating (1-5) for the no action, resistance, and resilience strategies averaged across all stands on the IPNF under the current and future climate scenarios.

| | IPNF Current Climate Scenario | | | IPNF Future Climate Scenario | | |
|---|---|---|---|---|---|---|
| | No Action | Resistance | Resilience | No Action | Resistance | Resilience |
| Year | Fire Hazard Rating | | | Fire Hazard Rating | | |
| 2018 | 2 | 1 | 1 | 2 | 1 | 1 |
| 2028 | 3 | 2 | 2 | 2 | 1 | 1 |
| 2038 | 3 | 2 | 2 | 2 | 2 | 2 |
| 2048 | 3 | 2 | 2 | 2 | 2 | 2 |
| 2058 | 4 | 2 | 2 | 3 | 1 | 1 |
| 2068 | 4 | 2 | 2 | 3 | 1 | 1 |
| 2078 | 4 | 3 | 3 | 3 | 2 | 2 |
| 2088 | 4 | 3 | 3 | 3 | 2 | 2 |
| 2098 | 4 | 3 | 3 | 3 | 3 | 2 |
| 2108 | 4 | 3 | 2 | 3 | 3 | 3 |
| 2118 | 4 | 4 | 3 | 3 | 3 | 3 |

### Resistance

The resistance option on the IPNF resulted in a decrease in large trees for all shade tolerance classes (Figure 16). An overall decrease in average TPA across diameter classes also occurred on the IPNF, especially the shade tolerant species (Figure 16). The average percent basal area ($ft.^2ac^{-1}$) results were mixed (Figures 18 and 19). Figure 18 shows that average percent basal area ($ft.^2ac^{-1}$) remained relatively constant despite the resistance treatment under current climate. The proportion of western larch decreased when the resistance option was applied under both climate scenarios (Figures 18 and 19). The moderate shade tolerant class performed the best to the resistance strategy, while the shade tolerant class decreased substantially under the climate change scenario (Figure 19). The fire hazard was maintained or reduced by the resilience option throughout all analysis years, excluding 2098, 2018 and 2118, under both climate scenarios when compared to the no action strategy (Table 8).



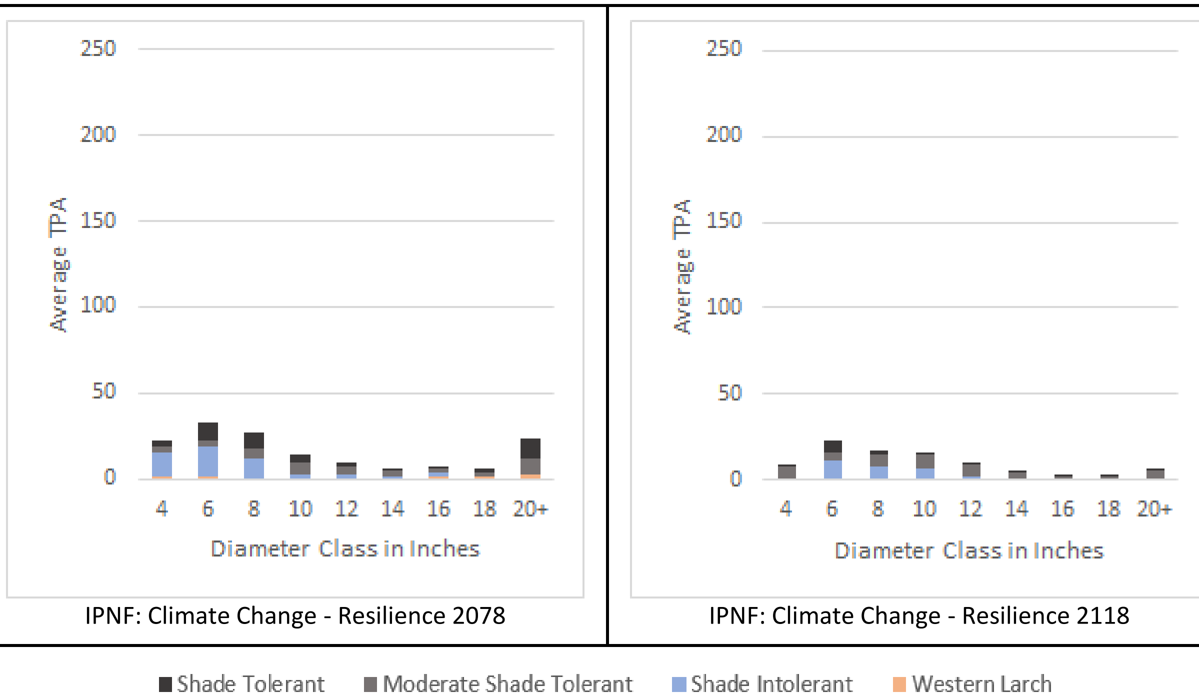

IPNF: Climate Change - Resistance 2078

IPNF: Climate Change - Resistance 2118

Figure 16. Comparison of the average trees per acre on the IPNF by diameter class in inches, grouped by shade tolerance class year 2078 (left) and year 2118 (right) for the Resistance strategy.

## Resilience

The resilience treatment caused substantial reductions in the average TPA overall on the IPNF, with most of the reduction attributed to loss of shade tolerant species (Figure 17). The average percent western larch basal area ($ft.^2ac^{-1}$) decreased under both climate scenarios, but less so with the resilience option under current climate compared to the no action or resistance options (Figures 18 and 19). The fire hazard was maintained or reduced by the resilience option throughout all analysis years, excluding 2018 and 2118, under both climate scenarios when compared to the no action strategy (Table 8).




IPNF: Climate Change - Resilience 2078

IPNF: Climate Change - Resilience 2118

Figure 17. Comparison of the average trees per acre on the IPNF by diameter class in inches, grouped by shade tolerance class year 2078 (left) and year 2118 (right) for the Resilience strategy.

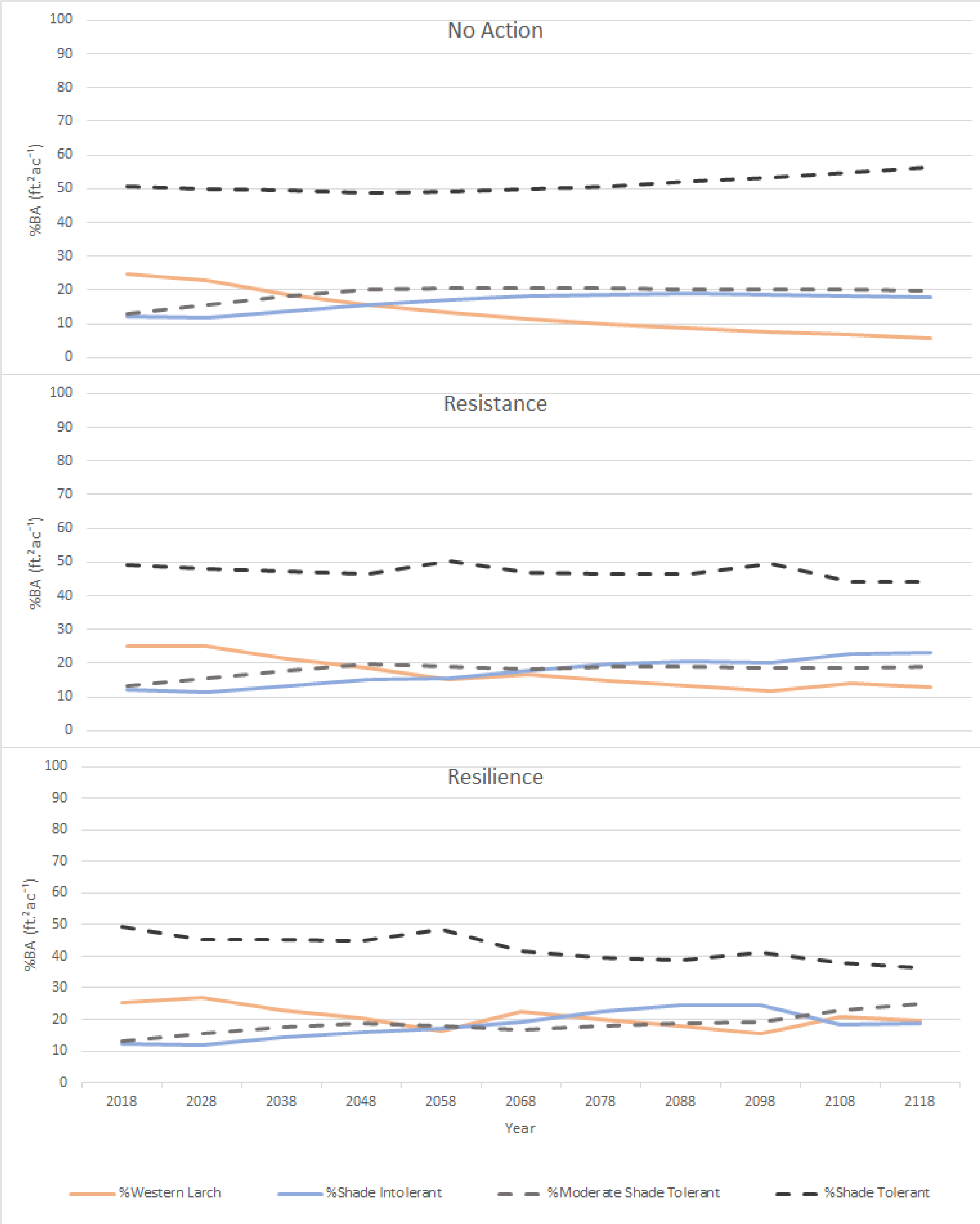



Figure 18. Percent basal area ($ft.^2ac^{-1}$) for western larch and the shade intolerant, moderate shade tolerant, and shade tolerant classes on the IPNF years 2018-2118 under the current climate (control) scenario.

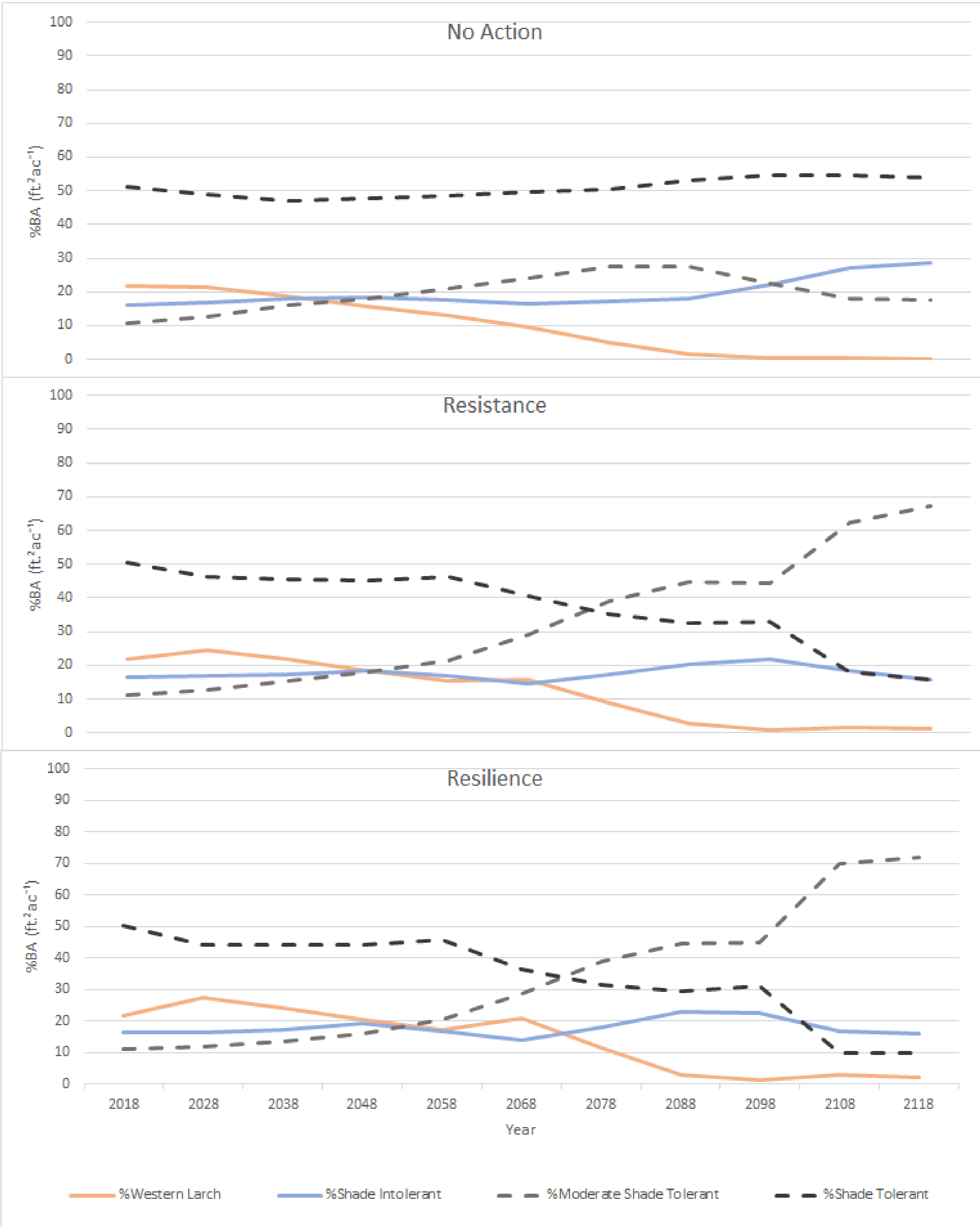



Figure 19. Percent basal area (ft.$^2$ac$^{-1}$) for western larch and the shade intolerant, moderate shade tolerant, and shade tolerant classes on the IPNF years 2018-2118 under the climate change scenario.

## Section IV: Discussion

The objectives of this study were to understand how climate change could affect western larch stands in Idaho and use silviculture to develop resistance and resilience strategies to climate change. Resistance actions should improve the defenses of forests against anticipated change or directly protect the forest against disturbance to maintain relatively unchanged conditions (Millar et al. 2007; Nagel et al. 2017). Comparatively, resilience actions should allow forests to accommodate a degree of change but facilitate a return to a desired reference condition after disturbance (Millar et al. 2007; Nagel et al. 2017).

When considering the effects of climate change on western larch, the no action results indicate that western larch will likely be negatively impacted by climate change. On both forests the average trees per acre and the average percent basal area for western larch decreased over time under the climate change scenario. However, it is important to note that the same was true for the no action under current climate scenario. This points to the influence of fire suppression and the composition shift from shade intolerant to more shade tolerant species over time. This forest composition trend adds to the importance of active management strategies in curbing successional development that can occur in the absence of fire in western larch dominated stands.

For the evaluation criterion of increasing the number of shade intolerant species in the large tree class (20” DBH and above) both the resistance and resilience strategies were successful. By the year 2118 significant increases in the number of shade intolerant species occurred on the BNF for both active strategies under the climate change scenario. However, the IPNF which is farther north than the BNF experienced higher relative losses in trees per acre under climate change by the end year 2118, especially in the bigger diameter classes. This indicates that climate change may have a stronger influence on growth and yield in the generally cooler, wetter, and more productive IPNF. The active strategies on the IPNF did prove to be effective in maintaining more trees per acre in the 12 inch and greater size classes versus the no action, albeit more in the moderate and shade tolerant classes than the shade intolerant class.

For the second evaluation criteria of maintaining or increasing average percent basal area ($ft.^2ac^{-1}$) of western larch and or the shade intolerant species class, both active strategies achieved an increase on the BNF. However, on the IPNF the active strategies were only slightly better than the no action at slowing an overall loss of average percent basal area ($ft.^2ac^{-1}$) of western larch. The active strategies were effective at maintaining shade intolerant species proportions throughout time and increasing the amount of moderate shade tolerant proportions on the IPNF. Although the objective was to increase the proportion of shade intolerant species, maintaining or increasing the moderate shade tolerant class is preferable to the shade tolerant class or complete forest cover loss. On both the BNF and IPNF the active strategies were effective at reducing the shade tolerant class average percent basal area ($ft.^2ac^{-1}$), which indicates a reduction in competition for the shade intolerant and moderate shade tolerant classes. Interestingly, on the IPNF, the resistance treatment had little effect on the proportion of shade tolerance classes under the current climate scenario, while the resilience treatment was only slightly more effective at reducing the proportion of the shade tolerant class and increasing the shade intolerant class. This could be due to under regenerating early successional species in the highly productive IPNF which creates more competitive growing conditions compared to the BNF.

The third evaluation criteria were very clearly met on the BNF by the active strategies when compared against the no action alternative, while results were more mixed for the IPNF. This is likely due to the higher proportion of shade tolerant species, or regional fire condition differences between the BNF and IPNF. By reducing densities through thinning or single tree selection on both forests, the crown connectivity and bulk density were reduced, effectively increasing the crowning and torching indexes, thereby reducing the fire hazard. Reducing the hazard of a catastrophic wildfire across stands increases the resistance of those stands by maintaining the current conditions. A reduced fire hazard not only decreases the likelihood of a catastrophic wildfire occurring in a stand but can also effectively increase the resilience of the stand.

The major differences in the effectiveness in treatments between the BNF and IPNF could be caused by several factors that will require more modeling consideration to understand. Potential causes may include under regenerating shade intolerant species on the more productive IPNF, differences in the FVS variants (Central Idaho and Inland Empire), insufficient removal of shade tolerant species during treatment on the IPNF, regional differences in the effects of climate change, or some combination of these factors. We plan on conducting future work to address what caused the response difference to the two treatments between forests. We would also like to include the Payette and the Nez-Perce-Clearwater National Forests in future modeling. These forests are regionally located between the BNF and IPNF in Idaho, which could be informative in regard to subtle differences in location between the four forests. Additionally, we would like to include prescribed fire in future modeling to create more appropriate treatments in a fire-adapted ecosystem. Prescribed fire would also more accurately replicate current management strategies on the National Forests in Idaho.

## CHAPTER V: Conclusion

Climate change research has shown beyond doubt that global temperatures are rising (e.g. Thomas et al. 2001; Walther et al. 2002; Parmesan and Yohe 2003; Root et al. 2003; Rehfeldt et al. 2006). Acknowledging this reality, the USFS Boise National Forest and Idaho Panhandle National Forests have created explicit management objectives to foster more resilient forests, and maintain or increase the occupancy of early successional, drought- and fire-tolerant tree species, such as western larch (USDA.b; USDA.c). This is a difficult task, with added complexity due to poor past land management practices, such as fire suppression and high-grade logging. The negative effects of climate change on western forests can be reduced by developing resistance and resilience strategies (Millar et al. 2007; Nagel et al. 2017). Forest resistance and or resilience can be achieved by actively managing for early successional (shade intolerant) species, through thinning and regeneration techniques (Nagel et al. 2017). Many objectives related to resilience can be met by implementing treatments that reduce stand densities (Millar et al. 2007; Nagel et al. 2017). For example, tree competition can be reduced, shade intolerant species can be regenerated in newly available growing space, and fire hazard can be reduced by raising the torching and crowning indexes.

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