# Using the Forest Vegetation Simulator to determine proposed restoration treatment effectiveness and maintenance interval: an analysis of the Four Forest Restoration Initiative

**Hall, WA[1]. Forest Fire Management Specialist / Master's of Forestry Graduate Student**
**Thode AE[2] PhD. Assistant Professor / Lead Advisor**
**Waring KM[2] PhD. Assistant Professor**
**Lata M[1] PhD. 4-FRI Fire Ecologist**
**McCusker L[1]. 4-FRI Siviculturist**
**Morfin V[1] MF. Forest Fuels Specialist**
**Wadleigh L[1] Region 3 Fire Ecologist**

[1]Coconino National Forest
Supervisors Office
1824 S. Thompson St., Flagstaff AZ 86001
Tel 928-526-3500, Fax 928-779-5267, wahall@fs.fed.us

[2]School of Forestry
Northern Arizona University
P.O. Box 15018, Flagstaff AZ 86011
Tel 928-864-7431, andi.thode@nau.edu

**December 16, 2011**

# Table of Contents

# Table of Figures

# Table of tables

## **Abstract**

*Recent large wildfires in Arizona, such as the Wallow and Rodeo-Chediski fires, have had some negative social and ecological impacts due to high intensity crown fire in ecosystems dependent on frequent surface fires. Large, landscape-scale restoration projects and treatments, such as those proposed under the Four Forest Restoration Initiative, are attempting to restore ponderosa pine ecosystems to more historical conditions. Since the effects of these treatments are largely unknown, analyses are often left to computer modeling. This study uses the Forest Vegetation Simulator to determine restoration treatment effectiveness by evaluating stand structure, potential fire behavior, and fuel loading as measures of trajectory towards historic and desired conditions. Long-term treatment effectiveness was established and evaluated by creating a burning maintenance interval in which prescribed fire treatments are repeated over time. Modeled treatments consist of a combination of individual tree selection only, individual tree selection and burn, and burn only treatments. Combination of individual tree selection and burn treatments were the most effective at achieving historical and/or desired conditions. In addition a seven year burning interval was the most effective at achieving historical and/or desired conditions in the shortest period of time.  Additional research is needed to compare model results with conditions following treatment implementation.*

## Introduction

Ponderosa Pine and Fire

Ponderosa pine (*Pinus ponderosa)* forests in the Southwest are under urgent need of ecological restoration (Covington et al. 1997, Moore et al.1999, Allen et al. 2002, Friederici 2003, Brown et al. 2004). Much of this need has arisen from the disruption of the natural frequent fire regime, the influence of large-scale livestock grazing and extensive logging practices that occurred following Euro-American settlement (Cooper 1960, Covington and Moore 1994b, Swetnam and Basin 1996). As a result of fire disruption, increased livestock grazing and logging practices, ponderosa pine ecosystems have changed both structurally and functionally (Covington and Moore 1994b, 1994c, Kolb et al.1994, Mast et al. 1999). The historical fire regime has been effectively eliminated from the system, resulting in a shift from frequent, low intensity fires to infrequent, high intensity fires that result in a magnitude of negative effects across the landscape (Cooper 1960, Fulé et al. 1997, Fulé et al. 2006). These negative effects are further magnified because of the increasing number of people that live, work and recreate in and around ponderosa pine forests (Duryea and Vince 2005). As a result of these changes in forest structure and fire behavior, there have been land management policy changes that favor the restoration of forests that are far removed from the historic range of variability (HFRA 2003, OPLMA 2009).

Historic Range of Variability and Desired Conditions

The historic range of variability (HRV) is defined by the literature as a method used to understand the dynamic nature of the particular forest structure, process, and disturbance regime that is prevalent on the landscape as it relates to the natural forest state (Morgan et al. 1994, Landres et al. 1999.Veblen 2003). In ponderosa pine ecosystems in the southwest the HRV of tree density on basalt soils is estimated to be 15-60 trees per acre (TPA) (Rasmussen 1941, White 1985, Covington and Moore 1994b, Covington et al 1997, Fulé et al 1997, 2002, 2006, Mast at al. 1999, Roccaforte et al. 2009, Abella et al. 2011, USDA Forest Service 2011a) and between 40-74 ($ft^2$/acre) in basal area (BA) (Sanchez Meador et al. 2008, Roccaforte et al. 2009). Land managers of the Coconino National Forest have used the HRV of tree density described in the literature to create a set of desired conditions (DCs) that take into account all concerns of functional areas of management including fire, fuels, range, wildlife, botany, stewardship etc. The Coconino National Forest Proposed Revised Forest Plan (USDA, Forest Service 2011a), has a mid-scale desired condition of 20 to 80 square feet of BA in ponderosa pine ecosystems. In addition, the Coconino National Forest has also established DCs in terms of stand structure using Stand Density Index (SDI) and the corresponding relative density index (RDI). SDI is often used to characterize stand structure because of its relationship between the number of TPA and the diameter of trees at breast height (Reineke 1933, Smith et al. 1997). The RDI of a stand shows the relative point of a stand in its growth trajectory. It is defined as the number of trees of an average size (SDI) divided by the maximum SDI that can exist of a given species which gives an overall value that represents a percentage of the maximum SDI (Smith et al. 1997). Long and Shaw (2005) identified for ponderosa pine a RDI of 0.15 represents the approximate point where a stand reaches canopy closure. Whereas, a RDI value of 0.55 represent a point in a stand growth trajectory where mortality begins to occur through stand self thinning. In addition, an SDI value of 450 (1.00 RDI) represents the maximum size-density relationship that a given ponderosa pine stand may develop to (Long and Shaw 2005). The DCs derived for the Coconino National Forest for RDI range from 0.15-0.40 (USDA Forest Service 2011c).

The HRV for fire behavior and fuel loading is not well represented in the literature. The literature does, however, discuss historic fire behavior as being low intensity, surface fire (Cooper 1960, Fulé et al. 1997, Fulé et al. 2006, Covington and Moore). Previous research in ponderosa pine ecosystems of the southwest have shown that fires historically burned on a regular interval ranging from two to twenty-one years (Weaver 1951, Cooper 1960, Swnetnam and Basin 1996, Fulé et al 1997, Fulé 2002, Heinlein et al 2005, Hunter 2007, Diggins 2010). The amount of fuel loading that should be represented across the forest has been determined by the Coconino National Forest (2011a) landscape-scale DC for coarse woody debris (CWD) of 3 to10 tons/acre. Furthermore, the Coconino National forest has addressed smoke and air quality as a critical issue related to the amount of fuel loading in the Coconino National Forest Draft Environmental Impact Statement (USDA Forest Service 2011a). The combination of developing HRV and DCs gives researchers and managers a basis to begin determining forest change since Euro-American settlement, large-scale livestock grazing and fire exclusion.

Structure Changes since Euro-American Settlement

Stand density conditions in ponderosa pine ecosystems has increased substantially when compared to HRV and DCs. Prior to Euro-American settlement, ponderosa pine forests consisted of small groups and clumps of 3 to17 trees (Kaufmann et al. 2000) with large openings and interspaces that created a parklike structure (Covington and Moore 1994). Covington and Moore (1994) reconstructed historical stand structure and determined that the density of ponderosa pine has increased from around 23 TPA and 65 square feet of BA prior to settlement, to over 800 TPA and 130 square feet of BA after settlement. Similarly, Covington et al. 1997 has estimated that the number of TPA has increased from around 25 TPA in 1876 to over 1,200 TPA in 1992.

Fire Behavior Changes since Euro-American Settlement

Fire behavior has also changed significantly since Euro-American settlement (Covington and Moore 1994, Covington et al. 1997). The low intensity surface fire that frequently moved across the landscape (Cooper 1960, Fulé et al. 1997, Fulé et al. 2006, Covington and Moore) has been replaced by infrequent, higher intensity crown fire that can disrupt many of the natural processes of an ecosystem (Campbell et al. 1977, Schoennagel et al. 2004, Fitzgerald 2005, Savage and Mast 2005). These wildfires often remove all of the overstory vegetation which can result in a multitude of negative consequences, including the destruction of watershed function (Campbell et al. 1977, Allen et al 2002, Miller 2002), accelerated soil erosion and nutrient mineralization (Neary et al. 1999, Ice et al. 2004), destruction of wildlife habitat (Allen et al. 2002, Brown et al. 2004), destruction of seed beds, critical for natural regeneration (Savage and Mast 2005), and the potential for type conversion  with impending climate change (Hurteau et al. 2010). Once a wildfire has moved from the surface fuels to the overstory (crown fuels), fire behavior increases (Van Wagner 1977). Crown fires have longer flame lengths, faster rates of spread, higher fire intensity, and increased resistance to control, making them both dangerous and difficult to manage by firefighters (Van Wagner 1977, Cohen and Butler 1998, Scott and Reinhardt 2001). Fire managers often measure crown fire potential as the probability that a crown fire will initiate and perpetuate through the canopies of trees and is dependent on canopy base height and canopy bulk density (Scott and Reinhardt 2001, Schaaf et al. 2007, NWCG 2008). Canopy base height and canopy bulk density have been determined as the most crucial factors for the initiation of crown fire (VanWagner 1977 Graham et al. 1999). Managers often evaluate crown fire potential and canopy base height through the use of torching index which is measured as the 20ft wind speed required to initiate crown fire in a forested stand. In addition, managers also evaluate crown fire potential and canopy bulk density through the use of crowning index which is measured as the 20ft wind speed required to perpetuate crown fire through a forested stand (Scott and Reinhardt 2001). These methods of measuring crown fire potential are fire manager's primary methods of accessing the risk of ecosystem loss and the loss of public life, health and property when a crown fire moves into a populated area.

<u>The Wildland Urban Interface</u>

The increase in wildfire activity over the recent decades has put the wildland urban interface (WUI) in danger of destruction from crown fire (Kohen 2008). The WUI according to the National Wildfire Coordinating Group (NWCG 2008) is any location where human developments meet or intermix with undeveloped vegetated lands. The largest concern to the management of wildfire in the WUI is the potential for a surface fire to transition to a crown fire (Biswell 1960, Scott and Reinhardt 2001). These fires are the most dangerous from a suppression perspective (Butler and Cohen 1998). Firefighters risk suppressing crown fires in the WUI in order to protect lives and property (Stratton 2004). If suppression efforts are not conducted, crown fire can sweep through the WUI and into the community, directly putting the public in the path of the fire (Stratton 2004). The WUI is a crucial location where fuel reduction treatments are at the forefront to protecting the public's property, lives, health, and welfare (Stratton 2004). This is due to the proximity and interactions with the public being in and around the forest (Stratton 2004). To help alleviate the risk of wildfire, land managers can implement treatments that help reduce the risk of wildfire (Agee and Skinner 2005). Fuel reduction treatments that target reducing stand density and canopy closure in combination with reducing fuelbed loadings have shown to be very effective at decreasing crown fire potential and can also improve ecosystem health and resilience (Feeney et al. 1998, Graham et al. 1999, Fitzgerald 2005, Mason et al. 2006, Roccaforte et al. 2009).

<u>Policy and Creation of the 4-FRI</u>

The realization of control issues surrounding more intense and severe wildfires and the inability of agencies to get treatments on the ground led to the signing of the Healthy Forest Restoration Act (HFRA) by President George Bush in year 2003. This act was initiated to decrease the risk of negative effects resulting from uncharacteristic wildfires while maintaining environmental standards and encouraging early public participation during the planning process (HFRA 2003). In year 2009 Title IV of the Omnibus Public Land management Act set aside the Collaborative Forest Landscape Restoration Fund to help support the planning and implementation of landscape scale restoration projects (OPLMA 2009). Since the signing of these two acts into law, many large-scale forest restoration projects have been proposed with the overall mission of restoring ecological structure and function. One of these large, landscape-scale restoration projects is directly aimed at restoring the resiliency and function of ponderosa pine forests in Arizona U.S.A. The Four Forest Restoration Initiative (4-FRI) consists of 2.4 million acres of ponderosa pine forests across four National Forests (Kaibab, Coconino, Tonto, Apache-Sitgraves National Forests). Approximately 600,000 of these acres are proposed for restoration on the Coconino National Forest (USDA Forest Service 2011c).

**Objectives**

Land management and resource specialists have done intensive research and analysis to determine the appropriate treatments to implement. The effectiveness of proposed 4-FRI treatments at returning stand structure to the HRV and DCs is unknown. Thus, the objectives of our research were to 1) Document the current stand structure, fire behavior, and fuel loading attributes in the WUI, 2) Examine the effectiveness of proposed treatments in terms of returning conditions within HRV or established DCs, 3) Determine the maintenance interval needed to maintain conditions within HRV and DCs. Our results are important for the 4-FRI planning process because they give an estimation of the likelihood or length of time required to achieve HRV and DCs.

# **Methods**

## Study Area

The location of the study area used in modeling consists of the approximately 80,000 acres WUI on the southwest side of Flagstaff, Arizona (latitude $35^{o}$03’-$35^{o}$14’ N, longitude $111^{o}$35’-$111^{o}$44’W) within the Coconino National Forest (Figure 1). Elevation of the study area ranges from 6,800 to 7,200 feet. We selected this area for modeling and analysis because of its high level of WUI interaction, high volume of forest use for recreation, and its relatively high level of values at risk to uncharacteristic wildfire (USDA Forest Service 2011a). In addition, the prevailing wind direction in Flagstaff is primarily from the southwest (USDA Forest Service 2011a). This adds to fire manager concern from fire entering the Flagstaff community from the southwest (USDA Forest Service 2011a).

## Stand Selection Criteria

The dominant overstory vegetation type located in the study area and used in modeling is ponderosa pine with a small component of Gambel oak (*Quercus gambelli*). Stands that contained a large portion (over 25%) of Gambel oak in the overstory were excluded to limit analysis to “pure” ponderosa pine dominated stands. Due to differences in stocking, growth and regeneration of ponderosa pine on basalt versus limestone soils (Puhlick 2011), all stands that fell on limestone soils were excluded from analysis (TES 2001), leaving only stands located on basaltic parent material.

For modeling purposes conditions were based on Common Stand Exam data (CSEs) that were collected between years 1987 and 2002. Stands consist of the cumulative data from multiple plots across a single stand. All data collected within a given stand was averaged to give an approximation of the average stand condition. All stands were grown to a common starting year of 2011 and all current conditions are based on modeled stand conditions at year 2011. Originally, one hundred and forty-six stands met our selection criteria and were queried out of the FSVeg database (NRIS 2011). We further limited our modeling to stands with cumulative plot data with a standard error less than 20 $ft^2$/acre of BA (FSH 2409.13) and less than 50 TPA (see Table 1, Appendix A for details). The last step in stratification resulted in 26 stands that met all criteria and were used in all modeling simulations. Only two stands contained fuel level data. In order to make inferences about the changes in fuel loading over time, we averaged the two loadings and matched a photoseries model (PNW-105-2-PP-1) that best matched the two stand loadings (NWCG 1997). The values in this photoseries were used to add fuel loading to stands without fuel loading data.

**FVS Model, Treatments, Parameters and Modifiers**

<u>FVS Model</u>

The Forest Vegetation Simulator (FVS), an individual growth and yield statistical model was used for all growth and yield modeling simulations (Dixon 2002). We used the Fire and Fuels Extension (FFE) for fire behavior and fuels consumption modeling (Reinhardt and Crookston 2003, Rebain et al. 2011). We used the Central Rockies/Southwestern Ponderosa Pine variant of FVS for all simulations. FVS was specifically selected because it is the most widely used model among national forests, and stand level data can be easily imported from the Forest Service FSVeg database (NRIS 2011).

Treatments

We modeled eight different treatment scenarios. These treatments were established to represent one of the uneven-aged mechanical treatments that that 4-FRI is proposing. Four treatment types were assessed, 1) a control, 2) individual tree selection only, 3) burn only, 4) individual tree selection and burn treatment combined. The individual tree selection treatment was modified under the 4-FRI project and includes larger canopy gaps than individual trees. These larger gaps were established to create regeneration or understory openings/interspaces that are similar to the historic structure in ponderosa pine (USDA Forest Service 2011c). Because the FVS model does not have the capacity to model spatial distributions, all modeling of individual tree selection treatments were simulated at the group level. Therefore, any larger canopy gaps proposed under 4-FRI could not be accurately simulated and were excluded from analysis. All individual tree selection treatments were simulated in year 2012 to show the effect mechanical treatment on stand structure, potential fire behavior and fuel loading over time.

In addition to proposed uneven-aged mechanical treatment, 4-FRI is proposing the use of prescribed fire as a maintenance tool. The modeled analysis treatments that include prescribed burning treatment were broken into three simulations with different burning maintenance intervals, 1) a seven year burning maintenance interval, 2) a twenty-two year burning maintenance interval, 3) an alternating seven and twenty-two year burning maintenance interval (Table 1). The seven, 22, and alternating seven and 22 year burning maintenance intervals were created by both conversations with local fire managers and reference to literature that took into account the ecological need of fire, and fire management capacity given timing, funding, personnel staffing and public health concerns. The seven year burning maintenance interval was established as a result of the current maintenance interval of NEPA approved treatments on the Flagstaff District assuming the 10,000 acre current target is treated annually in perpetuity (FACTS 2011). The twenty-two year interval arose through the need to determine the fire behavior and effects of an interval above the historic fire return interval of 2-21 years. We chose to also analyze the effectiveness of an alternating seven and 22 year burning maintenance interval. Table 1 displays years when the different treatment types and when they were simulated.

Parameters and Modifiers

We modified many of the default FVS and FFE parameters to limit the level of error built into the model, and to provide a more accurate representation of conditions on the Coconino National Forest (Table 2)(Crookston and Dixon 2005). All simulations were limited to a fifty year timeframe to avoid the compounding effect of error within the model as the simulation timeframe is extended (Crookston and Dixon 2005). All individual tree selection treatments were simulated at year 2012 and the prescription that was used within the model simulated mechanical individual tree selection across the entire diameter range with a target SDI of 100. The 100 SDI individual tree selection treatment was chosen to represent the average 4-FRI treatment for areas managed as Northern Goshawk forging areas (USDA Forest Service 2011c). The maximum SDI value for ponderosa pine was modified to 450 (Long and Shaw 2005, Shaw and Long 2010). The default calculation of SDI in FVS was used for all simulations. This method of SDI calculation erroneously assumes of even-aged stand conditions; however, for the purposes of this study they do give an estimate of trends over time. A portion of stems were left on site after mechanical treatment and biomass removal to show the effect of stems and branchwood left on fire behavior and fuel loading.  Sprouting was turned off (Liu and Ashton 1994). We based regeneration on a model developed by Sorensen et al. (2010). Therefore, regeneration was purposely added after all treatment, individual tree selection or prescribed fire, and the actual regeneration rates were based on previous research from Bailey and Covington (2002).

In addition to modifying the default FVS parameters, we used several keywords to modify potential fire behavior and fuels conditions to those similar to conditions observed on the Coconino National Forest (Table 2).  For all potential fire behavior modeling the 97$^{th}$ percentile for weather conditions was used. These conditions were determined by using a Coconino National Forest maintained database of weather observations from the Flagstaff RAWS (Remote Automated Weather Station) over the past eight years, and represent the top three percent of the worst fire weather days. We cross-checked all weather data by using Fire Family Plus 4.0.2 Beta to ensure that the collected weather observations were consistent with the historical trend of weather in Flagstaff, Arizona (Fire Family Plus 2009). We modified the burn parameters in FVS to the 97$^{th}$ percentile weather conditions of the Coconino National Forest for severe fires (see Appendix A, Table 2 fro detatils). All prescribed burning treatments that were used in the individual tree selection and burn and burn only simulations were simulated starting at year 2015, and were also modified using the Coconino National Forest weather database. Prescribed burning conditions were based on prescribed fire weather data that was collected on days when burning was implemented (see Appendix A, Table 2 for details). All prescribed burning simulations were simulated in the fall season. We tested multiple different fuel models (see Appendix B for detatils), and selected model 165 (very high load, dry climate timber-shrub) as it is a dynamic fuel model and includes the understory vegetation as a surface fuel (Anderson 1982, Scott and Burgan 2005).

**Analysis**

We analyzed forest stand structure using TPA, BA, and RDI as the variables of measure. We compared simulated conditions to both HRV and DCs shown in Table 3. These variables were all analyzed because of their importance in characterizing stand structure (Covington et al 2001, Heinlein et al 2005). In addition, a two inch diameter class distribution was created to show the potential effects that treatment will have on the diameter distribution of ponderosa pine. Potential fire behavior and crown fire potential were assessed using total flame length, probability of torching (p-torch), torching index and crowning index. We used the historic description of frequent, low intensity wildfire discussed in the introduction to evaluate potential fire behavior. Using this description of fire behavior, we can assume that lower total flame lengths (flame length including crown fire activity) are more desirable and closer to historic fire behavior. We chose to compare torching index and crowning index with the $90^{th}$ and $97^{th}$ percentile weather conditions for 20ft winds from the Flagstaff RAWS (Table 3). This method will help show which simulated treatment is better at reducing the potential for crown fire. We chose to also assess potential smoke concentration ($PM_{2.5}$) because of public concern of viewshed obstruction and health issues that can result from high concentrations of $PM_{2.5}$ (Ottmar et al. 1996, Bowman and Johnston 2005). The results of this study are expected to help show the impact that 4-Fri treatments will have at reducing over $PM_{2.5}$ emission over time. To assess the fuel loading condition of the forest, we chose to analyze fine woody debris (woody debris less than 3in. in diameter), CWD (woody debris greater than 3in. in diameter), litter, duff, and total fuel loading as the variables of measure. CWD was compared to the DCs from the Coconino National Forest (USDA Forest Service 2011a). The remaining fuel loading variables were not compared against a historic variability or desired condition, but rather used to show reductions of each fuel characteristic after different restoration treatments were modeled. Litter and duff loading are the largest contributors to increased smoke concentrations due to higher levels of smoldering often contributed to high fuel moisture (Einfeld et al.1991, Reinhardt et al. 1997). We understand that the fuel loading and the photoseries that was used to set initial fuel loadings may skew loadings, showing a higher range than is represented across the entire forest. However, higher fuel loading predictions give a worst case scenario of how effective and how long it will take for proposed treatments to achieve DCs. Modeling high levels of fuel loading will also help give fire managers an idea of the effects that high levels of fuel loading will have on fire behavior.

## **Results**

### **Pre-treatment Structure, Predicted Fire Behavior & Fuel Conditions**

The current condition of modeled stands within the WUI of Flagstaff, AZ is highly departed from the HRV and DCs (Table 4 & Appendix A, Table 3 for details). The modeled current average conditions for stand structure is 157 for TPA with a range from 87 to 267, BA is 104 with a range from 77 to 167 and, RDI is 0.41 with a range from 0.31 to 0.64. We also found fire behavior potential and fuel loading of the forest within the WUI of Flagstaff, AZ to be highly departed from HRV and DCs (Table 4 & Appendix A, Table 3 for details). The current average total flame length at 97$^{th}$ percentile weather conditions is estimated to be 103.54 ft. The current average probability of torching at 97$^{th}$ percentile weather conditions is estimated to be 0.88. This means that there is an 88% probability that crown fire will initiate through torching at some point within the stand (Rebain et al. 2011). The current average torching index at 97$^{th}$ percentile weather conditions is estimated to be 4.54 mph. The current average crowning index at 97$^{th}$

percentile weather conditions is estimated to be 34.91 mph. In terms of smoke concentration potential, simulations show that average current levels of $PM_{2.5}$ in smoke are 0.14 (tons/acre) at $97^{th}$ percentile weather conditions. The current level of CWD within the study area is estimated to be 19.62 tons/acre. Fine woody debris is currently estimated at 4.63 tons/acre. Litter is estimated to be 2.60 tons/acre. The current condition of duff is 2.26 tons/acre. Finally, combining coarse and fine woody debris, litter and duff yields a total average fuel loading within the study of 29.10 tons/acre.

## **Post-treatment Stand Conditions**

Tree Density

Tree density is reduced most heavily by the three individual tree selection and burn treatment simulations (Figures 2 & 4; Table 5). Under this treatment, tree density is immediately reduced to 73 TPA and enters HRV after the first entry with prescribed fire. Figure 4 shows that when looking at the control simulation after 50 years, the diameter distribution is bi-model with a node that represents 4 to 8 inch diameter trees and another node representing 12 to 18 inch diameter trees (Figure 4). The control simulation shows that in year 2062, 72.4% of trees are less than 18 inches in diameter (Figure 4). When individual tree selection and prescribed burning is modeled, there is a rightward shift in the diameter distribution (Figure 4). This distribution is also bi-model, however, the first node is represented by 2 to 4 inch diameter trees and the second node represents 22 to 30 inch trees (Figure 4). Under the three individual tree selection and burn scenario, 70-76% of trees are greater than 18 inches in diameter in year 2062.

When the three burn only scenarios are modeled, tree density is initially reduced to 86 TPA after the first prescribed fire entry, and the length of time in which it takes to reach HRV varies with the maintenance interval for burning. Figure 4 shows that at year 2062, 63-76% of trees will be 18 inches or larger in diameter. This diameter distribution also has a bi-model shape with the first node representing primarily 2 inch trees and the second node representing 14 to 26 inch trees. Lastly, the individual tree selection only treatment scenario is only effective at reducing tree density to 73 TPA in the short term (Figure 2; Table 5). Figure 4 shows that at year 2062, 59% of trees will be smaller than 18 inches in diameter. The diameter distribution is bi-model with the first node representing primarily 6 to 8 inch trees and the second node representing 12 to 26 inch trees.

Basal Area

Like density, BA is reduced most by the three individual tree selection and burn treatment scenarios (Figure 3; Table 6). BA is initially reduced to 63 $ft^2$/acre and then further reduced to 54 $ft^2$/acre after the first burn entry. Burn only treatments reduce BA less than tree density, and are only achieve DCs under a seven year burning maintenance interval. Under this treatment scenario, the initial burn entry reduces basal area to 89 $ft^2$/acre and then trends differently depending on the maintenance interval of burning. Individual tree selection achieves both DCs and HRV with an initial reduction to 63 $ft^2$/acre. This treatment does not remain within DCs unless followed by any of the simulated burning maintenance intervals (Figure 3).

Relative Density Index

Relative density index is reduced within DCs no matter what treatment burning maintenance interval is simulated (Figure 5; Table 7). This index is reduced the greatest by the three individual tree selection and burn treatment simulations. These simulations show an initial reduction to 0.23 RDI after the initial mechanical treatment, followed by a further reduction to 0.18 RDI after the first burn entry, and remains under a fairly static trend through the remainder of the simulation. Under this scenario, all burning maintenance intervals maintain DCs, but approach the lower end and continue to trend downward using a seven year burning maintenance interval. The three burn only treatments also RDI to within DCs, with an initial decrease to 0.32 RDI. Trends continue to decrease until the end of the simulation where the trend plateaus, becoming more static. The individual tree selection only treatment reduced RDI to 0.23 post-treatment, but as the simulation progresses, RDI continues to increase steadily (Table 7).

**Post-treatment Predicted Fire Behavior & Fuel Loading**

Results of all modeling simulations show that individual tree selection and burn or burn only treatment scenarios reduce fire behavior and fuel loading regardless of a burning maintenance interval (Figures 6-15; Tables 8-17). On the other hand, the modeled individual tree selection only treatment scenario reduces potential fire behavior and fuel loading less.

Total Flame Length

Total flame lengths are reduced most by the three individual tree selection and burn treatment simulations followed closely by the three burn only treatment simulations (Figure 6; Table 8). The individual tree selection only treatment scenario reduces total flame lengths in the short term, but over the simulation timeframe, a single individual tree selection only treatment does not hold its effectiveness over time. Under the seven year burning maintenance interval, total flame lengths are reduced from 103.5 to 20.0 and 23.6 ft. (Table 8). The second most effective burning maintenance interval at reducing total flame length for both individual tree selection and burn and burn only scenarios is the alternating seven and twenty-two scenario, reducing total flame lengths from 103.5 to 27.4 and 27.8 ft. (Table 8). Total flame lengths are reduced under a twenty-two year burning maintenance interval. However, under the burn only scenario, flame lengths are not reduced until the second burn entry (Figure 8).

Probability of Torching

The probability of torching is also reduced most when individual tree selection is combined with prescribed burning (Figure 7; Table 9). The probability of torching initially decreases from 0.88 to 0.65 following mechanical treatment. Prescribed burning then further decreases the probability to 0.53 following the first entry. Overall reductions in the probability of torching range from 0.59 to 0.50 depending on maintenance interval used. A seven year burning maintenance interval yields an overall reduction in probability from 0.88 in year 2011 to 0.29 in year 2062. Next, an alternating 7-22 year burning maintenance interval yields an overall reduction in probability from 0.88 in year 2011 to 0.32 in year 2062. The reduction in probability under 22 year burning maintenance interval is from 0.88 in year 2011 to 0.58 in year 2062. Using this variable as the measure of crown fire potential does not show a difference of reducing the potential of torching when comparing the individual tree selection only and burn only scenarios. However, under a 7 year burning maintenance interval, the burn only treatment is has a probability of torching that is 0.12 lower than the individual tree selection only treatment. Overall trends in both the individual tree selection and burn and burn only simulation tend to decrease over time regardless of burning maintenance interval, whereas, the individual tree selection only treatment has a more static trend.

Torching Index

Torching index remains below the 90$^{th}$ percentile for 20ft winds under all treatment scenarios (Figure 8; Table 10). On the other hand, torching index is increased from 4.5 mph to above 20 mph under both the individual tree selection and burn and burn only scenarios (Table 10). Individual tree selection and burn and burn only treatments maintain an increasing trend throughout the scenario and near the 90th percentile near year 2062. An individual tree selection only treatment increases torching index in the short term from 4.54 to 10.0, however, over time a torching index deceases to 1.6 mph.

Crowning Index

Crowning index is increased above the 90th and 97th percentile 20ft winds and remains above the control under all treatment scenarios (Figure 9; Table 11). Overtime, an individual tree selection and burn treatment scenario increases crowning index initially from 34.91 to 50.71 mph following mechanical treatment. The first entry of burning further increases crowning index to 66.85 mph, proving to be the most effective no matter burning maintenance interval (Figure 9; Table 11). Burn only treatments are the second most effective at increasing crowning index with an initial increase from 34.91 to 42.67 mph following the first entry of burning. The single individual tree selection only treatment is only slightly effective at increasing crowning index by 15.8 mph initially, and then shows a decreasing trend as the simulation progresses.

Coarse Woody Debris

The amount of CWD across the study area is most effectively reduced by the three individual tree selection and burn scenarios (Figure 10; Table 12). Figure 10 shows that an individual tree selection and burn treatment is effective at achieving DCs regardless of burning maintenance interval. Initial reductions following the first entry of burning range from 20.16 to 6.02 tons/acre under all burning maintenance intervals. Alternatively, a burn only treatment is only effective at achieving DCs under a seven or alternative seven and twenty–two year burning maintenance interval. A seven year burning maintenance interval shows an initial reduction from 19.59 to 8.45 tons/acre following the first entry of burning. Loading then increases to 12.22 tons/acre before the second burn entry which then decreases the loading to 6.35 tons/acre. After the second entry under both the seven year burning maintenance interval, the loading of CWD remains within DCs. An alternating seven and twenty-two year burning maintenance interval shows periods of time when CWD is within DCs and periods when loading is over DCs throughout the entire simulation. If prescribed burning is not implemented, CWD is not affected.

Fine Woody Debris

Fine woody debris is reduced by any of the modeled treatments over the fifty year simulation (Figure 11; Table 13). Figure 13 shows that mechanical treatment can increase fine woody debris in the short term. Fine woody debris is reduced initially from 7.24 to 0.12 tons/acre under an individual tree selection and burn scenario. A burn only treatment shows initial reductions to be from 4.64 to 2.02 tons/acre. In terms of burning maintenance interval, a seven year burning maintenance interval is the most effective at reducing and maintaining fine woody debris levels (Figure 11). When the burning maintenance interval is extended (22 and alternating 7-22 year interval), there are larger fluctuations in fine woody debris loading (Figure 11). Litter

Litter

The fuel loading of litter closely follows fine woody debris across treatment scenarios (Figures 11 & 12). Figure 12 shows an initial flush of litter following mechanical treatment from 2.6 to 3.14 tons/acre. This initial increase is reversed when burning is simulated, reducing the tons/acre from 3.14 to 0.29 (Figure 12; Table 14). Burn only simulations reduce the fuel loading of litter from 2.71 to 0.92 tons/acre after the first burn. Individual tree selection and burn simulations reduce litter from 2.6 to 0.40 following mechanical treatment and first burn entry. In terms of maintenance interval, a seven year interval is the most effective at reducing and maintaining litter levels (Figure 12). When the burning maintenance interval is extended (22 and alternating 7-22 year interval), there are larger fluctuations in litter loading (Figure 12).

### Duff

Duff is reduced by at least 60% over the 50 year simulation when prescribed burning is implemented (Figure 13; Table 15). There is little difference between duff levels between the control and individual tree selection only scenario. Individual tree selection and burn treatments initially reduce duff from 2.34 to 1.65 tons/acre. Burn only treatments initially reduce duff from 2.32 to 1.76 tons/acre. Overtime, a seven year burning maintenance interval is the most effective at reducing the amount of fuel loading represented by duff (Figure 13). Figure 13 also shows that the effectiveness of duff reduction decreases at the burning maintenance interval is increased.

### Total Fuel Loading

In terms of reducing overall total fuel loading, the individual tree selection and burn treatment is the most effective over time (Figure 14; Table 16). Initial reductions move the total fuel loading from 32.26 to 8.08 tons/acre following the first entry of burning. Burn only treatments are less effective at reducing total fuel loading, but do reduce loadings from 29.26 to 13.15 tons/acre initially.  Total fuel loading is the cumulative representation of CWD, fine woody debris, litter and duff. Therefore, the overall trend is similar to the above variables with a seven year burning maintenance interval being the most effective followed by the alternation seven and twenty-two year and twenty –two year interval respectively (Figure 16).

### Potential $PM_{2.5}$ Concentration

The amount of potential $PM_{2.5}$ released during a wildfire at $97^{th}$ percentile weather conditions is most effectively reduced when prescribed burning is implemented in the individual tree selection and burn or burn only scenarios (Figure15; Table 17). Single individual tree selection only treatments initially increase $PM_{2.5}$ concentrations by 0.02 tons/acre because of the assumption that 15% of stems and 10% of branchwood will be left on site following biomass removal. However, under a individual tree selection and burn treatment scenario, this initial increase is substantially reversed following the initial entry of prescribed fire (initial reduction from 0.16 to 0.05 tons/acre) Figure 15 shows that a seven year burning maintenance interval is most effective at reducing $PM_{2.5}$ concentration, followed by an alternating seven and twenty-two year burning maintenance interval and a twenty-two year burning maintenance interval.

## Discussion

### Current Conditions

Based on the current conditions of modeled stands, the ponderosa pine forest within the WUI of the Coconino National Forest is in urgent need for ecological restoration treatment (Appendix A, Table 1). Forest structure, potential fire behavior, and fuel loading are highly departed from HRV and DCs. Results show that if no treatment is done, stand density, smoke concentration, and total fuel loading will continue to increase over time. (Figures 3, 14 & 15). When compared to ponderosa pine HRV, current conditions are estimated to be now more than 3 times (486 - 630%) greater than historic conditions. When compared to the Coconino National Forest mid-scale DCs in ponderosa pine ecosystems, the forest is ranging from 23 to 83 (130-520%) square feet of BA greater than DCs.  In addition, when compared to the HRV of BA of ponderosa pine, the current BA is estimated to range from 30 to 64 (140-260%) over what is historic. When compared to the Four Forest Restoration Initiative DCs, currently RDI conditions range from 102 to 273% greater than DCs. The upper end of current condition range is currently within the zone of imminent mortality of 0.55 RDI (Long and Shaw 2005), leading to higher fire risk and forest health concerns.

Modeling does not show large increases in potential fire behavior above current conditions over time. Given the increasing intensity and severity of current wildfires (Miller and Yool 2002, Schoennagel et al. 2004, Stephens and Ruth 2005, Strom and Fulé 2007), higher levels of fire intensity, severity and extent would make suppression of these fires more difficult and expensive (Dombeck et al. 2004). In addition, the fuel loading trends that are represented by this analysis are likely to represent the upper end of conditions within the study area. These conditions give managers a worst case scenario of how fire behavior, wildlife, and scenic integrity will be affected by high levels of fuel loading (Reinhardt 1997, Brown et al. 2003, Farnsworth 2003, Mason et al. 2006 Kailies et al. 2010). Overall, the results of the modeling simulation stress the need for ecological treatment, and support the treatments that 4-FRI is proposing under the first phase of implementation (USDA Forest Service 2011c).

**Treatment Effectiveness**

Results of all modeling simulations show that some level of treatment (individual tree selection only, individual tree selection and burn, and burn only) moves stand conditions towards HRV and DCs regardless of burning maintenance interval (Figures 2-5; Tables 5-7). In terms of stand structure, the control scenario shows the highest TPA, BA and RDI of any treatment, and the highest departure from HRV and DCs throughout the fifty year simulation (Figures 2-5; Tables 5-7). Figure 4 shows that the diameter distribution in the control scenario is composed of primarily smaller trees with a lower proportion of trees in the larger diameter classes. This is inconsistent with the Coconino National Proposed Revised Plan, which has a landscape scale desired condition of "sufficient" groups of old growth to be representative across the landscape (USDA Forest Service 2011a). What is "sufficient" is not defined within the plan. On the other hand, from this desired condition, we can assume that treatments that increase the proportion of trees represented in larger diameter classes is more effective at moving towards DCs than the control. Modeled simulation results show that an individual tree selection and burn scenario is the most effective treatment at achieving HRV and DCs for all variables (Figures 2, 3, 5 & 10). An individual tree selection and burn treatment also shows a rightward shift in diameter distribution towards a larger percent of 18 inch and greater diameter trees (Figure 4). The three burn only treatments are a close second in terms of effectiveness at achieving HRV and DCs overtime. These treatment scenarios take longer to achieve HRV and DCs; however they do help move the diameter distribution towards larger diameter classes (Figure 2 and 4).Burn only treatments move towards DCs at a slower rate because of a lack of the initial decrease in density that occurs with mechanical treatment (Figures 2, 5 & 10). Lastly, over the simulation timeframe, a single individual tree selection only treatment does not hold its effectiveness over time (Figure 2).

When assessing treatment effectiveness by the reduction in potential fire behavior, a combination individual tree selection and burn treatment reduces overall fire behavior by the largest margin (Figures 6-9). This is likely due to a large initial decrease in stand density from individual tree selection followed by an increase in canopy base heights from prescribed fire (Hunter et al. 2007, Roccaforte et al. 2008). Burn only treatments also fire behavior, do not result in large initial decreases in fire behavior and thus take longer to decrease fire behavior overall. Finally, when assessing treatment effectiveness in terms of reduction in fuel loading, a combination individual tree selection and burn treatment shows larger overall reductions in fuel loading over time (Figure 14). Conversely, immediately after mechanical treatment, fuel loading of litter and fine woody debris increases (Figure 11 and 12). This is the result of the model assumption that a portion of stems and branchwood cut will remain on site after biomass removal. This initial increase is reversed when burning is simulated (Figure 11).When comparing the effectiveness of individual tree selection  and burn versus burn only treatments, burn only treatments trend closely when looking at duff and CWD (Figure 10 and13). DCs for CWD are only achieved when burning is added in treatment scenarios over the simulation timeframe (Figure 10).

**Maintenance Interval**

Seven Year Interval

The most effective prescribed burning maintenance interval at achieving and maintaining HRV and DCs for stand structure, while reducing overall fire behavior and fuel loading is the seven year interval (Figures 2, 3, 5 & 10). When looking at TPA, RDI, and CWD under an individual tree selection and burn treatment scenario at a seven year burning maintenance interval, stand conditions approach the lower end of HRV and DCs, and in most cases are still trending downwards. Therefore, caution is given when implementing a burning maintenance interval near seven years. Tables 5, 7 and 12 show a static trend at the end of the simulation; however, maintaining conditions at the lower end of HRV or DCs can easily fall below HRV and DCs, potentially causing unknown effects in light of climate change (Fulé 2008). In addition, on steep slopes, higher levels of CWD, litter and duff are required to maintain soil integrity (Agee 1973, Graham et al. 1994, Neary et al. 1999). A seven year burning maintenance interval has the potential to reduce the amount of litter and duff over a fifty year period (Figures 12 & 13). This is likely the result of greater needle cast following prescribed fire due to scorch. On the other hand, the overall reduction in total fuel loading helps to reduce the potential of $PM_{2.5}$ in smoke during a wildfire event (Reinhardt 1997) under both the seven year burn only and individual tree selection and burn treatments.

Alternating Seven then Twenty-two Year Interval

An alternating seven and twenty-two year burning maintenance interval is the second most effective interval when looking at achieving HRV, DCs, reducing overall fire behavior, reducing potential $PM_{2.5}$, and reducing overall fuel loading. Over the fifty year simulation timeframe, an alternating 7 and 22 year burning maintenance interval allows for fluctuations in stand structure and fuel loading which may make stands more resilient by proving a mosaic across the landscape (Allen et al. 2002, Savage and Mast 2005). Additionally, an alternating 7 and 22 year burning maintenance interval is nearly as effective at reducing total flame lengths, raising crowning index and reducing PM2.5 concentration as the 7 year burning maintenance interval (Figures 9 and 15). Total fuel loading is only slightly higher at the end of simulation than under a seven year burning maintenance interval (Table 16); whereas, the amount of fine woody debris, litter and duff are substantially higher (Tables 13, 14, 15). This could have positive implications when trying to maintain soil integrity on steep slopes; however, could also yield higher concentrations of $PM_{2.5}$ in smoke.

Twenty-two Year Interval

Lastly, a twenty-two year burning maintenance interval is the least effective at achieving HRV, DCs, reducing overall fire behavior, reducing potential $PM_{2.5}$, and reducing overall fuel loading. Tables 5-17 show that the trend towards the end of simulation is often not static and the long term effects of a twenty-two year burning maintenance interval are not shown by the fifty year simulation. When looking at stand structure alone, the given 7, 22, or alternating 7-22 burning intervals have less effect on the trajectory of a stand than the different simulated treatments (Figures 2, 3 & 5). Likewise, when using the probability of torching or torching index as measures of crown fire potential, the period of maintenance interval is less of a factor than the treatment itself. All results show positive trends towards HRV, DCs, reduced fire behavior, lower concentrations of $PM_{2.5}$, and reductions in fuel loading when prescribed fire is simulated. Uneven-aged mechanical individual tree selection treatments, on the other hand, are only effective when coupled with fire.

## Management Implications

### Ecological Need for fire

The ecological need for fire as the primary disturbance agent in ponderosa pine is well represented in the literature (Cooper 1960, Swnetnam and Basin 1996, Covington et al. 1997, Moore et al.1999, Covington and Moore 1994b, 1994c, Kolb et al.1994, Fulè  et al. 2006, Fulè et al. 1997, Mast et al. 1999, Allen et al. 2002, Friederici 2003, Brown et al. 2004). Ponderosa pine itself is a fire adapted species that shows physiologic traits such as thick bark, open crowns, self- pruning branches and needle fascicles that protect plant meristems as methods of resistance to fire effects (Zwolinski 1996, Kealy And Zedler 1998). These traits combined with the southwestern climate where summer monsoon season perpetuates prolific lightning help create the low intensity, frequent fire regime that was present prior to Euro-American settlement (Allen et al. 2002). The results of this study show the importance of fire on the landscape, and how the absence of fire makes achieving DCs and HRV more difficult when implementing an individual tree selection without prescribed burning.

#### Plant Physiology

Previous studies have shown that restoration treatments and prescribed fires can have beneficial effects on plant physiology (Feeney et al. 1998, Griffis et al. 2001). Overall tree productivity and growth of plants in both the overstory and understory increases after restoration treatments. Feeney et al. (1998) found that thin and burn treatments are extremely effective at improving soil water content, increasing leaf toughness, increasing leaf nitrogen content, basal area increment and resin flows due to increases in the amount of growing space and more access to sunlight given less canopy cover. The results of this study show that the reduction of TPA and BA should yield larger availability of growing space that may yield better overall tree growth. Griffis et al. (2001) found that the abundance of understory plants is very sensitive to treatment. Overall native and exotic plant diversity increases with restoration treatment, whereas, high intensity wildfire results in a lower abundance of native plants and a higher abundance on exotic plants (Griffis et al. 2001, McGlone and Egan 2009). These two studies support the findings of this modeling analysis. Figure 4 shows a shift towards larger diameter classes, with a well-represented portion of trees within the smaller diameter range. It seems reasonable that understory responses from modeled treatments will also increase in abundance and biodiversity based on findings from Griffis et al. (2001).

Soil Integrity

Soil integrity is very sensitive to treatment and fire severity (Reinhardt et al.1997, Neary et al 1999, Beschta et al. 2004). High intensity wildfire can degrade the soil profile, increase nutrient leaching and create soil hyrophobicty that can create accelerated erosion (Cambell et al. 1977, Ice et al. 2004). Other effects include mineralization of organic matter and interruption of root uptake (Ice et al. 2004). On the other hand, mechanical treatments that are directed at ecological restoration of the overstory have shown little to no effects on soil disturbance depending on the method of mechanical tree removal (Korb et al. 2007). In addition, prescribed fire has been shown to help convert the availability of nutrients bound in duff layers and regenerate nutrient cycling (Sackett and Haase 1998). Also, mechanical and prescribed fire treatments can substantially increase the amount of water yield from watersheds (Backer 1986). The results of this study show a decrease in potential fire behavior overtime when an individual tree selection and burn or burn only treatment is implemented. These reductions may help protect soil profiles during wildfire. These studies suggest that soil integrity, nutrient cycling and water yield may be improved if restoration treatments are implemented. As long as managers appropriately plan burning to prevent fire intensity that degrades soil properties, soil conditions have the potential to be improved or at least not harmed.

Wildlife

Kallies et al. (2010) discuss the need for individual tree selection and burning to create patchy arrangements across the landscape that can increase overall species diversity and density. Returning the historical density and disturbance regime can be beneficial to wildlife by increasing overall plant diversity (Allen et al. 2002). The results of modeling in this analysis suggest that the overall abundance of small mammals could increase. A shift to larger diameter trees, as shown with all burning treatments modeled in this study, yields greater opportunity for wildlife nesting and roosting sites (Scott 1978, Rabe et al.1998). In addition the overall fuel loading reduction results of the individual tree selection and burn or burn only modeling simulations achieve Coconino National Forest Proposed Revised Forest Plan DCs for CWD (Figure 10). This desired condition was created to balance the need for wildlife habitat with fire management. In addition, the repeated prescribed fire maintenance intervals that were simulated in this study will cause some tree mortality that will help create snags and large down logs, further promoting wildlife habitat.

**Realistic Management Capabilities**

Capacity

Under the first phase of the 4-FRI implementation, approximately 360,000 acres are proposed to be treated by uneven-aged mechanical treatment and prescribed burning on the Coconino National Forest (USDA Forest Service 2011c). In addition, once 4-FRI is implemented the Coconino National Forest has a yearly target of 30,000 acres per year to be treated with fire (USDA Forest Service 2011a). Based only on numbers, assuming that all 361,379 acres are available for treatment from prescribed fire, it will take approximately 12.5 years to complete the initial prescribed fire entry on all acres. Subsequent entries of prescribed fire will therefore be accomplished in locations where timing of fuel conditions, weather patterns, political pressure, local staffing levels, and funding is appropriate. This will cause alternating burning maintenance intervals across the landscape. When considering the results of this study, as long as the burning maintenance interval vary below the twenty-two year burning maintenance interval level, conditions will likely remain near or within DCs and HRV (Figures 2, 3, 5 & 11).

Smoke Management

Integrating smoke management issues into ecological restoration can be very challenging. Public issues and concerns including health issues, viewshed obstruction, and annoyance can often hinder or even prohibit the use of prescribed fire. Also, large uncharacteristic wildfires typically put off 3 to 4 times the smoke emission of prescribed fires (Brown and Bradshaw 1994, Ward and Hardy 1991). For managers, integrating smoke management is a constant endeavor. Communication and coordination with the Arizona Department of Environmental Quality (ADEQ), other forests, community members, and other interested persons is a daily affair during prescribed burning season (fall). The results of this study show burning treatments have the potential to greatly reduce the amount of $PM_{2.5}$ emitted during a wildfire (Figure 15). On the other hand, prescribed burning is required to reduce the amount of potential $PM_{2.5}$ emitted. In order to achieve this, managers must use prescribed fire at a larger scale and extent, initially increasing the amount of $PM_{2.5}$ in the air. This issue can often push the public towards selecting a no fire alternative and only use mechanical treatment to reduce tree density. A single mechanical treatment has little effect on the amount of potential $PM_{2.5}$ emitted (Figure 15). This is likely due to the fact that mechanical treatments do not address the uncharacteristic levels of fuel loadings that have built up since fire exclusion. The total amount of fuel loading, including all aspects of the fuel profiles (duff, litter, fine and CWD) are the primary contributors to smoke particulate emission (Reinhardt et al. 1997). Without fire, removing fuel loadings can be difficult, expensive, and relatively ineffective. In addition, the fuel loading biomass that is removed must also be transported to another location where it is often then burned.

Future Work Needed

The results from our modeling simulations have limitations. While we are able to estimate the effectiveness treatments will have, there are certainly errors and the actual effects of treatment will be unknown until implementation is completed and effectiveness is measured on the ground. In addition, the results of this study may yield forest conditions that are not sustainable, under changing climates and forest conditions. With the actual effects of climate change being unknown, managers can only try to make the forest more resilient (Fulè 2008). In addition, this modeling analysis did not address or predict mortality following treatment. Mortality predictions can be difficult due to many different variables and contributors to forest stress and mortality (Flewelling and Monserud 2002). Adaptive management should be used once 4-FRI implementation begins in order to adjust for any large-scale mortality causes.

Overall, the results of the study support that 4-FRI has the potential to achieve desired and historic conditions, and that fire is critical to this achievement. Without continued use of fire, forest conditions will likely be less healthy and may have less resistance or resilience to uncharacteristic wildfire and climate change. More research is needed to 1) analyze whether 4-FRI treatment are effective at achieving HRV and DCs after implementation, 2) Asses large-scale restoration treatment effect under changing climate, and 3) Measure actual decreases in $PM_{2.5}$ concentration in smoke after ponderosa pine restoration.

## Conclusion

This study represents a subset of the actual treatments that 4-FRI is proposing, and modeled conditions that best serve as an estimate or approximation of reality. Overall, this study demonstrates the need for ecological restoration and continued fire activity in ponderosa pine. From an ecological and fire management standpoint, prescribed burning is required in order to effectively move a stand towards HRV or DCs. Individual tree selection alone is not an effective alternative to burning and can inadvertently degrade current conditions if mechanical treatment is not repeated. Prescribed burning also helps move stands conditions by percentage towards larger diameter classes. This is a desired condition that helps support wildlife habitat, timber sustainability and wildfire resilience (Harrington and Sackett 1992, Kalies et al. 2010). Fire is an evolutionary process in ponderosa pine (Cooper 1960, Covington and Moore 1994b, Swetnam and Basin 1996). The modeled results of this study support this need and show how HRV and DCs cannot be achieved in the absence of fire or without continued mechanical treatment repeated over time.

## Literature Cited


Abella SR, Denton CW, Brewer DG, Robbie WA, Steinke RW, Covington WW. 2011. Using a terrestrial ecosystem survey to estimate the historical density of ponderosa pine trees. Research Note RMRS-RN-45. USDA Forest Service, Rocky Mountain Research Station. 9 p.

Agee JK. 1973. Prescribed fire effects on physical and hydrologic properties of mixed-confier forest floor and soil. Report 143, Univ. California resources Center, Davis, CA.

Agee J.K. 2002. The fallacy of passive management: managing for firesafe forest reserves. Conservation Biology. Practice 3 (1):18–25.

Agee JK, Skinner CN. 2005. Basic Principles of Forest Fuel reduction Treatments. Forest Ecology and Management 211:83–96.

Allen GD, Savage M, Falk DA, Suckling KF, Swnetnam TW, Schuke T, Stacey PB, Morgan P, Hoffman M, Klingel JT. 2002. Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. Ecological Applications. 12(5): 1418-1433.

Anderson HE. 1982. Aids to determining fuel models for estimating fire behavior. Intermountain Forest and Range Experiment Station. USDA Forest Service. General Technical Report. INT-122: 28 p.

Bailey JD, Covington WW. 2002. Evaluating ponderosa pine regeneration rates following ecological restoration treatments in northern Arizona, USA. Forest Ecology and Management. 155:271-278

Baker MB, Jr. 1986. Effects of ponderosa pine treatments on water yield in Arizona. Water Resources Research. 22(1): 67-73

Biswell HH. 1960. Danger of wildfire reduced by prescribed burning in ponderosa pine. California Agriculture 14(10):5–6.

Bowman DM, Johnston FH. 2005. Wildfire smoke, fire management, and human health. Eco Health. Short Communications. 2:76-80

Brown JK. 1970. Ratios of Surface Area to Volume for Common Fine Fuels. Forest Science. 16 (1): 101-105.

Brown JK, Bradshaw LS. 1994. Comparisons of particulate emissions and smoke impacts from presettlement, full suppression, and prescribed natural fire periods in the Selway-Bitterroot Wilderness. International Journal of Wildland Fire. 4(3):143-55.

Brown RT, Agee JK, Frankiln JF. 2004. Forest restoration and fire: principles in the context of place. Conservation Biology. 18(4):903-912.

Brown TC, Daniel TC. 1984. Modeling forest scenic beauty: concepts and application to ponderosa pine. USDA Forest Service, Rocky Mountain Forest and range Experiment Station. Research Paper. RM-256: 42 p.

Butler BW, Cohen JD. 1998. Firefighter safety zones: a theoretical model based on radiative heating. International Journal of Wildland Fire 8(2):73-77.

Campbell RE, Baker MB Jr, Ffolliott PF, Larson FR, Avery CC. 1977. Wildfire effects on a ponderosa pine ecosystem: An Arizona case study. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station.  12p.

Collins BM, Stephens SL., Moghaddas JJ., Battles J.2010. Challenges and Approaches in Planning Fuel Treatments across Fire-Excluded Forested Landscapes. Journal of Foresty. January/February: 24-31

Cooper C.1960. Changes in vegetation, structure, and growth of southwestern ponderosa pine forests since white settlement. Ecological Monographs. 30(2):129-162

Covington WW, Fulé PZ, Hart SC, Weaver RP. 2001. Modeling Ecological Restoration on Ponderosa Pine Forest Structure. Restoration Ecology. 9(4):421-431

Covington WW, DeBano, LF. 1994a. Sustainable ecological systems: implementing an ecological approach to land management. 1993 July 12-15; Flagstaff, Arizona. GTR RM-247. Fort Collins, CO: USDA Forest Service, Rocky Mountain Forest and Range Experiment Station. 363 p.

Covington WW, Moore MM.1994b. Postsettlement changes in natural fire regimes: ecological restoration of old-growth ponderosa pine forests. Journal of Sustainable Forestry 2:153-181

Covington WW, Moore MM.1994c. Southwestern ponderosa pine forest structure: changes since Euro-American settlement. Peer reviewed. Journal of Forestry. 92(1):39-47

Covington WW, Fulé PZ, Moore MM, Hart SC, Kolb TE, Sackett SS, Wagner MR. 1997. Restoring ecosystem health in ponderosa pine forests of the southwest. Journal of Forestry. 95(4):23-29.

Crookston NL, Dixon GE. 2005. The forest vegetation simulator: A review of its structure, content, and applications. Computers and Electronics in Agriculture. 49(1):60-80.

Diggins C, Fulé PZ, Covington WW. 2009. Modeling forest change and management alternatives on a restored landscape: Future climate affects management strategies for maintaining forest restoration treatments. [MSF Thesis]. Flagstaff (AZ): Northern Arizona University. 37 p.

Dixon GE. 2002. Essential FVS: A user's guide to the Forest Vegetation Simulator. Revised September 2010. USDA Forest Service. Forest Management Service Center. 219 p.

Dombeck MP, Williams JE, Wood CA. 2004. Wildfire policy and public lands: integrating scientific understanding with social concerns across landscapes. Conservation Biology. 18(4):883-889.

Duryea ML, Vince SW. 2005. Introduction: The city is moving to our frontier's doorstep. In: Forests at the Wildland-Urban Interface: Conservation and Management. Washington D.C: CRC Press. p.3-13

Einfeld W, Ward D, Hardy C. 1991. Effects of fire behavior on prescribed fire smoke characteristics- A case study. Global Biomass Burning-Atmospheric, Climatic, and Biospheric Implications. Cambridge, MA. MIT Press p:4112-419.

[FACTS] Forest Service Activity Tracking System. USDA Forest Service database. Accessed on 7-15-11.

Farnsworth A, Summerfelt P, Neary DG, Smith T. 2003. Flagstaff's wildfire fuels treatments: prescriptions for community involvement and a source of bioenergy. Biomass and Bioenergy. 24:269-276.

Feeney SR, Kolb TE, Covington WW, Wagner MR. 1998. Influence of thinning and burning restoration treatments on Presettlement ponderosa pines at Gus Pearson Natural Area. Canadian Journal of Forest Restoration. 28: 1295-1306.

Fire Family Plus. 2009. FireFamilyPlus Version 4: User guide. June 2009. Available at: http://www.firemodels.org/downloads/firefamilyplus/publications/FFP-4_1_Draft_Users_Guide.pdf

Fitzgerald SA. 2005. Fire ecology of ponderosa pine and the rebuilding of fire-resilient ponderosa pine ecosystems. USDA Forest Service, General Technical Report. PSW-GTR-198: 197-225.

Freiderici P. 2003. Ecological restoration of southwestern ponderosa pine forests. Book Excerpt. Ecological Restoration. 21(1):39-41

Fulé PZ. 2008. Does it make sense to restore wildland fire in changing climate?. Restoration Ecology. 16(4):526-531.

Fulé PZ, Covington WW, Moore MM. 1997. Determining reference conditions for ecosystem management of southwestern ponderosa pine forests. Ecological Applications. 7(3):895-908

Fulé PZ, Covington WW, Smith HB, Springer JD, Heinlein TA, Huisinga KD, Moore MM. 2002. Comparing ecological restoration alternatives: Grand Canyon, Arizona. Forest Ecology and Management. 170:19-41

Fulé PZ, Heinlein TA, Covington WW. 2006. Fire histories in ponderosa pine forests of Grand Canyon are well supported: reply to Baker. Letter to editor. International Journal of Wildland Fire. 15:439-445

[FSH] Forest Service Timber Resource Planning Handbook. 1992. Timber Inventory Data and Information Collection. Ch. 10. WO Amendment 2409.13-92-1. USDA Forest Service. 9 p.

Graham R T, Harvey A E, Jain TB, Tonn J R. 1999. The Effects of Thinning and Similar Stand Treatments on Fire Behavior in Western Forests., USDA Forest Service, Pacific Northwest Research Station, Portland, OR. PNW-GTR-463.

Graham RT, Harvey AE, Jurgensen MF, Jain TB, Tonn JR, Page-Dumroese DS. 1994. Managing coarse woody debris in forests of the Rocky Mountains. USDA Forest Service. Intermountain Research Center, Research Paper. INT-RP-477: 12 p.

Griffis KL, Crawford JA, Wagner MR, Moir WH. 2001. Understory response to management treatments in northern Arizona ponderosa pine forests. Forest Ecology and Management. 146: 239-245.

Harrington MG, Sackett SS. 1990. Using fire as a management tool in southwestern ponderosa pine forests. Pages 122–133 in J. S. Krammes, technical coordinator Effects of fire management of southwestern natural resources. Proceedings of the Symposium, 15–17 November 1988, Tucson, Arizona. USDA Forest Service General Technical Report RM-191.

Harrington MG, Sackett SS. 1992. Past and present influence on southwestern ponderosa pine old growth. USDA Forest Service, Intermountain Fire Sciences Laboratory: 44-50.

Heinlein TA, Moore MM, Fulé PZ, Covington WW. 2005. Fire history and stand structure of two ponderosa pine-mixed conifer sites: San Francisco Peaks, Arizona, USA. International Journal of Wildland Fire. 14:307-320.

[HFRA] Healthy Forest restoration Act 2003. H.R. 1904. Signed by president George Bush on Dec. 3rd 2003. 29 p.

Hunter ME, Shepperd WD, Lentile LB, Lundquist JE, Andreu MG, Butler JL, Smith FW. 2007. A comprehensive guide to fuels treatment practices for ponderosa pine in the black hills, Colorado Front Range, and the Southwest. Rocky Mountain Research Station. USDA Forest Service. General Technical Report. RMRS-GTR-198: 93 p.

Hurteau MD, Stoddard MT, Fulé PZ. 2010. The carbon cost of mitigating high-severity wildfire in southwestern ponderosa pine. Global Change Biology. 17(4):1516-1521.

Ice GG, Neary DG, Adams PW. 2004. Effects of wildfire on soils and watershed process. Journal of Forestry. September: 16-20.

Kalies EL, Chambers CL, Covington WW. 2010. Wildlife responses to thinning and burning treatments in southwestern conifer forests: A meta-analysis. 259:333-342.

Keeley JE, Zedler PH. 1998. Evolution of life histories in Pinus. In: Richardson, David M., ed. Ecology and biogeography of Pinus. Cambridge, United Kingdom: The Press Syndicate of the University of Cambridge: 219-250.

Kohen J. 2008. The Wildland-Urban Interface Fire Problem: A Consequence of the Fire Exclusion Paradigm. Forest History Today. (Fall):20-26.

Kolb TE, Wagner MR, Covington WW. 1994. Concepts of forest: utilitarian and ecosystem perspectives. Journal of Forestry. 92(2):10-15.

Korb JE, Fulé PZ, Gideon B. 2007. Different restoration thinning treatments affect level of soil disturbance in ponderosa pine forests of Northern Arizona, USA. Ecological Restoration. March 25(1):43-49.

Landres PB, Morgan P, Swanson FJ. 1999. Overview of the use of natural variability concepts in managing ecological systems. Ecological Applications. 9(4):1179-1188

Liu J, Ashton PS. 1994. Individual-based simulation models for forest succession and management. Forest Ecology and Management. 73:157-175.

Long JN. 2005. A density management diagram for even-aged ponderosa pine stands. Western Journal of Applied Forestry. 20(4):205-215

Mason CL, Lippke BR, Zobrist KW, Bloxton TD, Ceder KR, Comnick JM, McCarter JB, Rogers HK. 2006. Investments in fuel removals to avoid forest fires result in substantial benefits. Journal of Forestry. January/Februray:27-31.

Mast JN, Fulé PZ, Moore MM, Covington WW, Waltz AEM. 1999. Restoration of presettlement age structure of an Arizona ponderosa pine forest. Ecological Applications. 9(1):228-239.

McGlone CM, Egan D. 2009. The role of fire in the establishment and spread of nonnative plants in Arizona ponderosa pine forests: A review. Journal of the Arizona –Nevada Academy of Science 41 (2):75-86.

Miller JD, Yool SR. 2002. Mapping forest post-fire canopy consumption in several overstory types using multi-temporal Landsat TM and ETM data. Remote Sensing of Environment. 82:481-496.

Moore MM, Covington WW, Fulé PZ.1999. Reference Conditions and Ecological Restoration: A Southwestern Ponderosa Pine Perspective. Ecological Applications. 9(4):1266-1277.

Morgan P, Aplet GH, Haufler JB, Humphries HC, Moore MM, Wilson WD. 1994. Historical range of variability: a useful tool for evaluating ecosystem change. Journal of Sustainable Forestry. 2(1/2): 87-111.

Neary DG, Klopatek CC, deBano LF, Ffolliott PF. Fire effects on belowground sustainability: a review and synthesis. Forest Ecology and Management. 122:51-71.

[NRIS] Natural Resource Information System. 2011. FSVeg User Guide. USDA Forest Service. < http://www.fs.fed.us/nrm/fsveg/index.shtml>.

[NWCG] National Wildfire Coordinating Group. 1997. Photo series for quantifying forest residues in the southwestern region. PNW-105, 1980. 2-PP-1: 118-119.

[NWCG] National Wildfire Coordinating Group. 2008. Glossary of Wildland Fire Terminology. PMS 205: 183.

[OPLMA] Omnibus Public Land Management Act.2009. Title IV Forest Landscape Restoration Act of 2008. S.22. 111th Congress, 1st Session.

Ottmar RD, Schaaf MD, Alavardo E. 1996. Smoke considerations for using fire in maintaining healthy forest ecosystems. USDA Forest Service. Intermountain Research Station, General Technical Report. INT-GTR-341:24-28.

Puhlick JJ. 2011. Regional-and local-scale modeling of ponderosa pine seedling densities in the southwest. Thesis. Northern Arizona University: 89 p.

Rabe MJ, Morrell TE, Green TE, Green H, DeVos Jr JC, Miller CR. 1998. Characteristicsof ponderosa pine snag roosts used by reproductive bats in northern Arizona. The Journal of Wildlife Management. 62(2):612-621.

Rasmussen DI. 1941. Biotic communities of the Kaibab Plateau, Arizona. Ecological Monographs. 11:229-275

Rebain SA, Reinhardt ED, Crookston NL, Beukema SJ, Kruz WA, Greenough JA, Robinson DCE, Lutes DC. 2010. The Fire and Fuels Extension to the Forest Vegetation Simulator: Updated model documentation. Revised May 2011. USDA Forest Service. Forest Management Service Center. 387 p.

Reinhardt ED, Crookston NL. 2003. The Fire and Fuels Extension to the Forest Vegetation Simulator. USDA Forest Service. Rocky Mountain Research Station. General Technical Report. RMRS-GTR-116. 209 p.

Reinhardt ED, Keane RE, Brown JK. 1997. First Order Fire Effects Model: FOFEM 4.0, user guide. USDA Forest Service. Intermountain Research Station. General Technical Report. INT-GTR-344: 65 p.

Roccaforte JP, Fulé PZ, Covington WW. 2009. Monitoring landscape-scale ponderosa pine restoration treatment implementation and effectiveness. Restoration Ecology doi:10.111/j.1526-100x.2008.00508x. 14 p.

Sanchez Meador AJ, Parysow PF, Moore MM. 2010. Historical stem-mapped permanent plots increase precision of reconstructed reference data in ponderosa pine forests of Northern Arizona. Restoration Ecology. 18(2):224-234.

Savage M, Mast JN. 2005. How resilient are southwestern ponderosa pine forests after crown fires?. Canadian Journal of Forest Research. 35(4):967-977.

Schaaf MD, Sandberg DV, Schreuder MD, Riccardi CL. 2007. A conceptual framework for ranking crown fire potential in wildland fuelbeds. Canadian Journal of Forest Restoration. 37:2464-2478.

Schoennagel T, Veblen TT, Romme WH. 2004. The interaction of fire, fuel, and climate across Rocky Mountain forests. American Institute of Biological Sciences. 54(7):661-676.

Schubert GH. 1971. Growth response of even-aged ponderosa pines: Related to stand density level. Journal of Forestry. December: 857-860.

Scott JH. 1998. Fuel reduction in residential and scenic forests: a comparison of three treatments in a western Montana ponderosa pine stand. USDA Forest Service, Rocky Mountain Research Station. Research Paper. RMRS-RP-5: 22 p.

Scott JH., Burgan RE. 2005. Standard Fire Behavior Fuel Models: A Comprehensive Set for Use with Rothermel's Surface Fire Spread Model. USDA Forest Service. General Technical Report. RMRS-GTR-153: 72 p.

Scott VE. 1978. Characteristics of ponderosa pine snags used by cavity-nesting birds in Arizona. Journal of Forestry. January:26-28.

Shaw JD, Long JN. 2010. Consistent definition and application of Reineke's Stand Density Index in siviculture and stand projection. USDA Forest Service Proceedings. RMRS-P-61:199-209.

Shepperd WD. 2006. Long-term seedfall, establishment, survival, and growth of natural and planted ponderosa pine in the Colorado Front Range. Western Journal of Applied Forestry. 51(1): 19-26.

Smith DM., Larson BC., Kelty MJ., Ashton MS. 1997. The Practice of Siviculture: Applied Forest Ecology. 9th ed. New York: John Wiley & Sons, Inc. p. 69-98.

Sorensen SD, Finkral AJ, Huang CH. 2010. Short- and long-term effects of thinning and prescribed fire on carbon stocks in ponderosa pine stands in northern Arizona. Forest Ecology and Management. 261:460-472.

Stratton RD. 2004. Effectiveness of Landscape Fuel Treatments on Fire Growth and Behavior. Journal of Forestry. (October) 32-40.

Stephens SL, Ruth LW. 2005. Federal Forest-Fire Policy in the United States. Ecological Applications. 15(2):532-542.

Strom BA., Fulé PZ., 2007. Pre-wildfire fuel treatments affect long-term ponderosa pine dynamics. International Journal of Wildland Fire. 16: 128-138

Swnetnam TW, Basin CH. 1996. Historical fire regime patterns in the southwestern United States since AD 1700: In: CD Allen (ed) Fire Effects in Southwestern Forests: Proceedings of the 2nd La Mesa Fire Symposium, pp.11-32. USDA Forest Service, Rocky Mountain Research Station General Technical Report RM-GTR-286.

[TES] Terrestrial Ecosystem Survey. 2001. Terrestrial Ecosystem Survey of the Coconino National Forest. Website. Available from: http://alic.arid.arizona.edu/tes/tes.html

USDA Forest Service. 2011a. Coconino National Forest Proposed Revised Forest Plan. [DRAFT]. (USDA Forest Service: Southwestern Region).

USDA Forest Service. 2011b. Common Stand Exam Field Guide: Region 3. NRIS FSVeg. 119 p.

USDA Forest Service. 2011c. Proposed Action for Four-Forest Restoration Initiative: Coconino and Kaibab national Forest, Coconino County Arizona. [DRAFT]. (USDA Forest Service: Southwestern Region).

VanWagner CE. 1977. Conditions for the start and spread of crown fire. Canadian Journal of Forest Research 7:23–34.

Veblen TT. 2003. Historic range of variability of mountain forest ecosystems: concepts and applications. The Forestry Chronicle. 79(2):223-226.

Ward DE, hardy CC. 1991. Smoke emissions from wildland fires. Environmental International 17:117-134.

Weaver H. 1951. Fire as an ecological factor in the southwestern ponderosa pine forests. Journal of Forestry. 49:93-98

White AS. 1985. Presettlement regeneration patterns in southwestern ponderosa pine stand. Ecology. 66:589-594.

Zwolinski MJ. 1996. Effects of fire on montane forest ecosystems. In: Ffolliott, Peter F.; DeBano, Leonard F.; Baker, Malchus, B., Jr.; [and others], tech. coords. Effects of fire on Madrean Province ecosystems: a symposium proceedings; 1996 March 11-15; Tucson, AZ. Gen. Tech. Rep. RM-GTR-289. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 55-63.

Table 1: Years when treatment was simulated and maintenance entries for prescribed burning.

| Treatment | Individual tree selection Only | Individual tree selection & Burn 7 yr Interval | Individual tree selection & Burn 22 yr Interval | Individual tree selection & Burn 7-22 Alternating Interval | Burn Only 7 yr Interval | Burn Only 22 yr Interval | Burn Only 7-22 Alternating Interval |
|---|---|---|---|---|---|---|---|
| Mechanical | 2012 | 2012 | 2012 | 2012 | -- | -- | -- |
| 1st Entry Burn | -- | 2015 | 2015 | 2015 | 2015 | 2015 | 2015 |
| 2nd Entry Burn | -- | 2022 | 2037 | 2022 | 2022 | 2037 | 2022 |
| 3rd Entry Burn | -- | 2029 | 2059 | 2044 | 2029 | 2059 | 2044 |
| 4th Entry Burn | -- | 2036 | -- | 2051 | 2036 | -- | 2051 |
| 5th Entry Burn | -- | 2043 | -- | -- | 2043 | -- | -- |
| 6th Entry Burn | -- | 2050 | -- | -- | 2050 | -- | -- |
| 7th Entry Burn | -- | 2057 | -- | -- | 2057 | -- | -- |

Table 2: Keywords that were used in FVS to identify and modify the base modeling simulation

| FVS Keyword | Relevance and Modified Parameters |
|---|---|
| ThinSDI | Target =100 SDI, Species = ponderosa pine, smallest DBH cut = 0, largest DBH cut = 18 |
| SDIMax | Max SDI = 450, % where mortality begins = 55, % where stand reaches max density = 85 |
| YardLoss | Portion of stems left = 0.15, portion of stems down = 1.0, Portion of brachwood left = 0.1 |
| NoSprout | Used to eliminate automatic oak sprouting |
| Plant | Used to establish regeneration (Sorensen et al. 2010) |
| CycleAt | Used to force FVS to cycle on years when treatment was scheduled |
| PotMois | Used to modify fire behavior for 97th percentile conditions (Appendix A) |
| PotPAB | Used to modify the percentage of the stand burned = 100% for severe and moderate fires |
| PotTemp | Used to modify fire behavior for 97th percentile conditions (Appendix A) |
| PotSeas | Used to modify season when sever fire is simulated = 3 After greenup (before fall) |
| CanCalc | Used to modify the calculation of canopy base height and canopy bulk density: standard method, min = 6, cutoff = 3 |
| FuelModl | Used to modify the fuel model used for fire modeling = 165 TU5 very high load dry climate timber |

Table 3: Values for HRV and DCs that were established for each of the following variables. Includes references to where HRV and DCs were derived.

| Variable | Value | HRV or DC | References |
|---|---|---|---|
| TPA | 15-60 | HRV | Rasmussen 1941, White 1985, Covington and Moore 1994b, Covington et al 1997, Fulé et al 1997, 2002, 2006, Mast at al. 1999, Roccaforte et al. 2009, Abella et al. 2011, USDA Forest Service 2011b |
| BA ($ft^2$/acre) | 40-74 | HRV | Sanchez Meador et al. 2008, Roccaforte et al. 2009 |
| BA ($ft^2$/acre) | 20-80 | DC | USDA, Forest Service 2011a |
| SDI | 67.5-180 | DC | USDA Forest Service 2011c |
| RDI | 0.15-0.40 | DC | USDA Forest Service 2011c |
| CWD (tons/acre) | 3-10 | DC | USDA, Forest Service 2011a |
| 20 ft Wind (mph) | 40 | 97th Percentile | Fire Family Plus 2009 |
| 0 | 35 | 90th Percentile | Fire Family Plus 2009 |

Table 4: Pretreatment stand condition grown from CSE date until 2011. Values represent the average, minimum, and maximum for each variable out of the 26 stands used for analysis.

| Variable | Average | Minimum | Maximum |
|---|---|---|---|
| TPA | 168 | 87 | 267 |
| BA | 104 | 77 | 167 |
| SDI | 184 | 137 | 286 |
| RDI | 0.41 | 0.31 | 0.64 |
| Flame Length | 103.5 | 50.0 | 129.0 |
| Probability of Torching | 0.88 | 0.6 | 1.0 |
| Torching Index | 4.54 | 0.0 | 19.5 |
| Crowning Index | 34.9 | 19.7 | 51.0 |
| $PM_{2.5}$ | 0.14 | 0.1 | 0.2 |
| CWD | 19.6 | 18.8 | 20.7 |
| Fine Woody Debris | 4.6 | 3.5 | 5.7 |
| Litter | 2.6 | 1.5 | 4.3 |
| Duff | 2.2 | 2.1 | 2.4 |
| Total Fuel Loading | 29.1 | 26.1 | 32.6 |

Table 5: Change in average tree density (TPA) at the start of simulation, the minimum and maximum condition, condition after final treatment, condition at the end of the simulation, and overall condition trend. * refers to high points in the treatment interval at year 2062. **refers to low points in the treatment interval at year 2062.

| | Control | Individual tree selection Only | Individual tree selection & Burn 7 Yr Interval | Individual tree selection & Burn 22 Yr Interval | Individual tree selection & Burn 7-22 Yr Interval | Burn Only 7 Yr Interval | Burn Only 22 Yr Interval | Burn Only 7-22 Yr Interval |
|---|---|---|---|---|---|---|---|---|
| Starting Condition | 168 | 168 | 168 | 168 | 168 | 168 | 168 | 168 |
| HRV | 15-60 | 15-60 | 15-60 | 15-60 | 15-60 | 15-60 | 15-60 | 15-60 |
| Minimum Condition | 139 | 73 | 19 | 24 | 23 | 36 | 51 | 46 |
| Maximum Condition | 170 | 168 | 168 | 168 | 168 | 170 | 170 | 170 |
| Final Treatment (2012, 51, 57, 59) | N/A | 73 | 19 | 24 | 23 | 36 | 51 | 46 |
| Ending Result (2062) | 139** | 110* | 28* | 27** | 40* | 40* | 52** | 53* |
| Trend at end of Simulation | Decreasing | Increasing | Decreasing | Decreasing | Decreasing | Decreasing | Decreasing | Decreasing |
| Range | 139-170 | 73-168 | 19-168 | 34-168 | 23-168 | 36-170 | 51-170 | 46-170 |

Table 6: Change in average BA ($ft^2$/acre) at the start of simulation, the minimum and maximum condition, condition after final treatment, condition at the end of the simulation, and overall condition trend. * refers to high points in the treatment interval at year 2062. **refers to low points in the treatment interval at year 2062.

| | Control | Individual tree selection Only | Individual tree selection & Burn 7 Yr Interval | Individual tree selection & Burn 22 Yr Interval | Individual tree selection & Burn 7-22 Yr Interval | Burn Only 7 Yr Interval | Burn Only 22 Yr Interval | Burn Only 7-22 Yr Interval |
|---|---|---|---|---|---|---|---|---|
| Starting Condition | 104 | 104 | 104 | 104 | 104 | 104 | 104 | 104 |
| Minimum Condition | 104 | 63 | 53 | 54 | 54 | 79 | 89 | 87 |
| Maximum Condition | 137 | 104 | 104 | 104 | 104 | 107 | 107 | 107 |
| HRV | 40-74 | 40-74 | 40-74 | 40-74 | 40-74 | 40-74 | 40-74 | 40-74 |
| Desired Condition | 20-80 | 20-80 | 20-80 | 20-80 | 20-50 | 20-80 | 20-80 | 20-80 |
| Final Treatment (2012, 51, 57, 59) | N/A | 63 | 53 | 66 | 61 | 79 | 102 | 92 |
| Ending Result (2062) | 137* | 95* | 53 | 66 | 63 | 80 | 102** | 96 |
| Trend at end of Simulation | Increasing | Increasing | Static | Increasing | Static | Decreasing | Increasing | Static |
| Range | 104-137 | 104-63 | 104-53 | 104-54 | 104-54 | 107-79 | 107-89 | 107-87 |

Table 7: Change in average relative density index (SDI/450) at the start of simulation, the minimum and maximum condition, condition after final treatment, condition at the end of the simulation, and overall condition trend. * refers to high points in the treatment interval at year 2062. **refers to low points in the treatment interval at year 2062.

| | Control | Individual tree selection Only | Individual tree selection & Burn 7 Yr Interval | Individual tree selection & Burn 22 Yr Interval | Individual tree selection & Burn 7-22 Yr Interval | Burn Only 7 Yr Interval | Burn Only 22 Yr Interval | Burn Only 7-22 Yr Interval |
|---|---|---|---|---|---|---|---|---|
| Starting Condition | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 |
| Desired Condition | 0.15-0.40 | 0.15-0.40 | 0.15-0.40 | 0.15-0.40 | 0.15-0.40 | 0.15-0.40 | 0.15-0.40 | 0.15-0.40 |
| Minimum Condition | 0.41 | 0.23 | 0.16 | 0.18 | 0.18 | 0.25 | 0.32 | 0.29 |
| Maximum Condition | 0.49 | 0.41 | 0.41 | 0.41 | 0.41 | 0.42 | 0.42 | 0.42 |
| Final Treatment (2012, 51, 57, 59) | N/A | 0.23 | 0.16 | 0.19 | 0.18 | 0.24 | 0.32 | 0.29 |
| Ending Result (2062) | 0.49* | 0.35* | 0.17* | 0.20** | 0.21* | 0.25* | 0.32** | 0.31 |
| Trend at End of Simulation | Increasing | Increasing | Static | Static | Static | Static | Static | Static |
| Range | 0.41-0.49 | 0.23-0.41 | 0.16-0.41 | 0.18-0.41 | 0.18-0.41 | 0.24-0.42 | 0.32-0.42 | 0.29-0.42 |

Table 8: Change in average total flame length (ft) at the start of simulation, the minimum and maximum condition, condition after final treatment, condition at the end of the simulation, and overall condition trend. * refers to high points in the treatment interval at year 2062. **refers to low points in the treatment interval at year 2062.

| | Control | Individual tree selection Only | Individual tree selection & Burn 7 Yr Interval | Individual tree selection & Burn 22 Yr Interval | Individual tree selection & Burn 7-22 Yr Interval | Burn Only 7 Yr Interval | Burn Only 22 Yr Interval | Burn Only 7-22 Yr Interval |
|---|---|---|---|---|---|---|---|---|
| Starting Condition | 103.5 | 103.5 | 103.5 | 103.5 | 103.5 | 103.5 | 103.5 | 103.5 |
| Minimum Condition | 102.8 | 54.5 | 19.2 | 21.0 | 22.1 | 23.6 | 29.4 | 27.8 |
| Maximum Condition | 111.5 | 103.5 | 103.5 | 103.5 | 103.5 | 105.1 | 105.1 | 105.1 |
| Final Treatment (2012, 51, 57, 59) | N/A | 60.7 | 19.2 | 21.0 | 22.1 | 23.6 | 29.4 | 28.0 |
| Ending Result (2062) | 102.8 | 79.2 | 20.1 | 21.0** | 27.4 | 23.6 | 29.4** | 27.8 |
| Trend at End of Simulation | Static | Static | Static | Decreasing | Decreasing | Decreasing | Decreasing | Decreasing |
| Range | 102.8-111.5 | 54.5-103.5 | 19.2-103.5 | 21.0-103.5 | 22.1-103.5 | 23.6-105.1 | 29.4-105.1 | 27.8-105.1 |

Table 9: Change in average probability of torching (p-torch) at the start of simulation, the minimum and maximum condition, condition after final treatment, condition at the end of the simulation, and overall condition trend. * refers to high points in the treatment interval at year 2062. **refers to low points in the treatment interval at year 2062.

| | Control | Individual tree selection Only | Individual tree selection & Burn 7 Yr Interval | Individual tree selection & Burn 22 Yr Interval | Individual tree selection & Burn 7-22 Yr Interval | Burn Only 7 Yr Interval | Burn Only 22 Yr Interval | Burn Only 7-22 Yr Interval |
|---|---|---|---|---|---|---|---|---|
| Starting Condition | 0.88 | 0.88 | 0.88 | 0.88 | 0.88 | 0.88 | 0.88 | 0.88 |
| Minimum Condition | 0.78 | 0.62 | 0.29 | 0.38 | 0.32 | 0.50 | 0.62 | 0.56 |
| Maximum Condition | 0.91 | 0.88 | 0.88 | 0.88 | 0.88 | 0.88 | 0.88 | 0.88 |
| Final Treatment (2012, 51, 57, 59) | N/A | 0.65 | 0.30 | 0.41 | 0.36 | 0.53 | 0.62 | 0.60 |
| Ending Result (2062) | 0.78 | 0.64 | 20.1 | 0.43 | 0.37 | 0.53 | 0.63 | 0.56 |
| Trend at End of Simulation | Decreasing | Static | Decreasing | Decreasing | Decreasing | Decreasing | Decreasing | Decreasing |
| Range | 0.78-0.91 | 0.62-0.88 | 0.29-0.88 | 0.38-0.88 | 0.32-0.88 | 0.50-0.90 | 0.62-0.90 | 0.56-0.90 |

Table 10: Change in average torching index (mph 20 ft winds) at the start of simulation, the minimum and maximum condition, condition after final treatment, condition at the end of the simulation, and overall condition trend. * refers to high points in the treatment interval at year 2062. **refers to low points in the treatment interval at year 2062.

| | Control | Individual Tree Selection Only | Individual Tree Selection & Burn 7 Yr Interval | Individual Tree Selection & Burn 22 Yr Interval | Individual Tree Selection & Burn 7-22 Yr Interval | Burn Only 7 Yr Interval | Burn Only 22 Yr Interval | Burn Only 7-22 Yr Interval |
|---|---|---|---|---|---|---|---|---|
| Starting Condition | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 |
| 90th Percentile | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 |
| 97th Percentile | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| Minimum Condition | 4.5 | 0.4 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 |
| Maximum Condition | 6.9 | 10.5 | 29.3 | 26.8 | 25.3 | 27.4 | 27.7 | 28.0 |
| Final Treatment (2012, 51, 57, 59) | N/A | 8.2 | 29.3 | 26.8 | 25.3 | 26.9 | 27.7 | 26.9 |
| Ending Result (2062) | 6.9 | 1.6 | 28.9 | 26.8 | 24.3 | 27.4 | 27.7 | 28.0 |
| Trend at End of Simulation | Increasing | Static | Increasing | Increasing | Increasing | Increasing | Increasing | Increasing |
| Range | 4.4-6.9 | 0.4-10.5 | 4.5-29.3 | 4.5-26.8 | 4.5-25.3 | 4.5-27.4 | 4.5-27.7 | 4.5-28.0 |

Table 11: Change in average crowning index (mph 20 ft winds) at the start of simulation, the minimum and maximum condition, condition after final treatment, condition at the end of the simulation, and overall condition trend. * refers to high points in the treatment interval at year 2062. **refers to low points in the treatment interval at year 2062.

| | Control | Individual Tree Selection Only | Individual Tree Selection & Burn 7 Yr Interval | Individual Tree Selection & Burn 22 Yr Interval | Individual Tree Selection & Burn 7-22 Yr Interval | Burn Only 7 Yr Interval | Burn Only 22 Yr Interval | Burn Only 7-22 Yr Interval |
|---|---|---|---|---|---|---|---|---|
| Starting Condition | 34.9 | 34.9 | 34.9 | 34.9 | 34.9 | 34.9 | 34.9 | 34.9 |
| 90th Percentile | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 |
| 97th Percentile | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| Minimum Condition | 33.5 | 34.9 | 34.9 | 34.9 | 34.9 | 34.9 | 34.9 | 34.9 |
| Maximum Condition | 35.8 | 55.4 | 103.3 | 88.7 | 90.5 | 71.5 | 57.0 | 61.0 |
| Final Treatment (2012, 51, 57, 59) | N/A | 50.7 | 103.3 | 88.7 | 90.5 | 71.5 | 57.0 | 61.0 |
| Ending Result (2062) | 35.8 | 46.0 | 92.1** | 88.7* | 69.6** | 68.6** | 57.0 | 56.1** |
| Trend at End of Simulation | Static | Static | Increasing | Increasing | Increasing | Increasing | Static | Increasing |
| Range | 33.5-35.8 | 34.9-55.4 | 34.9-103.3 | 34.9-88.7 | 34.9-90.5 | 34.5-71.5 | 34.5-57.0 | 34.5-61.0 |

Table 12: Change in CWD >3" (tons/acre) at the start of simulation, the minimum and maximum condition, condition after final treatment, condition at the end of the simulation, and overall condition trend. * refers to high points in the treatment interval at year 2062. **refers to low points in the treatment interval at year 2062.

| | Control | Individual Tree Selection Only | Individual Tree Selection & Burn 7 Yr Interval | Individual Tree Selection & Burn 22 Yr Interval | Individual Tree Selection & Burn 7-22 Yr Interval | Burn Only 7 Yr Interval | Burn Only 22 Yr Interval | Burn Only 7-22 Yr Interval |
|---|---|---|---|---|---|---|---|---|
| Starting Condition | 19.62 | 19.62 | 19.62 | 19.62 | 19.62 | 19.62 | 19.62 | 19.62 |
| Desired Condition | 3-10 | 3-10 | 3-10 | 3-10 | 3-10 | 3-10 | 3-10 | 3-10 |
| Minimum Condition | 19.58 | 19.62 | 2.98 | 4.83 | 3.42 | 5.04 | 8.29 | 6.52 |
| Maximum Condition | 25.65 | 22.28 | 20.20 | 20.20 | 20.20 | 19.62 | 19.62 | 19.62 |
| Final Treatment (2012, 51, 57, 59) | N/A | 20.20 | 3.45 | 5.14 | 3.72 | 6.47 | 9.41 | 7.00 |
| Ending Result (2062) | 26.5 | 22.28 | 4.52 | 5.49** | 6.33* | 8.01 | 9.88** | 10.80* |
| Trend at End of Simulation | Increasing | Increasing | Static | Static | Static | Static | Static | Static |
| Range | 19.6-25.7 | 19.6-22.3 | 2.7-20.2 | 4.8-20.2 | 3.4-20.2 | 4.4-19.6 | 8.3-19.6 | 6.4-19.6 |

Table 13: Change in fine woody debris <3” (tons/acre) at the start of simulation, the minimum and maximum condition, condition after final treatment, condition at the end of the simulation, and overall condition trend. * refers to high points in the treatment interval at year 2062. **refers to low points in the treatment interval at year 2062.

| | Control | Individual Tree Selection Only | Individual Tree Selection & Burn 7 Yr Interval | Individual Tree Selection & Burn 22 Yr Interval | Individual Tree Selection & Burn 7-22 Yr Interval | Burn Only 7 Yr Interval | Burn Only 22 Yr Interval | Burn Only 7-22 Yr Interval |
|---|---|---|---|---|---|---|---|---|
| Starting Condition | 4.63 | 4.63 | 4.63 | 4.63 | 4.63 | 4.63 | 4.63 | 4.63 |
| Minimum Condition | 4.63 | 4.09 | 0.12 | 0.12 | 0.12 | 1.12 | 1.82 | 1.61 |
| Maximum Condition | 5.92 | 7.68 | 7.68 | 7.68 | 7.68 | 4.63 | 4.63 | 4.63 |
| Final Treatment (2012, 51, 57, 59) | N/A | 7.68 | 0.68 | 0.95 | 0.91 | 1.12 | 2.11 | 1.86 |
| Ending Result (2062) | 5.92 | 4.15 | 1.04 | 1.09** | 1.82* | 1.87 | 2.31** | 3.16* |
| Trend at End of Simulation | Increasing | Static | Static | Static | Static | Static | Static | Static |
| Range | 4.6-5.9 | 4.1-7.7 | 0.1-7.7 | 0.1-7.7 | 0.1-7.7 | 1.0-4.6 | 1.8-4.6 | 1.8-4.6 |

Table 14: Change in litter (tons/acre) at the start of simulation, the minimum and maximum condition, condition after final treatment, condition at the end of the simulation, and overall condition trend. * refers to high points in the treatment interval at year 2062. **refers to low points in the treatment interval at year 2062.

| | Control | Individual Tree Selection Only | Individual Tree Selection & Burn 7 Yr Interval | Individual Tree Selection & Burn 22 Yr Interval | Individual Tree Selection & Burn 7-22 Yr Interval | Burn Only 7 Yr Interval | Burn Only 22 Yr Interval | Burn Only 7-22 Yr Interval |
|---|---|---|---|---|---|---|---|---|
| Starting Condition | 2.60 | 2.60 | 2.60 | 2.60 | 2.60 | 2.60 | 2.60 | 2.60 |
| Minimum Condition | 2.60 | 3.14 | 0.20 | 0.29 | 0.29 | 0.51 | 0.80 | 0.63 |
| Maximum Condition | 3.36 | 1.92 | 3.14 | 3.14 | 3.14 | 2.71 | 2.71 | 2.71 |
| Final Treatment (2012, 51, 57, 59) | N/A | 2.79 | 0.34 | 0.52 | 0.42 | 0.71 | 1.05 | 0.88 |
| Ending Result (2062) | 3.35 | 2.52 | 0.59 | 0.66** | 1.12* | 1.05 | 1.25** | 1.61* |
| Trend at End of Simulation | Increasing | Increasing | Static | Static | Static | Static | Static | Static |
| Range | 2.6-3.4 | 1.9-3.1 | 0.2-3.1 | 0.3-3.1 | 0.2-3.1 | 0.4-2.7 | 0.8-2.7 | 0.6-2.7 |

Table 15: Change in duff (tons/acre) at the start of simulation, the minimum and maximum condition, condition after final treatment, condition at the end of the simulation, and overall condition trend. * refers to high points in the treatment interval at year 2062. **refers to low points in the treatment interval at year 2062.

| | Control | Individual Tree Selection Only | Individual Tree Selection & Burn 7 Yr Interval | Individual Tree Selection & Burn 22 Yr Interval | Individual Tree Selection & Burn 7-22 Yr Interval | Burn Only 7 Yr Interval | Burn Only 22 Yr Interval | Burn Only 7-22 Yr Interval |
|---|---|---|---|---|---|---|---|---|
| Starting Condition | 2.26 | 2.26 | 2.26 | 2.26 | 2.26 | 2.26 | 2.26 | 2.26 |
| Minimum Condition | 2.26 | 2.26 | 0.20 | 0.96 | 0.64 | 0.42 | 1.34 | 0.96 |
| Maximum Condition | 3.18 | 2.99 | 2.34 | 2.34 | 2.34 | 2.34 | 2.34 | 2.34 |
| Final Treatment (2012, 51, 57, 59) | N/A | 2.32 | 0.20 | 0.96 | 0.64 | 0.42 | 1.35 | 0.97 |
| Ending Result (2062) | 3.18 | 2.99 | 0.24 | 0.96** | 0.68 | 0.45 | 1.35** | 1.03 |
| Trend at End f Simulation | Increasing | Increasing | Decreasing | Decreasing | Decreasing | Decreasing | Decreasing | Decreasing |
| Range | 2.3-3.2 | 2.3-3.0 | 0.2-2.3 | 1.0-2.3 | 0.6-2.3 | 0.4-2.3 | 1.3-2.3 | 1.0-2.3 |

Table 16: Change in total fuel loading (tons/acre) at the start of simulation, the minimum and maximum condition, condition after final treatment, condition at the end of the simulation, and overall condition trend. * refers to high points in the treatment interval at year 2062. **refers to low points in the treatment interval at year 2062.

| | Control | Individual Tree Selection Only | Individual Tree Selection & Burn 7 Yr Interval | Individual Tree Selection & Burn 22 Yr Interval | Individual Tree Selection & Burn 7-22 Yr Interval | Burn Only 7 Yr Interval | Burn Only 22 Yr Interval | Burn Only 7-22 Yr Interval |
|---|---|---|---|---|---|---|---|---|
| Starting Condition | 29.10 | 29.10 | 29.10 | 29.10 | 29.10 | 29.10 | 29.10 | 29.10 |
| Minimum Condition | 29.10 | 29.10 | 3.98 | 6.96 | 5.50 | 6.73 | 12.50 | 9.48 |
| Maximum Condition | 38.10 | 33.31 | 33.31 | 33.31 | 33.31 | 33.31 | 33.31 | 33.31 |
| Final Treatment (2012, 51, 57, 59) | N/A | 32.75 | 4.67 | 7.57 | 6.1 | 8.92 | 13.92 | 10.46 |
| Ending Result (2062) | 38.10 | 31.94 | 6.39* | 8.19** | 9.69* | 11.37* | 14.79** | 16.59* |
| Trend at End of Simulation | Increasing | Increasing | Static | Decreasing | Static | Static | Static | Static |
| Range | 29.1-38.1 | 29.1-33.3 | 3.8-33.3 | 7.0-33.3 | 4.9-33.3 | 6.7-29.3 | 12.5-29.3 | 9.5-29.3 |

Table 17: Change in average smoke concentration of $PM_{2.5}$ (tons/acre) at the start of simulation, the minimum and maximum condition, condition after final treatment, condition at the end of the simulation, and overall condition trend. * refers to high points in the treatment interval at year 2062. **refers to low points in the treatment interval at year 2062.

| | Control | Individual Tree Selection Only | Individual Tree Selection & Burn 7 Yr Interval | Individual Tree Selection & Burn 22 Yr Interval | Individual Tree Selection & Burn 7-22 Yr Interval | Burn Only 7 Yr Interval | Burn Only 22 Yr Interval | Burn Only 7-22 Yr Interval |
|---|---|---|---|---|---|---|---|---|
| Starting Condition | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 |
| Minimum Condition | 0.14 | 0.13 | 0.02 | 0.04 | 0.03 | 0.04 | 0.07 | 0.05 |
| Maximum Condition | 0.18 | 0.16 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 |
| Final Treatment (2012, 51, 57, 59) | N/A | 0.16 | 0.02 | 0.04 | 0.03 | 0.04 | 0.07 | 0.05 |
| Ending Result (2062) | 0.18 | 0.15 | 0.03 | 0.04** | 0.05* | 0.05 | 0.07** | 0.07* |
| Trend at End of Simulation | Increasing | Increasing | Decreasing | Decreasing | Decreasing | Decreasing | Decreasing | Decreasing |
| Range | 0.14-0.18 | 0.13-0.16 | 0.02-0.16 | 0.04-0.16 | 0.03-0.16 | 0.04-0.14 | 0.07-0.14 | 0.05-0.14 |

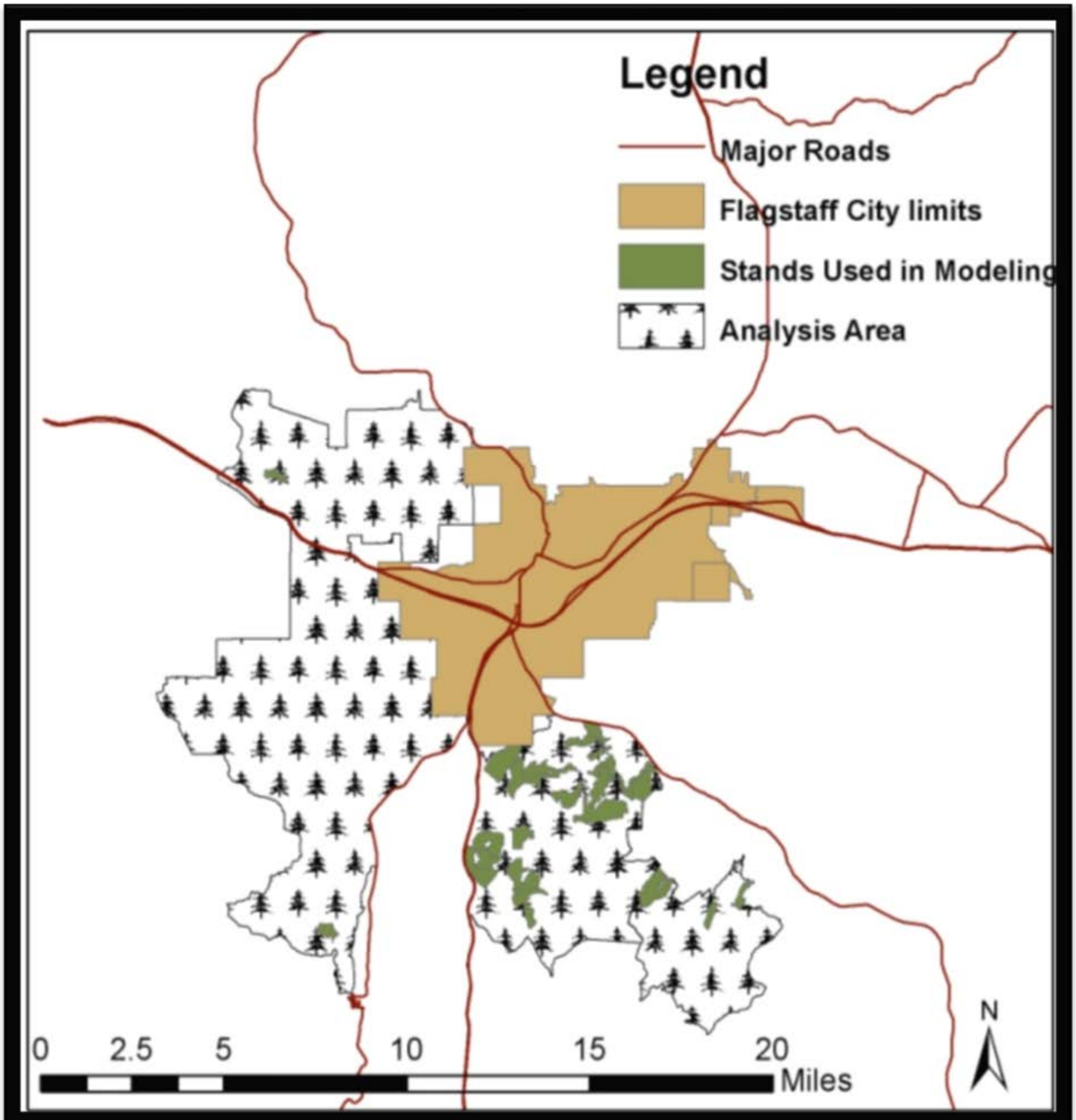


Figure 1: Flagstaff, Arizona located with the Coconino National Forest WUI. Stands that were selected to use in modeling simulations were limited to those that fit under selected criteria, and were located within the analysis area.

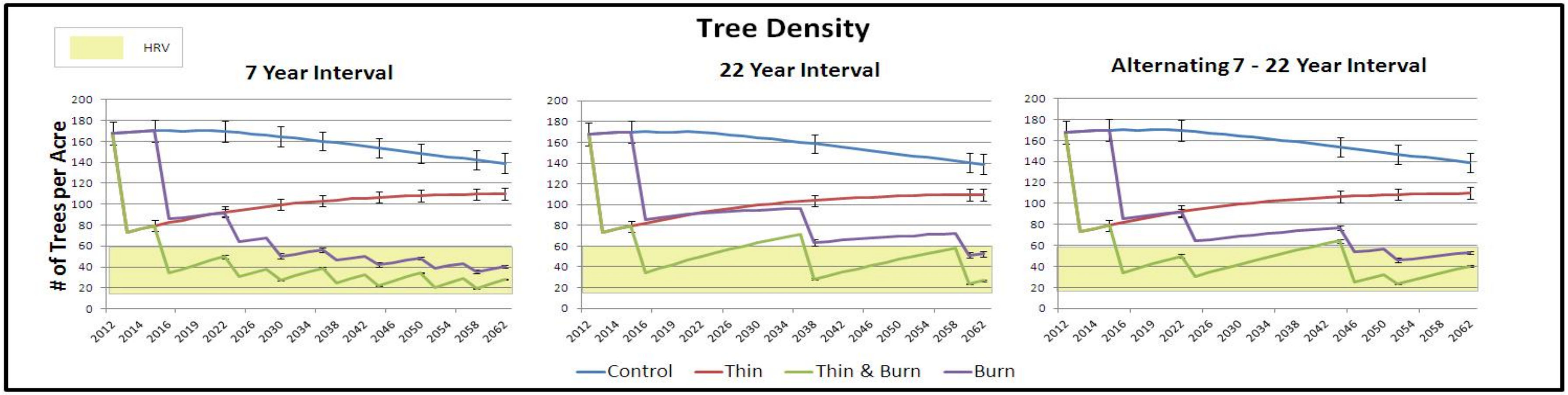


Figure: 2 Simulation results for tree density defined in the number of TPA. The portion of the figure defined in yellow displays where the HRV (15-60 TPA). The control is displayed by the blue line. The individual tree selection only treatment is displayed by the red line. The individual tree selection and burn treatment is displayed by the green line. The burn only treatment is displayed by the purple line. The 7, 22, and 7-22 year intervals define the period of time between entries with prescribed fire

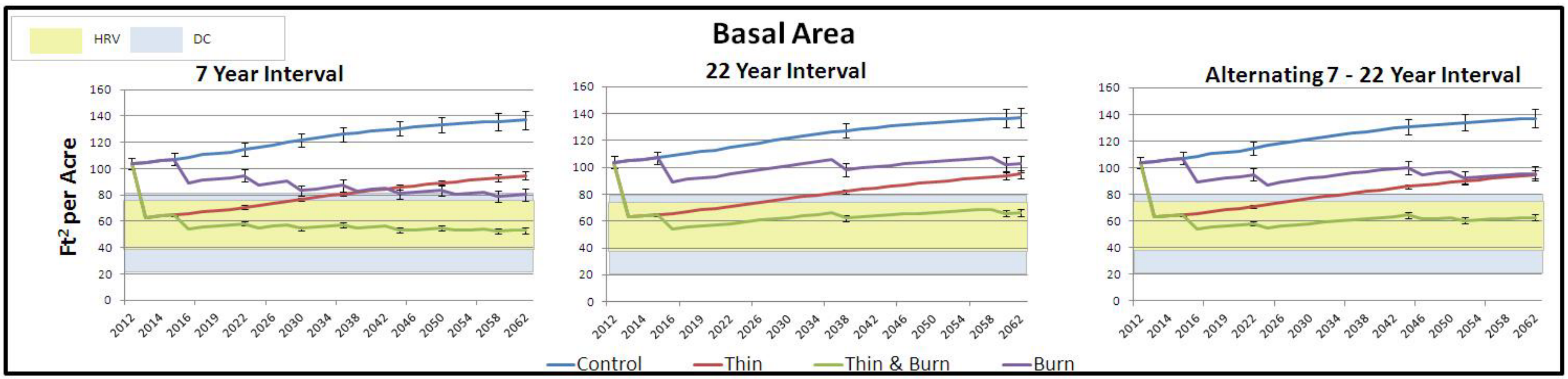


Figure 3: Simulation results for basal area defined in the $ft^2$/acre. The portion of the figure defined in yellow displays where the HRV (40-74 $ft^2$/acre). The portion defined in blue displays the DCs defined by the Coconino National Forest Proposed Revised Forest Plan (20-80 $ft^2$/acre). The control is displayed by the blue line. The thin only treatment is displayed by the red line. The thin and burn treatment is displayed by the green line. The burn only treatment is displayed by the purple line. The 7, 22, and 7-22 year intervals define the period of time between entries with prescribed fire

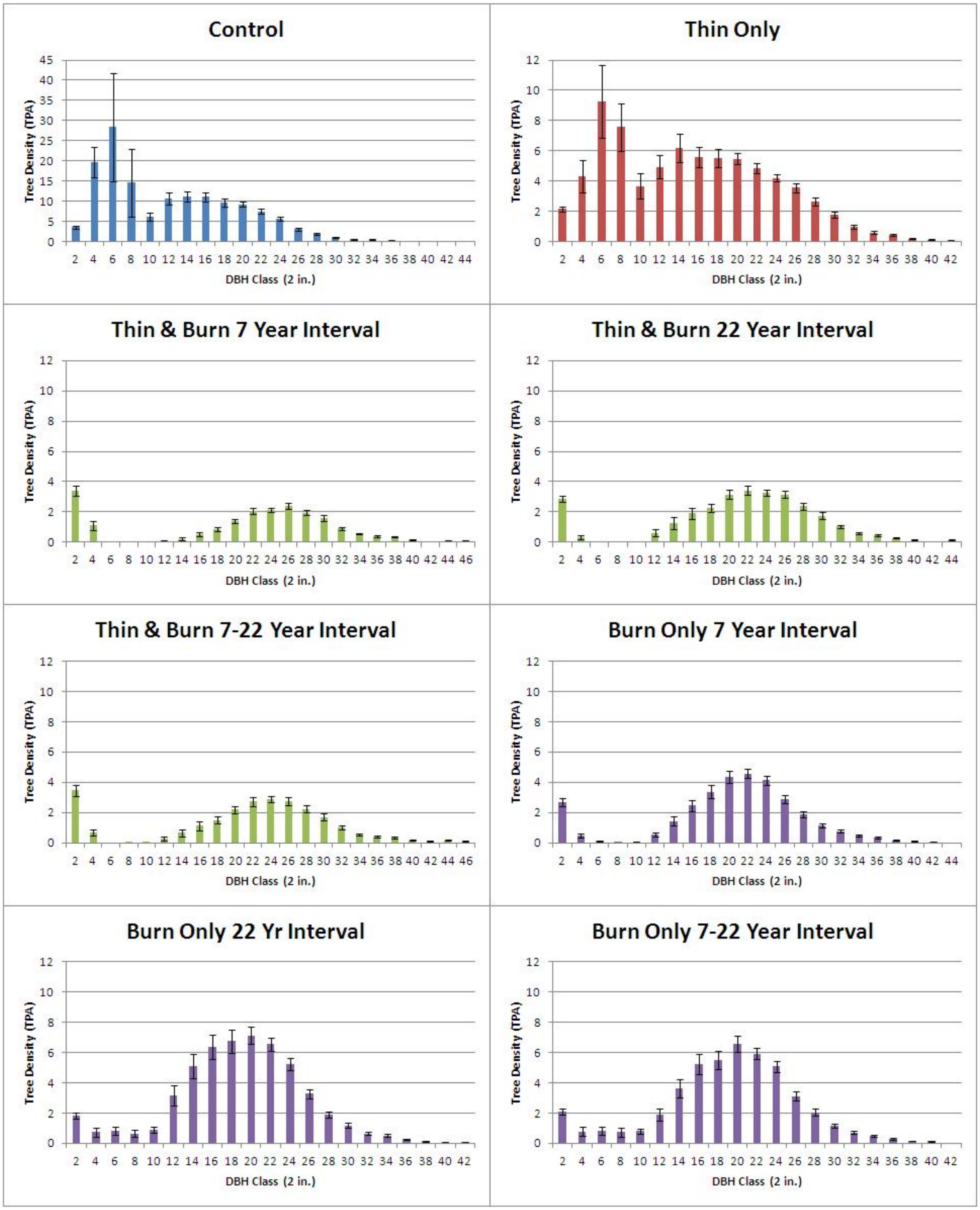


Figure 4: Diameter distribution at the end of the simulation timeframe (2062) for each treatment and maintenance interval used in simulation. NOTE: The control is on a different Y axis than the simulated treatment distributions.

1300 .

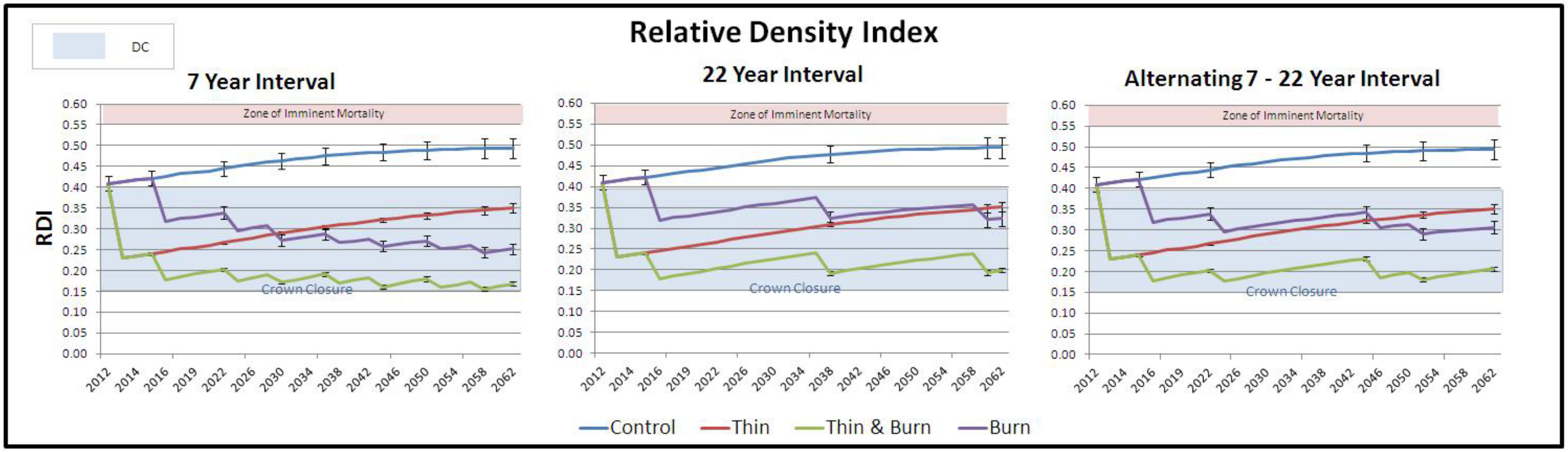


Figure 5: Simulation results for relative density index. The portion of the figure defined in blue displays where the DCs from the 4-FRI Proposed Action (0.15-0.40). The portion of the figure in pink displays the zone of imminent mortality (0.55). Crown closure is identified by the blue text (0.15). The control is displayed by the blue line. The thin only treatment is displayed by the red line. The thin and burn treatment is displayed by the green line. The burn only treatment is displayed by the purple line. The 7, 22, and 7-22 year intervals define the period of time between entries with prescribed fire.

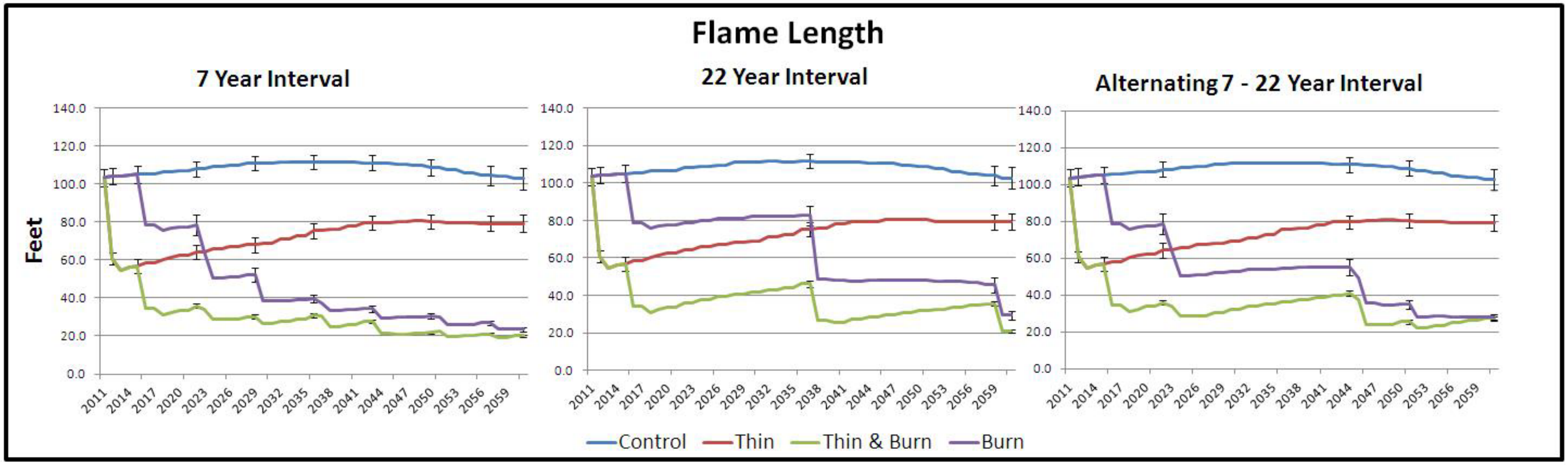


Figure 6 Simulation results for total flame length defined in ft. The control is displayed by the blue line. The thin only treatment is displayed by the red line. The thin and burn treatment is displayed by the green line. The burn only treatment is displayed by the purple line. The 7, 22, and 7-22 year intervals define the period of time between entries with prescribed fire.

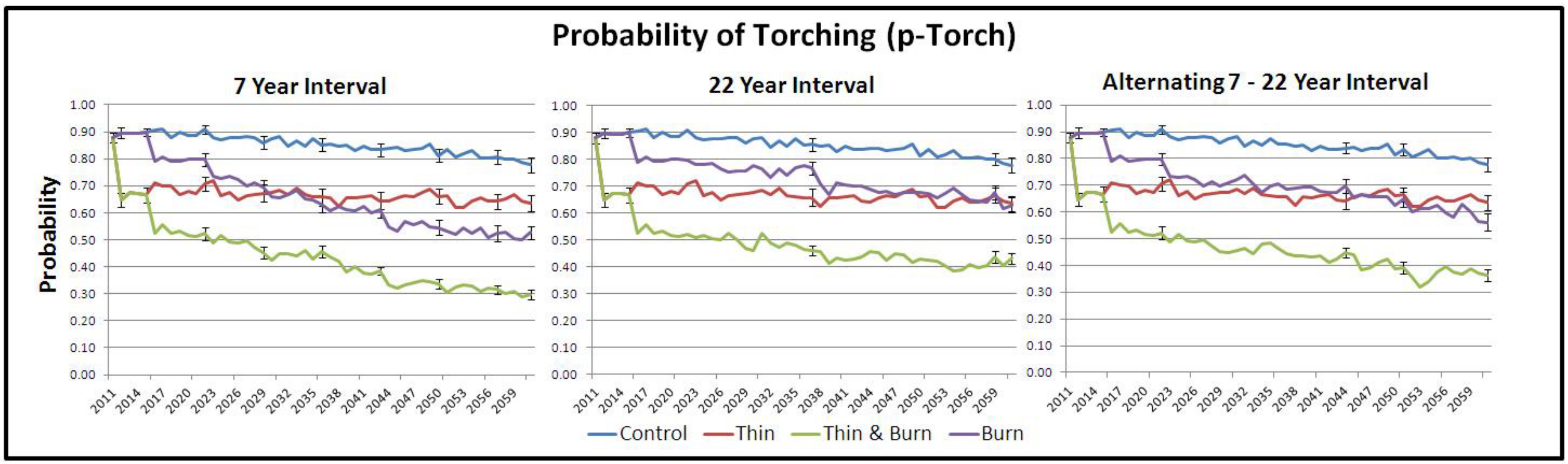


Figure 7 Simulation results for the probability of torching (p-torch). The control is displayed by the blue line. The thin only treatment is displayed by the red line. The thin and burn treatment is displayed by the green line. The burn only treatment is displayed by the purple line. The 7, 22, and 7-22 year intervals define the period of time between entries with prescribed fire.

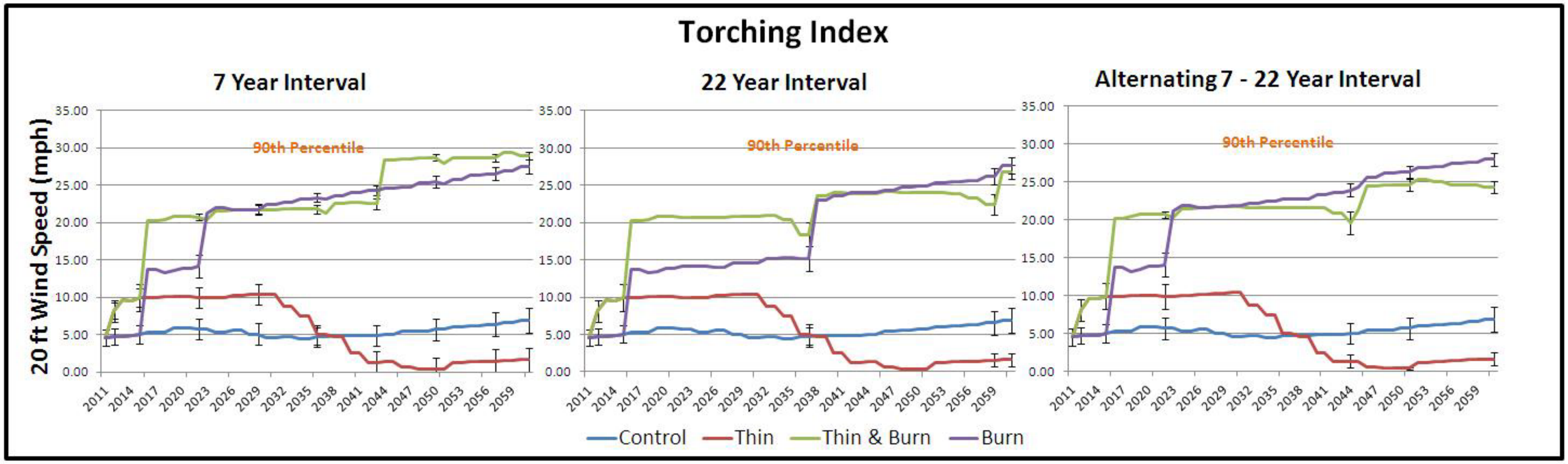


Figure 8: Simulation results for torching index defined in mph. The 90th percentile for 20ft winds is displayed with orange text. The control is displayed by the blue line. The thin only treatment is displayed by the red line. The thin and burn treatment is displayed by the green line. The burn only treatment is displayed by the purple line. The 7, 22, and 7-22 year intervals define the period of time between entries with prescribed fire.

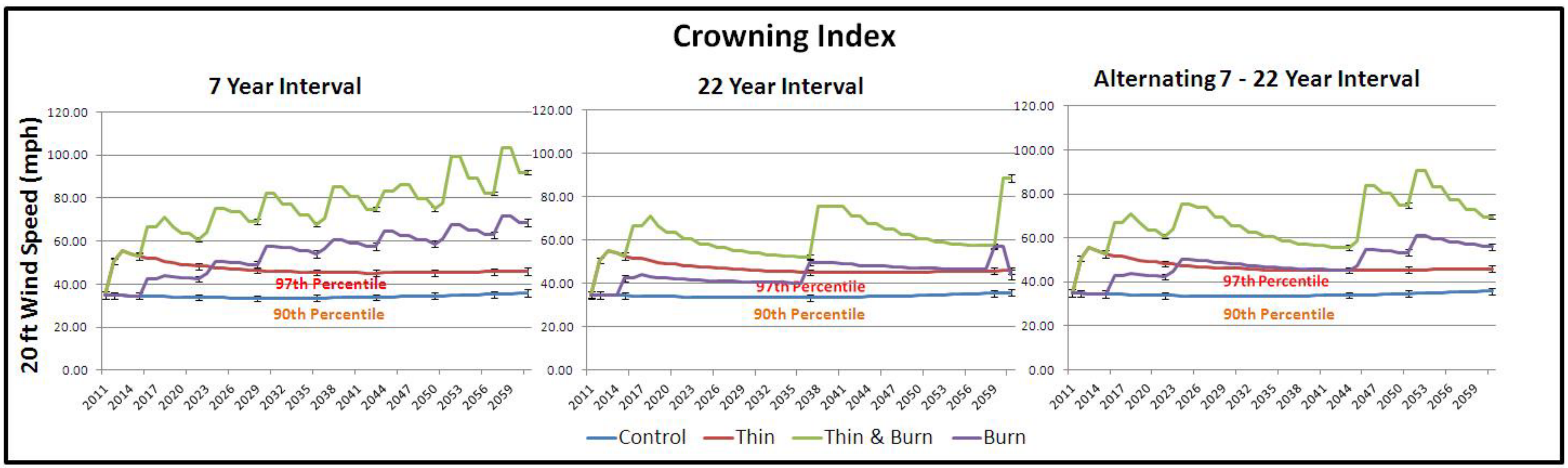


Figure 9: Simulation results for crowning index defined in mph. The 90th percentile for 20ft winds is displayed with orange text. The 97th percentile for 20ft winds is displayed with red text. The control is displayed by the blue line. The individual tree selection only treatment is displayed by the red line. The individual tree selection and burn treatment is displayed by the green line. The burn only treatment is displayed by the purple line. The 7, 22, and 7-22 year intervals define the period of time between entries with prescribed fire.

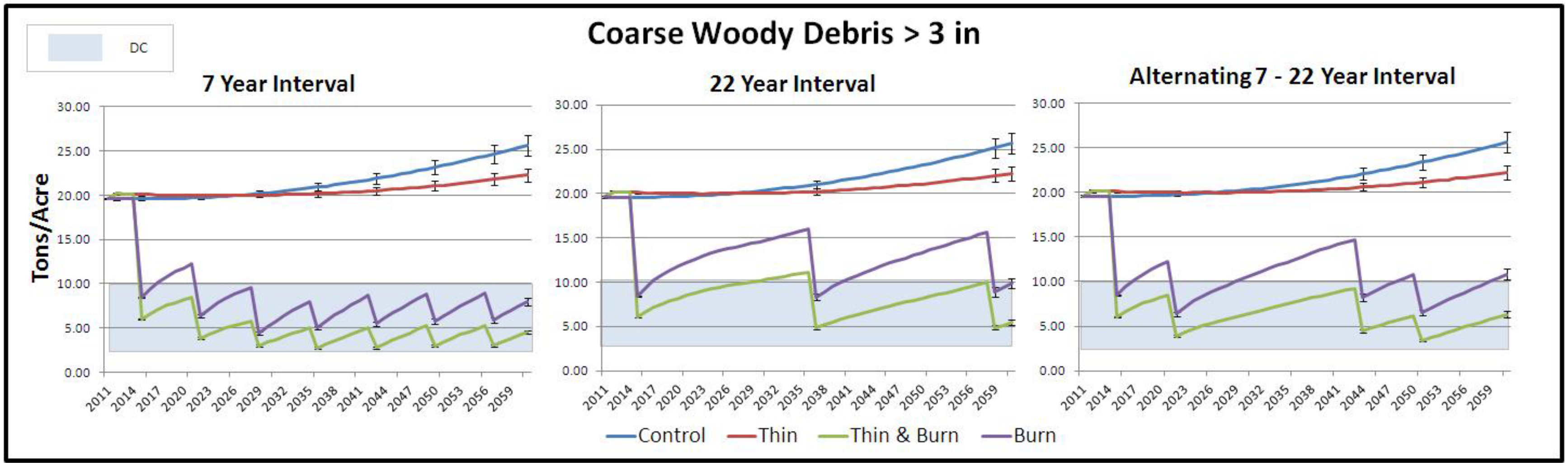


Figure 10: Simulation results for the coarse woody debris defined in tons/acre. The portion of the figure defined in blue displays the desired condition for the forest from the Coconino National Forest Proposed Revised Forest Plan (10-30). The control is displayed by the blue line. The thin only treatment is displayed by the red line. The thin and burn treatment is displayed by the green line. The burn only treatment is displayed by the purple line. The 7, 22, and 7-22 year intervals define the period of time between entries with prescribed fire.

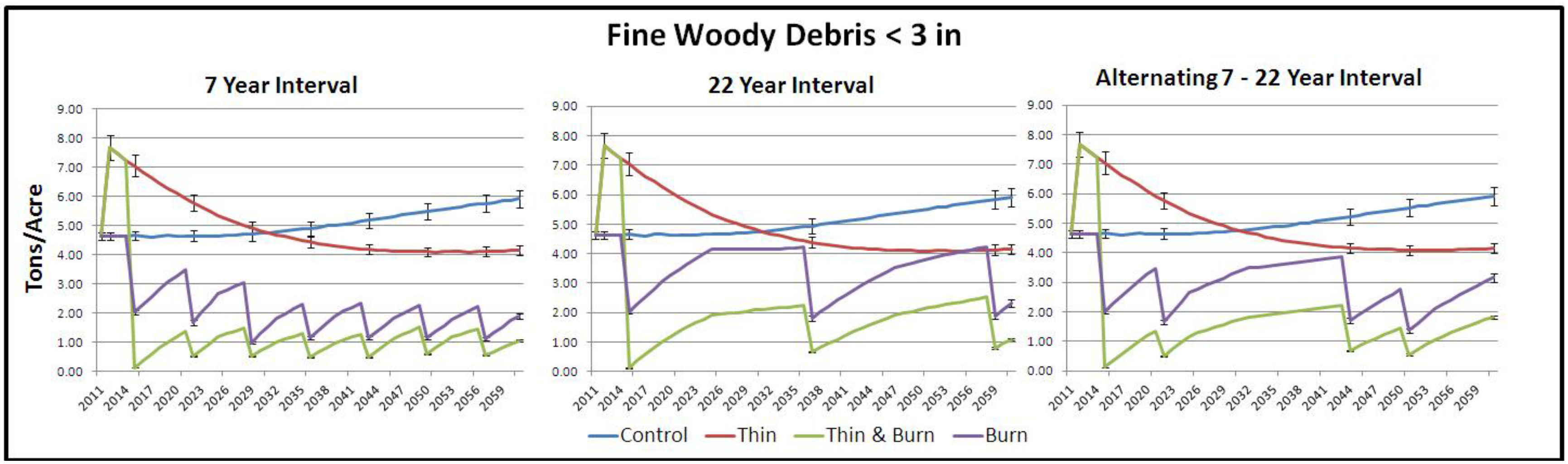


Figure 10: Simulation results for the fine woody debris defined in tons/acre. The control is displayed by the blue line. The thin only treatment is displayed by the red line. The thin and burn treatment is displayed by the green line. The burn only treatment is displayed by the purple line. The 7, 22, and 7-22 year intervals define the period of time between entries with prescribed fire

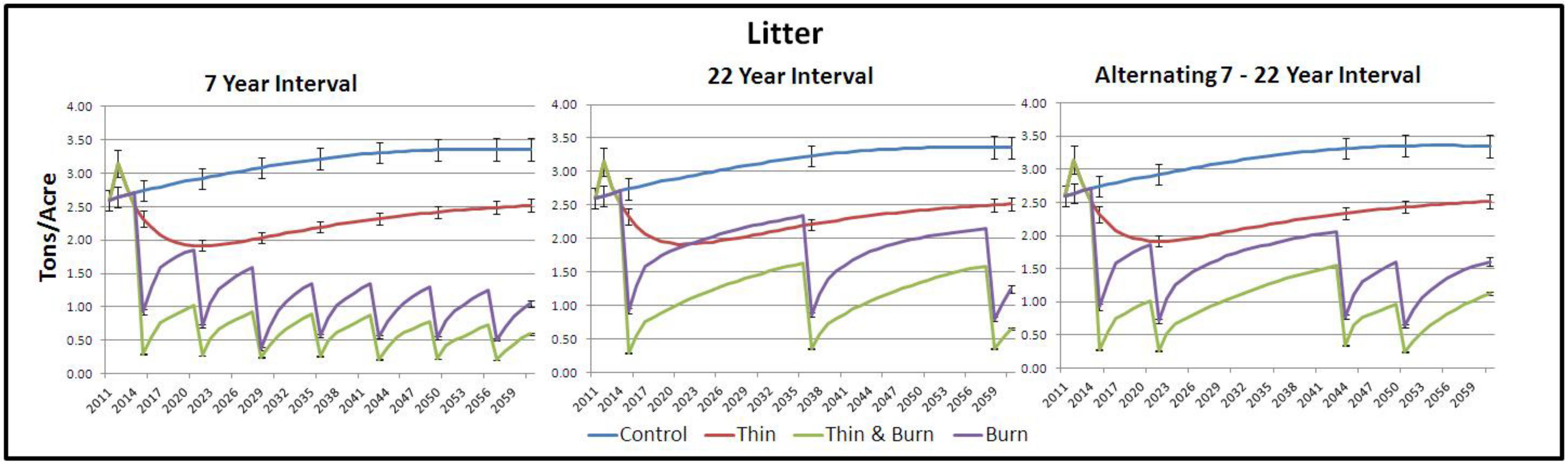


Figure 11: Simulation results for the litter defined in tons/acre. The control is displayed by the blue line. The thin only treatment is displayed by the red line. The thin and burn treatment is displayed by the green line. The burn only treatment is displayed by the purple line. The 7, 22, and 7-22 year intervals define the period of time between entries with prescribed fire.

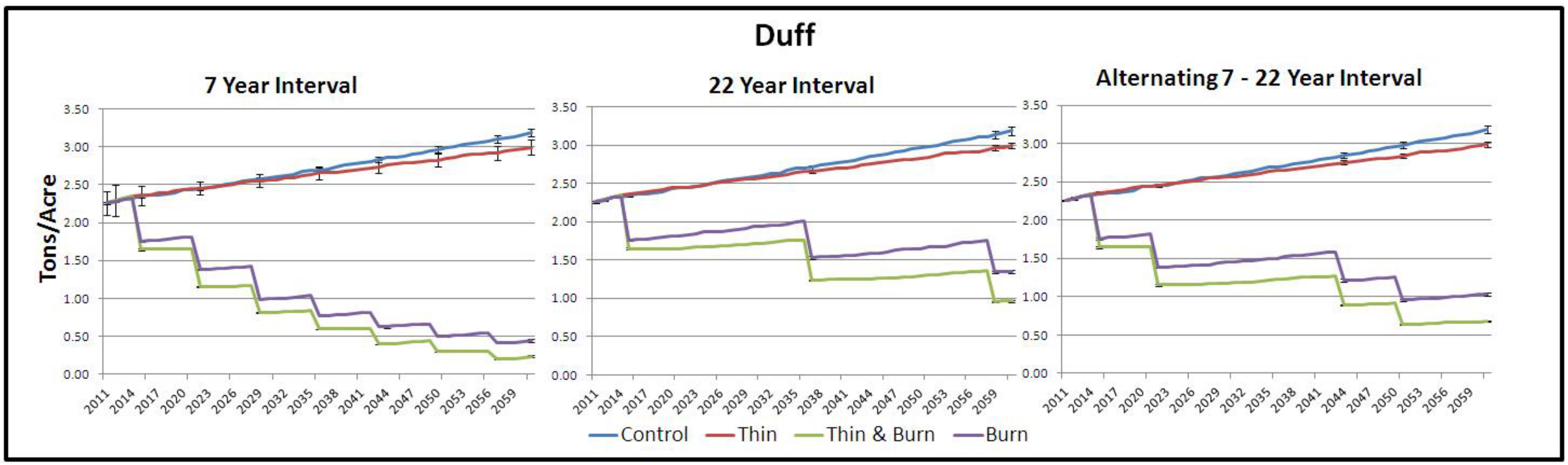


Figure 12: Simulation results for duff defined in tons/acre. The control is displayed by the blue line. The thin only treatment is displayed by the red line. The thin and burn treatment is displayed by the green line. The burn only treatment is displayed by the purple line. The 7, 22, and 7-22 year intervals define the period of time between entries with prescribedd fire.

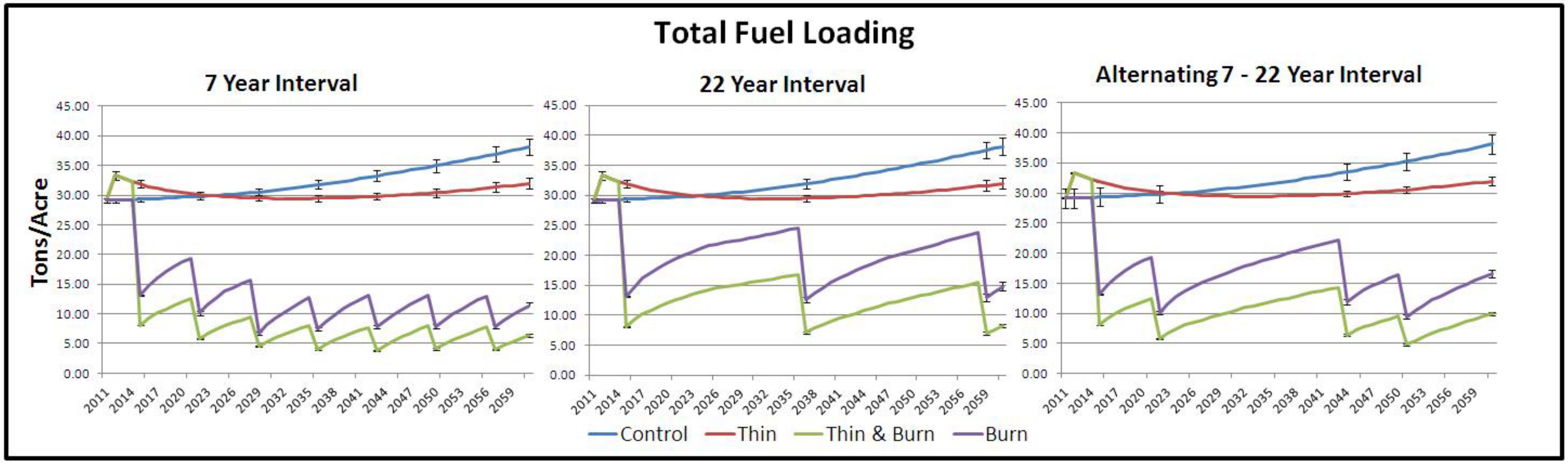


Figure 13: Simulation results for the total fuel loading defined in tons/acre. The control is displayed by the blue line. The thin only treatment is displayed by the red line. The thin and burn treatment is displayed by the green line. The burn only treatment is displayed by the purple line. The 7, 22, and 7-22 year intervals define the period of time between entries with prescribed fire.

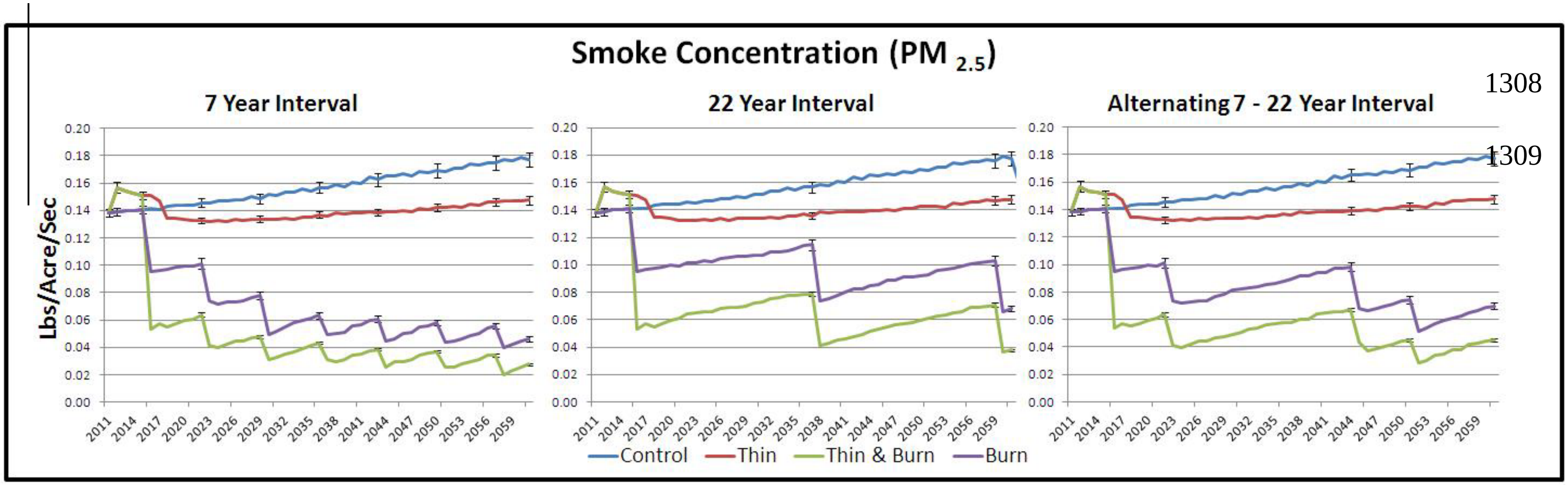


Figure 14: Simulation results for potential smoke concentration of $PM_{2.5}$ defined in lbs./acre/sec. The 90th percentile for 20ft winds is displayed with orange text. The control is displayed by the blue line. The thin only treatment is displayed by the red line. The thin and burn treatment is displayed by the green line. The burn only treatment is displayed by the purple line. The 7, 22, and 7-22 year intervals define the period of time between entries with prescribed fire.

# APPENDIX A: Extra data used in deriving methods

Appendix Table 1: Statistical plot variation information that was used to cull the final 26 stands used for modeling simulation.

| Stand # | # Plots | SE TPA | SE BA/A |
|---|---|---|---|
| 0304020000940 003 | 11 | 38.14809 | 14.1585 |
| 0304020001740 016 | 10 | 23.13948 | 11.64613 |
| 0304050003240 007 | 18 | 43.77115 | 10.65583 |
| 0304050003240 009 | 14 | 44.38405 | 7.090484 |
| 0304050003240 010 | 10 | 36.14099 | 12.17521 |
| 0304050003240 020 | 14 | 23.53619 | 7.254585 |
| 0304050003250 002 | 14 | 16.36556 | 10.63179 |
| 0304050003250 010 | 15 | 45.36609 | 6.613399 |
| 0304050003260 002 | 18 | 15.58696 | 7.7771 |
| 0304050003260 005 | 10 | 23.1237 | 11.35959 |
| 0304050003260 008 | 11 | 11.25795 | 7.424123 |
| 0304050003270 002 | 12 | 35.87484 | 12.68441 |
| 0304050003270 006 | 20 | 24.61723 | 11.15573 |
| 0304050003270 011 | 40 | 25.75462 | 7.636871 |
| 0304050003280 004 | 12 | 25.86446 | 10.52085 |
| 0304050003280 005 | 21 | 33.99625 | 10.32007 |
| 0304050003460 001 | 12 | 9.702631 | 43626177 |
| 0304050003460 002 | 10 | 8.949516 | 3.240102 |
| 0304050003460 008 | 10 | 16.59792 | 7.118052 |
| 0304050003460 009 | 11 | 28.7482 | 11.28884 |
| 0304050003470 001 | 11 | 28.36293 | 8.181818 |
| 0304050003500 004 | 14 | 38.60311 | 9.944074 |
| 0304050003560 001 | 11 | 29.60675 | 13.50849 |
| 0304050003560 002 | 10 | 25.04182 | 9.287088 |
| 0304050003590 001 | 34 | 31.85995 | 10.04114 |
| 0304050003620 004 | 10 | 48.3168 | 19.21879 |

Appendix Table 2: 97th percentile and prescribed fire weather and fuel moisture conditions used for modeling. Conditions based on Coconino National Forest weather database collected over the past 8 years.

| | Temp (°F) | Wind (20ft) | I hr | 10 hr | 100 hr | Duff | Live Woody | Live Herb |
|---|---|---|---|---|---|---|---|---|
| 97th Percentile | 85 | 40 | 1 | 2 | 3 | 25 | 80 | 30 |
| Prescribed Fire | 70 | 8 | 8 | 8 | 10 | 15 | 110 | 95 |

Appendix Table 3: Current stand structure, fire behavior and fuel loading at year 2011 in the Wildland Urban Interface of Flagstaff, AZ

| Stand ID | # of Plots | Trees per Acre | Basal Area ($ft^2$/acre) | Relative Density Index | Flame Length (ft) | Probability of Torching | Torching Index (mph) | Crowning Index (mph) | Smoke Production (PM 2.5) (lbs/sec/acre) | Ave. Fine Woody Debris (tons/acre) | Ave. Coarse Woody Debris (tons/acre) | Ave. Litter (tons/acre) | Ave. Duff (tons/acre) | Ave. Total Fuel Loading (tons/acre) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0940003 | 11 | 157 | 114 | 0.44 | 116 | 0.92 | 19.5 | 30.9 | 0.15 | 5.4 | 20.7 | 2.4 | 2.3 | 30.8 |
| 1740016 | 15 | 152 | 123 | 0.46 | 118 | 0.96 | 9.1 | 31.8 | 0.15 | 5.1 | 19.7 | 2.8 | 2.3 | 29.9 |
| 3240007 | 10 | 267 | 128 | 0.54 | 124 | 0.96 | 0.0 | 25.9 | 0.15 | 4.9 | 19.5 | 3.6 | 2.4 | 30.4 |
| 3240009 | 18 | 237 | 117 | 0.49 | 121 | 0.86 | 0.0 | 27.8 | 0.14 | 4.1 | 19.4 | 3.1 | 2.3 | 28.9 |
| 3240010 | 10 | 156 | 123 | 0.47 | 120 | 0.80 | 0.5 | 26.8 | 0.14 | 4.5 | 19.3 | 3.1 | 2.3 | 29.2 |
| 3240020 | 14 | 197 | 76 | 0.33 | 118 | 0.85 | 0.4 | 30.6 | 0.14 | 4.2 | 19.1 | 2.7 | 2.3 | 28.3 |
| 3250002 | 14 | 114 | 99 | 0.37 | 72 | 0.76 | 2.7 | 45.7 | 0.12 | 4.3 | 20.1 | 1.6 | 2.2 | 28.2 |
| 3250010 | 15 | 167 | 94 | 0.38 | 92 | 0.93 | 2.8 | 39.9 | 0.13 | 3.7 | 19.2 | 2.2 | 2.3 | 27.4 |
| 3260002 | 18 | 143 | 119 | 0.45 | 118 | 0.90 | 0.4 | 31.8 | 0.14 | 4.3 | 19.4 | 2.8 | 2.3 | 28.8 |
| 3560005 | 10 | 124 | 122 | 0.44 | 117 | 0.95 | 4.6 | 34.6 | 0.14 | 4.7 | 19.8 | 2.5 | 2.3 | 29.3 |
| 3260008 | 11 | 85 | 84 | 0.30 | 78 | 0.59 | 3.5 | 44.0 | 0.13 | 4.1 | 19.5 | 1.9 | 2.2 | 27.7 |
| 3270002 | 12 | 194 | 118 | 0.47 | 120 | 0.87 | 0.0 | 24.9 | 0.16 | 5.7 | 20.3 | 4.3 | 2.3 | 32.6 |
| 3270006 | 20 | 235 | 125 | 0.51 | 124 | 0.93 | 0.0 | 25.1 | 0.16 | 5.7 | 20.1 | 3.7 | 2.3 | 31.8 |
| 3270011 | 40 | 218 | 105 | 0.44 | 120 | 1.0 | 1.9 | 30.30 | 0.15 | 5.1 | 20.0 | 3.2 | 2.3 | 30.6 |
| 3280004 | 12 | 156 | 118 | 0.45 | 117 | 0.99 | 3.4 | 30.2 | 0.14 | 5.3 | 19.8 | 2.4 | 2.2 | 29.7 |
| 3280005 | 21 | 304 | 128 | 0.55 | 129 | 0.97 | 0.5 | 19.7 | 0.17 | 5.7 | 20.0 | 4.3 | 2.3 | 32.3 |
| 3460001 | 12 | 146 | 67 | 0.28 | 101 | 0.73 | 0.0 | 37.7 | 0.13 | 4.8 | 20.0 | 2.0 | 2.1 | 28.9 |
| 3460002 | 11 | 99 | 62 | 0.25 | 58 | 0.73 | 10.4 | 50.2 | 0.12 | 3.5 | 18.8 | 1.6 | 2.2 | 26.1 |
| 3460008 | 10 | 103 | 74 | 0.29 | 50 | 0.79 | 16.9 | 51.0 | 0.12 | 3.7 | 19.0 | 1.5 | 2.2 | 26.4 |
| 3460009 | 10 | 130 | 72 | 0.29 | 75 | 0.86 | 11.4 | 42.6 | 0.12 | 3.8 | 18.9 | 1.5 | 2.2 | 26.4 |
| 3470001 | 11 | 135 | 90 | 0.35 | 100 | 0.93 | 8.8 | 37.1 | 0.12 | 3.9 | 19.2 | 2.0 | 2.2 | 27.3 |
| 3500004 | 11 | 233 | 74 | 0.34 | 86 | 1.0 | 0.0 | 41.9 | 0.13 | 4.5 | 19.6 | 2.0 | 2.2 | 28.3 |
| 3560001 | 14 | 114 | 117 | 0.42 | 118 | 0.93 | 8.5 | 33.6 | 0.14 | 4.7 | 19.7 | 2.9 | 2.3 | 29.6 |
| 3560002 | 10 | 115 | 105 | 0.38 | 70 | 0.85 | 9.0 | 45.4 | 0.13 | 4.2 | 19.3 | 2.8 | 2.3 | 28.6 |
| 3590001 | 34 | 215 | 144 | 0.56 | 118 | 0.93 | 2.0 | 31.5 | 0.14 | 5.3 | 20.0 | 2.7 | 2.2 | 30.2 |
| 3620004 | 10 | 171 | 99 | 0.40 | 107 | 0.83 | 1.7 | 36.6 | 0.13 | 5.3 | 19.6 | 2.3 | 2.2 | 29.4 |
| **Average** | **15** | **168** | **104** | **0.41** | **103.5** | **0.88** | **4.54** | **34.91** | **0.14** | **4.63** | **19.62** | **2.6** | **2.2** | **29.1** |
| **Minimum** | **10** | **87** | **77** | **0.31** | **50.0** | **0.6** | **0.0** | **19.7** | **0.1** | **3.5** | **18.8** | **1.5** | **2.1** | **26.1** |
| **Maximum** | **40** | **267** | **167** | **0.64** | **129.0** | **1.0** | **19.5** | **51.0** | **0.2** | **5.7** | **20.7** | **4.3** | **2.4** | **32.6** |

# APPENDIX B: Fuel Model Selection Runs

Appendix Table 4: Fuel model selection run for fuel model 165 (XXX). The Green highlighted portions represent the variables that seemed consistent with observed fire behavior on the Coconino National Forest.

| | Flame Length Surface | | (FT) Total | | Fire Type | | Prob of Torching | | Torch Index Severe | Crown Index Severe | Canopy Base HT | Canopy Bulk Density | Potential Mortality | | | | Potential Smoke T/A < 2.5 | | Fuel Models | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | SEV | MOD | SEV | MOD | S | M | S | M | MI/HR | MI/HR | Ft | KG/M3 | SEV %BA | MOD %BA | SEV Cu Vol. | MOD Cu Vol. | SEV | MOD | MOD | %WT |
| 2011 | 11.6 | 5.7 | 115 | 6 | A | S | 0.98 | 0.23 | 29.5 | 32.1 | 24 | 0.056 | 100 | 33 | 2269 | 632 | 0.1 | 0.06 | 165 | 100 |
| 2012 | 13.8 | 6.7 | 36 | 7 | P | S | 0.77 | 0.22 | 24.4 | 53.5 | 27 | 0.028 | 97 | 43 | 1221 | 449 | 0.12 | 0.09 | 165 | 100 |
| 2013 | 13.8 | 6.7 | 35 | 7 | P | S | 0.86 | 0.23 | 24.5 | 54 | 27 | 0.027 | 97 | 42 | 1251 | 447 | 0.11 | 0.09 | 165 | 100 |
| 2015 | 13.7 | 6.7 | 37 | 7 | P | S | 0.93 | 0.28 | 24.7 | 52.2 | 27 | 0.029 | 97 | 40 | 1313 | 452 | 0.11 | 0.09 | 165 | 100 |
| 2016 | 13.9 | 6.7 | 29 | 7 | P | S | 0.83 | 0.19 | 28 | 54.5 | 30 | 0.027 | 96 | 38 | 1285 | 420 | 0.11 | 0.09 | 165 | 100 |
| 2019 | 13.8 | 6.7 | 30 | 7 | P | S | 0.76 | 0.19 | 28.3 | 52.7 | 30 | 0.028 | 96 | 35 | 1368 | 415 | 0.1 | 0.08 | 165 | 100 |
| 2020 | 13.8 | 6.7 | 30 | 7 | P | S | 0.76 | 0.14 | 28.4 | 51.4 | 30 | 0.029 | 96 | 34 | 1396 | 410 | 0.1 | 0.08 | 165 | 100 |
| 2022 | 13.7 | 6.7 | 31 | 7 | P | S | 0.76 | 0.16 | 28.5 | 50.2 | 30 | 0.03 | 96 | 32 | 1448 | 406 | 0.1 | 0.08 | 165 | 100 |
| 2032 | 13.6 | 6.6 | 24 | 7 | P | S | 0.63 | 0.11 | 31.7 | 49.2 | 32 | 0.031 | 95 | 22 | 1665 | 335 | 0.11 | 0.08 | 165 | 100 |
| 2042 | 13.5 | 6.6 | 18 | 7 | P | S | 0.56 | 0.04 | 33.5 | 50.3 | 33 | 0.03 | 94 | 17 | 1813 | 281 | 0.11 | 0.08 | 165 | 100 |
| 2052 | 13.5 | 6.6 | 14 | 7 | P | S | 0.55 | 0.03 | 34.8 | 52.7 | 34 | 0.028 | 93 | 14 | 1899 | 240 | 0.12 | 0.09 | 165 | 100 |

Appendix Table 5 Fuel model selection run for fuel model 183 (XXX). The Green highlighted portions represent the variables that seemed consistent with observed fire behavior on the Coconino National Forest. The Red highlighted portions represent the variables that seemed inconsistent with observed fire behavior on the Coconino National Forest.

| | Flame Length Surface | | (FT) Total | | Fire Type | | Prob of Torching | | Torch Index Severe | Crown Index Severe | Canopy Base HT | Canopy Bulk Density | Potential Mortality | | | | Potential Smoke T/A < 2.5 | | Fuel Models | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | SEV | MOD | SEV | MOD | S | M | S | M | MI/HR | MI/HR | Ft | KG/M3 | SEV %BA | MOD %BA | SEV Cu Vol. | MOD Cu Vol. | SEV | MOD | MOD | %WT |
| 2011 | 2 | 0.9 | 48 | 1 | C | S | 0 | 0 | 594 | 32.1 | 24 | 0.056 | 100 | 18 | 2269 | 368 | 0.1 | 0.05 | 183 | 100 |
| 2012 | 2.4 | 1 | 2 | 1 | S | S | 0 | 0 | 476.5 | 53.5 | 27 | 0.028 | 15 | 15 | 171 | 171 | 0.1 | 0.09 | 183 | 100 |
| 2013 | 2.4 | 1 | 2 | 1 | S | S | 0 | 0 | 479.5 | 54 | 27 | 0.027 | 15 | 15 | 173 | 173 | 0.1 | 0.09 | 183 | 100 |
| 2015 | 2.4 | 1 | 2 | 1 | S | S | 0 | 0 | 483.7 | 52.2 | 27 | 0.029 | 15 | 15 | 176 | 176 | 0.1 | 0.08 | 183 | 100 |
| 2016 | 2.4 | 1 | 2 | 1 | S | S | 0 | 0 | 534.3 | 54.5 | 30 | 0.027 | 14 | 14 | 164 | 164 | 0.1 | 0.08 | 183 | 100 |
| 2019 | 2.4 | 1 | 2 | 1 | S | S | 0 | 0 | 539.6 | 52.7 | 30 | 0.028 | 13 | 13 | 167 | 167 | 0.09 | 0.07 | 183 | 100 |
| 2020 | 2.4 | 1 | 2 | 1 | S | S | 0 | 0 | 540.8 | 51.4 | 30 | 0.029 | 13 | 13 | 168 | 168 | 0.09 | 0.07 | 183 | 100 |
| 2022 | 2.4 | 1 | 2 | 1 | S | S | 0 | 0 | 543.9 | 50.2 | 30 | 0.03 | 12 | 12 | 170 | 170 | 0.09 | 0.07 | 183 | 100 |
| 2032 | 2.3 | 1 | 2 | 1 | S | S | 0 | 0 | 596.4 | 49.2 | 32 | 0.031 | 10 | 10 | 173 | 173 | 0.09 | 0.07 | 183 | 100 |
| 2042 | 2.3 | 1 | 2 | 1 | S | S | 0 | 0 | 624.9 | 50.3 | 33 | 0.03 | 9 | 9 | 168 | 168 | 0.09 | 0.08 | 183 | 100 |
| 2052 | 2.3 | 1 | 2 | 1 | S | S | 0 | 0 | 645.4 | 52.7 | 34 | 0.028 | 8 | 8 | 160 | 160 | 0.1 | 0.09 | 183 | 100 |

Appendix Table 6 Fuel model selection run for fuel model 189 (XXX). The Green highlighted portions represent the variables that seemed consistent with observed fire behavior on the Coconino National Forest. The Red highlighted portions represent the variables that seemed inconsistent with observed fire behavior on the Coconino National Forest.

| | Flame Length Surface | | (FT) Total | | Fire Type | | Prob of Torching | | Torch Index Severe | Crown Index Severe | Canopy Base HT | Canopy Bulk Density | Potential Mortality | | | | Potential Smoke T/A < 2.5 | | Fuel Models | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | SEV | MOD | SEV | MOD | S | M | S | M | MI/HR | MI/HR | Ft | KG/M3 | SEV %BA | MOD %BA | SEV Cu Vol. | MOD Cu Vol. | SEV | MOD | MOD | %WT |
| 2011 | 8.4 | 4 | 77 | 4 | C | S | 0.77 | 0.01 | 50.8 | 32.1 | 24 | 0.056 | 100 | 18 | 2269 | 373 | 0.1 | 0.05 | 189 | 100 |
| 2012 | 10.5 | 4.8 | 10 | 5 | S | S | 0.72 | 0.02 | 40.7 | 53.5 | 27 | 0.028 | 94 | 17 | 1171 | 181 | 0.11 | 0.09 | 189 | 100 |
| 2013 | 10.4 | 4.7 | 10 | 5 | S | S | 0.77 | 0.03 | 40.9 | 54 | 27 | 0.027 | 93 | 16 | 1197 | 183 | 0.11 | 0.09 | 189 | 100 |
| 2015 | 10.4 | 4.7 | 10 | 5 | S | S | 0.84 | 0.03 | 41.3 | 52.2 | 27 | 0.029 | 93 | 16 | 1248 | 185 | 0.11 | 0.08 | 189 | 100 |
| 2016 | 10.5 | 4.8 | 11 | 5 | S | S | 0.75 | 0.02 | 45.4 | 54.5 | 30 | 0.027 | 93 | 15 | 1229 | 172 | 0.11 | 0.08 | 189 | 100 |
| 2019 | 10.5 | 4.7 | 10 | 5 | S | S | 0.67 | 0.02 | 45.9 | 52.7 | 30 | 0.028 | 92 | 14 | 1300 | 174 | 0.1 | 0.07 | 189 | 100 |
| 2020 | 10.4 | 4.7 | 10 | 5 | S | S | 0.65 | 0.01 | 46 | 51.4 | 30 | 0.029 | 92 | 13 | 1322 | 174 | 0.1 | 0.07 | 189 | 100 |
| 2022 | 10.4 | 4.7 | 10 | 5 | S | S | 0.68 | 0.01 | 46.2 | 50.2 | 30 | 0.03 | 92 | 13 | 1363 | 173 | 0.1 | 0.07 | 189 | 100 |
| 2032 | 10.3 | 4.7 | 10 | 5 | S | S | 0.54 | 0.03 | 50.6 | 49.2 | 32 | 0.031 | 90 | 11 | 1545 | 173 | 0.1 | 0.07 | 189 | 100 |
| 2042 | 10.2 | 4.6 | 10 | 5 | S | S | 0.45 | 0 | 52.9 | 50.3 | 33 | 0.03 | 88 | 10 | 1663 | 170 | 0.11 | 0.08 | 189 | 100 |
| 2052 | 10.2 | 4.6 | 10 | 5 | S | S | 0.38 | 0 | 54.6 | 52.7 | 34 | 0.028 | 87 | 9 | 1729 | 163 | 0.11 | 0.09 | 189 | 100 |

Appendix Table 7 Fuel model selection run for fuel model 2 (XXX). The Green highlighted portions represent the variables that seemed consistent with observed fire behavior on the Coconino National Forest. The Red highlighted portions represent the variables that seemed inconsistent with observed fire behavior on the Coconino National Forest.

| | Flame Length Surface | | (FT) Total | | Fire Type | | Prob of Torching | | Torch Index Severe | Crown Index Severe | Canopy Base HT | Canopy Bulk Density | Potential Mortality | | | | Potential Smoke T/A < 2.5 | | Fuel Models | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | SEV | MOD | SEV | MOD | S | M | S | M | MI/HR | MI/HR | Ft | KG/M3 | SEV %BA | MOD %BA | SEV Cu Vol. | MOD Cu Vol. | SEV | MOD | MOD | %WT |
| 2011 | 12.9 | 4.4 | 71 | 4 | A | S | 0.9 | 0.87 | 7.3 | 26.3 | 7 | 0.074 | 100 | 20 | 2429 | 368 | 0.1 | 0.06 | 2 | 100 |
| 2012 | 18.4 | 6 | 36 | 6 | P | S | 0.47 | 0.14 | 16.4 | 46.3 | 22 | 0.034 | 97 | 22 | 1273 | 240 | 0.13 | 0.1 | 2 | 100 |
| 2013 | 18.2 | 5.9 | 30 | 6 | P | S | 0.47 | 0.14 | 18.5 | 52.1 | 25 | 0.029 | 96 | 21 | 1294 | 232 | 0.12 | 0.1 | 2 | 100 |
| 2015 | 18.1 | 5.9 | 32 | 6 | P | S | 0.47 | 0.15 | 18 | 49.2 | 24 | 0.031 | 96 | 19 | 1367 | 226 | 0.12 | 0.09 | 2 | 100 |
| 2016 | 18.1 | 5.9 | 29 | 6 | P | S | 0.37 | 0.12 | 19.3 | 54.7 | 26 | 0.027 | 95 | 18 | 1377 | 220 | 0.11 | 0.09 | 2 | 100 |
| 2019 | 17.9 | 5.8 | 30 | 6 | P | S | 0.3 | 0.1 | 18.9 | 51.6 | 25 | 0.029 | 95 | 17 | 1482 | 212 | 0.1 | 0.07 | 2 | 100 |
| 2020 | 17.9 | 5.8 | 32 | 6 | P | S | 0.4 | 0.1 | 19 | 49.8 | 25 | 0.03 | 95 | 16 | 1518 | 207 | 0.1 | 0.07 | 2 | 100 |
| 2022 | 17.7 | 5.8 | 34 | 6 | P | S | 0.4 | 0.2 | 18.5 | 47.6 | 24 | 0.032 | 96 | 15 | 1590 | 205 | 0.1 | 0.07 | 2 | 100 |
| 2032 | 17.2 | 5.6 | 35 | 6 | P | S | 0.7 | 0.24 | 19.2 | 45.7 | 24 | 0.034 | 96 | 11 | 1924 | 182 | 0.1 | 0.07 | 2 | 100 |
| 2042 | 16.6 | 5.5 | 36 | 5 | P | S | 0.73 | 0.21 | 20.7 | 44.5 | 25 | 0.036 | 95 | 10 | 2242 | 181 | 0.1 | 0.07 | 2 | 100 |
| 2052 | 16.2 | 5.4 | 34 | 5 | P | S | 0.7 | 0.15 | 22.9 | 44.3 | 27 | 0.036 | 95 | 10 | 2531 | 193 | 0.11 | 0.07 | 2 | 100 |

Appendix Table 8 Fuel model selection run for fuel model 9 (XXX). The Green highlighted portions represent the variables that seemed consistent with observed fire behavior on the Coconino National Forest. The Red highlighted portions represent the variables that seemed inconsistent with observed fire behavior on the Coconino National Forest.

| | Flame Length Surface | | (FT) Total | | Fire Type | | Prob of Torching | | Torch Index Severe | Crown Index Severe | Canopy Base HT | Canopy Bulk Density | Potential Mortality | | | | Potential Smoke T/A < 2.5 | | Fuel Models | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | SEV | MOD | SEV | MOD | S | M | S | M | MI/HR | MI/HR | Ft | KG/M3 | SEV %BA | MOD %BA | SEV Cu Vol. | MOD Cu Vol. | SEV | MOD | MOD | %WT |
| 2011 | 5.8 | 2.3 | 55 | 2 | C | S | 0.24 | 0 | 77.5 | 32.1 | 24 | 0.056 | 100 | 18 | 2269 | 368 | 0.1 | 0.05 | 9 | 100 |
| 2012 | 7.5 | 2.8 | 8 | 3 | S | S | 0.38 | 0 | 60.4 | 53.5 | 27 | 0.028 | 38 | 15 | 392 | 171 | 0.1 | 0.09 | 9 | 100 |
| 2013 | 7.5 | 2.8 | 8 | 3 | S | S | 0.36 | 0 | 60.8 | 54 | 27 | 0.027 | 37 | 15 | 390 | 173 | 0.1 | 0.09 | 9 | 100 |
| 2015 | 7.5 | 2.8 | 7 | 3 | S | S | 0.43 | 0 | 61.3 | 52.2 | 27 | 0.029 | 36 | 15 | 392 | 176 | 0.1 | 0.08 | 9 | 100 |
| 2016 | 7.6 | 2.8 | 8 | 3 | S | S | 0.35 | 0 | 66 | 54.5 | 30 | 0.027 | 33 | 14 | 360 | 164 | 0.1 | 0.08 | 9 | 100 |
| 2019 | 7.5 | 2.8 | 8 | 3 | S | S | 0.31 | 0 | 66.6 | 52.7 | 30 | 0.028 | 30 | 13 | 352 | 167 | 0.09 | 0.07 | 9 | 100 |
| 2020 | 7.5 | 2.8 | 8 | 3 | S | S | 0.26 | 0 | 66.8 | 51.4 | 30 | 0.029 | 28 | 13 | 345 | 168 | 0.09 | 0.07 | 9 | 100 |
| 2022 | 7.5 | 2.8 | 7 | 3 | S | S | 0.29 | 0 | 67.1 | 50.2 | 30 | 0.03 | 27 | 12 | 338 | 170 | 0.09 | 0.07 | 9 | 100 |
| 2032 | 7.4 | 2.8 | 7 | 3 | S | S | 0.19 | 0 | 72.4 | 49.2 | 32 | 0.031 | 18 | 11 | 272 | 173 | 0.09 | 0.07 | 9 | 100 |
| 2042 | 7.3 | 2.8 | 7 | 3 | S | S | 0.1 | 0 | 75.3 | 50.3 | 33 | 0.03 | 14 | 9 | 233 | 169 | 0.09 | 0.08 | 9 | 100 |
| 2052 | 7.3 | 2.8 | 7 | 3 | S | S | 0.07 | 0 | 77.2 | 52.7 | 34 | 0.028 | 11 | 9 | 204 | 161 | 0.1 | 0.09 | 9 | 100 |