Wildland Fuel Conditions and Effects of Modeled Fuel Treatments on Wildland Fire Behavior and Severity in Dry Forests of the Wenatchee Mountains

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Abstract

Wildland Fuel Conditions and Effects of Modeled Fuel Treatments on Wildland Fire Behavior and Severity in Dry Forests of the Wenatchee Mountains

Michael Reese Lolley

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A pressing issue in fire management is understanding the immediate and long-term effects of fuel treatments on wildland fire behavior and severity. Intensive fuels data were collected as part of the pre-assessment for the Fire and Fire Surrogate Treatments Study at the Mission Creek site in the Wenatchee Mountains of Washington State. These data are summarized and a subset used to model treatment effects (intermediate thin, prescribed fire, and combination) on forest fuel profiles and loadings using the Forest Vegetation Simulator and Fire and Fuels Extension model (FVS-FFE). FVS-FFE is used to model the potential short and long-term effect of fuel treatments on wildland fire behavior and severity under 80 and 90+ percentile fire weather conditions.

Intermediate thin only had the short-term effect of reducing flame length and associated mortality; however, the reduced short-term flame length may be an artifact of the FFE model selection. Furthermore, the failure to increase canopy base height while simultaneously reducing canopy cover appears to reduce the effectiveness of the treatment over time. The thin and burn treatment was effective at increasing canopy base height overall, but at the cost of increasing mid-flame windspeeds, increasing flame length and tree mortality. The treatment was effective, but results were more erratic over the longer time period modeled. In addition, the thin and burn treatment had the greatest

effect on reducing crown fire hazard; however, crown fire hazard was low to start. The burn only treatment effectively increased canopy base height while maintaining higher tree canopy cover resulting in lower mid-flame windspeeds and therefore having the greatest overall reduction of flame length and severity over the time period modeled. When fire weather was increased to 90 percentile plus conditions, treatment effectiveness in reducing severity was minimal under one set of fuel conditions, and treatments actually increased the level of severity under the second set of fuel conditions.

This research modeling four fuel treatment scenarios in two fuel arrays indicates that the treatment of fuels can affect fire behavior and severity outcomes. However, the types of treatments have the potential to either increase or decrease intensity and severity. Furthermore, results indicate that response of wildland fire behavior and severity to fuel treatments depend on the existing conditions of vegetation fuel profile, design of prescriptions and fire weather extremes. Blanket statements purporting one method of fuel treatment is most effective over another in reducing fire intensity and severity have not fully considered the context of place and time. However, important components of fuel treatments include consideration of how the reduction in canopy cover affects mid-flame windspeed in the context of crown fire hazard and surface fuel loading and canopy base height.

FVS-FFE is powerful and complex combination of models integrated into one package that has the potential of helping managers decipher and understand tradeoffs between fuel treatment options; however, as this research has shown, if results are not analyzed in the context of assumptions woven into the model, they can misinform as well as inform management actions. Differentiating between model performance and preconceived expectations is difficult, but discrepancies can be identified, and ultimately should be resolved with empirical data.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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DEDICATION

To Thomas Gaines and Emmett Corvus Hungate Lolley – in this year you both have reminded me how precious life is.

INTRODUCTION

Recently the treatment of fuels to moderate wildland fire behavior and effects is receiving as much attention by politicians and managers as fire suppression has over the last century. Nonetheless, research on the effects of fuel treatments on wildland fire behavior and effects is limited. This research characterizes existing fuels in dry forests of the Wenatchee Mountains, and uses a subset of the data to model the effect of fuel treatments on wildland fire behavior and severity.

Exclusion of fire from dry forests that historically had short fire return intervals has changed the dominant composition and structure of fuel profiles of many forests in the West. Higher densities of low and mid-story trees, greater surface fuel volume, and an increase of fire intolerant species have led to higher intensity and severity fires that are predominantly uncharacteristic (Agee 1993, Allen et al. 2002), but not everywhere (Shinneman and Baker 1997, Meyer and Pierce 2003). Resource managers are under increasing pressure from legislative and regulatory action to treat fuels both in the wildland urban interface and wildlands (Western Governor's Association 2002, House of Representatives 2003, USGAO 2003). In response, resource managers are faced with choosing a suite of alternative fuel treatment practices involving fire and mechanical/manual “fire surrogates” with little information about the efficacy of options. Resource managers need better information and insights about the consequences of alternative management practices involving fire and mechanical/manual fuel treatments to inform decision making. This research is focused on the effects of fuel treatments on wildland fire behavior and severity.

This research samples and summarizes a range of fuel conditions found in dry forests of the Wenatchee Mountains and investigates the short-term and long-term efficacy of four fuel treatments: intermediate thin, prescribed burn, intermediate thin followed by prescribed burn, and continued fire exclusion in modifying fire behavior and severity. The thin treatment modeled in this research removes tree species of economic value to a specified basal area—thinning or slashing of smaller trees is not modeled. This treatment represents a real scenario where resources are not available to treat ladder fuels.

Variability of fuels is an important aspect in predicting fire behavior in the context of the landscape (Miller and Urban 1999b, Agee et al. 2000a, Miller and Urban 2000, Finney 2001, Miller and Yool 2002). Forest fuels vary in their spatial orientation, quantity, and composition from the scale of a single meter to an entire landscape. The composition of vegetation, topography, and the history of disturbance processes create forest fuel heterogeneity. Forest floor depth and type can vary within meters due to changes in vegetation structure, composition, and slope among other factors which can influence fire spread. A group of dead trees creates a very different fuel complex than a group of green trees. Because of this heterogeneity, large sample sizes are required to statistically analyze surface fuel characteristics at the stand level (Brown 1974). It is expected that variability of forest fuel attributes within stands will be high while between stand variability will be less, but great enough to influence potential fire behavior and severity between stands.

Wildland fire behavior and effects are dependent on: ignition source, ignition location, topography, weather, composition, structure and amount of live and dead vegetation, as well as its spatial arrangement within a patch and across a landscape (Agee 1993, Weatherspoon and Skinner 1996, Miller and Urban 1999a, Agee et al. 2000a). It has often been inferred that managers' only option in manipulating the fire triangle is fuels; however, managers can and do use ignition placement, timing, topography, and predicted weather conditions for prescribed and wildland fire use scenarios. Nonetheless, these variables are difficult to manipulate under extreme fire weather and unplanned wildland fire conditions. Therefore, management's influence over potential wildland fire behavior and effects is predominately limited to the manipulation of existing fuel arrays.

The difficulty of obtaining empirical observations, the number of variables that contribute to the process of wildland fire, and the effect of temporal and spatial scale on wildland fire behavior all present challenges to the research of wildland fire behavior and the influence of fuels. Fuels, topography and weather are core variables influencing wildland fire behavior (Countryman 1972). Each component encompasses many variables that present specific challenges for measurement and analysis. However, a synthesis of fire behavior theory and empirical investigations has been encapsulated in wildland fire behavior computer models as has knowledge of vegetation growth and fuel dynamics. This research uses the Forest Vegetation Simulator and Fire and Fuels Extension (FVS-FFE) to model differences of stated fuel treatments on potential wildfire behavior and severity.

It is proposed that fuel arrangement, quantity, and type can be manipulated to influence variables of wildland fire behavior such as flame length, fire intensity, passive fire, crown fire, and tree mortality (Byram 1959, Agee 1996, van Wagtendonk 1996, Scott 1998, Stephens 1998, Agee et al. 2000a, Swanson 2000, Fule et al. 2001, Brose and Wade 2002, Fule et al. 2002, Pollet and Omi 2002, Perry et al. 2004).

METHODS

Study Area

The study site is located in the Wenatchee Mountains east of the crest of the Cascade Mountain range in the Mission Creek watershed in Washington State. The 12 experimental units (EU) are 4 to 12 km to the south and southwest of the city of Cashmere in Chelan County on the Wenatchee National Forest, Leavenworth Ranger District (Figure 1, Latitude 47° 25' 50" N, Longitude 120° 32' 55" W). The primary parent material is the Chumstick sandstone, dating from the Middle to Upper Eocene (42-46 mybp). Four of the EUs (Crow 1, 3, 6, and Pendleton) are located on the Horse Lake Mountain Complex (29 mybp) which is characterized by intrusions of hornblende and andesite (Gressens 1982). A preliminary soil survey has mapped the following soils on the study site: Blag (Haploxerept), Blewett (Haploxeroll), Borland (Argixeroll), Brisky (Haploxeroll), Cle Elum (Haploxeralf), Dinkelman (Haploxeroll), Nard (Haploxeralf), Shaser (Vitrixerand), Varelum (Haploxeralf), and Yaxing (Argixeroll) (USDA 1995). Discrepancies were found between profiles collected and the mapped series by NRCS, but orders are consistent (Dolan 2002).

Climate and Weather

The climate east of the Cascade Mountains has been described as a combination of maritime and continental climates. The range of daily diurnal and seasonal temperatures is high but not extreme. Summer relative humidity is low and summers are dry with moderate levels of precipitation in the winter that predominantly falls in the form of snow (Franklin and Dyrness 1988). The climate of the Wenatchee Mountains is heavily influenced by the Cascade Mountains to the west and the Columbia Basin to the east. Regional winds are generally westerly and push marine air over the high Cascade Mountains having an orographic effect. This process results in lowering the moisture content of air masses that pass through the Wenatchee Mountains and descend onto the Columbia Basin. In addition, the Cascade Mountains reduce the ameliorating effects of the Pacific Ocean on temperature. Freezing temperatures are common in the winter, but

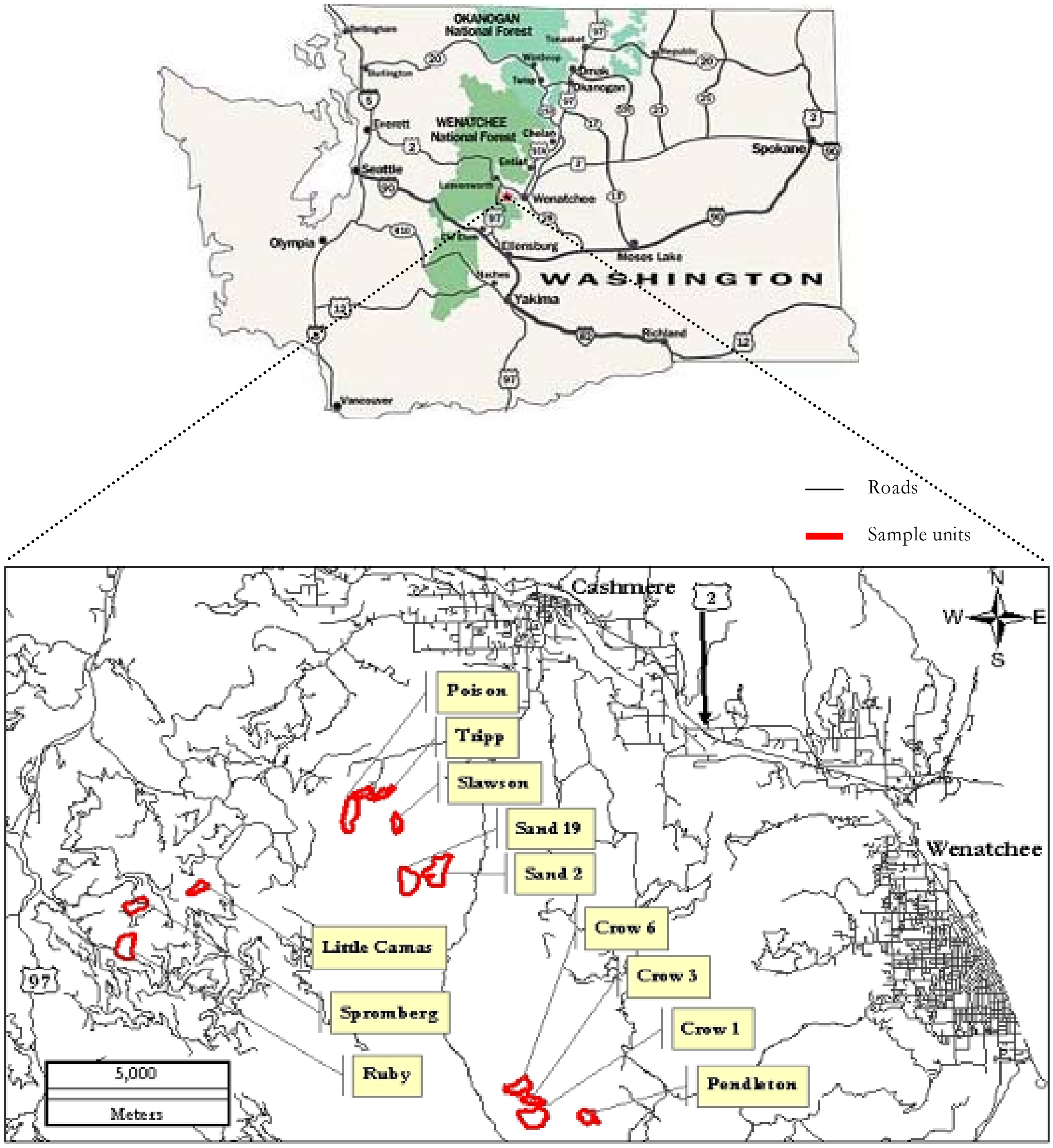


Figure 1: The study site is located in the Wenatchee Mountains east of the Cascade Mountain range in the Mission Creek watershed, Washington State. In Chelan County, 12 experimental units (EUs) are four to 12 km to the south and southwest of the city of Cashmere.

extreme cold is rare; however, cold air masses from the northeast do occasionally bring extended cold snaps. Local topography, including a west-east elevation gradient, has a strong effect on temperature and precipitation. Generally, mean annual precipitation declines from the Cascade crest west to east as elevation decreases. Along the same gradient, mean annual summer temperature increases and winter temperatures generally decrease (Franklin and Dyrness 1988).

Local weather was characterized using National Interagency Remote Automated Weather Station Network (RAWS) data at Dry Creek station is approximately 25 km to the north of the closest EU and Swauk approximately 15 km to the south of the closest EU (Watson et al. 2003). Dry Creek and Swauk receive 33 cm of precipitation on average annually, with daily mean averages ranging from as high as 6 cm in late October, to just less than one centimeter in late August and September; however, maximum mean daily precipitation often exceeds 10 cm of precipitation during the months of October and November, and minimum daily precipitation levels are near to zero for the months May through September.

Vegetation and Disturbance History

The experimental units selected for sampling fuels represent varying topography and existing conditions of dry type forests where fire has been excluded in the Wenatchee Mountains. Dry forests for this reasearch are defined as forests that are dominated by ponderosa pine (*Pinus ponderosa* P.& C. Lawson) or Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco.), but grand-fir (*Abies grandis* (Dougl. ex D. Don) Lindl.) is occasionally co-dominant. Specific site characteristics and plant associations are summarized in detail in the results section.

Grazing of sheep reached a peak in the late 1890s, before grazing was regulated on public lands. An allotment system was initiated in 1900; however, heavy grazing continued. While numbers before 1927 are not well documented in 1930 over 13,200 sheep months were located in the Mission Creek allotment, by 1933 that number was reduced to 2,400 (USDA 1938). Similar reductions were made on neighboring allotments, bringing total sheep months down to around 6,300. Mission Creek was used as a sheep driveway from 1925 to 1930 where it was estimated that over 30,000 sheep passed through the drainage each spring and fall. By the 1950s the number of grazing animals allotted had been reduced by three-fold (Holstine 1992). Currently there is no National Forest System Land with active sheep allotments in Mission Creek watershed (Keith Rowland, Range and Special Uses Program Manager, Okanogan-Wenatchee National Forests, March 2003, written communication). Sheep herders likely influenced vegetation in more ways than grazing sheep; they also set many fires from 1880 to 1910 (Holstine 1992).

Timber harvest in the lower and more accessible reaches of the Mission Creek watershed began in the late 1800s for railroad construction, mining, homesteading, and to supply a developing fruit industry. By 1931 it was estimated that the fruit industry demanded 100 MMBF annually to supply material for boxes to ship fruit (Holstine 1992). From 1928 to 1938, the Cashmere Mill processed over 200 MMBF a year (USDA 1938). Selective harvesting, or highgrading the biggest and the best, predominantly ponderosa pine, was the standard. Post World War II, the scale of timber harvesting and road building increased significantly (Holstine 1992).

The charge that modern society has been relatively successful in excluding fire from the landscape over the last century is corroborated with fire history research. Research by Everett et al. (2000) in dry forests of the east Cascade Mountains indicate that the occurrence of fire was reduced from the period of 1910 to 1996 compared to the period from 1700 to 1860. Mean fire free intervals were reported near forty years and 7 years respectively. A fire history study in the Teanaway River drainage, just to the SW of Mission Creek, notes that fire size and frequency declined dramatically after 1900 (Wright and Agee 2004).

Field Methods

Experimental Unit Selection

As part of the Fire and Fire Surrogates research at the Mission Creek site, 12 experimental units (EUs) were selected from approximately 30 candidate Forest Service timber sales that met the following criteria:

1. average unit slope less than 40 percent;

2. less than 10 percent rock and non-forest vegetation;
3. areas without known plant or animal species of concern, except for survey and manage species.
4. ten hectares or greater

Plot Selection

Within each experimental unit, sampling was conducted with a systematic design. A 40 m x 40 m grid was installed over each experimental unit. Thirty to thirty-six grid points for sampling fuels were selected prior to site visits by selecting alternating grid intersections and staggering starting points for each grid row (Figure 2).

Field Data Collection

Fuel and vegetation data were collected during the summers of 2000 and 2001. Physical site data, crown and understory fuels, and surface fuels were measured at each sampled grid point.

Physical Site Data

Each sample grid point was permanently marked and a point coordinate was obtained with a Garmin 12 XL global positioning system (GPS) unit. Basic data such as aspect and percent slope were recorded. Elevation for each data point was derived from overlaying the GPS point coordinate over a 10 m rectified digital elevation model using ArcGIS geographic information software.

Canopy Fuel Profile

Canopy fuels or overstory vegetation data were collected on square plots, which were increased at 5 m increments on a side to obtain a minimum of 10 trees in order to represent canopy fuels at each sample point. This was usually obtained with a 400 m^2 plot, but was altered to a sample size as small as 25 m^2 and as large as 3600 m^2. Both conifers and broadleaf species were counted in the vegetation plot.

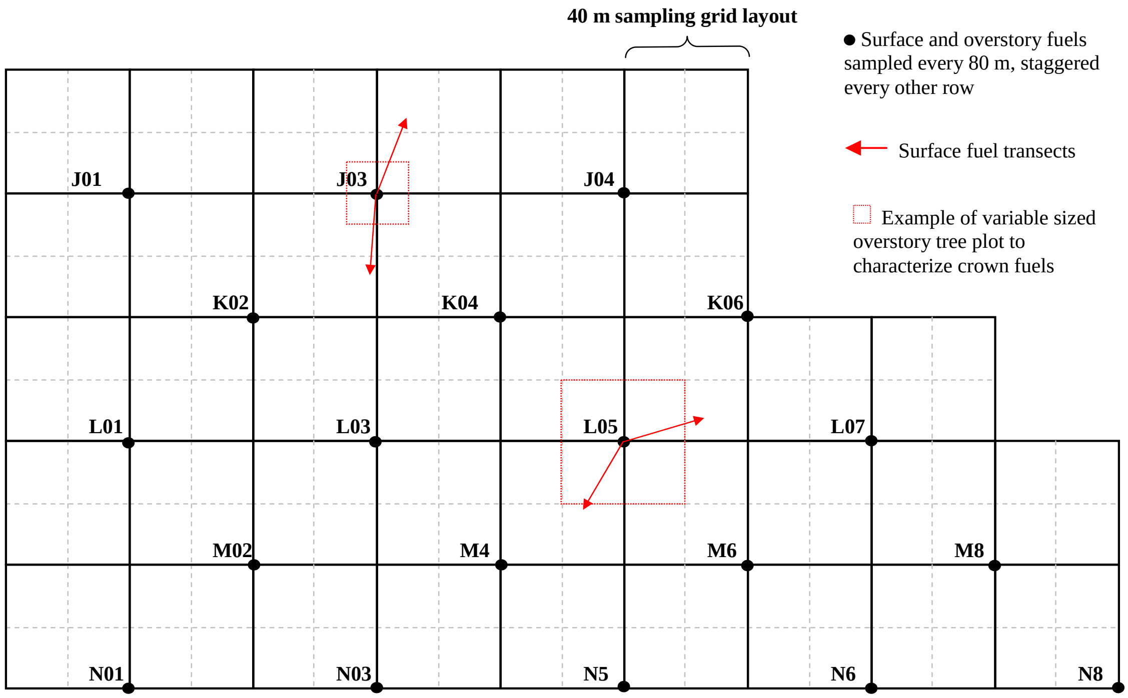


Figure 2: Labeling convention of grid point numbering for each of the 10 hectare units (40-m interval). Thirty to thirty-six grid points for sampling fuels were selected prior to site visits by selecting alternating grid intersections and staggering starting points for each grid row. Two fuel transects were sampled and variable size tree plot was established to characterize canopy fuels.

After a plot size was determined, data for each tree were collected, including species, diameter of bole at breast height (1.4 m), and three height measurements: height to dead crown, height to live crown, and total height. Height to dead and live crown on each tree was measured at the lowest point on the bole where dead or live branches were spaced continuously spaced within 0.5 m of each other. Trees from 1 m to 1.4 m height were recorded with a diameter of zero; trees less than one meter tall were included in the shrub fuel component, but not counted as conifer understory. Canopy closure, the proportion of open sky obscured by vegetation, was measured using a Lemmon Spherical Densiometer Model-A, (Lemmon 1957) at each sampled grid point.

Canopy base height was calculated using two methods: one is simply the stand mean of height to live crown measurements (Cruz et al. 2003), and the other is based on a canopy bulk density threshold (Scott and Reinhardt 2001). Stand mean canopy base heights were calculated taking the mean of all live crown base measurements sampled at each fixed area plot sampled, and calculating the grand mean for all samples at a given EU. The second method defines canopy base height as the lowest height of all samples that have at least 0.011 kg m^{-3} (30 lb $acre^{-1}$ ft^{-1}) of available canopy fuel (Scott and Reinhardt 2001). FVS-FFE model was used to calculate the second method, and will be referred to as canopy base height throughout the remainder of this document. A description of the method for calculating canopy bulk density is described under Model Description and Assumptions in this thesis.

Surface Fuel Profile

Down dead woody material data were collected using Brown's (1974) fuel transect method in which two 25 m transects were deployed at random azimuths from sampled grid points; the second at least 90 degrees from the first (Figure 3). No measurements were made in the first 5 m of the transect to avoid ground disturbance to the area sampled. Sampling for each of the timelag class fuels began at the 5 m mark of the Brown's transect. Timelag is the amount of time necessary for a dead wood fuel component to move 63% of the way to its equilibrium moisture content (Lancaster 1970). For example, a 10 hour fuel would take 10 hours to change by 63% of the difference between the initial fuel moisture and the equilibrium moisture content. One hour timelag fuel was sampled from 5-7 m (2m sample), ten hour fuel from 5-8 m (3 m sample), hundred hour fuel from 5-10 m (5 m sample), and thousand hour plus fuel from 5-25 m (20 m sample). Thousand hour plus fuels were divided into 5 decay classes: 1 through 3 being sound, and remainder rotten. Average diameter squared and specific gravity values used in calculated fuel weight are the average values of dominant species in the study (Douglas-fir and ponderosa pine) as reported by (Brown 1974, Table 1). For each 1-100 hour timelag fuel, fuel loading (Mg ha^{-1}) was calculated as the average of all transect samples in each EU. For 1000+ hour sound and rotten fuels, fuel weight was calculated for each log sampled, summed for the transect (Brown, 1974), and average of all transects was calculated for each EU.

Table 1: Values used in the calculation of fuel weight using Brown's (1974) method and length of transect sampled for each diameter class of fuel. Average diameter squared and specific gravity values are the average values of dominant species in the study (Douglas-fir and ponderosa pine) reported by Brown.

Timelag class (hr)	Diameter class (cm)	Avg. diameter squared (cm^2)	Specific gravity	Sample transect length (m)
1	0 – 0.635	0.0589	0.48	2
10	0.636 – 2.54	0.688	0.48	3
100	2.55 - 7.63	7.61	0.40	5
sound 1000+	7.63 - 15.2	NA	0.40	20
rotten 1000+	7.63 - 15.2	NA	0.30	20

Forest floor depth was measured at 10, 15, and 20 m points along each Brown's transect (Figure 3). Two components of the forest floor were identified: litter, which is recognizable organic matter, and duff, which is intermediately decomposed materials that are difficult to identify to source. Litter and duff are analogous to the soil horizons Oi and Oe, respectively.

Down dead woody fuel depth was measured from above the duff layer to the height of the tallest down dead wood fuel particle in three closely spaced (9-10 m, 10-11 m, and 11-12 m) points along each fuel transect (Figure 3). Down dead woody fuel depth was calculated as an average for each transect sample, and averaged across each EU, as was calculated for timelag fuels.

Forest Floor - Modeling Depth-Mass Relationship

In a separate sampling effort litter and duff were sampled to model the relationship between depth and mass. Destructive samples were collected on Ruby, Poison, and Pendleton EUs (Figure 1). Samples were obtained at three to four grid points per experimental unit. Grid points for sampling were chosen *a priori*. A random azimuth was used to direct a transect on which ten 100 cm^2 samples were collected spaced 1 m apart, starting at 5 m from the grid point (van Wagtendonk et al. 1998). A 10 x 10 cm board with a handle was used to press down on the substrate while cutting through litter and duff material with a sharp knife. Four depth measurements were made on each 10 cm side of

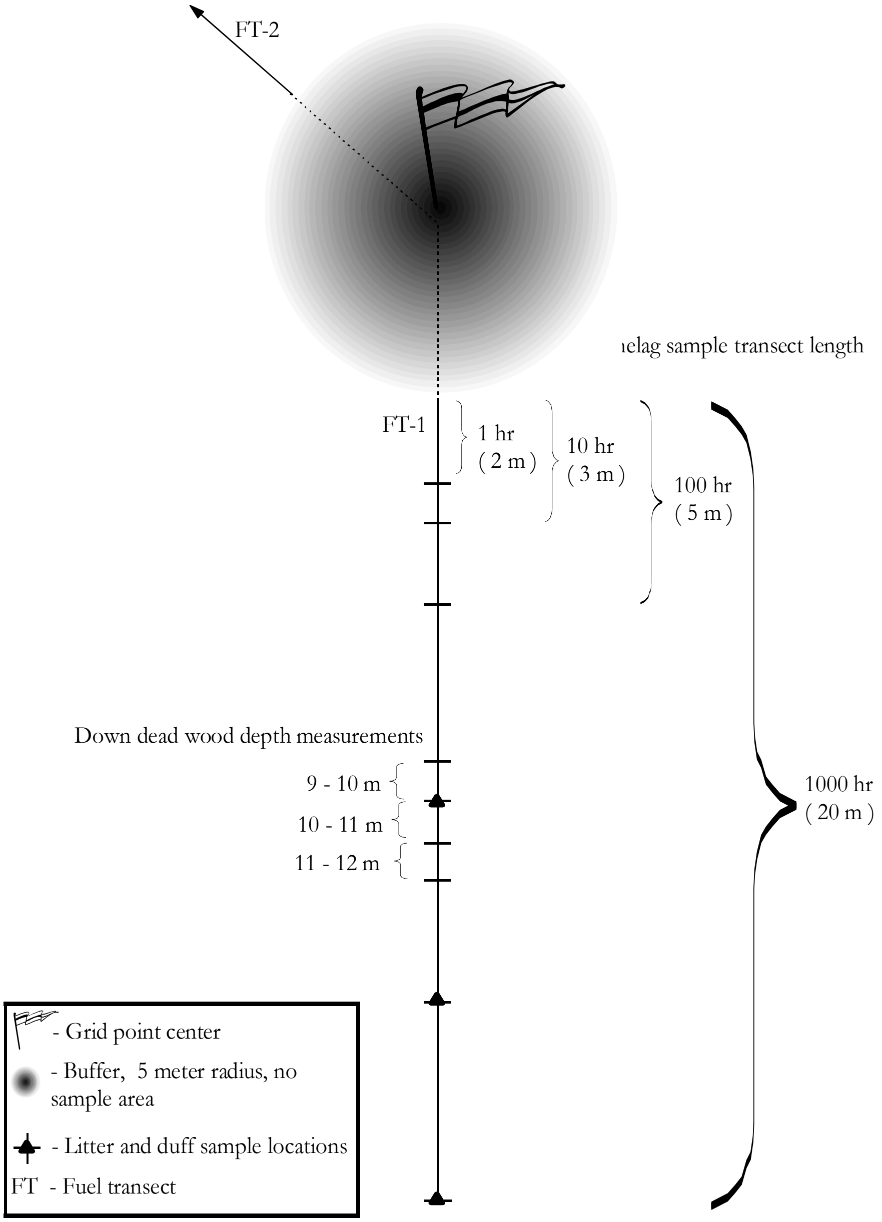


Figure 3: Fuel transect sample design based on Brown's (1974) method. A permanent marker was set at sampled grid points. Timelag fuels, litter (O_i), duff (O_i), and deadwood depth were sampled.

the sample. Litter and duff were differentiated as defined above on 108 litter and 21 duff samples. This method provided for well-differentiated, clean cuts for the 100 cm^2 plane and marginally affected volume as litter and duff sprung back to original volume after being lightly compressed. Measurements were made in early fall when substrate was very dry. Duff collections were made in a manner as to reduce the collection of mineral fraction.

All mass measurements are reported as dry weight. Litter and duff samples were oven dried at 70°C until a constant mass was obtained. If any mineral (sand and rock) or dead wood less than 0.635 cm in diameter was observed in sample, it was removed and weighed separately, but not included in the models. Three cubic centimeters of each sample were ashed to determine mineral content to provide a mineral sampling correction factor. The mineral fraction for litter was 14.6% and 21.6% for duff, 107 and 21 samples respectively. As mineral content of Douglas-fir and ponderosa pine foliage is approximately 4% (Agee et al. 2002), the litter correction factor was reduced to 10.6%. The mass of each oven dried sample was reduced by its respective mineral correction factor before developing regression models.

Simple linear regression was used to develop models with depth of duff or litter as the predictive variable, and mass the dependent variable. Three separate general models were developed: litter only, duff only, and total forest floor. The general models were developed from all samples collected. Additional litter models were produced representing overstory dominated by ponderosa pine or Douglas-fir using the Pendleton and Ruby EU samples respectively as fuel weight mass relationship significantly vary by tree species (van Wagtendonk et al. 1998). Using the litter and duff depth measurements obtained from each fuel transect sampled, the general models were used to calculate estimates of litter and duff fuel loading for each EU.

Herbaceous and Shrub Fuels

A 400 m^2 area centered on each grid point was sampled by ocularly estimating cover, height, and density and dominant type (Burgan and Rothermel 1984).

Herbaceous fuels were classed into one of two types: Grass Type 1, fine fuel such as cheatgrass (*Bromus tectorum* L.); and Grass Type 2, a heavier fuel like pinegrass (*Calamagrostis rubescens* Buckl.) or elk sedge (*Carex geyeri* Boott) (Burgan and Rothermel 1984). One of three average density classes (1, 3, and 5) was assigned from the Burgan and

Rothermel (1984) photo key. Cover classes were assigned as: 1 = 10-40% cover, 2 = 40-70% cover, 3 = 70-100% cover. Average depth of shrub and herbaceous plants were recorded based on 70% of the maximum leaf or stalk height (Burgan and Rothermel 1984).

Three shrub types were identified based on stem diameter and leaf thickness: Shrub Type 1 has thin stems and thin leaves, Shrub Type 2 has thick stems but thin leaves, and Shrub Type 3 has thick stems and thick leaves (Table 2). One of three average density classes (1, 3, and 5) was assigned from the Burgan and Rothermel (1984) photo key. Cover and depth were measured and recorded as for herbaceous fuels.

Table 2: Example of plant species (scientific name, common name) located in EUs that were classified into 1 of 3 Burgan and Rothermel's (1984) shrub types.

Shrub Type 1	Shrub Type 2	Shrub Type 3
Spiraea betulifolia Pallis, shiny leaf spiraea	*Holodiscus discolor* (Pursh) Maxim., ocean spray	*Ceanothus* spp. L., ceanothus
Rosa spp. L., rose	*Purshia tridentata* (Pursh) DC., bitterbrush	*Mahonia* spp. L., barberry
Amelanchier alnifolia Nutt., serviceberry	*Symphoricarpos* spp. Duhamel, snowberry	
	Salix scouleriana Barratt, Scouler willow	

Herbaceous and shrub data were formatted in Microsoft Access and exported to FUELCALC (Scott and Lansing 2001). FUELCALC uses the same calculations as Burgan and Rothermel's (1984) NEWMDL to calculate fuel loadings, but is advantageous as all calculations are made in a Microsoft Excel spreadsheet, all functions are transparent, and multiple records can be processed at once. Fuel loads are calculated for 1.) one hour timelag class of herbaceous plants and live equivalent, 2.) one hour shrub and live equivalent, and 3.) 10 and 100 hour shrub. For example, live herbaceous fuel load is calculated as:

$$\text{Herb Fuel Load (Mg ha}^{-1}\text{)} = \text{depth (cm)} * \%\ \text{cover} * \%\ \text{alive} * \text{bulk density lbs ft}^{-3} * 1.602$$

where bulk density is obtained from Burgan and Rothermel's (1984) tables based on herbaceous class and type (Scott and Lansing 2001, Table 3). The last term is a conversion factor. The proportion of dead woody and live material for shrub one hour, 10 hour, and

100 hour were calculated using data published by Agee and Pickford (1985), see Table 4. Dead herbaceous fuels were calculated as 5% of the total live fuel estimate; however, the proportion of dead to live herbaceous fuels is dependent on the time of year the measurement was made, and therefore could be much larger.

Table 3: Bulk density values used in calculating herbaceous and shrub fuel weights in FUELCALC spreadsheet program, from Burgan and Rothermel (1984).

Density Class	Bulk Density (lb ft^{-3})				
low and high shrub			Type		
	1	2	3	4	5
1	0.0115	0.0115	0.0115	0.0918	0.2296
3	0.0345	0.0459	0.0459	0.2701	0.4591
5	0.0918	0.1148	0.1148	0.5739	0.6559
herbaceous			Type		
	1	2	3	4	
1	0.0050	0.0050	0.0255	0.0255	
3	0.0255	0.0353	0.0459	0.0459	
5	0.0459	0.0765	0.0765	0.0765	

Table 4: Proportion of total shrub load allocated to timelag fuel size classes and type based on Agee and Pickford (1985).

shrub 1 hr	shrub 10 hr	shrub 100 hr	live shrub equivalent 1 hr
2.4	1.2	2.0	94.4
2.2	1	0.2	96.6
3.1	1.4	0.5	95.0

Fire Behavior Fuel Models

Northern Forest Fire Lab (NFFL) fire behavior fuel models were defined using Anderson's (1982) stylized fuel model classification. From each grid point, an ocular estimate of the percent area representing each fuel model was made within a 400 m^2 area. A fuel model type was not recorded if it was present but represented less than 10% area.

An additional fuel model was created to describe ground cover that did not have enough fuel to carry a flame front, i.e. high cover of rock or bare soil.

Data Processing and FVS-FFE Modeling Description and Assumptions

Multiple computer programs were utilized to produce results. A relational database structure was designed in Microsoft Access (Appendix A) to enter, error check, store, and format data for output for analysis in Microsoft Excel, Statistical Program for Social Sciences (SPSS), and GraphPad InStat software. In addition to Access, UltraEdit -32 text editor and Format4FVS programs were used to format data for input into the Forest Vegetation Simulator and Fire and Fuels Extension (FVS-FFE) model. Suppose, a graphical user interface to FVS, was used to input all commands in FVS-FFE. FVS-FFE v. 04-01-2003, Pacific Northwest, East Cascades variant release date 07-02-2003 was used to model tree growth, apply mechanical and prescribed fire fuel treatments and to model fuel dynamics and potential wildland fire behavior and effects. Keywords, similar to commands, were used to set or change parameters, run reports, and simulate actions such as thinning, or burning when using FVS-FFE. Data formatting was done using numerous post-processor programs designed to read and format FVS-FEE output data into reports and text files. Fire Family Plus v 3.0.1. was used to calculate percentile fire weather. Fire Family Plus and all FVS-FFE associated programs are available free of charge. Sigma Plot 2000 was used for presentation of data.

Statistical Analysis of Existing Fuels

Non-parametric analysis of variance (ANOVA) by ranks (Kruskal-Wallis H test) was used to test for differences in median fuel loads between EUs. Existing fuel variable data were rarely normally distributed, or had equal variance, and transformations were successful on a limited number of variables excluding the use of a standard single factor ANOVA. The Kruskal-Wallis test is 95 percent as powerful as parametric single factor ANOVA (Zar 1999). Not all sampled fuel population variables have the same dispersions and shapes, an assumption of the Kruskal-Wallis test; however, the test is typically robust (Zar 1999). The null hypothesis that there is no difference in median fuel variable x between EUs, where x equals fuel variables: canopy closure, stand canopy base height, timelag fuels, litter, duff, one hour timelag herbaceous fuel, timelag shrub fuels, equivalent one hour timelag live herbaceous fuel, and down dead woody fuel depth were tested at the $\alpha = 0.05$ level. Following a rejection of the null hypothesis with the Kruskal-Wallis test, the location of statistically significant differences between groups at $\alpha = 0.05$ level was determined using the Dunn test, a nonparametric multiple comparison with unequal sample sizes statistic which takes into account the number of comparisons made.

The Forest Vegetation Simulator and Fire and Fuels Extension (FVS-FFE) model is used to simulate fuel treatments and to compare the effects of fuel treatments on wildland fire behavior and severity over time. For complete model description, refer to Reinhardt and Crookston (2003) from which the following section is summarized with other pertinent publications as it pertains to methods and results of this work. All FVS-FFE inputs and outputs are based on the U.S. System of Measurements.

Individual Tree Growth Model

The Forest Vegetation Simulator (FVS) is a forest stand development model that is widely used in the U.S. and Canada. FVS simulates tree growth, mortality, regeneration, and implementation of silvicultural treatment options by summarizing individual tree data plots to a stand level. It is a distant-independent individual tree growth and yield model. To model individual tree growth, FVS uses diameter growth regression equations. Growth is dependent on as many as 13 predictor variables, including stand variables such as slope, aspect, elevation, site index, and stand location, as well as individual tree variables such as DBH, crown ratio, and basal area (Johnson 1990). FVS assigns random error to the diameter growth prediction from the error distribution of the diameter growth regression equation (Wykoff et al. 1982). The assignment of the random error is controlled by a random number seed in FVS and is assigned at each growth cycle. If the random number seed is set to the same number each time FVS runs, unless changed by the user, the results are the same and FVS is deterministic. However, if the random number seed is reset, different results would be produced (Chad Keyser, Forester, Forest Management Service Center, Fort Collins, personal communication). The random number seed was not reset for the following simulations, therefore FVS simulations are deterministic, and differences in modeling of growth will not account for differences between various fuel treatments influence on wildland fire behavior and effects over time.

FVS growth model is calibrated based on 10 year growth cycles. Data are reported at each growth cycle in FVS. Because FFE is based on an annual cycle, 10 year growth cycles can create punctuated changes in fuel loadings and fire behavior outputs. The growth cycle length can be increased or decreased but may introduce bias; however, the bias associated with period lengths shorter than those used to fit the model is small (Dixon 2002). Therefore, a five year growth cycle was used in this research to smooth the transition in addition to four one year cycles for means of reporting values from the treatments.

Growth measurement data were not available to calibrate growth for the sites; however, stand index values were modified based on local expertise at the Crow 6 EU. Adjustment of site index was not made at Ruby EU as better information was not available; however, regression equations are generally representative of growing conditions in the East Cascades (EC) variant, and the models produce relatively unbiased estimates of growth (Dixon 2002). The FVS East Cascades variant typically uses values for site index (SI) and maximum stand density index for individual tree species from the user provided plant association. SI is an important predictor variable in the growth equation. SI curves for the modeled sites were not available, but were adjusted based on local knowledge for individual species using the keyword SiteCode (Table 5, Richy Harrod, Fire Ecologist, Wenatchee National Forest, written communication). "Other species" values were used to model a suite of broadleaf tree species.

Mortality in FVS is modeled using maximum stand density index and is species specific. As stand density index (SDI) approaches the maximum density related mortality begins to occur. Typically FVS defines maximum SDI as growth basal area (ft^2 ac^{-1}): (GBA) * 1.5 * 1.84, where the GBA is obtained from the plant association for a given stand. GBA is defined as the basal area at which dominant trees grow 1 inch diameter per decade (Hall 1982). The factor, 1.5, is included to calculate suppression mortality GBA and 1.84 is a conversion factor from BA (ft^2 ac^{-1}) to SDI, or the number of 10 inch trees per acre (Fred C. Hall, Plant Ecol NW, March 2005, written communication). Crow 6 maximum SDI values were changed using MaxSDI keyword to reflect values calculated from a sample of 70 ponderosa pine stands near the project area where average full stocking was around 210, and maximum SDI of 310 was identified based on the assumption that average full is two thirds of maximum (William E. Hartl, Silviculturist, Leavenworth Ranger District, Forest Service, March 2003, written communication). In addition, the maximum SDI value of "other tree" species representing shade intolerant broadleaf species was lowered. Percentage of maximum SDI where mortality begins was set at 55 for "other tree" species, and the default percentage of 85 was used for all the remaining tree species in Crow 6 and Ruby.

Table 5: Site index values used to model growth and maximum SDI values used to model mortality by species at modeled EUs.

Tree species	Max. Stand Density Index		Site Index	
	Crow 6	Ruby	Crow 6	Ruby
ponderosa pine	315* (179)	402	75* (49)	88
Douglas-fir	400* (213)	478	50* (31)	58
grand fir	-	478	-	56
other species	200* (213)	200* (478)	23* (15)	27

* value changed based on local knowledge
() represent default values that would have been used in FVS East Cascades variant

Natural regeneration of tree species was simulated using the partial establishment model in FVS. For Crow 6 and Ruby EUs, regeneration was simulated as occurring at one pulse the year after treatment occurred. The density of regeneration was based on the basal area ft^2 ac^{-1}(BA) of the stand after treatment, where: trees per acre (TPA) = 400*exp (-0.02*[BA]) (Wedin 1999). As BA increases, regeneration decreases. The proportion of TPA per tree species, where DF equals Douglas-fir and GF equals grand-fir, in the Ruby unit was calculated as:

$$\%DF\&GF = .000004*(BA^3) - 0.0034*(BA^2) + 0.9667*(BA) + 8.9337$$

The remaining proportion is ponderosa pine i.e. 100 - %DF&GF = proportion ponderosa pine. A further assumption was made that two-thirds of the proportion of DF and GF would be Douglas-fir, the remaining one-third grand-fir. For Crow 6 TPA was calculated as for Ruby; however, the proportion of species regeneration composition was calculated simply based on stand composition: 90% ponderosa pine and 10% Douglas-fir. Regeneration data used in FVS are presented in SI units; however, all inputs into FVS-FFE are imperial (Table 6). No regeneration was modeled in the control (CTRL) treatment. The Fire and Fuels Extension to FVS links existing fire behavior and effects models that had been previously developed; however, new models were developed to simulate fuel and snag dynamics. FFE is composed of three submodels: fire behavior and effects, fuel dynamics, and snag dynamics. A summary of fire behavior and effects, and fuel dynamics sub-models follow. All simulations are calculated at the individual stand level independent of neighboring stands. The spread of fire between stands is not modeled, nor is the potential fire behavior of neighboring stands accounted for (Reinhardt and Crookston 2003).

Surface Fire Behavior and Fire Behavior Fuel Models

Surface fireline intensity is modeled in FVS-FFE using the Rothermel's (1972) surface fire spread equations as it was modified by Albini (1976b) in FIREMOD and implemented by Andrews (1986) in BEHAVE (Reinhardt and Crookston 2003). The same assumptions of the application of Rothermel's (1972) spread equation in FVS apply, namely, fire spread is modeled as the steady progression of a forward-moving fire fueled by a uniform fine surface fuel profile (fuels < 7.63 cm diameter, including litter) that is continuous, and not greater than 1.8 m from the ground surface (Rothermel 1983). Fires that burn in a mosaic are not modeled, 100% is of a stand is affected. Flanking and backing fires are not modeled. Fire behavior is only predicted at the head of a fire where fine fuels are consumed, whereas compact and large fuels burning behind a head fire are not modeled (Rothermel 1983). Furthermore, outputs represent mean predictions; variability of fire behavior is not modeled for a given stand or prediction (Rothermel 1972).

Fireline intensity is calculated by integrating Rothermel's (1972) surface fire spread rate model with Anderson's (1969) model of residence time (Andrews and Rothermel 1982). Therefore, predicting rate of surface fire spread is more reliable than predicting fireline intensity, but is the best model currently available (Scott and Reinhardt 2001). FFE does not simulate the spread of fire, but does calculate fireline intensity. In FVS-FFE, surface fireline intensity is used as a variable in the calculation of flame length, tree scorch height, and an index of torching. Surface fireline intensity is affected by slope, mid-flame wind speed based on canopy cover, fuel moisture and fuel loading (Reinhardt and Crookston 2003).

Table 6: Natural regeneration of tree species was simulated using the partial establishment model in FVS. The number of trees per hectare was established based on live basal area (BA) of the stand after treatment (Rx). No regeneration was modeled in the Control. Percent survival, average age, height, and shade code are all projected for five years post-establishment.

	Crow 6						Ruby								
BA m^2 ha^{-1}*	14.0		18.4		12.2		18.4			25.3			15.4		
Rx**	TO		BO		TB		TO			BO			TB		
species ***	PP	DF	PP	DF	PP	DF	PP	DF	GF	PP	DF	GF	PP	DF	GF
trees ha^{-1}	43	5	29	3	50	6	11	15	7	4	10	5	17	17	8
% survival	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90
avg. age	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
avg. ht. (m)	1.2	0.9	1.2	0.9	1.2	0.9	1.2	0.9	0.6	1.2	0.9	0.6	1.2	0.9	0.6
shade code****	2	1	2	1	2	0	2	0	1	2	0	1	2	0	1

* Post treatment BA used to calculate natural regeneration rates
** Fuel treatment: CTRL = control, TO = thin only, BO = prescribed fire only, TB = thin and prescribed fire
*** PP = ponderosa pine, DF = Douglas fir, GF = grand fir
**** Shade Code- Seedlings occur: 0 - uniformly on plots throughout the stand, 1 - more frequently on plots with more overstory basal area, 2.- more frequently on plots with less overstory basal area.

Slope is a constant that is entered in FVS-FEE by the user initially and can not be changed between simulations. Surface fireline intensity increases as slope steepness increases when all other variables are held constant.

Expected mid-flame wind speed is calculated by multiplying 6.1 m wind speed times a correction factor based on canopy cover (Albini and Baughman 1979). Wind speed can be changed between simulations. Wind speed is entered using the FFE keyword SimFire and or PotFWind. With increasing wind speed, fireline intensity increases.

Canopy cover is calculated in FVS using a method developed by Crookston and Stage (1999) that corrects for crown overlap. This method assumes that tree crowns are randomly distributed within the stand.

Fuel moisture can be specified by the user for all timelag fuels, duff, and live fuels using the keyword Moisture, or choose from one of four default values that range from very dry to wet. Only the moisture level of fuels less than 7.63 cm diameter is used in calculating fireline intensity. Drier fuels are assumed to increase fireline intensity or flame lengths.

Initial fuel loading can be entered by the user; however, actual or estimated fuel loads are not used directly by the Rothermel's fire spread model in FFE. Instead, Anderson's (1982) 13 predefined stylized fire behavior fuel models based on Albini's (1976a) fire behavior models are used to model fire behavior (Reinhardt and Crookston 2003). FVS-FFE uses predefined or stylized fuel models because of the difficulty of tracking and defining necessary fuel characteristics such as surface-to-volume-ratio, depth, moisture of extinction, heat of combustion, dry density, total mineral content, and silica free-mineral content (Reinhardt and Crookston 2003).

FFE selects a fire behavior fuel model that best represents the fuel profile based on fuel loading and forest type. Specifically, combinations of categorical measures, including dominant tree species, canopy cover, quadratic mean diameter, and stand structure are used to select a fuel model for the East Cascades variant (Reinhardt and Crookston 2003). Heavy fuel loading is defined as coarse fuel loads (> 7.63 cm diameter) greater than 34 Mg ha^{-1} *and* when the fine fuels (< 7.63 cm diameter) are greater than 11 Mg ha^{-1}. Stylized fuel models 10-13 are represented by heavier fuel loads (Anderson 1982).

Lighter fuel loads, when lower than loads previously described, are represented by stylized models 1-9 (Anderson 1982). There are 11 logical rule sets for the FFE East Cascade variant (Reinhardt and Crookston 2003). Decision criteria used to select the appropriate rule set and stylized fuel model include cover type, species basal area dominance, canopy cover, quadratic mean diameter, and stand structure. One of 15 cover types is used to select a rule set. If the basal area of a single species is more than half of the total basal area, then that species rule set is used. If the prior criterion is not met, three stand types composed of two dominant species are searched for: Douglas-fir/grand fir, ponderosa pine/Douglas-fir, and lodgepole pine/western larch. The last three stand types possible are subalpine fir, moist habitat mixed conifer, and dry habitat mixed conifer. Stand structure variables include single or multistory canopy layers. The FVS base model provides measures of canopy cover and stand structure (Crookston and Stage 1999). This approach assumes that there is a correlation between species basal area dominance, percent canopy cover, and multistory structure, and characteristics of the fuel array used for modeling fireline intensity. Users are provided with options to override fuel model choices.

The dynamic fire behavior option in FFE was developed to simulate a continuous transition in fire behavior versus ordinal type transition that occurs between fire behavior fuel models. The dynamic option calculates fire behavior in three steps:

1. typically two, but up to four fuel models, are selected based on fuel loading;
2. fire behavior is calculated for each fuel model selected; and
3. a weighted average of values produced in step two is calculated (Reinhardt and Crookston 2003).

This method provides for a smoother transition in fire behavior as fuels change over time or from fuel treatments; however, an assumption is made that there is a linear relationship in fire behavior calculated and between Albini (1976a) fire behavior fuel models.

Crown Fire Behavior

The transition of surface fire to crown fire is predicted using approaches developed by Van Wagner (1977), and Scott and Reinhardt (2001). Crown fire behavior is modeled by using information about surface fuel and stand structure to predict the likelihood of an active or passive crown fire. This information is expressed by FVS-FEE in the form of two hazard indices, torching index and crowning index.

The torching index (TI) is a measure of passive crown fire initiation. A lower torching index or wind speed, defines a greater hazard or chance that passive crown fire will occur. It is defined as the 6.1 m (20 ft) wind speed in which a surface fire is expected to move into and ignite crown fuels given canopy base height, fine surface fuel load and moisture content, foliar moisture content, slope, and wind reduction caused by the canopy.

As slope increases, fuel moisture decreases, or canopy base height lowers, torching index will decrease; that is, it will take a lower wind speed for surface fire to move into and ignite canopy fuels.

Surface fireline intensity and canopy base height are used to determine the occurrence of fire transitioning from surface to crown fuels. If passive crown fire occurs, surface fireline intensity and flame length are recalculated using methods developed by Scott and Reinhardt (2001). Individual or groups of trees burning are termed as "torching" or "candling," which is passive fire behavior. Active crown fire occurs when surface and crown fuels are fully ignited, but fire spread in canopy fuels continue to be dependent on heat released from surface fuels (Scott and Reinhardt 2001).

Crowning index (CI) is a measure of crown fire spread or propagation; it is the windspeed needed for a fire to be sustained in the canopy *after* it has made the transition from surface fuels to crown fuels. The lower the crown fire index or windspeed, the greater chance of crown fire. The crowning index is defined as 6.1 m wind speed at which active crown fire is possible based on canopy bulk density, slope, and surface fuel moisture content. As stand density or slope increases, or fuel moisture decreases, a lower wind speed is required for an active crown fire to occur. Active crowning occurs if conditions support torching and canopy bulk density is great enough given wind speed and fuel moisture conditions.

Crown fires that burn independently of surface fires are not modeled in FVS-FEE; however, the potential of crown fire hysteresis is indicated when TI is high (a high wind speed required for passive crown fire initiation), and the CI is low (low wind speed, greater chance of active crown fire). This condition represents a hypothetical fire behavior scenario—crown fire hysteresis, "the persistence of active crowning after the fire environment has changed such that crown fire could no longer initiate" (Scott and Reinhardt 2001, p 45). For example, if an active crown fire initiated in a stand that had a low TI and a low CI (e.g. high surface fuel loads, low canopy base height, and high canopy bulk density) moved into a stand that had a high torching index and a low crown index (e.g. low surface fuel loads, high canopy base height, and high canopy bulk density), an active crown fire may persist in the absence of surface fire initiation. As individual stands are modeled in FVS-FEE, crown fire hysteresis is not modeled, but is indicated by interpretation of CI and TI in the FVS-FEE potential fire report. Plume dominated fire behavior is not modeled in FVS-FEE.

Fire Effects

FFE calculates potential fire effects: tree mortality, crown scorch, fuel reduction, mineral soil exposure, and smoke production. The latter two variables are not summarized as results in this research, and therefore not reviewed here.

The probability of tree mortality is based on the bark thickness and amount of crown volume scorched (Reinhardt and Crookston 2003). Tree death may occur for thin barked species even in the absence of crown scorch. When crown scorch occurs, but does not kill the tree, FFE-FVS calculates the new reduced live crown ratio and reduces tree growth for one simulated growth cycle. At the time of the second simulated growth cycle, the tree is assumed to have recovered from fire effects and is grown as a healthy tree (Reinhardt and Crookston 2003). If a passive crown fire occurs, additional mortality is calculated based on the amount of crown fraction burned (Scott and Reinhardt 2001). If an active crown fire occurs, there is always 100% mortality (Reinhardt and Crookston 2003).

The model does not take into account secondary effects of fire, such as interactions of insects and disease, nutrient availability, or fine root damage; however, the model decreases growth based on reduction of crown ratio and assumes increased growth in surviving trees from a decrease in tree density after the first FVS growing cycle.

Fuel consumption is modeled using simplified algorithms from Reinhardt et al. (1997). Three attributes determine fuel consumption: moisture content, size, and type. Fireline intensity does not directly affect fuel consumption in FFE.

Fuel Dynamics

Accumulation and decomposition of duff litter, and six classes of dead wood are modeled by FVS-FFE, each representing separate fuel pools. Accumulation, decomposition, and canopy characteristics are modeled on an annual basis. All biomass is reported as oven dry weight. The transfer rate of biomass to each fuel pool is based on the growth, death, and management activity including fire.

Accumulation of fuel includes sources such as tree crown components, tree boles, and shrub and herbaceous plants. Tree crown components and tree boles are modeled separately.

Crown material is predicted using regression equations developed by Brown and Johnston (1976). Live and dead material per tree is proportioned into foliage and four size classes of branchwood: 0-0.635 cm, 0.636-2.54 cm, 2.55-7.63 cm diameter and greater than 7.63 cm diameter. Predictor variables used by Brown and Johnston (1976) include tree species, diameter at breast height, height, crown ratio, and the tree's dominance in the stand. All variables except tree dominance are provided by the user. FVS-FFE determines tree dominance by looking at a tree's height relative to the heights of the other trees in the stand. These estimates of crown material are used to model canopy characteristics such as canopy bulk density and base height.

Canopy bulk density and canopy base height are calculated using a method based on Scott and Reinhardt (2001) and Sando and Wick (1972). Rather than assuming uniform canopy distribution throughout a stand to calculate canopy bulk density, the vertical distribution of fine canopy fuel is characterized; however, the amount of crown for each tree is assumed to be evenly distributed along the length of live crown. Weight of fine crown fuel in the form of foliage and small live branches (only one-half of the 0-0.635 cm diameter branchwood is included) for all trees is summed in 0.3048 m (1 ft) horizontal sections from ground level to the height of the tallest tree. Canopy bulk density is defined as the maximum of the 4 meter running mean (Reinhardt and Crookston 2003). The running mean is calculated for each 0.3048 m section as the average of the 4 m (13 ft) sections around the section that is calculated, e.g. for the mean value at 20 m, the average of sections from 18 m to 22 m are calculated. Canopy base height is defined as the lowest height at which 0.9144 m (3 ft) running mean has at least 0.011 kg m^{-3} (30 lb $acre^{-1}$ ft^{-1}) of available canopy fuel present.

Biomass of live tree boles and hard snags are calculated by using volume calculations from FVS and density values from The Wood Handbook (USDA 1999).

Density values of the two main species found on Ruby and Crow 6 EUs, Douglas-fir and ponderosa pine, are 524 kg m^{-3} and 423 kg m^{-3}, respectively (Reinhardt and Crookston 2003). If the bole of a snag is soft, it is assumed to have 80% of the density of hard snags; however, for this research, all snags were entered as hard.

Shrubs and herbaceous plants are assigned biomass values based on dominant tree species and canopy cover (Reinhardt and Crookston 2003). If canopy cover is greater than 60%, an "established" value is assigned; if less than 10%, an "initiating" value is assigned (Reinhardt and Crookston 2003). Established refers to a stand where the overstory trees are well established. Initiating refers to a stand where there has been a recent disturbance and overstory trees are not well established. Between 60% and 10% canopy cover, understory live fuel loads are linearly interpolated between established and initiating values (Table 7). Initiating loads are typically greater than established in the EC variant, except when ponderosa pine is the dominant overstory species. FEE assumes that total fuel load of the understory is roughly constant after canopy closure (established condition). Fire does not have a direct modeled effect on live surface fuels unless the fire modifies the overstory tree component. Live surface fuels are calculated annually with other fuels; however, changes will only occur if canopy cover or cover type have changed enough by actions such as fire, growth, mortality or harvest. Live herbaceous and shrub surface fuel estimates are not used in selecting fire behavior fuel models or in predicting fire behavior.

Table 7: Live herbaceous and shrub fuel loading values used in the FFE-EC for dominant tree species in this research. Load is linearly interpolated between the "initiating" (I) and "established" (E) values when tree canopy cover is between 10 and 60 percent. Table adapted from Reinhardt and Crookston. (2003). Only values used in this research are presented.

Species		Herbs ($Mg\ ha^{-1}$ dry wt.)	Shrubs ($Mg\ ha^{-1}$ dry wt.)
Douglas-fir	E	0.4484	0.4484
	I	0.8968	4.484
ponderosa pine	E	0.4484	0.5605
	I	0.5605	0.2242

Movement of crown components and bole material to surface pools occurs annually based on tree growth, mortality, live tree and snag damage, fires, and management. Processes that result in accumulation and movement of fuel between pools are modeled, including: snag decay, leaf litterfall, crown lifting, live crown breakage, scorched crowns, and slash creation. Structure of trees is also tracked, including: canopy base height, and canopy bulk density.

Branchwood of crowns is distributed to the surface fuel component by species and size classes described above, as well as an additional size class of 7.63 cm to 15.24 cm diameter, which includes all branchwood greater than 7.63 cm diameter (Reinhardt and Crookston 2003). The bole is modeled as the shape of a cone based on diameter at breast height and the total height. The bole, or cone, is divided into as many as six size classes. The biomass for each sizeclass is calculated using the volume routine in FVS and density values from The Wood Handbook (USDA 1999).

Foliage loss, or annual litterfall, is modeled as the ratio between foliage weight and leaf lifespan. The model assumes that 100% of the current foliage will fall within the given species leaf lifespan. Leaf lifespan estimates are from Keane and Arno (1989). The dominant species for this research, ponderosa pine and Douglas-fir, leaf lifespan is 4 and 5, respectively.

Crown lifting occurs when the lower branches of trees die as the tree grows. Crown lifting is estimated in FEE by calculating the ratio of lower branches that die back each FVS (growth) cycle to the total length of the crown in the previous cycle. That proportion of dead branches is assumed to fall and become surface fuel each FVS cycle. All branch material is assumed to be hard. Weight is calculated and distributed to surface fuels based on size class. This method assumes that crown material is distributed evenly in cylinder form. Timing of debris inputs is thought not to be biased by the previous assumption because crowns tend to be broader across their base and less dense (Reinhardt and Crookston 2003).

Live crown breakage occurs from factors such as wind, snow, and disease, among others. FFE sets a constant 1% per crown per year to account for such breakage. The crown weight is not reduced, as it is assumed that growth will replace all losses (Reinhardt and Crookston 2003).

For trees with scorched crowns, all foliage and 50% of small branch wood (<0.64 cm diameter) is assumed to be consumed if within the flames of a surface or crown fire. The portion not consumed is assumed to be dead. All scorched foliage and branches are assumed killed. Tree parts that are burned or scorched are added to the fuel profile at modeled rates for crowns and snags (Reinhardt and Crookston 2003).

A simple proportional loss model is used to simulate decay over time (Reinhardt and Crookston 2003). Decay is modeled on an annual basis, where the rate of loss is dependent on the size class, where 1.3 percent of the total annual loss for all size class fuels is transferred to the duff pool (Table 8). The remaining portion is modeled as lost CO_2. The decomposition of large fuel classes into smaller fuel classes is not modeled. For the EC variant, decomposition is scaled one third greater or less based on whether the stand is in a mesic or dry habitat type (Reinhardt and Crookston 2003). Both stands that are modeled in this research are classified as a dry habitat type.

Table 8: Annual loss rates based for dry sites modeled by FFE for Crow 6 and Ruby. Table modified from Reinhardt and Crookston (2003).

Diameter size class (cm)	Annual loss rate	Proportion of loss to duff
0 – 0.635 0.636 – 2.54	0.08	0.013
2.55 – 7.63	0.06	
7.63 - 15.2 15.3 - 30.5 > 30.6	0.01	
litter	0.33	
duff	0.0013	

Modeling Fuel Treatments with FVS-FFE

FVS-FFE was used to model fuel treatments: thinning only, prescribed fire only, thinning and prescribed fire, and a no treatment scenario. All fuel treatments were simulated one year post inventory year. Each of the treatments is applied to Crow 6 and Ruby EUs using FVS-FFE. These two units exemplify differences of the fire environment represented in the Wenatchee Mountains dry type forests sampled. For each EU a formatted tree list representing existing conditions was imported into FVS. Snags are represented in the tree list and were all entered as hard. This list included a unique plot and tree number, species, dbh, crown ratio, total height, live or dead status, and tree count number used to calculate tree density at a per acre basis. The tree list for Ruby and Crow 6 EUs represent 31 and 35 vegetation plots respectively (see existing fuels methods section). Broadleaf tree species are not modeled in the East Cascade variant (Reinhardt and Crookston 2003); however, when broadleaf trees are present, they are coded as "other tree" and included in the model.

Using the Suppose interface to FVS-FFE, a series of keywords were used to produce the simulation for each fuel treatment. The keyword FuelInit command was used to set initial surface fuels representing pretreatment conditions (Table 9).

Table 9: Individual initial fuel variables and average loading for Crow 6 and Ruby EUs used to model fuel treatments. Data obtained from measured fuels as described in existing fuels methods section. Values were entered into FVS-FFE by using the keyword FuelInit.

Fuel variable - model parameter	Crow 6	Ruby
	Mg ha^{-1}	
0 – 2.54 cm, 1 + 10 hour	1.65	2.36
2.55 – 7.63cm, 100 hour	4.43	6.56
7.64 – 15.2 cm, 1000+ hour	1.67	1.80
15.3 - 30.5 cm, 1000+ hour	3.44	4.54
> 30.6 cm, 1000+ hour	2.22	12.17
litter – Oi	27.01	28.19
duff – Oe	17.88	12.17
total	58.31	67.79

Thin Only Simulation Treatment

The FFS thinning prescription was created with the objective of creating a stand density that increases stand resilience to pine beetles (Cochran 1992, Cochran et al. 1994, Harrod et al. 1999) and that reduces crown fire hazard (William E Hartl, Silviculturist, written communication). In addition, information from historic stand structure research in proximity to the sites was integrated for the FFS prescription (Anderson 1982).

For this research, a simplified thinning prescription was developed for use in FVS based on actual prescriptions developed for the units; however, understory or non-commercial fuels treatment was not simulated. The mechanical thinning treatment simulated the effect of an intermediate thin, where only commercial material was removed in this scenario. Preferences for selecting low vigor trees over high vigor trees, non-even spacing, and species leave preference for ponderosa pine, were not modeled, but prescribed on the ground. The keyword ThinBBA was used to simulate a thinning from below down to 14.0 m^2 ha^{-1} BA in Crow 6, and 18.7 m^2 ha^{-1} BA at Ruby, a more mesic stand, starting with removal of ponderosa pine at 15.2 cm and Douglas-fir at 20.3 cm or greater in diameter at breast height. These criteria were based on desired tree density and commercial contract requirements for helicopter logging. The cutting efficiency was set at 80%, so that 20% of trees of each size class are left. This method is likely to simulate on the ground objectives of removing a greater number of small diameter trees (15.2-50.8 cm) than larger diameter trees (50.9-76.2 cm) to meet overall BA objectives. Trees below the diameter criteria above were not treated. Only the harvested boles were removed from the site; all foliage, branches, and tops were left on site.

Tops of Douglas-fir and ponderosa pine were defined as a stem diameters less than 10.2 and 15.2 cm diameter respectively when harvested. The western FFE variant assumes that the unmerchantable top is part of the bole (is not included with branchwood fuels) when a harvest is simulated, the unmerchantable top is taken from the site along with the large tree boles. To estimate the amount of unmerchantable fuel material that would be left on site from harvested trees, Compute keyword was used to calculate weight of unmerchantable tops. The calculated weight was then added to the 7.63-15.2 cm branchwood fuel category after the harvest using the FuelMove keyword, making the assumption that the majority of weight is in the 7.63-15.2 cm category. No further mechanical fuel treatments were applied in the model.

Burn Only Simulation Treatment

The primary objective in the burn only treatment was to use surface fire to reduce surface and ladder fuels, and reduce basal area; however, an overriding objective was to maintain a controllable fire, defined as flame lengths near one meter. Therefore, flame length was a constraint that had to be met even if surface fuel reduction and basal area objectives were not met.

Using the keyword FuelModl in FVS-FFE, percentages of Anderson's (1982) stylized fuel models collected on Crow 6 and Ruby were set in the model for simulating prescribed burns (Table 10). These data represent existing conditions.

Table 10: The percentage of Anderson (1982) NFFL fire behavior fuel models used to simulate prescribed fire only treatment using FVS-FFE on EUs Crow 6 and Ruby. FVS-FFE interpolates between fuel models to calculate fire behavior. Percentage of fuel model data was collected while characterizing existing conditions (See Figure 13).

Crow 6		Ruby	
NFFL model	% weight	NFFL model	% weight
2	85	2	35
5	3	5	30
9	7	8	15
10	5	10	20

The SimFire keyword was used to model a prescribed burn for Crow 6 and Ruby EUs at their respective mean percent slope values, 20 and 52, with an ambient air temperature of 15.6 ^{o}C, and 6.1 m windspeeds ranging from 14.5 to 16.1 km hr^{-1}. Using the keyword Moisture, fuel moisture conditions were adjusted to produce a flame-length not greater than one meter or a resulting live basal area not less than as prescribed for the thin prescription (Table 11). Prescribed fire simulations assume that all ground cover in the unit is treated.

Table 11: Environmental parameters used to simulate prescribed burns in FVS-FFE for two different treatments at Ruby and Crow 6 EUs.

Environmental parameters	Crow 6		Ruby	
	Burn Only	Thin & Burn	Burn Only	Thin & Burn
slope (percent)	20	20	52	52
ambient temperature (^{o}C)	15.6	15.6	15.6	15.6
6.1 m ht. wind speed (km hr^{-1})	16.1	14.5	16.1	16.1
1- hour fuel moisture (% water)	10	11	19	20
10- hour fuel moisture (% water)	10	10	21	18
100- hour fuel moisture (% water)	12	12	24	23
1000+ hour fuel moisture (% water)	20	20	50	50
duff moisture (% water)	90	90	100	100
live fuel moisture (% water)	130	130	130	120

Thin and Burn and Control Simulation Treatment

Thinning and prescribed fire were applied as the Thin and Burn treatment using the same methods as for the individual treatments (Table 11). A control simulation was simulated where vegetation and fuel succession were simulated with no treatment.

Modeling Effects on Potential Wildland Fire Behavior and Severity

FVS-FFE Model Runs, Timing, Keywords and Reports

In eight separate FVS-FFE model runs keyfiles were developed for FVS-FFE to simulate wildland fire occurring at 80 percentile weather conditions at two years post fuel treatments for each of the four fuel treatments in the EUs Crow 6 and Ruby.

Wildland fire is simulated two years post fuel treatments using the keyword SimFire in FVS-FFE. When a fire is simulated in FVS-FFE, burn conditions including flame length, scorch height, tree mortality, and fuel consumption data are reported by using the keywords: BurnRept, MortRept, and FuelRept. For each of the model runs, these keywords were included, and the results were compiled to make comparisons between the simulated effect of four treatments on simulated wildland fire behavior and effects. The use of the keyword SimFire results in direct changes to tree and fuel data, thus influencing how the stand will progress into the future. SimFire calculates and reports fire behavior, effects, and fuel characteristics for only the year the fire occurs, whereas the PotFire keyword produces potential fire behavior data annually, but does not influence calculations in the following year.

To run the potential fire data, the simulated wildland fire keyword was removed from the keyfile, and each of the eight data files were processed again. This way the effect of treatments on wildland fire can be analyzed over a long period, 19 years, using the potential fire report. The keyword PotFire was used to produce an annual report of potential: flame length, fire type, index of passive (torching) and crown fire hazard, and percentage of basal area mortality. Each of these variables is reported under the affects of two sets of environmental conditions, severe and moderate. The defaults for severe and moderate conditions were changed to represent 90 plus and 80 percentile weather conditions using the keywords: PotFMoisture, PotFTemp, and PotFWind (Table 12); thus, providing a summary of 90 plus and 80 percentile effects on most of the fire variables listed above annually as the stand progresses.

Wildland Fire Percentile Weather

Environmental conditions for 80 and 90 percentile plus fire weather conditions were calculated using Fire Family Plus software data from Dry Creek and Swauk weather stations. For the months May through October, historic average daily 90 and 80 percentile values were calculated for maximum temperature and average wind speed; and 10 and 20 percentile values for timelag fuels, duff, and live herbaceous moisture (Table 12). Severity of fire weather conditions for modeling fire behavior were increased by using 97 percentile wind values, and 90 percentile moisture conditions—"90 percentile plus fire weather conditions". These data were used to model the environmental conditions for calculations in the potential fire report and for the simulation of wildland fire.

Table 12: Daily average environmental site and fuel moisture variables representing 80th and 90th percentile plus fire weather conditions (wind represents 97 percentile). Values were derived from Swauk and Dry Creek RAWS weather station data using Fire Family Plus software. Average values between the two stations were used for simulated and potential wildland fire calculations in FVS-FFE.

	80 Percentile			**90 Percentile**		
Daily average	Dry Creek	Swauk	**Avg**	Dry Creek	Swauk	**Avg**
max. temperature (^{o}C)	26.1	26.1	**26.1**	28.9	28.9	**28.9**
avg. 6.1 m ht. wind speed* (km hr^{-1})	19.3	11.3	**15.3**	29.0	16.0	**22.5***
1 - hour fuel moisture** (% water)	4.1	3.8	**4.0**	3.3	3.1	**3.2**
10 - hour fuel moisture** (% water)	5.0	5.0	**5.0**	4.2	4.0	**4.1**
100 - hour fuel moisture** (% water)	7.8	8.2	**8.0**	6.8	7.1	**6.9**
1000+ - hour fuel moisture** (% water)	9.6	10.5	**10.1**	8.7	9.5	**9.1**
duff moisture** (% water)	33.8	32.9	**33.4**	17.2	16.1	**16.7**
herb/live fuel moisture** (% water)	31.9	45.9	**38.9**	30.0	32.1	**31.1**

*represents 97 percentile conditions, ** Values are 20 and 10 percentile conditions that represent dry fire weather conditions.
Dry Creek 1987-2000; 4526 daily records, Swauk 1972-2000; 4804 daily records.

Wildland Fire - Fire Behavior Fuel Models

While fire behavior fuel models observed on Crow 6 and Ruby (existing conditions) were used to model fire behavior and effects for the simulated prescribed burns, default FVS-FFE fuel models are used to simulate wildland fires.

RESULTS

Existing Fuel Conditions

Topographic Gradient

Elevation, aspect, slope, and disturbance history among other factors interact to influence composition and physiognomy of vegetation, and therefore, fuels.

Average elevation between EUs ranges from 702 m at Sand 2, to 1135 m at Little Camas; however, all but two of the EUs, Spromberg and Little Camas, have an average elevation of less than 921 m (Table 13). Aspect and slope vary considerably (Figure 4, Table 13, Appendix D).

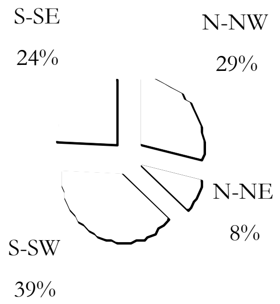


Figure 4: Percent of cardinal directions representing aspect sampled at grid points at 12 experimental units.

Site Disturbance History

Various agents of disturbance are evident in each of the EUs. While currently EUs are not within any grazing allotments, historically, they all were (Holstine 1992); however, it is unlikely that the level of grazing was uniform across the EUs. Fire history data are not available at the stand level; however, obvious evidence of fire was observed in the form of fire scars and blackened boles to various degrees in each of the EUs.

Fire suppression has been documented at Slawson in 1975, Sand 19 in 1993, and at Crow 1 and Crow 3 in 1999. Dates were obtained from a lightning strike map and verified at the Leavenworth Ranger District (Hatten, personal communication). In addition, fires in the neighboring landscape have been suppressed, and likely would have burned in many of the EUs but have not been substantiated. Selective logging of large overstory trees occurred pre-1930s on most of the EUs, with commercial operations on three of the EUs in the 1970s (Table 14). Stands currently dominated by ponderosa pine had a pre-

Table 13: Summary of vegetation and site characteristics of experimental units (EU) sampled for existing fuel conditions. The numbers across each row represent the stratification of six vegetation plots by Harrod into pla nt associations. Slope and aspect for each EU were sampled systematically at 80 m intervals. On the landscape, the 12 EUs form three groups in closest spatial proximity to each other (represented by 3 font groups) that are distributed from east, to northeast, to west.

					Hot Dry	Warm Dry	Warm Mesic		Cool Dry			Cool Mesic		
Percent Plant Association Group (PAG) represented by EUs →					**6%**	**17%**	**12%**		**28%**			**37%**		
experimental unit	general east to west gradient	percent southern aspect	mean slope (percent)	mean elevation (meters)	* Ponderosa pine /pinegrass-bluebunch wheatgrass	Douglas-fir/shiny-leaf spirea	Douglas-fir/Mt. Snowberry	Douglas-fir/common nowberry	Douglas-fir/common snowberry/pinegrass	Grand fir/common snowberry/pinegrass	Douglas-fir/elk sedge	Douglas-fir/pinegrass	Douglas-fir/shiny-leaf spirea/pinegrass	Grand fir/Cascade Oregon grape
Percent of each plant association represented by EUs→					**6%**	**17%**	**1%**	**11%**	**10%**	**1%**	**17%**	**25%**	**8%**	**4%**
Crow 6	East	86 %	25	732								**6**		
Crow 1		88 %	26	756	**4**			**1**				**1**		
Crow 3		57 %	42	781				**1**	**2**			**3**		
Pendleton		89 %	22	848					**2**		**1**	**3**		
Sand 2		20 %	63	702		**1**					**2**	**1**	**2**	
Poison		70 %	50	750			**1**	**2**	**1**		**2**			
Tripp		0 %	66	793		**4**					**2**			
Sand 19		71 %	53	836					**2**		**2**	**2**		
Slawson		10 %	41	895		**3**					**2**		**1**	
Ruby		74 %	52	921		**2**		**1**		**1**		**1**	**1**	
Spromberg		100 %	61	1110				**3**				**1**	**2**	
Little Camas	West	77 %	42	1135		**2**					**1**			**3**

*See Appendix C for plant association scientific names and ecoclass codes.

commercial thin in the 1970s. Douglas-fir mistletoe is prominent in Little Camas, Ruby, and Tripp, whereas mortality of ponderosa pine from pine beetles is evident in Crow 1, Crow 3, Crow 6, and Pendleton EUs.

Table 14: Summary of logging and vegetation management at each of the EUs. Information obtained from unpublished report by Dick Schellhaas and Don Spurbeck of the USDA Forest Service Wenatchee Research Lab and personal observations.

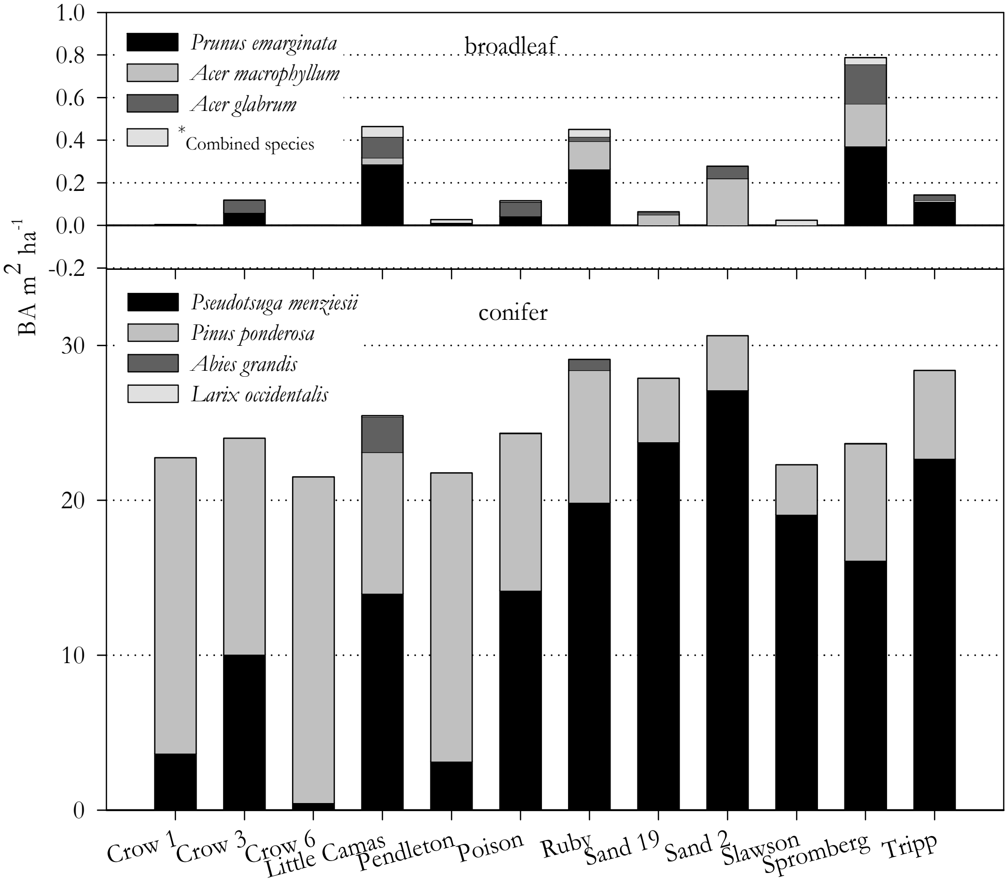
EU	Selective overstory removal Pre-1930s	Commercial logging ~ 1970s	Pre-commercial thin ~ 1970s
Crow 1	X	-	X
Crow 3	X	-	X
Crow 6	X	-	X
Little Camas	X	X	-
Pendleton	X	-	X
Poison	X	-	-
Ruby	X	X	-
Sand 19	-	-	-
Sand 2	-	-	-
Slawson	Restricted to ridge	-	-
Spromberg	X	X	-
Tripp	-	-	-

Plant Associations

Twelve experimental units are dominated by 10 plant associations and five plant association groups (Richy Harrod, personal communication, Lillybridge et al. 1995). Douglas-fir or ponderosa pine was dominant or codominant at all EUs. While no one plant association dominates, the Douglas-fir/pinegrass association (CDG131) represents 25% of the samples, and Douglas-fir/elk sedge (CDG132) and Douglas-fir/shiny-leaf spirea (CDS640) each represent 17% of the sample. Sample plant association groups represent a gradient from hot-dry to cool mesic. Moist to wet plant association groups found in the study landscape are deliberately not represented. Cool-mesic and cool-dry plant association groups are best represented with 66% of the sample, with the smallest proportion in the hot-dry plant association group (Table 13). EUs represent a broad spectrum of dry type forest vegetation and site characteristics that are found in various combinations, which along with unique disturbance history, has likely given rise to existing vegetation and fuel conditions.

Canopy Fuel Profile

Tree species, density, and size-class distribution can be important indicators of potential fire behavior and effects. Density, size-class distribution, and basal area of live tree species provide a summary of composition and relative dominance in each EU. All density values (trees ha^{-1}) reported include only those trees that are at least 1.4 m in height. Average density of conifers ranges from 287 ± 176 trees ha^{-1} at Crow 6, to 1065 ± 986 trees ha^{-1} at Slawson (Figures 6 and 7, Appendix B). Trees are not evenly distributed within EUs, as variability in density is high both between and within EUs. Conifer basal area is less variable, with a range between 22 ± 11 m^2 ha^{-1} at Crow 6 and 31 ± 20 m^2 ha^{-1} at Sand 2 (Figure 5, Appendix B).



*Combined species include: *Prunus virginiana*, *Salix scouleriana*, *Robinia pseudoacacia*

Figure 5: Basal area (m^2 ha^{-1}) of live conifer and broadleaf trees. Note scale between broadleaf and conifer basal area is not equal and that Larix occidentalis *only is present in Little Camas, and with such minimal basal area that it is not indicated on graph.*

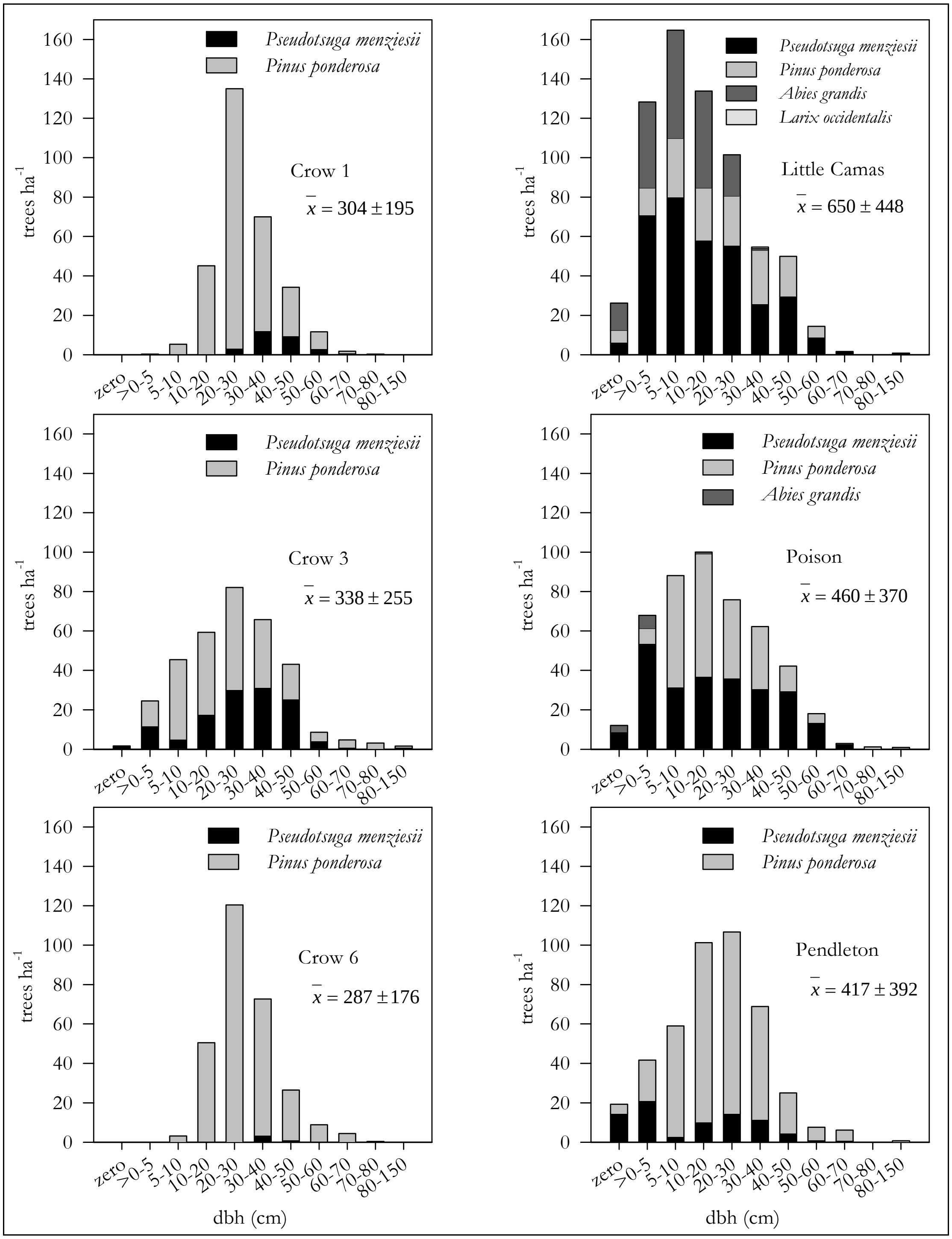


Figure 6: Distribution of conifer density and species by size class for six of the 12 EUs. Average conifer density (trees ha^{-1}*) reported for trees with a dbh greater than zero with one standard deviation reported. Zero size class represents trees 1 m to less than 1.4 m in height. See Appendix C for common names to tree species. Note* Larix occidentalis *is present on Little Camas but at less than one tree ha*$^{-1}$ *in the 30-40cm size class.*

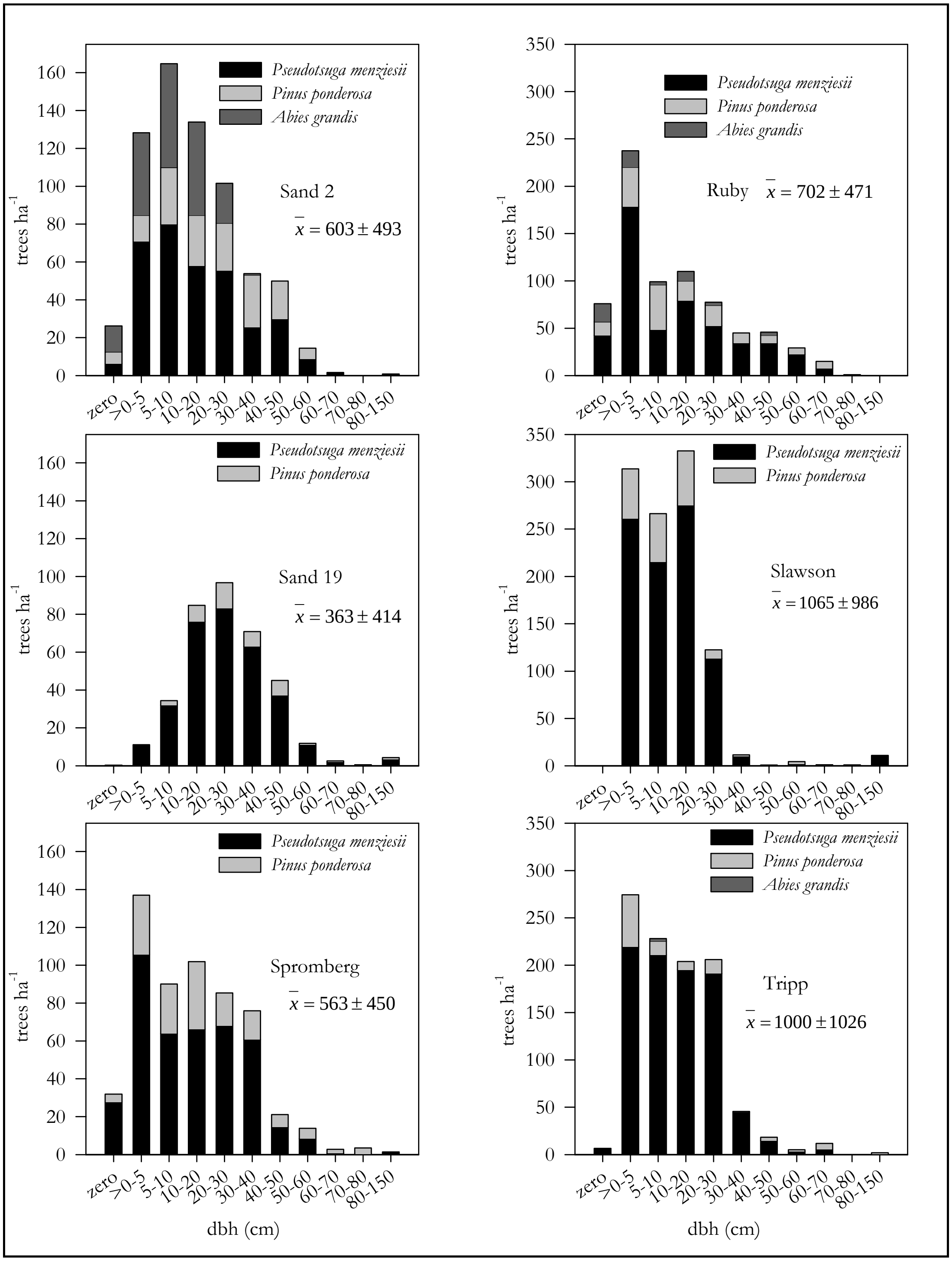


Figure 7: Distribution of conifer density and species by size class for six of the 12 EUs. Average conifer density (ha^{-1}) reported for trees with a dbh greater than zero with one standard deviation reported. Zero size class represents trees 1 m to less than 1.4 m in height. Note that the graphs to the right, Ruby, Slawson, and Tripp, the scale of the y-axis is over twice that of the graphs to the left. See Appendix C for common names to tree species.

The average total height of conifers per EU ranges from 8 ± 5. 1 m to 19 ± 9 m, with the lowest average height at Slawson, approximately 4 m lower than the next lowest average height at Tripp. Variability of total height between EUs is low. The same trend follows for both conifer height to live crown and height to dead crown (Figure 8). The average height of broadleaf species per EU is much lower, ranging between 2.2 ± 0.9 m at Pendleton, to 5.3 ± 2.0 m at Ruby. Variability in maximum height between EUs is much greater for broadleaf species than for conifers (Figure 8).

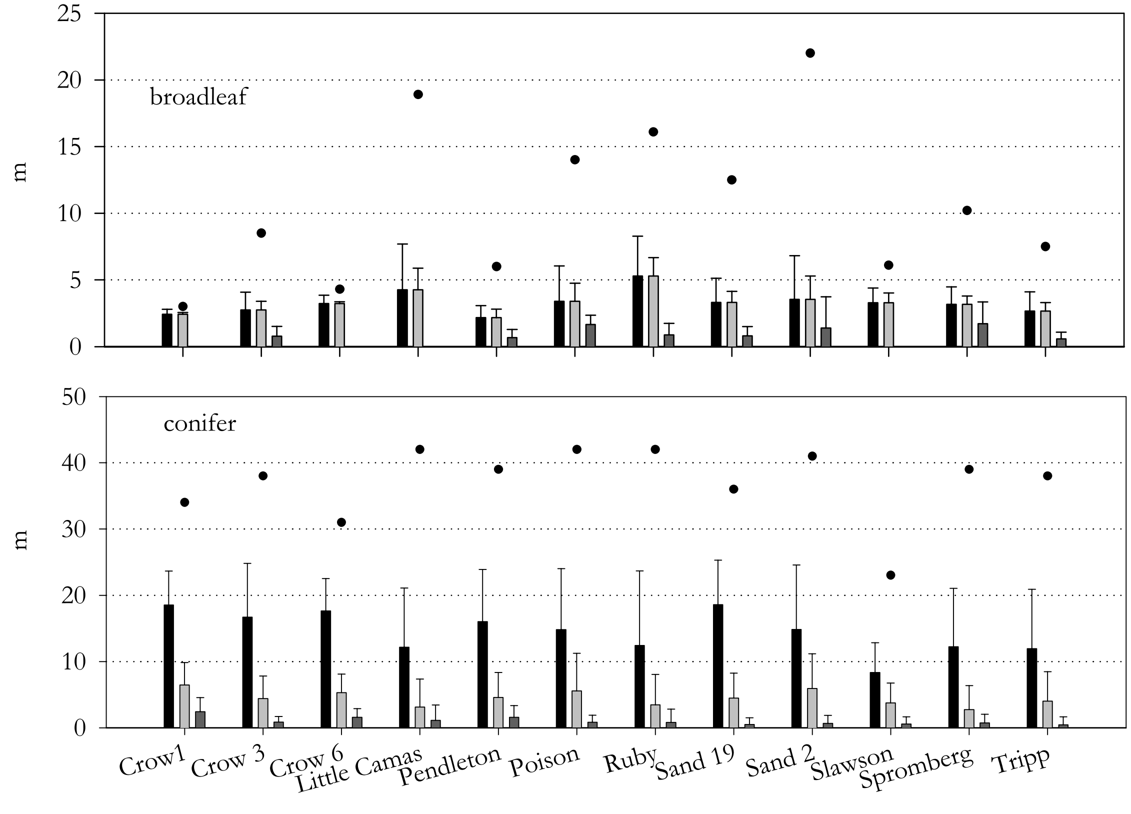


Figure 8: Mean live conifer and broadleaf tree height, height to live crown (Cruz et al. 2003), and height to dead crown for trees greater than 1.4 m tall in each EU. Whisker represents one standard deviation. Note that maximum of broadleaf y-axis is half of conifer y-axis.

Canopy closure sampled within EUs ranged from 100 percent, no open sky, to near zero percent, nearly all open sky. In spite of negatively skewed distributions caused by outlying samples that were very open, average EU values were in the upper range, ranging from 55 ± 22 percent canopy closure at Crow 6, to 80 ± 14 percent canopy closure at Slawson (Figure 9, Appendix B). There is at least one inequality between EU median canopy closure. Variation among canopy closure medians is significantly greater than expected by chance (Kruskal-Wallis test statistic = 41.916, d. f. =11, P <0.0001). Dunn's multiple comparison test indicates significant differences at $\alpha < 0.05$ level between Crow 6 and Ruby, Sand 2, Slawson, and Spromberg, as well as Crow 1 and Spromberg (Appendix E).

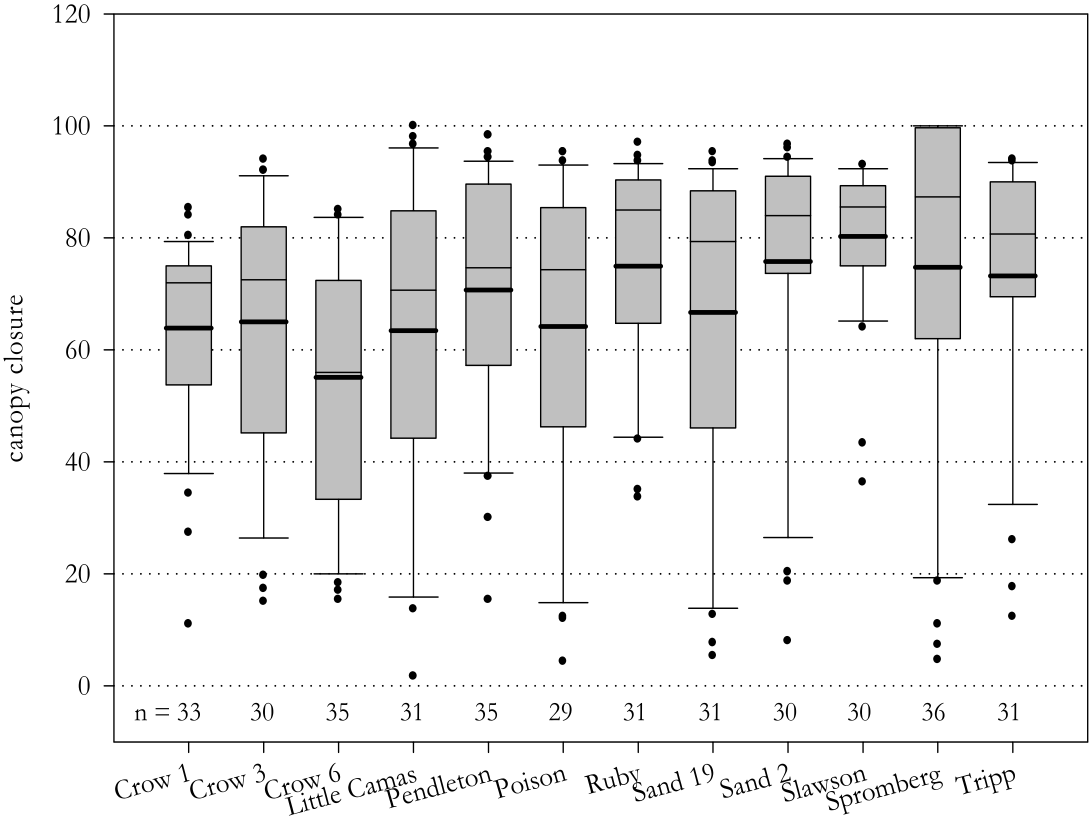


Figure 9: Distribution of canopy closure values sampled at EUs. The box is bound at the 25th percentile at the lower end, and at the 75th percentile at the upper end. The thin line within the box marks the median and the bold the mean. Whiskers below and above the box indicate the 10^{th} and 90^{th} percentiles with outlying values below and above.

FVS-FFE canopy base heights ranged from 1.2 m to 4.6 m, whereas mean stand canopy base height was consistently higher, ranging from 2.7 ± 3.6 m to 6.5 ± 3.4 m at Sand 2, but certainly in the range if standard deviation is considered (Figure 10, Appendix

B). Five EUs had FVS-FFE canopy base heights of less than 1.6 m, five more EUs between 2.4 m and 3.0 m, and the remaining two EUs between 4.3 m and 4.6 m (Table 15). Comparing EU mean stand canopy base height indicates variation among canopy closure medians is significantly greater than expected by chance (Kruskal-Wallis test statistic = 72.144, d. f. =11, P <0.0001). Dunn's multiple comparison test indicates the location of significant differences at $\alpha < 0.05$ level between 12 EU groups, many of which include Crow 1 (Appendix E). Canopy bulk density values range from 0.043 kg m^{-3} at Crow 1, to 0.116 kg m^{-3} at Slawson (Table 15, Appendix B). Mean variation between EUs is low, 0.062 ± 0.02 kg m^{-3}.

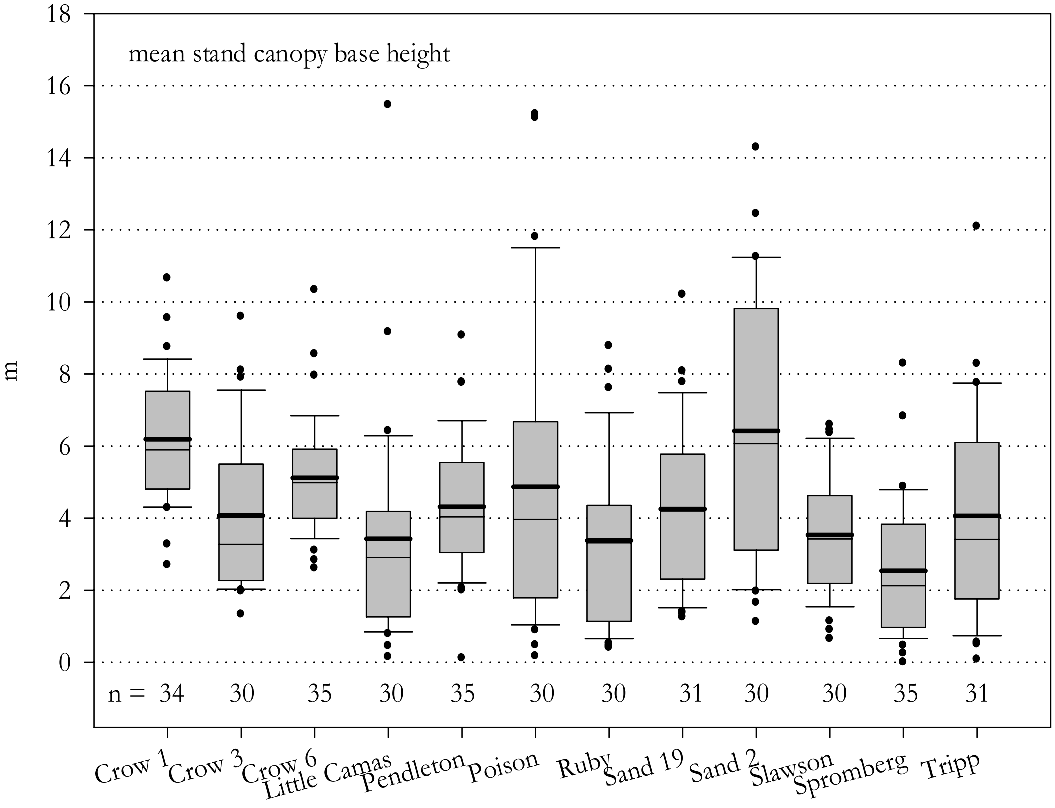


Figure 10: Distribution of mean stand canopy base height per EU (Cruz et al. 2003). Crown base height of individual trees were measured at n fixed area plots per EU, and a mean canopy base height was calculated. The box is bound at the 25th percentile at the lower end, and at the 75th percentile at the upper end. The thin line within the box marks the median and the bold the mean. Whiskers below and above the box indicate the 10th and 90th percentiles with outlying values below and above.

Table 15: Canopy base height and canopy bulk density values calculated using FVS-FFE.

EU	Mean Canopy Base Height* measured (m)	FVS-FFE Canopy Base** Height (m)	FVS-FFE Canopy Bulk Density (kg m^{-3})
Crow 1	6.5 ± 3.4	4.6	0.043
Crow 3	4.4 ± 3.4	2.7	0.056
Crow 6	5.3 ± 2.8	4.3	0.044
Little Camas	3.1 ± 4.2	1.2	0.056
Pendleton	4.6 ± 3.8	3.0	0.052
Poison	5.6 ± 5.7	2.4	0.052
Ruby	3.5± 4.6	1.5	0.051
Sand 19	4.5± 3.8	3.0	0.062
Sand 2	5.9 ± 5.3	2.4	0.072
Slawson	3.8± 3.0	1.2	0.116
Spromberg	2.7 ± 3.6	1.2	0.060
Tripp	4.0 ± 4.4	1.5	0.082

[*] One standard deviation

[**] The lowest height at which 0.9144 m running mean has at least 0.011 kg m^{-3} of available canopy fuels is present. Standard deviation not calculated by FVS-FFE.

Surface Fuel Profile

Sampled one, 10 and 100 hour timelag fuels in all the EUs show positively skewed distributions with a high number of zero values and 5 or more outliers common beyond the 90th percentile (Figure 11). The spread of sample means between the 12 EUs for fuel loads one, 10, and 100 hour fuels are: 0. 28 – 1.88, 0. 81 – 2.6 and 2.1 – 6.9 Mg ha^{-1}, respectively. Variability of timelag fuels within units is high. Standard deviations are greater than the mean, except for one hour fuels at Slawson and Spromberg, and it is not uncommon for the standard deviation to be twice the mean. Comparison of EUs sampled one, 10 and 100 hour timelag fuels indicates variation among each of the timelag fuel medians is significantly greater than expected by chance (Table 16). Dunn's multiple pairwise comparison test indicates the location of significant differences at $\alpha < 0.05$ level between 12 EUs (Appendix E). Two to four times the number of significant differences was located between one hour and other dead wood timelag fuel groups (Table 16).

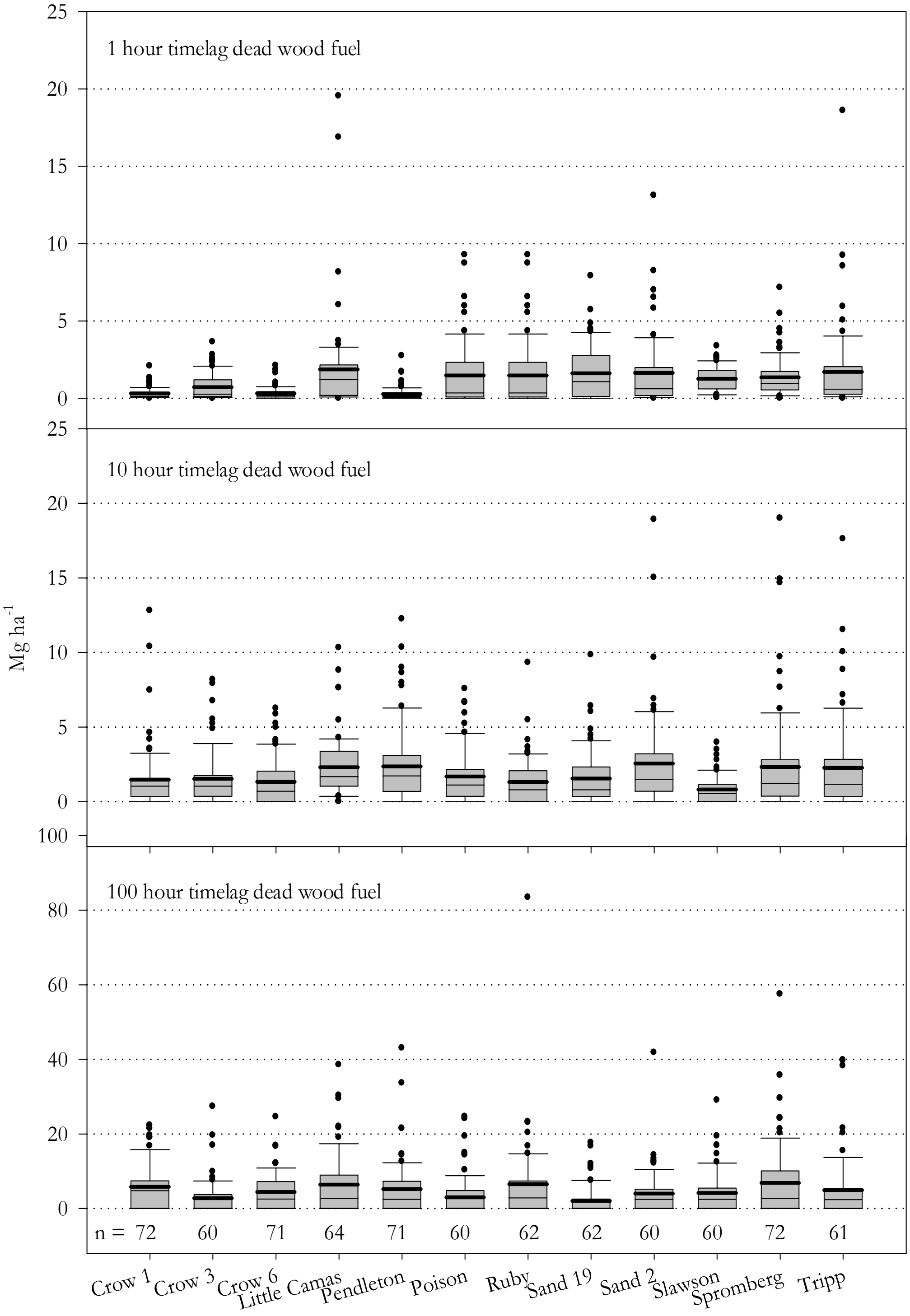


Figure 11: Distribution of 1, 10, and 100 hour dead wood timelag fuel loads across EUs. Note 100hr y- axis scale is four times 1hr and 10hr axis scale. See Figure 10 for a description of box plot parameters.

Table 16: Summary of timelag fuels with significant ($\alpha < 0.0001$, df = 11) median differences between EUs and the number of significant ($\alpha < 0.05$) post-hoc comparisons.

timelag fuel	# significant post-hoc comparisons *
1 hour	25
10 hour	6
100 hour	10
1000+ hour sound	12
1000+ hour rotten	12

* Dunn's post-hoc statistic, see Appendix E, for specific location of group significance

The same trends occur in coarse dead wood fuels, except with greater magnitude. On average, 56 percent of transects sampled had no sound or rotten thousand hour plus fuels. Maximum values of coarse dead wood fuels sampled in each of the EUs ranged from 69.1 Mg ha^{-1} at Sand 2 to 243.8 Mg ha^{-1} at Ruby, with an average maximum across all EUs of 149.5 Mg ha^{-1}(Figure 12). Average sound and rotten 1000+ hour timelag fuel loads ranged from 6.1 ± 19.5 Mg ha^{-1} at Sand 19 to 33.5 ±49.2 Mg ha^{-1} Ruby, with one standard deviation typically nearly twice the mean, but as great as three times the mean. Kruskal Wallis test indicated that significant differences in median sound and rotten fuel load exist (Table 16). Dunn's post hoc test located significant differences at $\alpha < 0.05$ level for 12 EU group comparisons in each the rotten and sound dead wood variables (Appendix E).

Again, trends similar to timelag fuels are found in down dead woody fuel depth; distributions that are positively skewed, extreme outliers are common and standard deviations are large (Figure 13). Mean values range from 6.3 ± 6.5 cm at Slawson, to 18.1 ± 28.1 cm at Tripp. Comparing EU down dead wood depth indicates variation among down dead wood depth medians is significantly greater than expected by chance. (Kruskal-Wallis test statistic = 63. 119, d. f. =11, P <0. 0001). Dunn's multiple comparison test indicates the location of significant differences between 9 EU group comparisons, many of which include Tripp (Appendix E).

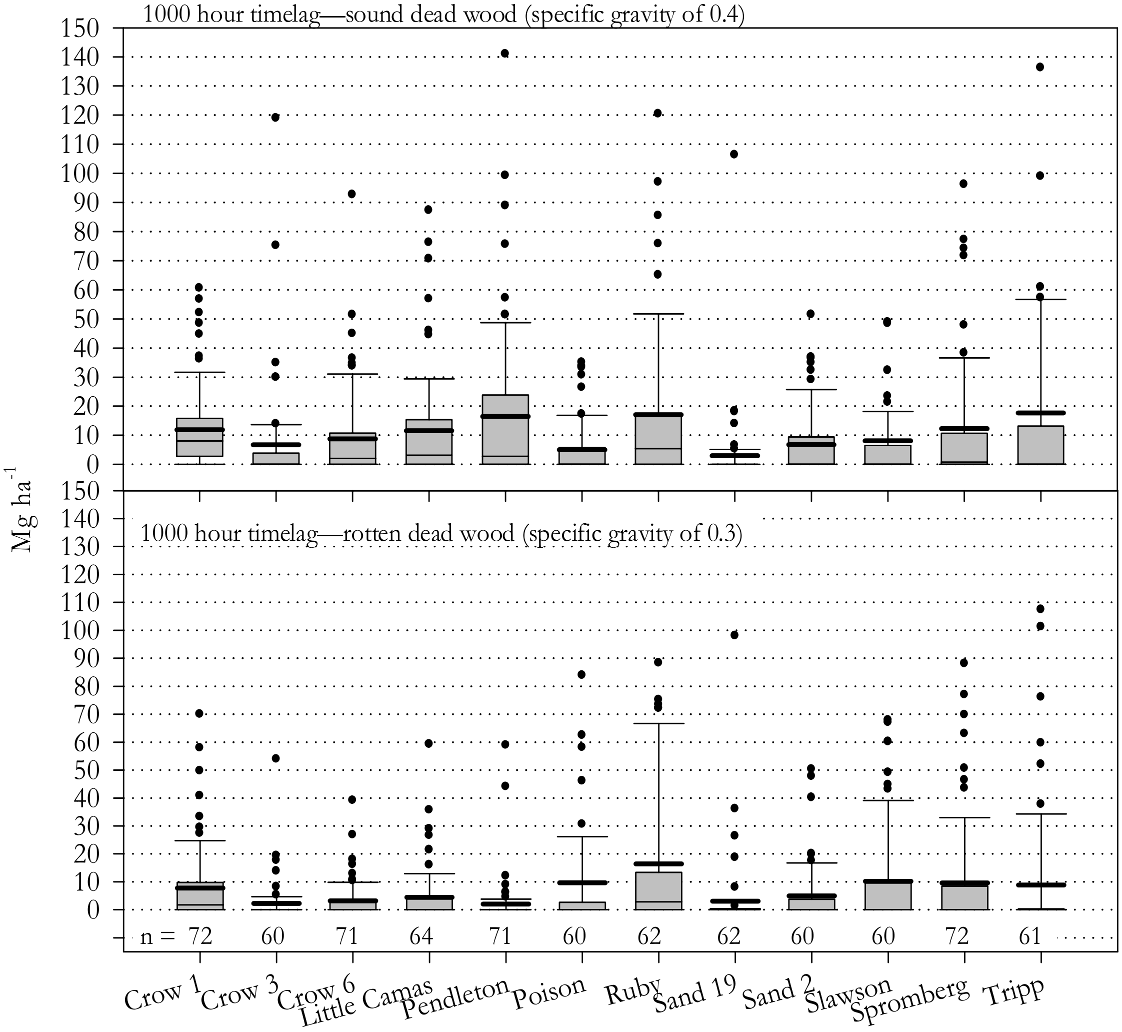


Figure 12: Coarse dead wood fuel loads. Distribution of sound and rotten 1000+ hour timelag fuel loads across EUs. See Figure 10 for a description of box plot parameters.

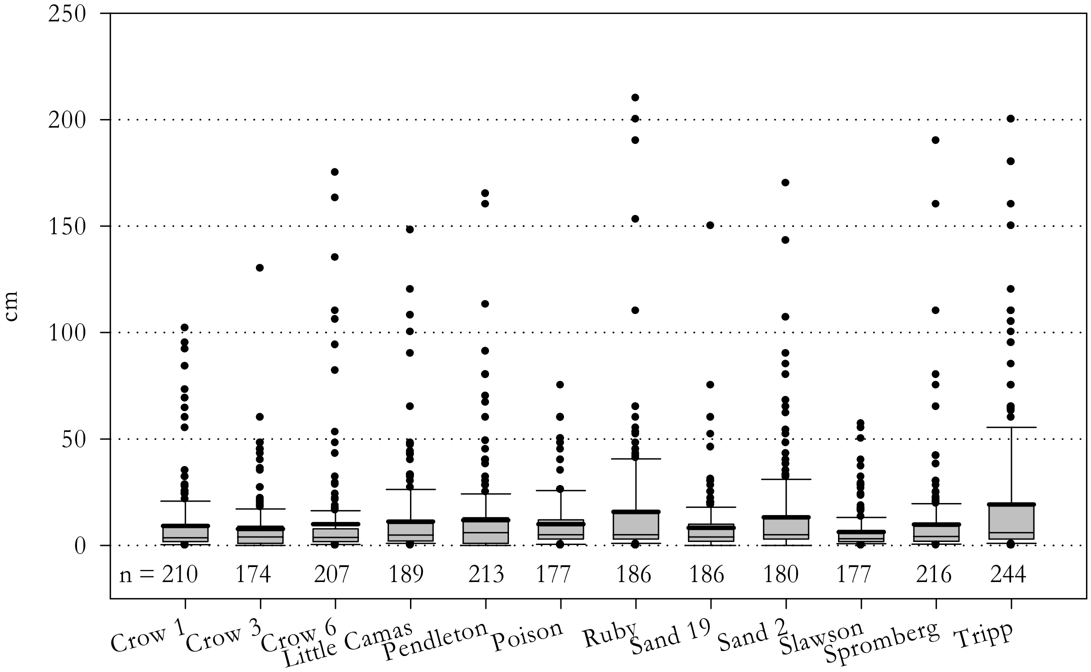


Figure 13: Down dead wood depth. The box is bound at the 25th percentile at the lower end, and at the 75th percentile at the upper end. The thin line within the box marks the median and the bold the mean. Whiskers below and above the box indicate the 10th and 90th percentiles with outlying values below and above.

Forest Floor - Depth-Mass Models and Fuel Loading

Simple linear regression was used to develop models where depth of duff or litter is defined as the predictive variable, and mass, the dependent variable. Three separate general models were developed: litter only, duff only, and combined litter and duff, i.e. forest floor. Additional litter models were produced representing overstory dominated by ponderosa pine or Douglas-fir. Q-Q plots indicate slight residual spread. The proportion of variance explained by the equations ranged from 0.75 to 0.87. Models specific to dominant overstory species explained the largest proportion of variance (Figure 14). All models show a positive relationship between depth of duff or litter and mass. The general duff model predicts greater mass per unit depth than litter. Of the 108 samples collected, 87 contained no duff. Nine duff samples were collected at Ruby, and six each at Poison and Pendleton. Average litter depth was equal to eight times the depth of average duff sample values, and litter deviations from the mean were greater than duff

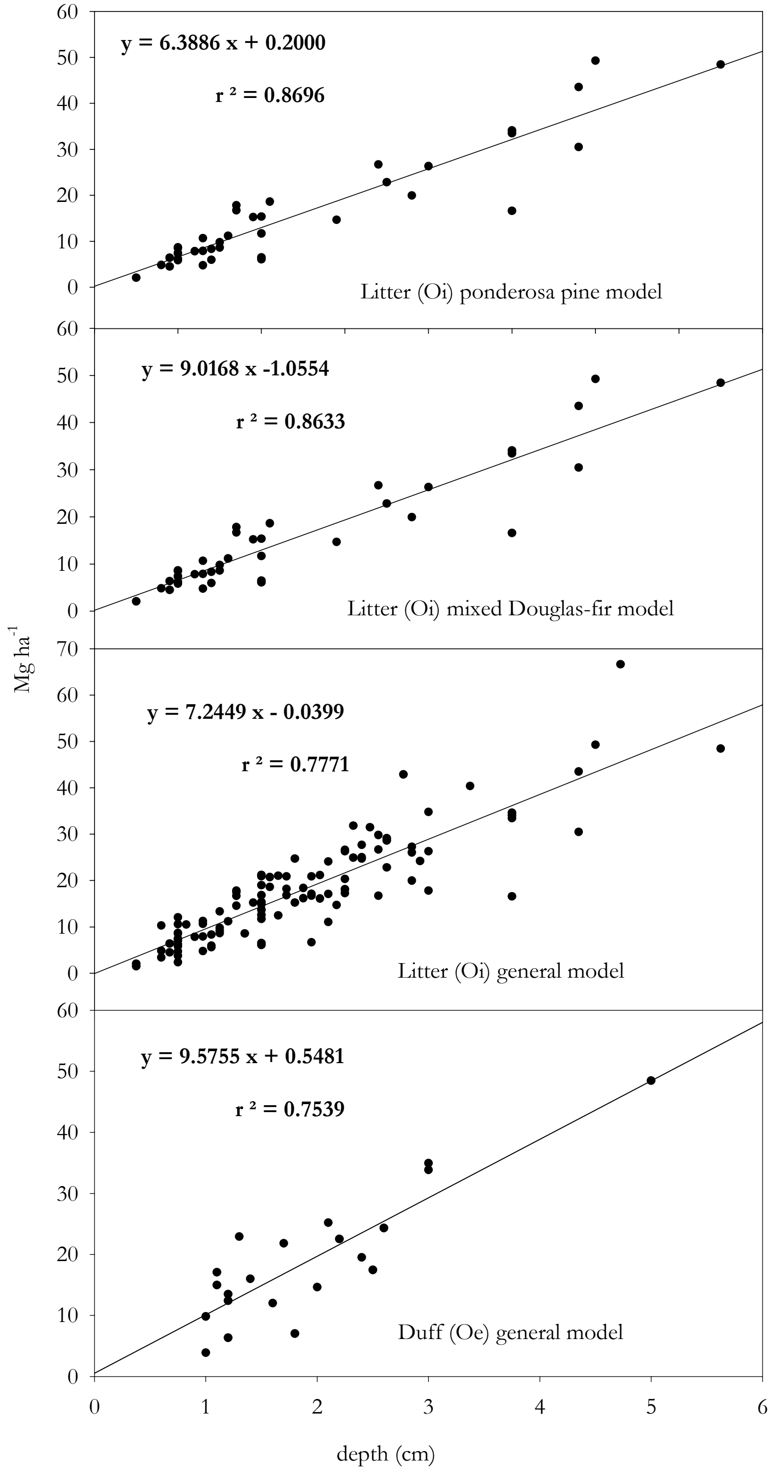


Figure 14: Litter (Oi) and Duff (Oe) depth to mass simple linear regression models. Two general models were developed from samples collected at Ruby, Poison, and Pendleton. A ponderosa pine model was developed from the Pendleton unit and a mixed Douglas-fir model was developed from Ruby EU samples where ponderosa and grand fir are codominants.

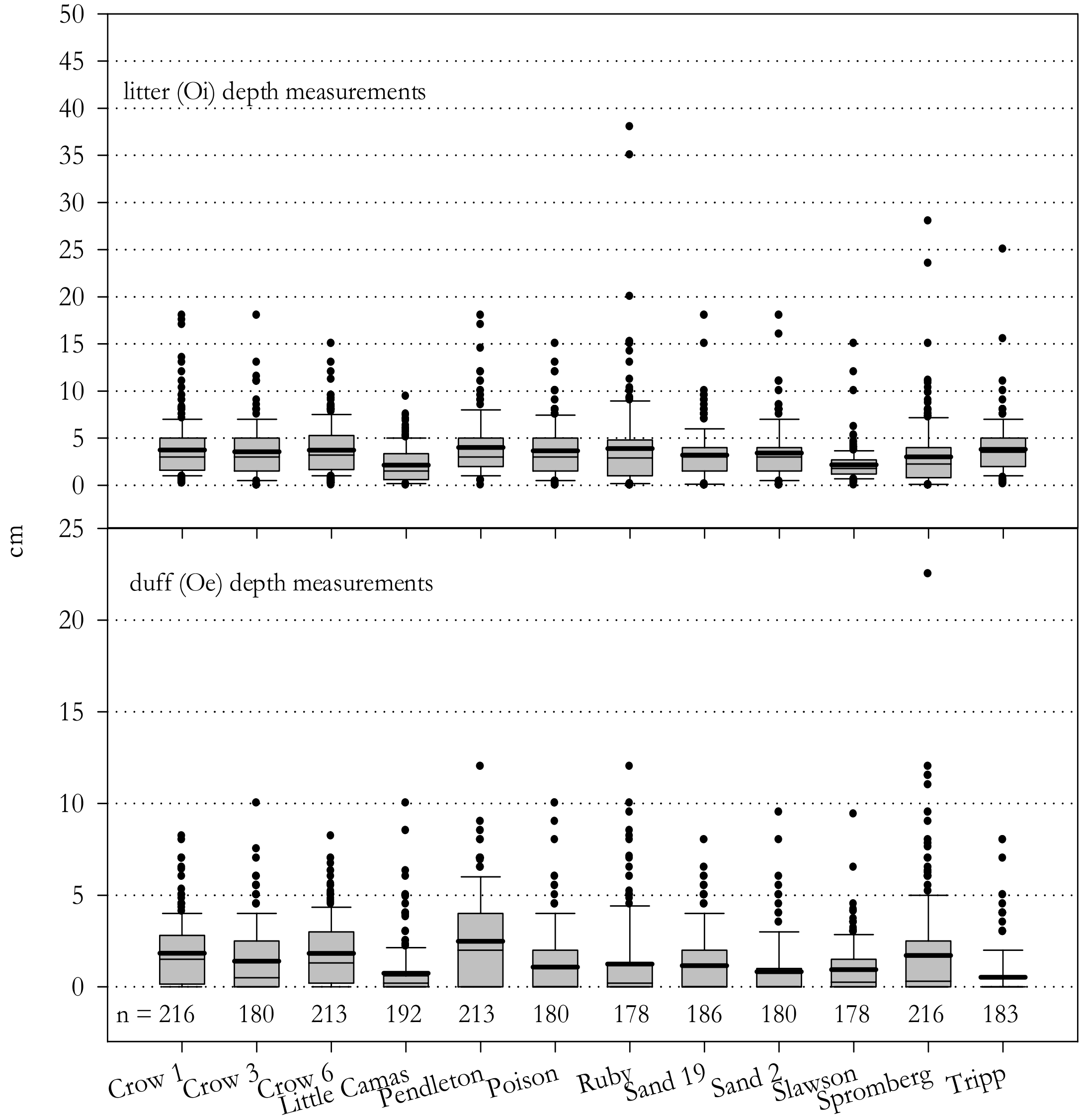


Figure 15: Distribution of sampled litter and duff depths for each EU. n represents the number of litter and duff depth samples measured at each EU; up to three depth measurements per transect, and two transects per grid point. Note the scale of the litter depth y-axis is twice as small as the duff y-axis. See Figure 10 for a description of box plot parameters.

depths (Figure 15). Across all EUs a high number of samples had no duff, ranging from 22% at Crow 1, to 85% at Tripp, with duff absent on average 48% of the time. Litter was rarely absent, with the greatest number of zero depth values measured at Sand 19, at 10%, and an average of 3% across all EUs. Average duff depth ranged from 0.52 ± 1.4 cm at

Tripp, to 2.5 ± 2.4 cm at Pendleton, with a between EU mean of 1.3 ± 0.54 cm; whereas, litter average depth ranged from 2.2 ± 1.9 cm at Little Camas, to 4.0 ± 3.0 cm at Pendleton.

Using the litter and duff depth measurements obtained from each fuel transect sampled, the general litter and duff regression models were used to calculate estimates of litter and duff fuel loading for each EU (Figures 14 and 15). Little Camas and Slawson had the lowest average litter fuel loading, 15.6 ± 10.7 Mg ha^{-1} and 15.7 ± 8.3 Mg ha^{-1}, respectively, 6.4 Mg ha^{-1} less than the next highest, Spromberg 22.0 ± 18.6 Mg ha^{-1}. The mode was 27.0 Mg ha^{-1}, and the highest average litter fuel load occurred at Pendleton, 29.1 ± 15.1 Mg ha^{-1}. Extreme outlying litter fuel loads were common, with ten or more outliers beyond the 90 percentile common. Comparing EU litter fuel loading indicates variation among litter fuel loading medians is significantly greater than expected by chance (Kruskal-Wallis test statistic = 136. 88, d. f. =11, P < 0. 0001). Dunn's multiple comparison test indicates the location of significant differences ($\alpha < 0.05$) between 23 EU groups, 18 of which include Little Camas and Slawson EUs (Appendix E).

Duff fuel loads are 2.1 to 5.5 less than litter fuel loads in each of the EUs. Duff fuel loads range from very low at Tripp, 5.0 ± 8.6 Mg ha^{-1}, to 24.2 ± 16.7 Mg ha^{-1} at Pendleton. As with litter fuel loads, duff fuel load variation is high and there are many extreme outliers; however, there is a higher number of zero duff fuel load values (Figure 16). Significant differences in median duff fuel load exist (Kruskal-Wallis test statistic = 280. 46, d. f. =11, P < 0. 0001). Dunn's post hoc test located significant differences of duff fuel loading at the $\alpha < 0.05$ level for 36 combinations of EUs (Appendix E). The majority of significant groupings (27) include Crow 1, Crow 6, Pendleton, and Tripp EUs.

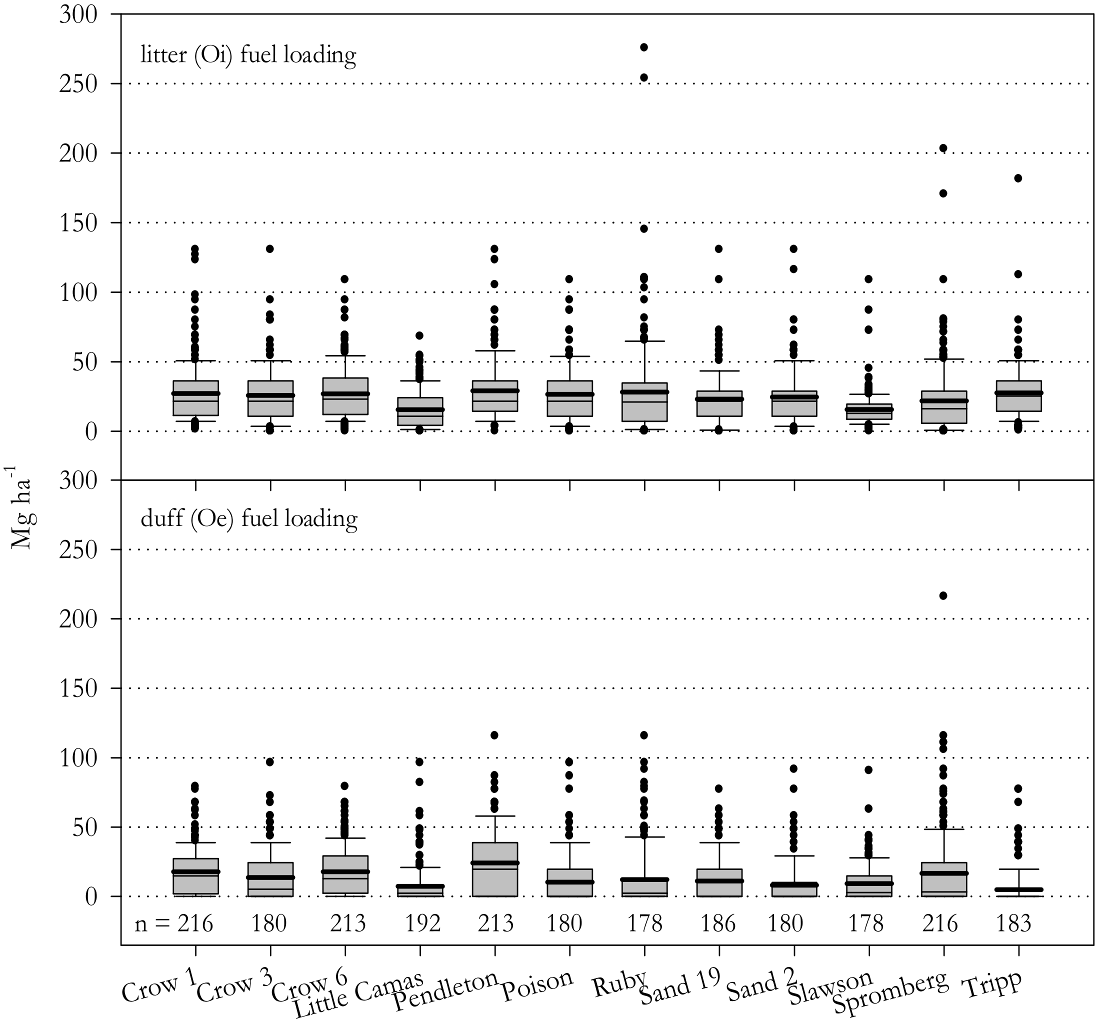


Figure 16: Litter (Oi) and duff (Oe) fuel loading based on depth-mass general linear regression models presented in Figure 14. The box is bound at the 25th percentile at the lower end, and at the 75th percentile at the upper end. The thin line within the box marks the median and the bold the mean. Whiskers below and above the box indicate the 10th and 90th percentiles with outlying values below and above.

Herbaceous and Shrub Fuels

The average herbaceous live equivalent one hour timelag fuel load ranged 0.10 ± 0.14 Mg ha^{-1} at Little Camas, to 1.12 ± 0.80 Mg ha^{-1} at Crow 1 (Figure 17). Dominant herbaceous species include pinegrass (*Calamagrostis rubescens* Buckl.), bluebunch wheatgrass (*Pseudoroegneria spicata [Pursh] A. Löve ssp. spicata*), Geyer's sedge (*Carex geyeri* Boott), arrowleaf balsamroot (*Balsamorhiza sagittata* [Pursh] Nutt.), among others. Average live shrub equivalent one hour timelag fuel load ranged 1.03 ± 2.45 Mg ha^{-1} at Pendleton, to 4.62 ± 6.74 Mg ha^{-1} at Poison (Figure 17). Dominant shrubs are summarized in Table 2. Live fuel loads comprise a greater proportion of the total shrub-herb load; however, a larger proportion of dead herbaceous one hour load would be expected if based on a late summer or fall sample. As herb and shrub fuel classes are a proportion of total loads, statistics were only calculated for total fuel loads: which includes one hour live equivalent and dead timelag fuels, and for shrub include one hour equivalent live shrub and 1 through 100 hour timelag shrub fuels. Significant differences in median total herb and shrub fuel loads are indicated. Post hoc tests reveal significant median differences of total herb and shrub fuel loads at the $\alpha < 0.05$ level; 23 pairwise combinations of EUs in total herb, and 8 in the total shrub fuel loading (Appendix E).

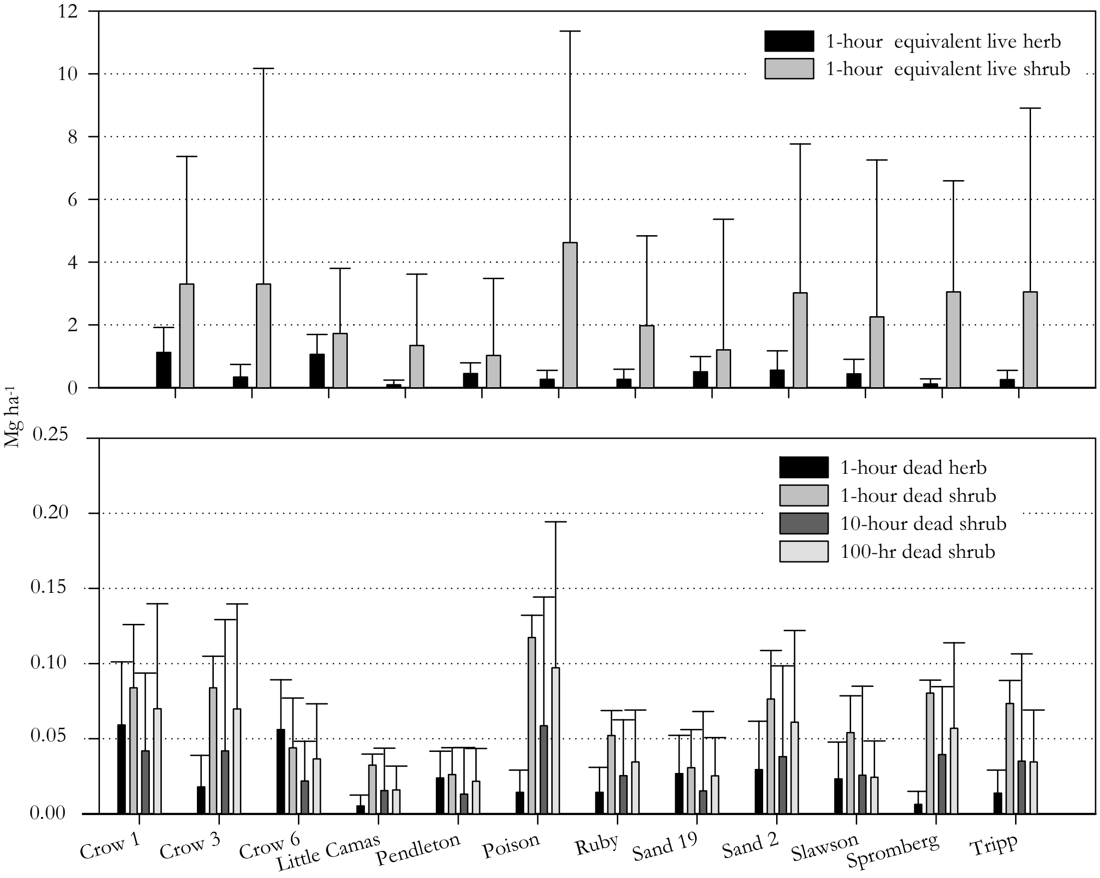


Figure 17: Average live and dead herbaceous and shrub timelag-class fuel loading across each EU. Whisker represents one standard deviation. Note that equivalent live and dead timelag graphs are not presented at the same scale.

Fire Behavior Fuel Models

Six Northern Forest Fire Lab (NFFL) surface fire behavior models were fit to each of the EUs using Anderson's (1982) stylized fire behavior fuel models. No EU was represented by a single NFFL model type (Figure 18). As few as four, but as many as six NFFL models are represented in each EU. NFFL 2, consisting of a typical fuel complex of timber with a grass understory, was the single model which dominated the fuel complex, except for Little Camas, where NFFL 5, a low shrub fuel complex, was slightly greater than NFFL 2 coverage. Given the greater flammability of ceanothus, Model 7 represents concentrations of ceanothus species; however, Model 7 is not well represented in the EUs, with the greatest cover, 6.5% measured at Tripp (Figure 18). Model 8, where short-needled conifer is the dominant forest floor and understory vegetation and CWD are sparse, is moderately represented, 4.2% to 15.7%, except in EUs dominated by ponderosa pine. NFFL 9 is represented by closed stands of ponderosa pine where litter fall is the primary surface fuel. The dominant tree species at Crow EUs and Pendleton is ponderosa pine, and NFFL 9 ranges from 6.2% to 19.7%. NFFL 9 is also characterized by broadleaf litterfall, as represented at the Ruby EU. NFFL model 10 represents the highest surface fuel load measured, with greater amounts of dead woody fuels greater than 7.6 cm diameter. Model 10 is represented in all EUs, ranging from 11.3% at Sand 2, to 1.2% at Crow 3 (Figure 18).

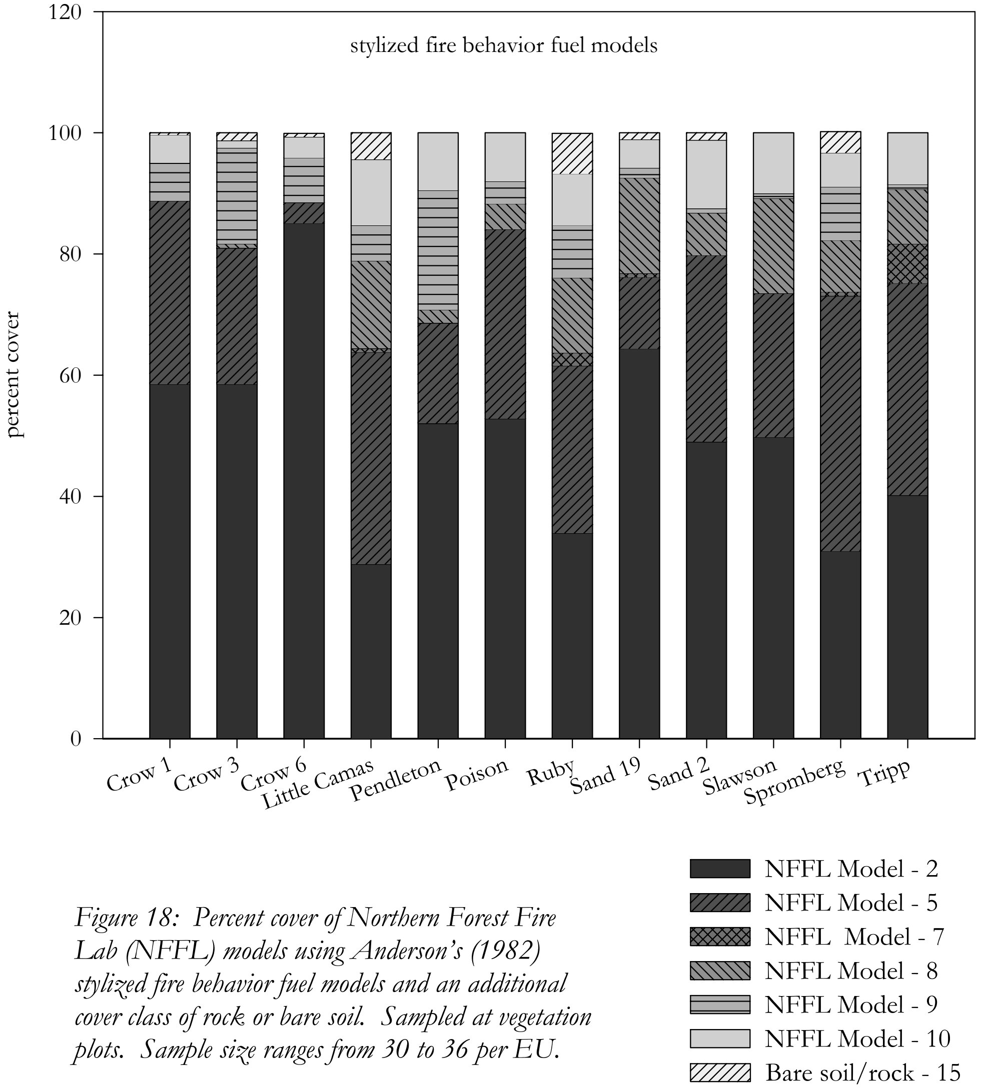


Figure 18: Percent cover of Northern Forest Fire Lab (NFFL) models using Anderson's (1982) stylized fire behavior fuel models and an additional cover class of rock or bare soil. Sampled at vegetation plots. Sample size ranges from 30 to 36 per EU.

Simulated Fuel Treatment Effects

Two EUs are selected for analysis in FVS-FFE model to compare and contrast differences in the effect of fuel treatments on fire behavior and severity. Summary of existing conditions indicates that Crow 6 and Ruby EUs exemplify differences and variability of conditions in dry forest fuel profiles in the Wenatchee Mountains. Initial pre-treatment starting fuel loads in the control are higher at Ruby than at Crow 6 in all cases except for standing dead fine and coarse wood, duff, and live herb. Average slope at Ruby is greater and tree species dominance and composition is very different between the stands (Figures 6 and 7). Existing conditions from these units are used to model fuel treatments in FVS-FFE. The effect of fuel treatments on fire behavior and severity are summarized by short and long-term response. Short-term response represents two years post fuel treatments and long-term represents a period of nineteen years. The long-term period of nineteen years was modeled for three reasons: 1.) it is the shortest reasonable period of time for considering maintenance or re-entry of a stand, 2.) accurate predictions are more likely modeled in shorter than longer intervals by FVS-FFE, especially in terms of fuel dynamics, and 3.) it is a reasonable time period to evaluate long-term effects and performance of the FVS-FFE model. This section will be followed by a critical analysis of FVS-FFE in context of model results.

Prescribed Fire Treatment Summary

Simulated prescribed fire flame length varied from 0.91 m to 1.01 m (Table 17); however, the prescription for the burn treatment was achieved by maintaining flame length to just under a meter by adjusting environmental parameters such as moisture and wind speed (Table 11). The range of scorch height was narrow, from 3.4 m resulting from the TB at Crow 6, to 3.8 m resulting from the TB at Ruby. The range and the values of midflame wind speed were low. Surface fire type was characteristic of Crow 6, and passive at Ruby, albeit the percent of trees with torching at Ruby was very low, one percent or less (Table 17).

Table 17: Prescribed fire treatment output fire variables from FVS Burn Conditions report. Environmental parameters were adjusted to obtain a 0.91 m (3 ft.) flame length (see Methods Table 11).

	Crow 6		Ruby	
Fire behavior variables	burn only	thin & burn	burn only	thin & burn
flame length (m)	0.91	0.91	1.01	0.95
midflame wind speed (km hr $^{-1}$)	3.5	4.2	2.6	3.4
fire type	Surface	Surface	Passive	Passive
scorch height (m)	3.5	3.4	3.7	3.8
trees with torching (%)	0	0	1	< 1

Total Biomass, Removal and Consumption

Modeled total biomass was reduced the greatest by the thin and burn (TB) treatment, a 41% reduction at Crow 6 and 39% at Ruby (Table 18). Relative differences between the percent reduction of total biomass in the thin only (TO) and the burn only (BO) treatments were not large. Modeled harvest treatment removed 26.9 Mg ha^{-1} from the mechanical treatments at Crow 6, and 56.0 Mg ha^{-1} at Ruby. Biomass consumed effect was less for the BO than the TB treatment for both EUs: 29.2 Mg ha^{-1} and 40.4 Mg ha^{-1}, and 35.9 Mg ha^{-1} and 40.4 Mg ha^{-1} for Crow 6 and Ruby respectively (Table 18).

Table 18: Summary of treatment effect of thin only (TO), burn only (BO), and thin burn (TB) on total biomass, biomass consumed, and biomass removed at Ruby and Crow 6 EUs modeled with FVS-FFE reported from results of All Fuels Report one year post fuel treatments. Values represent treatment fuel loading result and the percent increase or decrease in relation to the Control.

Mg ha^{-1}/ % increase - decrease	**Crow 6**				**Ruby**			
	CTRL	TO	BO	TB	**CTRL**	TO	BO	TB
Total Biomass	**163.7**	136.8 -16%	134.5 -18%	96.4 -41%	**246.6**	190.6 -23%	210.7 -15%	150.2 -39%
biomass consumed	0.0	0.0	29.2	40.4	0.0	0.0	35.9	40.4
biomass removed	0.0	26.9	0.0	26.9	0.0	56.0	0.0	56.0

Surface Fuel Profile Change

TO treatment increased surface fuel loading for all surface fuel profile variables except for live shrub, which decreased slightly at Crow 6, and no change occurred in duff loading in either EU (Table 19). TO treatment increased dead fine loading the greatest, 71% and 81% at Crow 6 and Ruby respectively. BO treatment reduced surface fuels across all variables except live herb and live shrub for which there was no change;

however, the latter can be attributed to assumptions made in the model. Dead coarse wood at Crow 6 was reduced nearly twice the amount at Ruby by the BO treatment, but otherwise, relative reduction of surface fuels was nearly equal between the EUs under the BO treatment. Trends within TB treatment and between EUs are not as consistent. The reduction in total surface load under the Ruby TB is 24% less than that of Crow 6. A large reduction in litter, duff, and dead fine wood occurred at both EUs with TB treatment, although the reduction at Crow 6 was 20% greater. TB treatment increased dead coarse wood by 11% at Ruby, while it was reduced by 58% at Crow 6. Live shrub modeled response to the TB at Ruby was largest percent increase, 129%, while at Crow 6, there was a 24% reduction in live shrub fuel load. TB live herb load increased at Ruby by 25% and 4% at Crow 6 (Table 19).

Table 19: Summary of treatment effect of thin only (TO), burn only (BO), and thin burn (TB) on surface fuel profile variables at Ruby and Crow 6 EUs modeled with FVS-FFE reported from results of All Fuels Report one year post fuel treatments. Values represent treatment fuel loading result and the percent increase or decrease in relation to the control (CTRL).

Mg ha^{-1}/ % increase - decrease	**Crow 6**				**Ruby**			
	CTRL	TO	BO	TB	**CTRL**	TO	BO	TB
Total Surface	**48.0**	56.3 17%	18.8 -61%	17.0 -64%	**62.3**	76.5 23%	27.1 -56%	36.3 -42%
litter (Oi)	**13.2**	13.9 5%	1.2 -91%	0.9 -93%	**18.9**	21.0 11%	1.6 -91%	0.9 -95%
duff (Oe)	**18.4**	18.4 0%	10.1 -45%	10.1 -45%	**12.8**	12.8 0%	7.6 -40%	7.6 -40%
fine dead *	**7.9**	13.5 71%	3.4 -57%	1.4 -83%	**10.3**	18.6 81%	4.0 -61%	3.8 -63%
coarse dead **	**7.8**	9.9 26%	3.4 -57%	4.0 -49%	**19.1**	21.1 11%	12.3 -35%	21.1 11%
live herb	**0.516**	0.538 4%	0.516 0%	0.538 4%	**0.516**	0.650 25%	0.628 22%	0.785 52%
live shrub	**0.381**	0.292 -24%	0.336 -12%	0.269 -29%	**1.009**	2.287 127%	2.152 113%	3.430 240 %

* < 2.53 cm diameter of dead wood
** > 2.53 cm diameter of dead wood

Standing-Canopy Fuel Profile Change

Standing fuel loading treatment effect trends are consistent between EUs, but the magnitude varies. The TO treatment reduced total standing fuel load by 29% at Crow 6 and by 38% at Ruby (Table 20). In terms of total standing fuel reduction, the TB treatment replicated the TO treatment; reducing total standing load by the same percentage. The BO treatment had no effect on total standing loading; however, there were large shifts between live and dead fuels. Large increases in dead fine and dead coarse fuels resulted from the BO and TB treatments, with greater increases from the BO treatment; BO treatment increased dead fine fuels by 1171% at Crow 6 and 2818% at Ruby (Table 20). The TO treatment had no effect on dead fine or dead coarse fuels. Live fine, live coarse, and foliage were reduced by all treatments, ranging from 13% to 58% reduction. Canopy bulk density (CBD) was reduced by all treatments with the greatest reductions occurring in the TB treatment and the TO at Ruby. Canopy base height (CBH) was lengthened in all cases except for the TO treatment at Ruby. CBH was increased by 475% and 600% by the BO and TB treatments at Ruby, but was less at Crow 6 (Table 20).

Table 20: Summary of treatment effect of thin only (TO), burn only (BO), and thin burn (TB) on tree or standing fuel variables at Crow 6 and Ruby EUs modeled with FVS-FFE reported from results of All Fuels Report one year post fuel treatments except canopy bulk density and canopy base height which are reported in the Potential Fire Report. Values represent treatment fuel loading result and the percent increase or decrease in relation to the control (CTRL).

Mg ha^{-1}/ % increase - decrease	**Crow 6**				**Ruby**			
	CTRL	TO	BO	TB	CTRL	TO	BO	TB
total standing	114.3	80.7 -29%	114.3 0%	80.7 -29%	183.8	114.3 -38%	183.8 0%	114.3 -38%
dead fine *	0.4	0.4 0%	4.8 1171%	2.8 629%	0.2	0.2 0%	7.2 2818%	3.9 1491%
dead coarse **	4.7	4.7 0%	16.8 257%	11.2 138%	3.8	3.8 0%	21.3 459%	11.7 206%
foliage	5.4	3.8 -29%	4.7 -13%	3.4 -38%	9.9	5.4 -45%	7.6 -23%	4.0 -59%
live fine *	23.5	15.9 -32%	20.0 -15%	14.1 -40%	27.8	17.0 -39%	23.1 -17%	14.3 -48%
live coarse **	80.7	56.1 -31%	69.5 -14%	49.3 -39%	141.2	87.4 -38%	123.3 -13%	80.7 -43%
CBD (kg m-3)	0.0420	0.025 -40%	0.033 -21%	0.019 -55%	0.057	0.025 -56%	0.040 -30%	0.020 -65%
CBH (m)	7.0	8.2 17%	7.6 9%	8.8 26%	1.2	1.2 0%	7.0 475%	8.5 600%

* < 2.53 cm diameter of dead wood
** > 2.53 cm diameter of dead wood

The greatest reduction in tree density occurred by the TB treatment, from 284 trees ha^{-1} to 109 trees ha^{-1} at Crow 6, a 62% decrease, and from 909 trees ha^{-1} to 121 trees ha^{-1} at Ruby, a 87% decrease (Table 21). The BO treatment reduced tree density by 74% at Ruby, while reducing 25% at Crow 6. As for TO treatment, the inverse was true between the EUs, stem density was reduced by 17% at Ruby and 47% at Crow 6. Amount and trend of reduction of BA were similar between EUs, which is expected for the thin treatments because a similar prescription was used. BO treatment reduced BA around 18% for both EUs (Table 21). Quadratic mean diameter (QMD) increased in all treatments, except for the BO at Ruby, in which QMD decreased by 14% to 18 cm. Reduction in QMD in the Ruby TO treatment is somewhat surprising, but can be explained by the thin prescription. The thin treatment was developed as an intermediate thin or commercial thin based on merchantable material via helicopter logging Douglas-fir greater than 20.3 cm dbh and ponderosa pine greater than 15.2 cm dbh, to a specified basal area. Removal of understory smaller than those size classes was not modeled. As the dominant tree species at Ruby was Douglas-fir, a greater proportion of larger trees were removed, combined with no removal by slashing of smaller size classes resulted in a decrease of QMD (Figure 7, Ruby), whereas as Crow 6, the species composition and size class distribution resulted in an increase in QMD (Figure 6, Crow 6). The BO treatment at Crow 6 increased QMD by 6% to 33 cm. The largest QMD gain occurred at the Ruby TB treatment, with a 90% increase, whereas the TB treatment at Crow 6 increased QMD by 19% (Table 21). There was no treatment effect on dominant height at Crow 6,

Table 21: Summary of treatment effect of thin only (TO), burn only (BO), and thin burn (TB) treatment on tree density, basal area, diameter, and dominant height at Crow 6 and Ruby EUs modeled with FVS-FFE reported from results of simulated treatments and Summary Statistics report one year post fuel treatments. Values represent treatment result and the percent increase or decrease in relation to the control (CTRL).

	Crow 6				Ruby			
% increase - decrease	**CTRL**	TO	BO	TB	**CTRL**	TO	BO	TB
density (trees ha^{-1})	**284**	151 -47%	213 -25%	109 -62%	**909**	751 -17%	240 -74%	121 -87%
BA (m^2 ha^{-1})	**22**	14 -36%	18 -18%	12 -45%	**31**	18 -42%	25 -19%	15 -52%
QMD (cm)	**31**	34 10%	33 6%	37 19%	**21**	18 -14%	37 76%	40 90%
dominant height (m)	**20**	21 5%	20 0%	20 0%	**30**	30 0%	25 -17%	26 -13%

whereas the BO and TB treatment at Ruby reduced dominant height by 17% and 13% respectively (Table 21).

Fuel Treatment Effects on Simulated Wildland Fire Behavior and Severity

Simulated fire in FVS-FFE implements fire effects in the following FVS cycle and presents a report for the year of the simulation under one set of fire weather conditions, whereas information reported in potential fuel and fire reports present data based over time as if wildland fire occurred each year, but does not integrate the calculations into the following years presentation of data. Furthermore, not all variables are reported in each of the reports, therefore results are presented in the context of both reports. Short or immediate effects of fuel treatments on fire behavior and severity are presented under simulated effects, whereas effects over time are presented in the context of potential fire behavior and severity.

Flame Length, Fire Type and Fuel Models – Year Two

The expression of intensity–flame length is influenced by slope, temperature, moisture content of fuels, fine fuel loading, mid-flame windspeed, and type of modeled fire behavior, all of which but the latter three are held constant for treatment calculations (see Methods). All simulated short-term results were modeled under 80 percentile weather conditions (Table 12).

Little difference in simulated wildland fire flame length was modeled two years following fuel treatments at Crow 6; flame length ranged from 1.4 m at the thin only (TO) treatment and 1.6 m at the thin and burn (TB) treatment (Figure 19). The largest difference between mid-flame windspeed was small as well, 1.1 km^{-hr} between TB and control (CTRL) at Crow 6 (Table 22). At Crow 6 the longest flame length was modeled in the TB treatment–higher than the CTRL, corresponds with the lowest canopy cover, highest mid-flame windspeed, but the lowest fine fuel loading as well (Table 22). Surface fire behavior was modeled in all of the Crow 6 treatments except the TB (Figure 19).

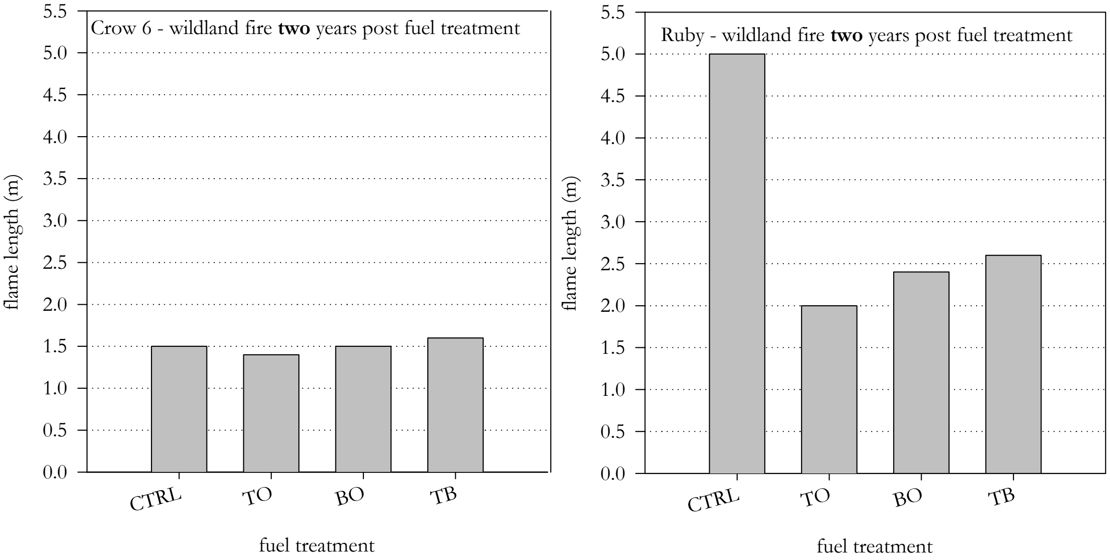


Figure 19: Response of simulated 80 percentile wildland fire flame length to fuel treatments. Simulated wildland fire at two years post fuel treatments: control, thin only, burn only, and thin and burn on Crow 6 and Ruby experimental units.

Simulated wildland flame length was reduced by all fuel treatments that occurred two years post fuel treatments on the Ruby EU; from 2.0 m at the TO treatment, to 2.6 m in the TB, compared to 5 m at the CTRL (Figure 19). Mid-flame windspeed increased from 2.4 km^{-hr} at the CTRL at Ruby, to 4.2 km^{-hr} at TB and 3.1 km^{-hr} at TO and BO treatments (Table 22).

Table 22: Selected variables influencing 80 percentile wildland fire flame length at two years post fuel treatments: control, thin only, burn only, and thin & burn at Crow 6 and Ruby experimental units.

	Crow 6				Ruby			
	CTRL	TO	BO	TB	**CTRL**	TO	BO	TB
mid-flame windspeed (km hr^{-1})	3.4	4.3	3.9	4.5	2.4	3.1	3.1	4.2
canopy cover (%)	33	21	28	18	53	38	39	23
litter (Mg ha^{-1})	8.0	7.6	2.9	1.9	11.9	11.4	4.7	2.6
≤ 3 hr. timelag fuels (Mg ha^{-1})	10.5	13.5	7.2	3.4	13.0	17.0	8.1	5.2

Surface fire was modeled in all the Crow 6 treatments except the TB where passive crown fire occurred; however, in less than 1% of the trees (Figure 19). Surface fire was only modeled in the BO treatment at Ruby, passive crown fire was modeled in the remaining treatments. Passive crown fire was modeled in Ruby CTRL, TO, and TB treatments, occurring in respective 38%, 7%, 5%, of the trees.

Scorch Height and Basal Area Mortality – Year Two

Simulated scorch height mirrored flame lengths, but at a magnitude of about seven times, a near linear function of the model. Scorch height was lowest (9.3 m) at the Crow 6 TO treatment, and greatest (10.9 m) at the TB treatment. Scorch heights for Ruby TO, BO, and TB were half to nearly half that of the CTRL, ranging from 14.4 m to 20.9 m (Figure 20).

At Crow 6, the greatest amount of basal area mortality from 80 percentile wildand fire occurred in the CTRL, 5.57 m^2 ha^{-1}, and the least amount of mortality occurring in the TO treatment, 2.63 m^2 ha^{-1}; however, the TB treatment resulted in the lowest density of trees (Table 23). No mortality was modeled in the largest size class at Crow 6, including the CTRL, and 100% mortality was modeled in the smallest size class when present. The greatest difference in mortality between treatments occurred in the 25.4 – 50.8 cm size class grouping. In this size class, 17% of the trees were killed in the TO treatment, whereas, in the TB, 32% of the trees were killed and these treatments had similar pre-wildland fire tree densities within this size class.

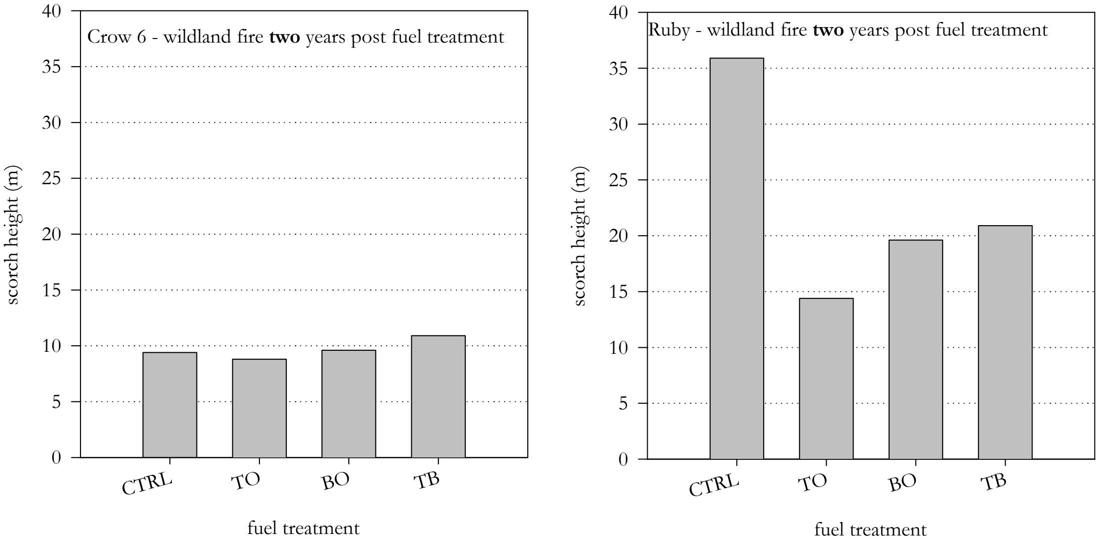


Figure 20: Response of simulated 80 percentile wildland fire tree scorch height to fuel treatments. Simulated wildland fire at two years post fuel treatments: control, thin only, burn only, and thin and burn on Crow 6 and Ruby experimental units.

Larger differences in total basal area mortality are modeled between treatments at Ruby EU–treatment differences are two to five times that of the CTRL, indicating the relationship between mortality, flame length and scorch height. TB and TO treatments had a similar effect, resulting in respective basal area mortality values of 8.70 m^2 ha^{-1} and 6.36 m^2 ha^{-1}, about half of the BO treatment (Table 23). There is little difference between treatment effects on tree mortality in the two smallest size classes, each the treatments resulted in near to total mortality. Across all size classes, the 80 percentile wildland fire resulted in near stand replacing consequences in the CTRL. In the size class, 25.4 – 50.8 cm, 50% to as great as 80% of the trees remaining after each treatment type were killed, with the TO with the lowest relative percent and the TB with the greatest; however, the greatest number of trees removed, 79 trees ha^{-1}, occurred in the BO treatment. In the largest size class, 50.8 – 76.2 cm, total density is close to equal. In this size class, the highest level of mortality occurred in the TB, followed by the BO and TO, 20 trees ha^{-1}, 12 trees ha^{-1}, 7 trees ha^{-1} respectively (Table 23).

Survivorship increased with greater size classes, and except for in the larger size classes, was limited to ponderosa pine and Douglas-fir. The resulting response of tree density and composition to fuel treatments and 80 percentile wildland fire is varied. A high level of survival in the Crow 6 CTRL results in the greatest stand density, 170 trees ha-1, whereas at Ruby, fire severity resulted in lowest stand density, 2 trees ha-1 (Table 23). In terms of active treatments, TB resulted in the lowest tree density, 59 trees ha-1, and 25 trees ha-1, at Crow6 and Ruby respectively. The TO treatment resulted in lower tree densities in both EUs; however, there was little difference between the TO and BO treatment results at Ruby.

Table 23: Mortality report by size class and species from simulated wildland fire at 80 percentile weather conditions two years post fuel treatments. A zero value represents less than one tree per hectare. Sums may not total due to conversion and rounding.

		tree mortality/pre-fire density (trees ha^{-1})					
		0.0 - 12.7 (cm)	12.7 - 25.4 (cm)	25.4 - 50.8 (cm)	50.8 - 76.2 (cm)	BA mortality (m^2 ha^{-1})	post/pre density (trees ha^{-1})
Crow 6							
CTRL	PSME			0/ 2		0.09	
	PIPO	2/ 2	62/ 99	40/ 156	0/ 12	5.48	
	Other	0/ 0				0.00	
	Total	**5/ 5**	**62/ 99**	**40/ 161**	**0/ 12**	**5.57**	**170/277**
TO	PSME			0/ 0		0.04	
	PIPO	2/ 2	40/ 57	12/ 69	0/ 12	2.59	
	Other	0/ 0				0.00	
	Total	**5/ 5**	**40/ 57**	**12/ 72**	**0/ 12**	**2.63**	**89/146**
BO	PSME			0 2		0.08	
	PIPO	0/ 0	37/ 62	35/ 128	0/ 12	4.45	
	Other	0/ 0				0.00	
	Total	**0/ 0**	**37/ 62**	**35/ 133**	**0/ 12**	**4.53**	**135/207**
TB	PSME			0/ 0		0.05	
	PIPO	0/ 0	27/ 32	17/ 59	0/ 12	3.12	
	Other	0/ 0				0.00	
	Total	**0/ 0**	**27/ 32**	**20/ 62**	**0/ 12**	**3.18**	**59/106**
Ruby							
CTRL	PSME	262/ 264	84/ 84	86/ 89	27/ 27	20.04	
	ABGR	20/ 20	12/ 12	2/ 2		0.82	
	PIPO	121/ 121	22/ 22	32/ 32	12/ 12	8.62	
	Other	200/ 200	2/ 2			0.49	
	Total	**605/ 605**	**124/ 124**	**124/ 126**	**40/ 42**	**29.97**	**2/897**
TO	PSME	267/ 267	30/ 32	7/ 20	5/ 27	3.74	
	ABGR	20/ 20	10/ 10	0/ 0		0.34	
	PIPO	119/ 119	15/ 17	2/ 7	0/ 12	1.77	
	Other	200/ 200	2/ 2			0.51	
	Total	**608/ 608**	**62/ 64**	**15/ 30**	**7/ 42**	**6.36**	**52/744**
BO	PSME	10/ 10	42/ 44	54/ 77	10/ 25	10.24	
	ABGR	0/ 0	2/ 2	0/ 2		0.46	
	PIPO	2/ 2	10/ 12	22/ 27	2/ 12	3.40	
	Other	10/ 12	0/ 0			0.11	
	Total	**27/ 27**	**59/ 62**	**79/ 106**	**12/ 40**	**14.21**	**58/235**
TB	PSME	10/ 10	12/ 12	15/ 17	15/ 27	6.34	
	ABGR	0/ 0	0/ 0	0/ 0	0/ 0	0.14	
	PIPO	2/ 2	7/ 7	5/ 5	2/ 12	2.12	
	Other	10/ 10	0/ 0			0.11	
	Total	**27/ 27**	**25/ 25**	**20/ 25**	**20/ 40**	**8.70**	**25/117**

Fuel Treatment Effects on Potential Fuels, Wildland Fire Behavior and Severity

Potential Changes of Surface Fuel Profile – 19 Year Period

In both EUs, weight of fine dead surface fuels increased to the highest levels in response to the modeled TO treatment, but then drops rapidly over the modeled time frame (Figure 21). After an initial post BO treatment drop in fine dead wood loading, increase occurs through 2007 at both EUs, and than levels off at Crow 6, while there is a gradual decline to the end of the modeled timeframe at Ruby. The greatest decrease is modeled in the TB treatment, with an initial reduction of 3.3 Mg ha^{-1} at Crow 6 and 3.8 Mg ha^{-1} at Ruby; however, compared to the CTRL for the same year, the difference is over two times as great. Interestingly, in the CTRL, FFE models a rapid increase in fine surface fuel loading in the first few cycles, which slowly increases at Crow 6, and slowly declines at Ruby over the time modeled (Figure 21).

There is a rapid decrease of litter (Oi) fuel loading in response to all the treatments, including the CTRL; however, the relative reduction is greatest in response to the burn treatments in both EUs. Initial reduction of litter by the burn treatments was over twice that of the TO treatment. Over time, differences between treatments are reduced and litter loads stabilize in both EUs, but there is a greater treatment effect modeled at Ruby (Figure 22). Duff response follows a different pattern than litter.

The same trend in duff loading is modeled in Crow 6 and Ruby; however, duff loading is greater in Crow 6. Unlike litter loading, modeled duff loading in the CTRL does not make any major adjustments, but gradually increases over the modeled timeframe. There is no real response to duff following the TO treatment. There is little difference between the BO and TO response, both burn treatments reduce duff load substantially, although by a slightly greater magnitude at Crow 6 (Figure 23).

There was little to no treatment effect on shrub fuel loading at Crow 6 (Figure 24). Treatment differences in shrub loading were modeled at Ruby. The TB treatment resulted in the largest increase, from 1.1 Mg ha^{-1} to 3.4 Mg ha^{-1}, minor decreases are modeled over the remaining time period modeled. There was little difference in response

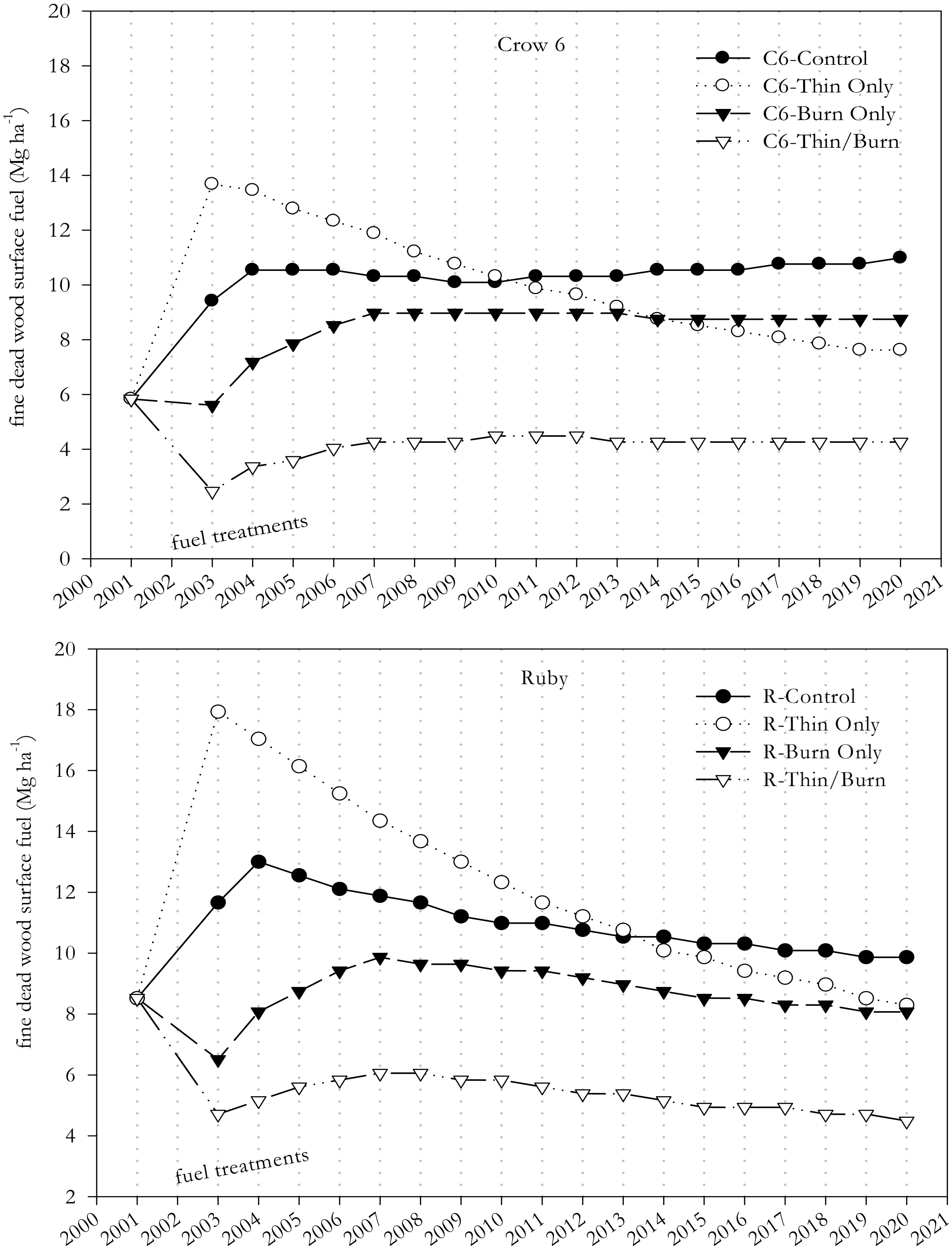


Figure 21: Fine dead wood surface fuel (Mg ha^{-1}) ≤ 100 hr timelag under four fuel treatment scenarios with FVS-FFE over a 19 year period for Crow 6 and Ruby EUs. Treatments applied in 2002 and initial effect displayed in 2003. FVS cycle boundaries are set at 2001-05 and at 5 year intervals thereafter.

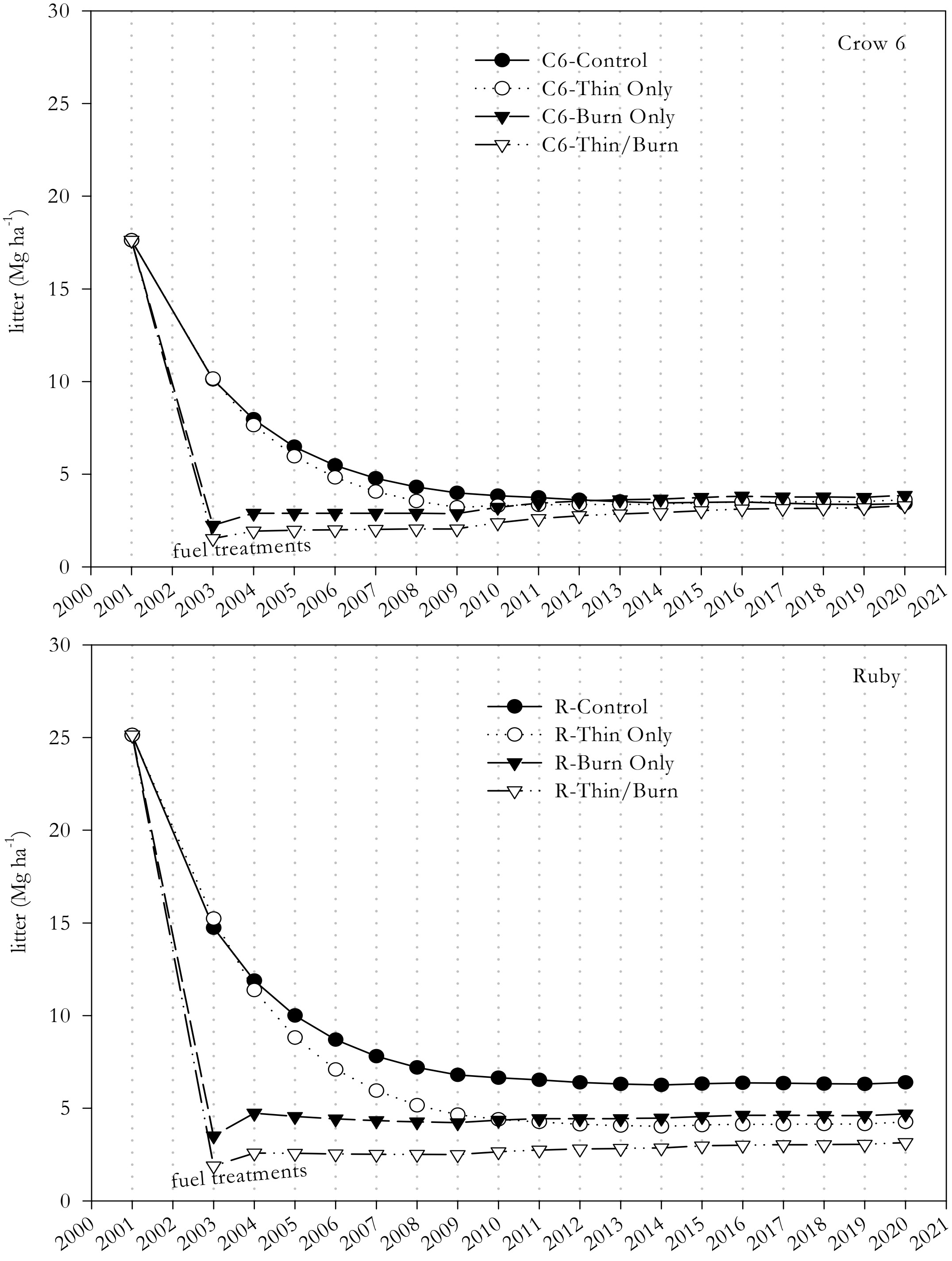
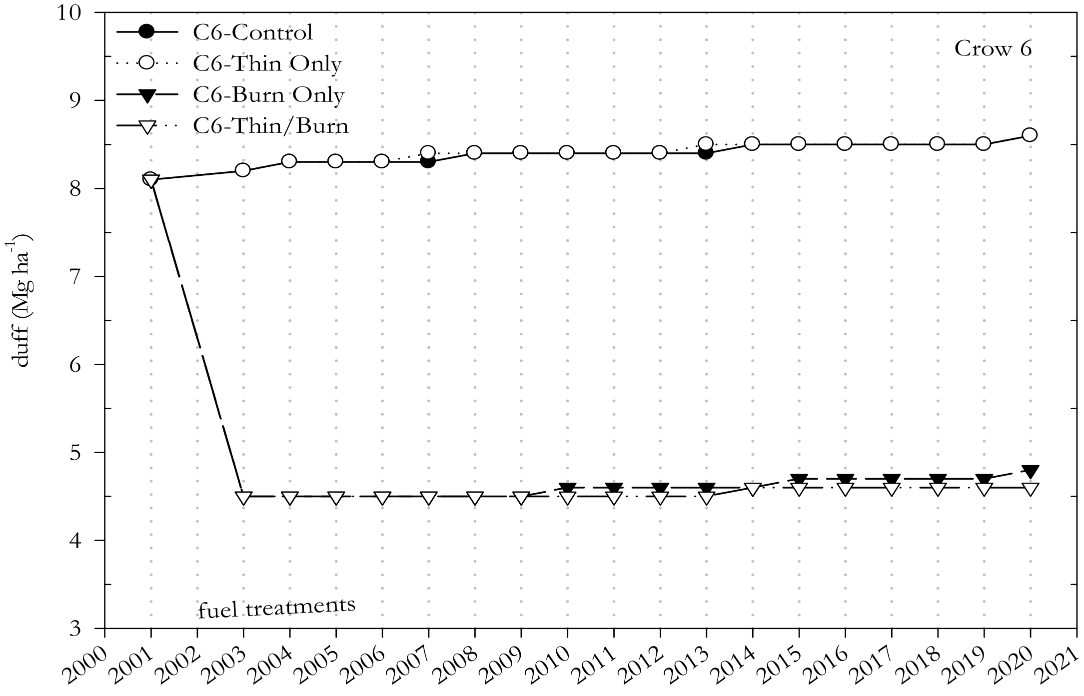


Figure 22: Litter or Oi (Mg ha^{-1}) modeled under four fuel treatment scenarios with FVS-FFE over a 19 year period for Crow 6 and Ruby EUs. Treatments applied in 2002 and initial effect displayed in 2003. FVS cycle boundaries are set at 2001-05 and at 5 year intervals thereafter.



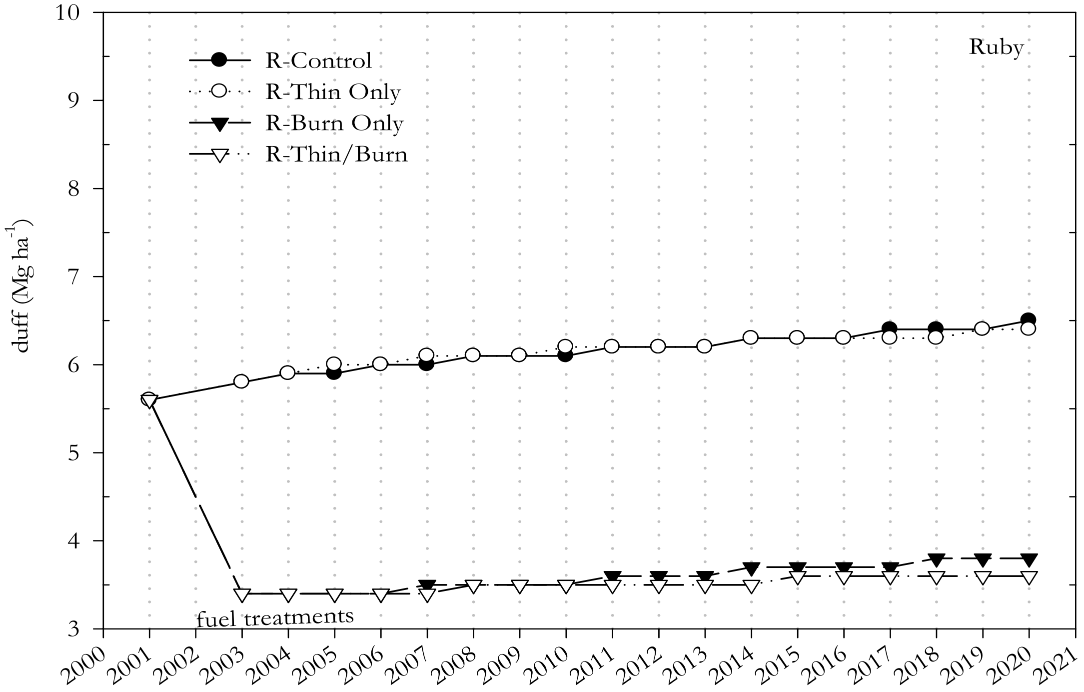


Figure 23: Duff or Oe (Mg ha^{-1}) modeled under four fuel treatment scenarios with FVS-FFE over a 19 year period for Crow 6 and Ruby EUs. Treatments applied in 2002 and initial effect displayed in 2003. FVS cycle boundaries are set at 2001-05 and at 5 year intervals thereafter.

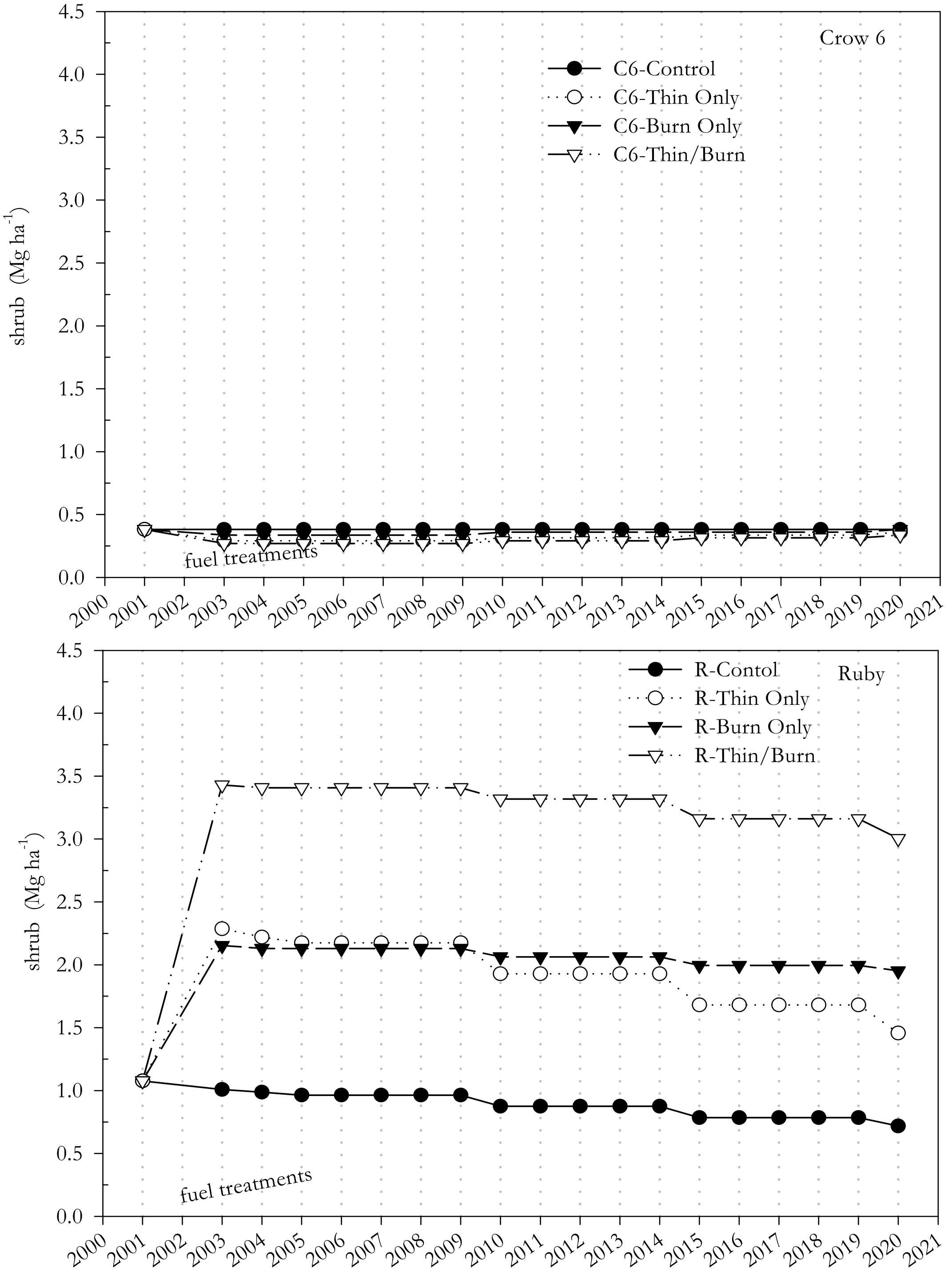
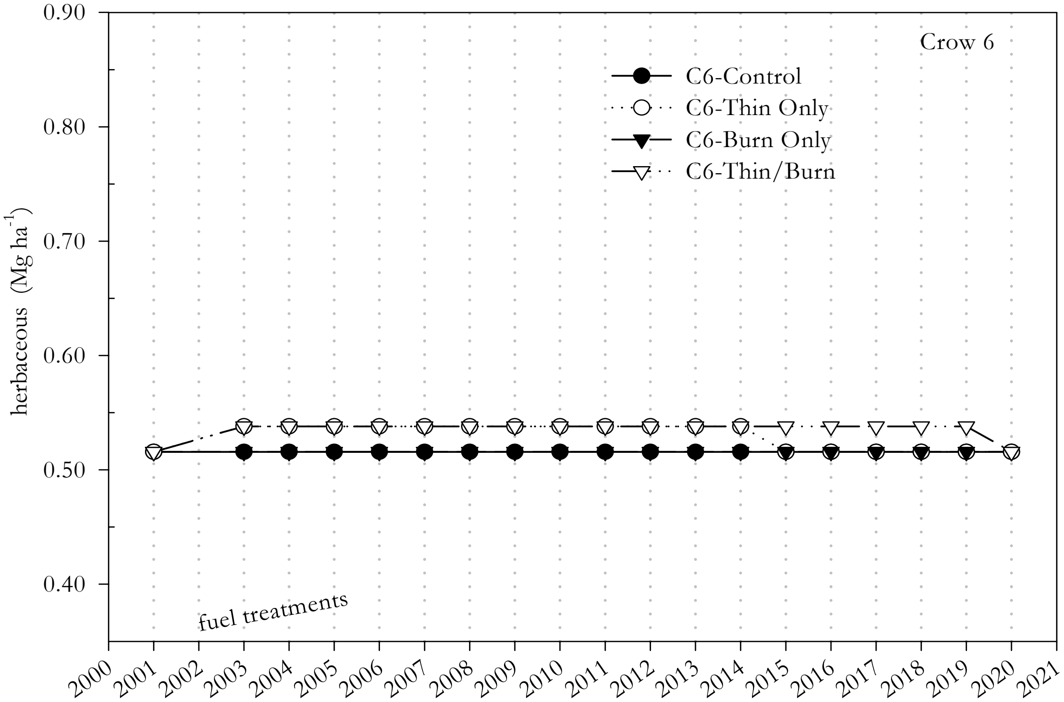


Figure 24: Shrubs (Mg ha^{-1}) modeled under four fuel treatment scenarios with FVS-FFE over a 19 year period for Crow 6 and Ruby EUs. Treatments applied in 2002 and initial effect displayed in 2003. FVS cycle boundaries are set at 2001-05 and at 5 year intervals thereafter.



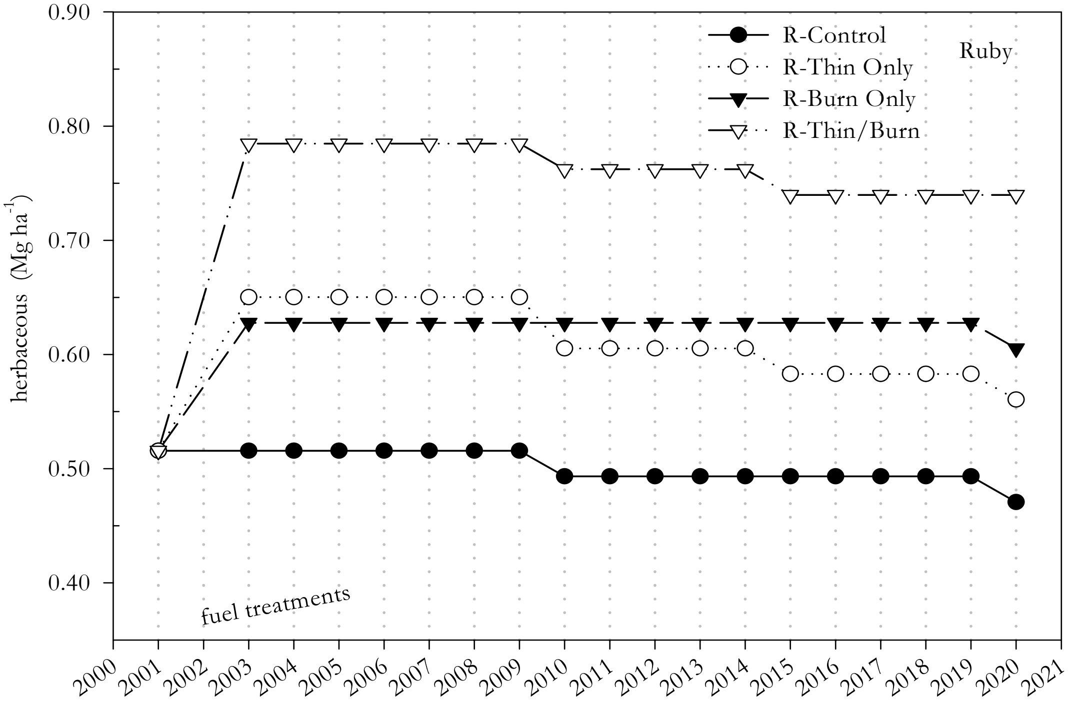


Figure 25: Herbaceous (Mg ha^{-1}) modeled under four fuel treatment scenarios with FVS-FFE over a 19 year period for Crow 6 and Ruby EUs. Treatments applied in 2002 and initial effect displayed in 2003. FVS cycle boundaries are set at 2001-05 and at 5 year intervals thereafter.

between the BO and TO treatments–both increased shrub loading to near 2.3 Mg ha^{-1}; however, reduction in shrub load occurs at a greater rate toward the end the modeled timeframe. The response of herbaceous fuel loading follows the same pattern in both EUs as shrub loading; however, total weight of herbaceous fuel loading is several times less than that of the shrub (Figure 25).

Potential Changes in Canopy Fuel Profile – 19 Year Period

Initial effects of fuel treatments are described in detail under Simulated Effects of Fuel Treatments. Figure 26 indicates the initial effects of fuel treatments on tree density, but also indicates the rate of simulated tree regeneration. The first pulse of tree regeneration modeled in 2005 (Table 6) and presented in the next FVS cycle in 2010 (Figure 26). Modeled regeneration has large influence on canopy base height (CBH), and therefore fire behavior. TB treatment resulted in the greatest immediate reduction in tree density, 109 trees ha^{-1}, followed by the TO and BO treatments. With a pulse of modeled regeneration modeled at the FVS 2010 cycle at Crow 6, tree density is increased from 385 trees ha^{-1} at the BO treatment to around 415 trees ha^{-1} at the TO and TB treatments (Figure 26, Crow 6). There is a constant decline modeled at similar rates for all the treatments in the remaining FVS cycles. No regeneration was modeled in the CTRL and therefore indicates reduction in stems by mortality. The modeled effect of regeneration at Ruby is more varied than at Crow 6. As with Crow 6, initial treatment effects are summarized in detail previously. With the pulse of regeneration modeled in 2010, the TO and TB increase to 324 trees ha^{-1} and 353 trees ha^{-1} respectively, far below the CTRL for the same year, 877 trees ha^{-1} (Figure 26, Ruby). The TO treatment grows above the CTRL in the 2010 FVS cycle and the decline over the period is slightly less in comparison to the CTRL.

Each fuel treatment reduced canopy cover at Crow 6; although at different magnitudes. Two years post treatment resulted in the greatest reduction by TB, followed by TO, and BO, with respective canopy cover values of 18%, 21%, and 28%, compared to 33% in the CTRL (Figure 27). Over the modeled time period, treatment differences are reduced; however, the BO treatment gain in canopy cover is greater. The same trend occurred at the Ruby EU except for a few notable differences. Starting canopy cover values were greater, CTRL in 2004 at 53%, reduced by TO to 39%, BO 37%, and TB 23%; furthermore canopy cover increases at a greater rate in the TO treatment than in the BO treatment (Figure 27).

There is an initial increase in canopy base height (CBH) at Crow 6 including the CTRL, from just over 4 m to near 9 m (Figure 28). Relative differences between the treatments at Crow 6 are small until 2015, when TO and TB CBH is reduced from around 8 m to just under 1m; however, a near equal reduction CBH occurs in the BO and TO treatment the following FVS-cycle. The same trend does not occur at Ruby. There is little initial or long-term difference between CBH in the CRTL and TO–they are consistently 1 m to 2 m. The BO and the TB treatment make an initial increase from 1.5 m to 8.5 m. In 2015, TB CBH drops to below a meter (Figure 28).

Reductions in canopy bulk density (CBD) were modeled across all fuel treatments at Crow 6; however, by 2010 CBD increases above the CTRL. The greatest overall reduction in CBD at Crow 6 occur with the TB treatment, from 0.04 kg m^{-3} to 0.02 kg m^{-3} two years following treatment, followed by TO and BO treatment (Figure 29). Once the initial treatment was modeled, CBD increased over time in all treatments at Crow 6, expect for a decrease in the CTRL at year 2015. The same general trend of CBD was modeled at Ruby as at Crow 6, except for the CTRL increases at a greater rate over the modeled time period.

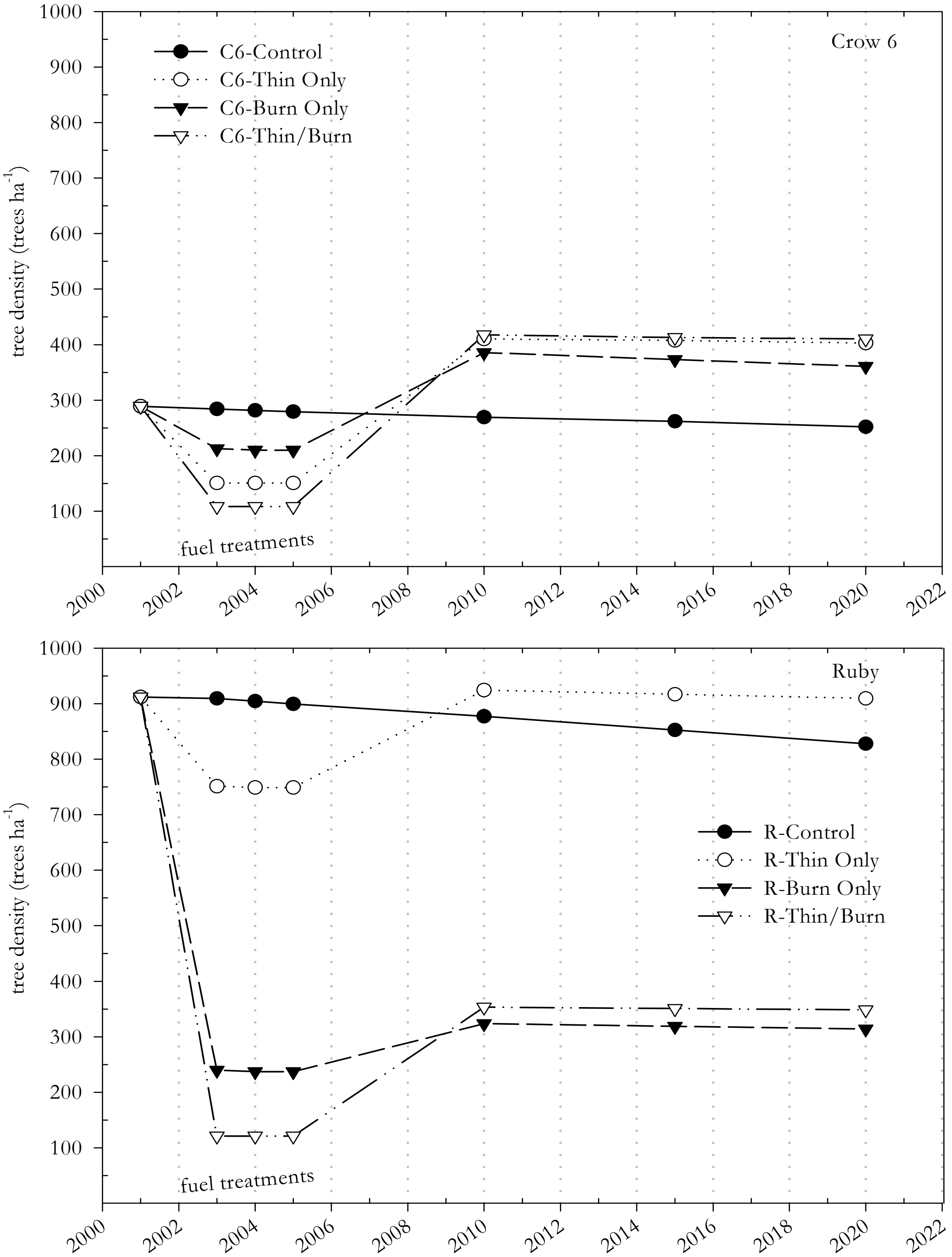


Figure 26: Tree density (trees ha^{-1}) modeled under four fuel treatment scenarios with FVS-FFE over a 19 year period for Crow 6 and Ruby EUs. Treatments applied in 2002 and initial effect displayed in 2003. FVS cycle boundaries are set at 2001-05 and at 5 year intervals thereafter.

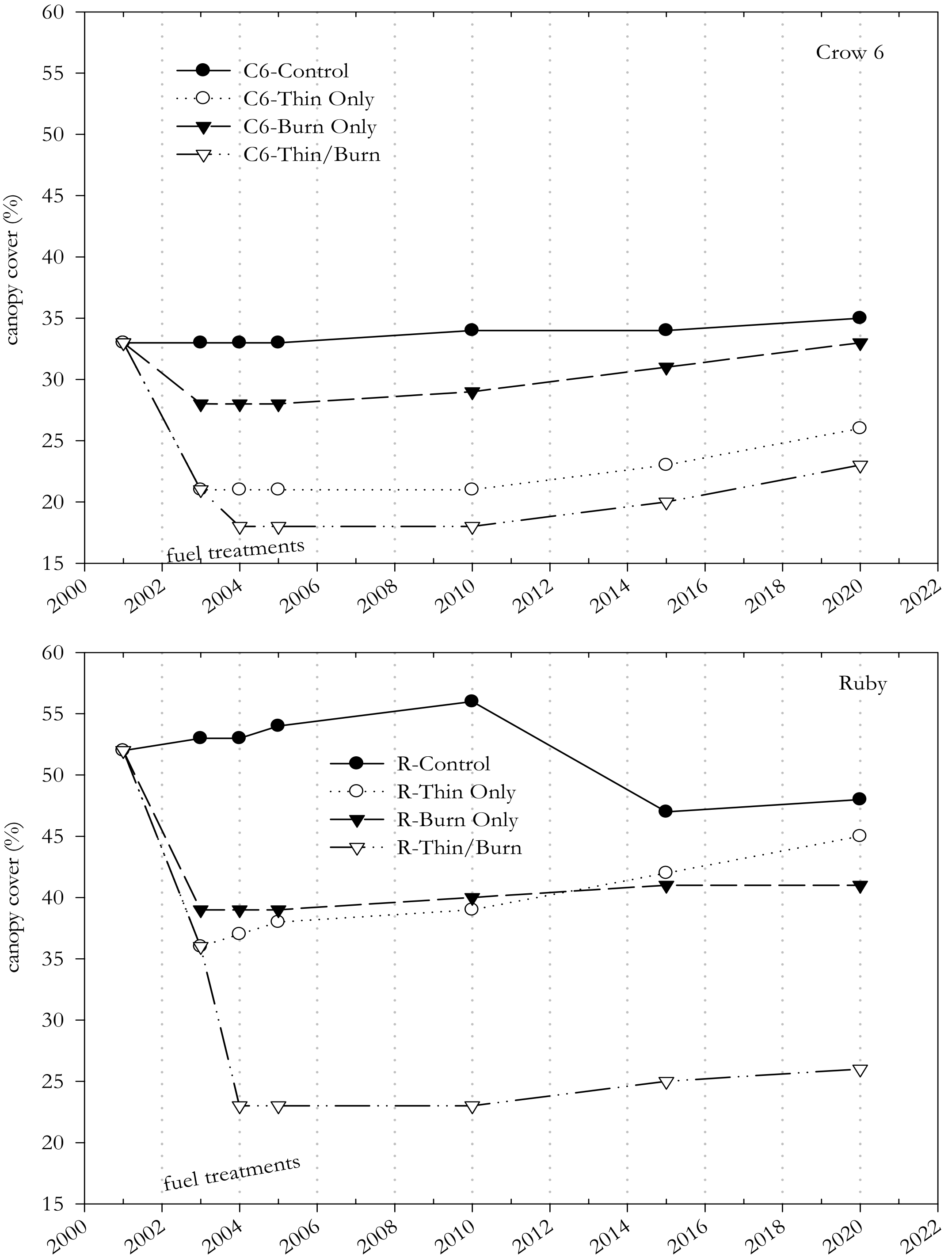


Figure 27: Canopy cover (percent) modeled under four fuel treatment scenarios with FVS-FFE over a 19 year period for Crow 6 and Ruby EUs. Treatments applied in 2002 and initial effect displayed in 2003. FVS cycle boundaries are set at 2001-05 and at 5 year intervals thereafter.

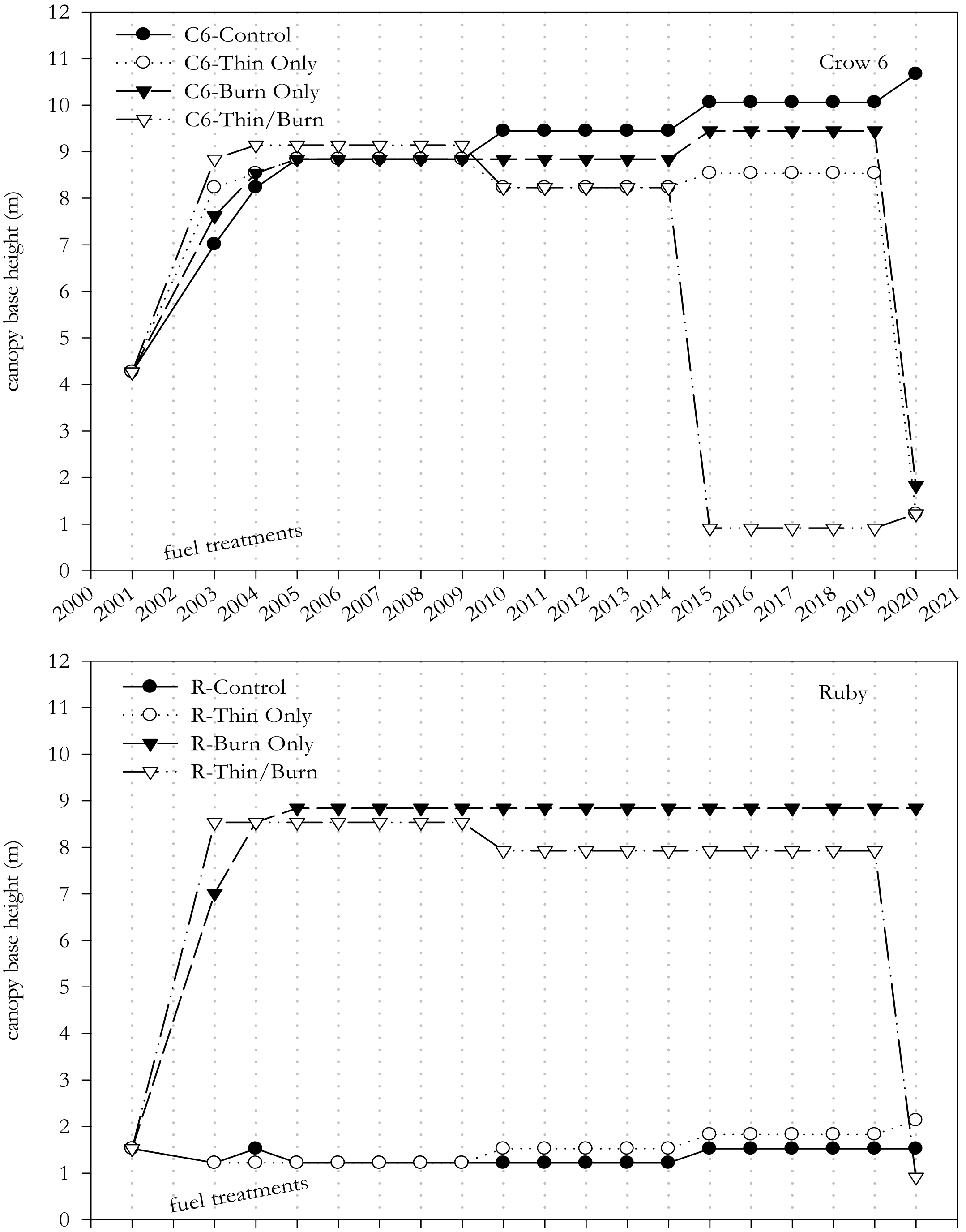
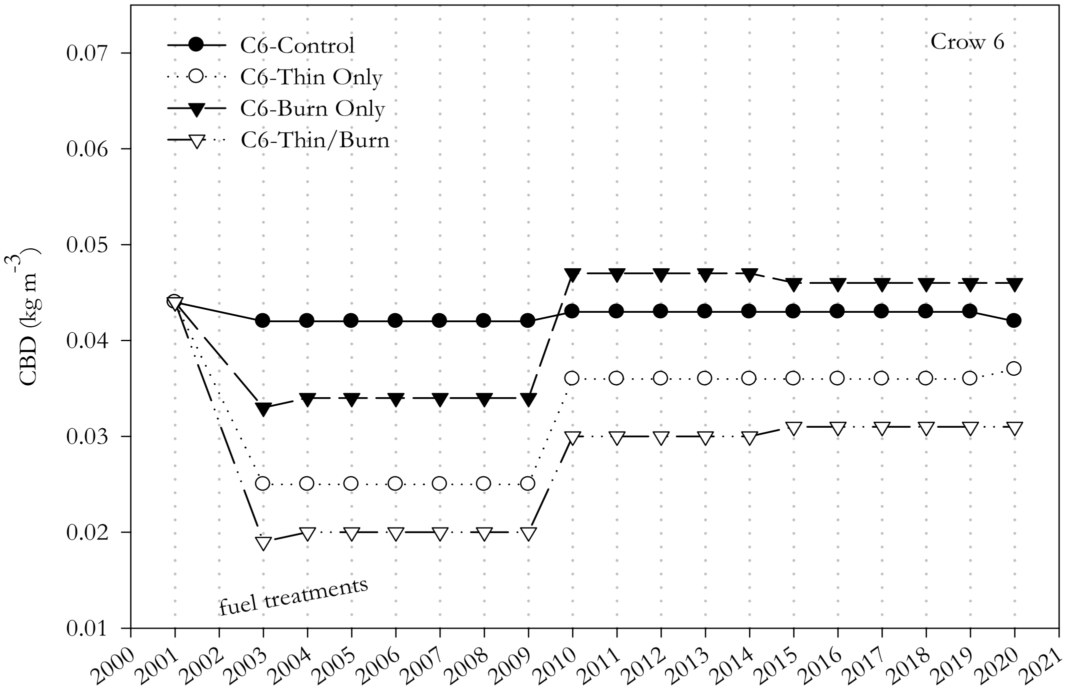


Figure 28: Canopy base height (m) modeled under four fuel treatment scenarios with FVS-FFE over a 19 year period for Crow 6 and Ruby EUs. Treatments applied in 2002 and initial effect displayed in 2003. FVS cycle boundaries are set at 2001-05 and at 5 year intervals thereafter.



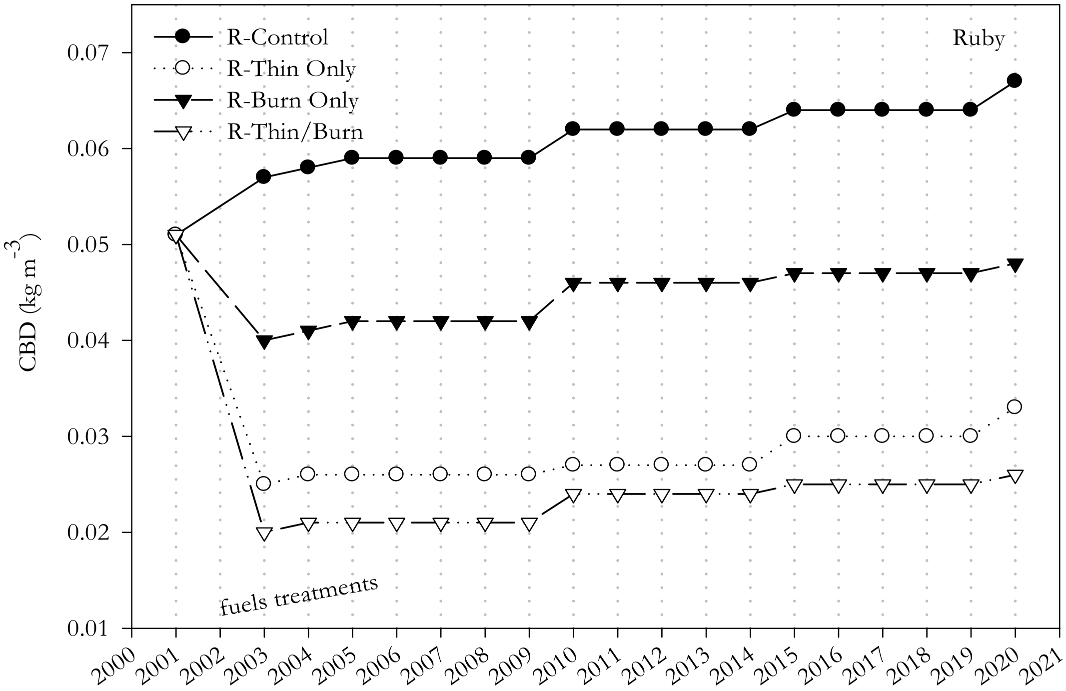
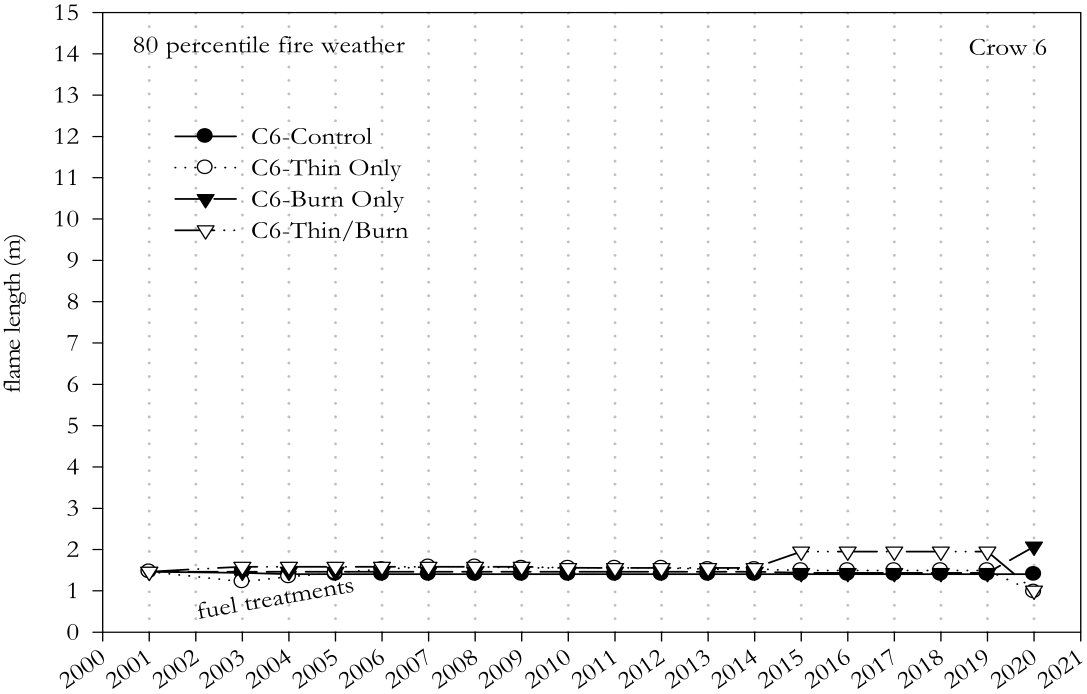


Figure 29: FFE canopy bulk density (kg m^{-3}) modeled under four fuel treatment scenarios with FVS-FFE over a 19 year period for Crow 6 and Ruby EUs. Treatments applied in 2002 and initial effect displayed in 2003. FVS cycle boundaries are set at 2001-05 and at 5 year intervals thereafter.

Potential Changes in Fire Behavior – 19 Year Period

Treatments had little effect on modeled wildland fire flame length at Crow 6; however, divergence between treatment flame length occurs at the FVS cycle boundaries at 2015 and 2020 in two treatment types (Figure 30). In 2015 TB flame length increases from 2.1 m to 3.7 m under 90 percentile plus weather conditions (Figure 31), which is associated with a drop in CBH from 8.2 m to 0.9 m (Figure 28), and a shift fire behavior fuel model weight, from fuel model 6 increasing from 48% to 65%. In the next cycle, 2020, TO flame length is reduced to less than one meter under 80 percentile conditions and just two meters under 90 percentile plus conditions (Figures 30 and 31). Corresponding changes include: 1.) slight increase in canopy base height, from 0.9 m to 1.2 m; 2.) total standing biomass increasing 6.7 Mg ha^{-1} with the majority of change occurring in fine dead fuel loading; and 3.) most significantly, a major shift in fire behavior models, primarily model 6 at 65% changing to model 9 at 81%. With the cycle change in 2020, TB flame length increases from 1.9 m to 4.6 m under 90 percentile plus weather conditions. Associated changes include a drop in CBH from 9.4 m to 1.8 m, and a transition from surface to passive fire modeling.

Differences in flame length in response to treatments under 90 and 80 percentile fire weather conditions at Crow 6 are small (Figures 30 and 31). The greatest mean increase of flame length over the modeled timeframe occurred in the TB treatment, an increase of 0.9 m. The lowest minimum increase of 0.4 m occurred in the CTRL and TO treatments, and the greatest maximum increase occurred in the BO treatment, with an increase of 2.6 m.



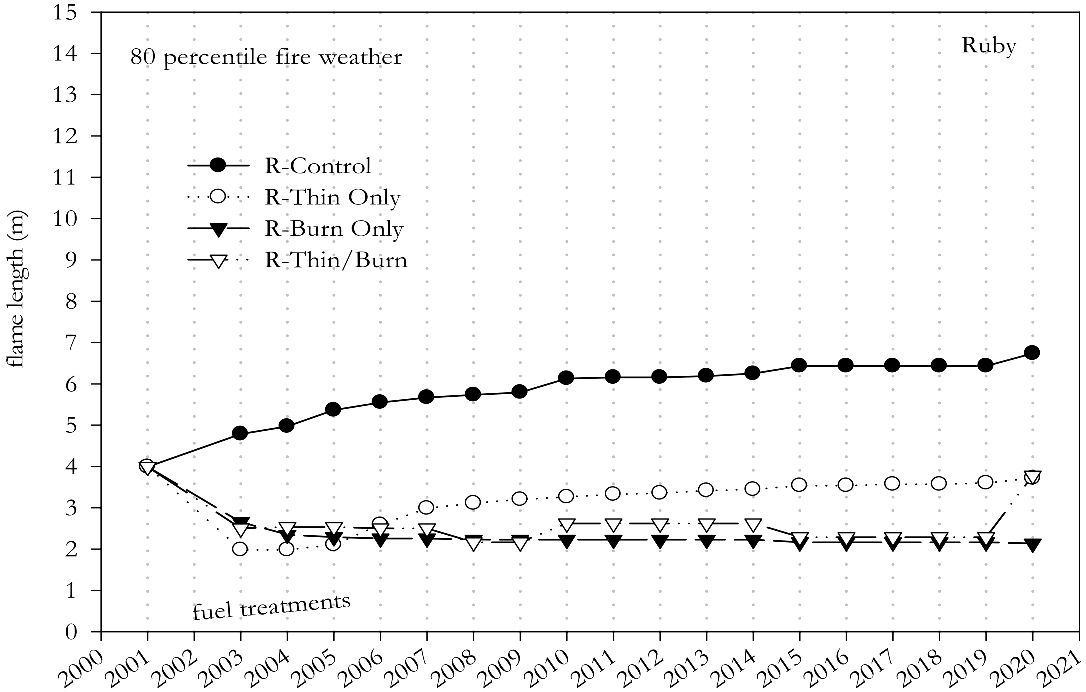
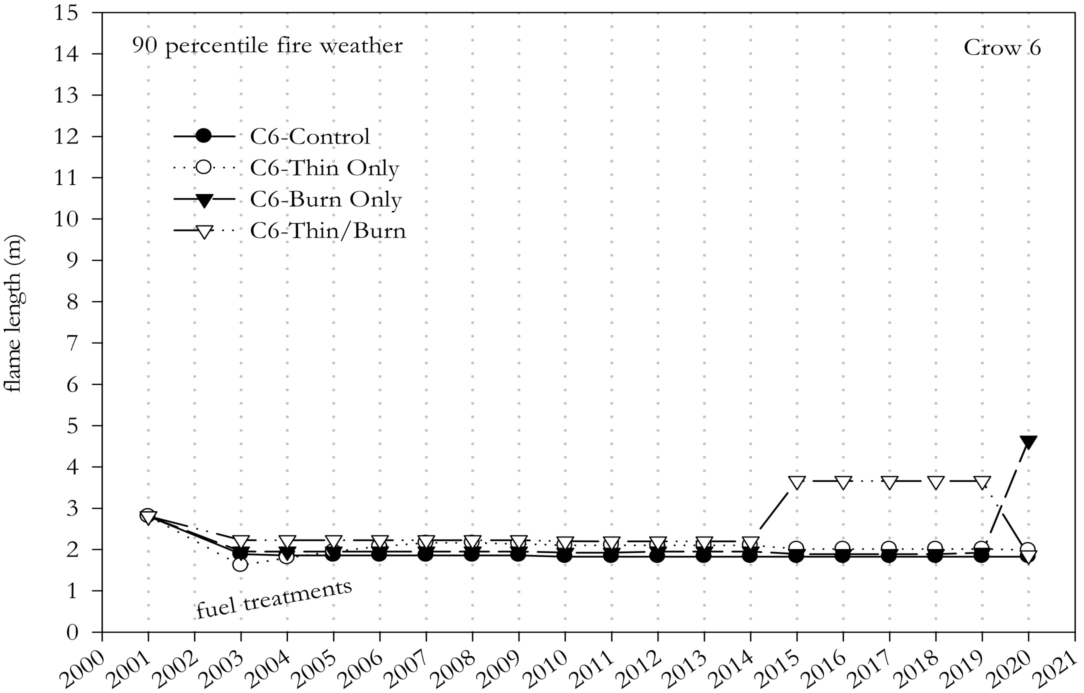


Figure 30: Potential flame length (m) resulting from 80 percentile wildland fire modeled each year under four fuel treatment scenarios with FVS-FFE over a 19 year period for Crow 6 and Ruby EUs. Treatments applied in 2002 and initial effect displayed in 2003. Each year represents the potential effect if an 80 percentile wildland fire occurred. FVS cycle boundaries are set at 2001-05 and at 5 year intervals thereafter.



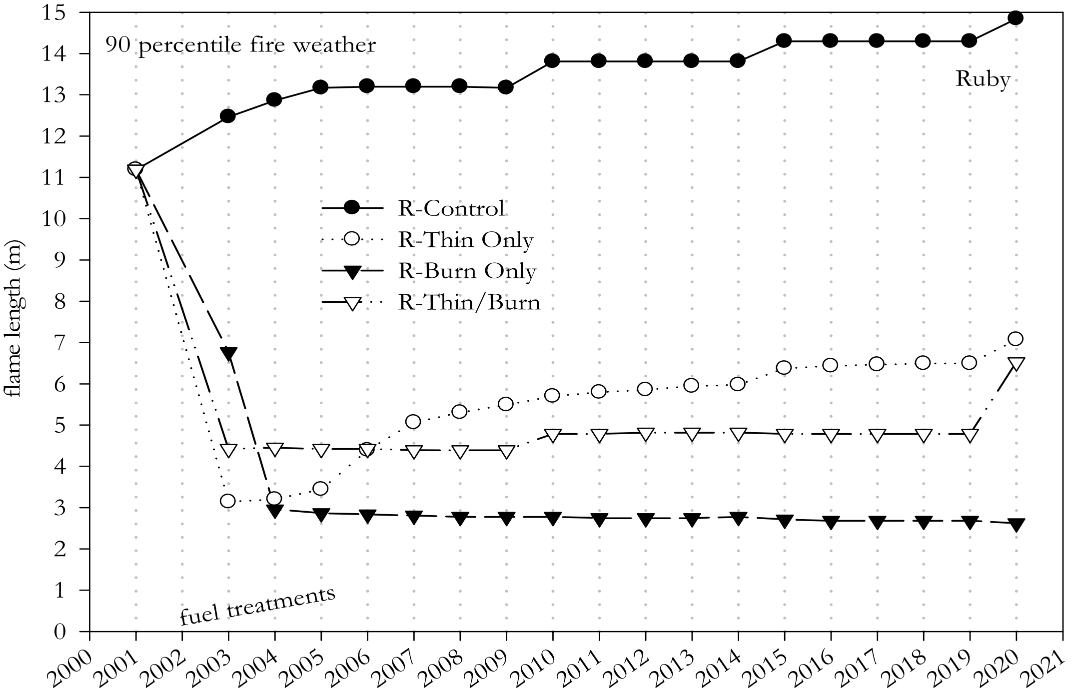


Figure 31: Potential flame length (m) resulting from 90 percentile plus wildland fire modeled each year under four fuel treatment scenarios with FVS-FFE over a 19 year period for Crow 6 and Ruby EUs. Treatments applied in 2002 and initial effect displayed in 2003. Each year represents the potential effect if a 90 percentile plus wildland fire occurred. FVS cycle boundaries are set at 2001-05 and at 5 year intervals thereafter.

The largest treatment effect on flame length occurs at the Ruby EU. Flame length gradually increases in the CTRL from 4.8 m in 2003 to 6.7 m in the last FVS cycle under 80 percentile conditions (Figure 30, Ruby). Under 90 percentile plus conditions, CTRL flame length is 2.5 times greater over most of the modeled time period (Figure 31, Ruby). Passive fire is modeled throughout the time period under 80 and 90 percentile plus fire weather conditions. Fire behavior fuel model timber group 10 in 2003 is 90% of the calculation weight with shrub group 5 at 10%; however, by 2014 the two groups share near equal weighting. Differences between 80 and 90 percentile plus fire weather flame length were greatest in the CTRL. Over the given modeled timeframe at Ruby CTRL, there is a mean increase of 90 percentile plus fire weather flame length of 7.7 m with a minimum of 7.4 m and a maximum of 8.1 m over 80 percentile fire weather flame length.

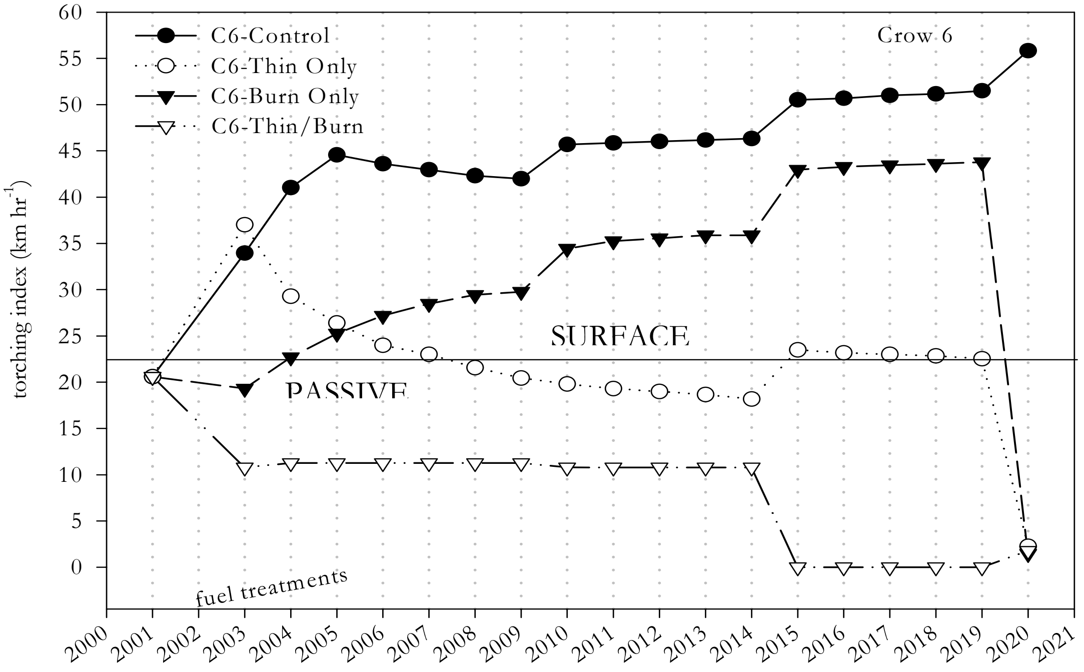
The Ruby TO treatment has the greatest initial effect on flame length, with a modeled reduction of 2.8 m less than the CTRL under 80 percentile fire weather. While that difference is maintained, TO flame length gradually increases to 3.9 m over the modeled time period. Passive fire behavior is modeled throughout the time period under 80 and 90 percentile plus fire weather conditions. Slash fuel models represent from half to over half of the percent weight the first few FVS cycles post thinning treatment and the remaining cycles are modeled in the heavy timber group (NFFL fuel model 10). Fuel model 10 and 5 dominate over the rest of the time period, but with percent dominance reversing from 10 to 5. Over the given modeled timeframe at Ruby TO treatment, there is a mean increase of 90 percentile plus fire weather flame length of 2.4 m with a minimum of 1.2 m and a maximum of 3.4 m over the 80 percentile fire weather flame length.

The Ruby BO treatment under 80 percentile fire weather conditions reduces flame length to 2.7 m with further gradual reductions to 2.1 m over the modeled time period, overall reduction greater than other treatments (Figure 30, Ruby). Passive fire behavior is modeled the immediate year post treatment, but surface fire behavior is modeled from the remaining time period under 80 and 90 percentile plus fire weather conditions. Heavy timber fuel model 10 and shrub fuel model 5 dominate the fire behavior fuel models used for calculations throughout the modeled time period. Over the given modeled timeframe at Ruby BO treatment, there is a mean increase of 90 percentile plus fire weather flame length of 2.4 m with a minimum of 1.2 m and a maximum of 3.4 m over the 80 percentile fire weather flame length (Figures 30 and 31, Ruby).

Effects of the Ruby thin and burn treatment are more erratic than the other treatments, but similar to BO treatment under 80 percentile fire weather and similar to TO treatment under 90 percentile plus conditions. Flame length varies between 2.1 m and 2.6 through 2019. Flame length makes a large increase at the 2020 FVS cycle boundary to 3.8 m under 80 percentile conditions (Figure 30, Ruby). From the initial treatment canopy base height increase from 1.5 m to 8.5 m, makes a slight drop in 2010 before dropping to 0.9 m in 2020 (Figure 28, Ruby). Under 90 percentile plus fire weather conditions, fire behavior is modeled as passive; however, under 80 percentile fire weather surface fire behavior is modeled in the years 2008-09 and 2015-19. Fire behavior fuel model 5 represents over half percent weight used to model flame length post fuel treatment, but percent weight increases to 76% by the last cycle modeled. The remaining 50% of fuel model weight is divided between fire behavior fuel model 1 (grass) and 10 (heavy timber). Fuel model 1 represents a greater proportion until 2009, at which time fuel model 10 increases and fuel model 1 decreases. Over the given modeled timeframe at Ruby TB treatment, there is a mean increase of 90 percentile plus fire weather flame length of 2.2 m with a minimum of 1.9 m and a maximum of 2.7 m over the 80 percentile fire weather flame length.

All fuel treatments at the Ruby EU had a large effect on flame length in comparison to the CTRL (Figure 30 and 31). Differences between the BO and TB were small under 80 percentile fire weather, but increased under 90 percentile plus weather. Over the time period modeled, the TO treatment flame length was reduced the least.

Torching index (TI) indicates the 6.1 m windspeed at which the threshold from surface to passive crown fire would initiate. TI was modeled under 90 percentile plus fire weather conditions. All TI data points that are greater than the 6.1 m windspeed, 22.5 km hr^{-1} 90 percentile plus fire weather, are modeled as surface fire, all those less than the 6.1 m windspeed are modeled as passive crown fire (Reinhardt and Crookston 2003,



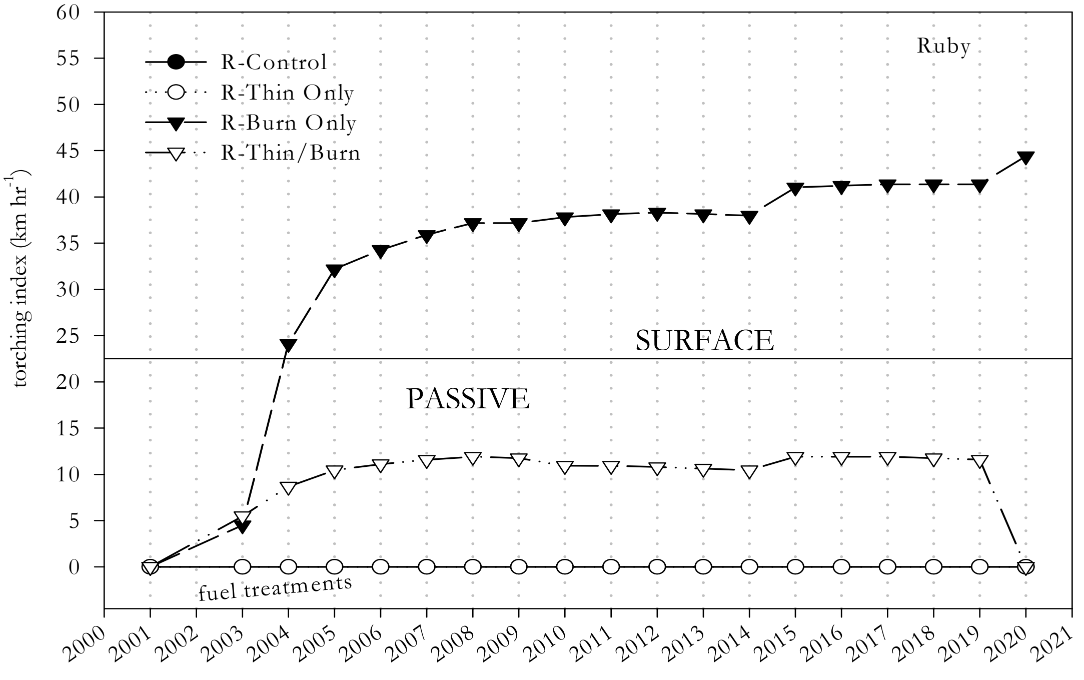


Figure 32: Torching index (km hr^{-1}) resulting from 90 percentile plus wildland fire modeled each year under four fuel treatment scenarios with FVS-FFE over a 19 year period for Crow 6 and Ruby EUs. Surface fire behavior is modeled when the torching index is above the 97 percentile wind speed, 22.5 km hr^{-1}, and passive fire when below. Treatments applied in 2002 and initial effect displayed in 2003. Each year represents the potential hazard if a 90 percentile plus wildland fire occurred. FVS cycle boundaries are set at 2001-05 and at 5 year intervals thereafter. Control and Thin Only are equal at Ruby, therefore Control not shown.

Figure 32). All treatments had a lower TI relative to the CTRL at Crow 6, with one minor exception. Immediately post treatment, TO torching index is the highest, at 37 km hr^{-1}, but drops rapidly. TB maintains the lowest TI, just over 10 km hr^{-1} through the FVS transition in 2015, where it drops to zero km hr^{-1} (Figure 32, Crow 6). BO treatment results in an increasing TI value, starting post treatment of 19 km hr^{-1}, increasing up to 45 km hr^{-1} before dropping to just above 1 km hr^{-1}.

Response of TI to fuel treatments at Ruby is very different than the response at Crow 6. In this case, the CTRL and TO Torching Index treatment response never is greater than zero km hr^{-1}—torching occurs with no wind (Figure 32, Ruby). The TO and BO Torching Index make an initial jump from zero to just below 5 km hr^{-1}, at which point the BO jumps to about 30 km hr^{-1}, and gradually climbs to near 45 km hr^{-1} over the remainder of the modeled time period. Whereas, the TO is modeled near 10 km hr^{-1} until the last FVS cycle period where it drops back down to zero km hr^{-1}.

Crowning Index (CI) is the 6.1 m windspeed needed for a fire to be sustained in the canopy *after* it has made the transition from surface fuels to crown fuels and is dependent on canopy bulk density, slope steepness, and surface fuel moisture content. As all variables are held constant except canopy bulk density, CI follows patterns of reduction of canopy bulk density (Figure 29).

CI was modeled under 90 percentile plus fire weather conditions. As canopy bulk density decreases, CI increases–Figure 29of CBD is nearly the inverse of CI graph (Figure 33). The CTRL and BO after 2010 at Crow 6 have the highest chance of crowning with lowest windspeeds in both Crow 6 and Ruby: CI values range from 47 km hr^{-1} to 90 km hr^{-1} at Crow 6, and 31 km hr^{-1} to 83 km hr^{-1} at Ruby over the time period modeled. The BO treatment results in an increase in CI near 10 km hr^{-1} immediately post treatment until the 2010 FVS-cycle in both EUs, but at which point CI drops by 3 km hr^{-1} at Ruby, and four times that at Crow 6. In the short-term, TO treatment increases CI above 70, and TB treatment above 80 in both EUs. CI for the TB and TO declines in both EUs after 2010, but there still is a large difference in relation to the BO and CTRL treatments; however, the difference is greater at Ruby than Crow 6 (Figure 33). Active crown fire is defined as CI values that fall below the 6.1 m windspeed, 22.5 km hr^{-1} under 90 percentile plus fire weather (Reinhardt and Crookston 2003). No active crown fire was modeled in either EU (Figure 33).

Active crown fire is modeled when the torching index is below the 6.1 m windspeed, which represents 97 percentile windspeed in this research (22.5 km hr^{--1}) AND the crowning index is less than the 6.1 m windspeed (Figures 32 and 33). Passive fire is modeled in all the treatments except for in the BO treatment from 2004 on at Ruby. Surface fire dominates at Crow 6, except the TB treatment and period of time in the TO treatment

Potential Changes in Basal Area Mortality – 19 Year Period

Under 90 and 80 percentile fire weather conditions at Crow 6, treatments increased basal area (BA) mortality above the CTRL, except for a short period immediately post treatment when TO is less (Figures 34 and 35, Crow 6). Percent mortality (BA) at Crow 6 tends to follow a similar pattern as flame length; however, there are deviations. All treatments show a sharp decrease in mortality, including the CTRL through 2005; however, initial TO mortality drops twice that of the other treatments. There is little difference in treatment effect over the short-term, but differences are more pronounced under 90 percentile plus conditions (Figures 34 and 35, Crow 6). Under 80 percentile conditions, from 2005 to 2014, BA mortality hovers around 20%, but under 90 percentile plus conditions range from and 55% to 75%. In the next FVS cycle, 2015-2019, TB percent BA mortality increases from 18% to 55% while there is little change in the other treatments. In the last cycle, the TB treatment percent BA mortality drops back down to 23%, BO increases to 51%, and the TO makes a slight increase to 21% under 80 percentile weather conditions.

Percent BA mortality is greater in all treatment under 90 percentile plus weather conditions vs. 80 percentile weather conditions (Figure 34 and 35). The mean increase between 80 and 90 percentile plus conditions in the treatments is 35% for the CTRL, 44% for the TO and BO treatments, and 51% in the TB treatment. Maximum increases in levels of mortality range from 42% to 54% in all the treatments over the modeled timeframe. Minimum increases in levels of mortality range from 18% to 38%.

Another scenario plays out at the Ruby EU; near 100% mortality is modeled in the CTRL for the duration of the timeframe under 80 and 90 percentile plus fire weather conditions (Figures 34 and 35, Ruby). The TO treatment models the largest decrease and lowest percent BA mortality, from 94% to 33% in respective years 2001 and 2003, but then increases rapidly to reach a peak of 89% 18 years post treatment under 80 percentile conditions. There is also a rapid decrease in percent BA mortality following treatment in the BO and TB treatments, while initial reduction is not as great as in the TO, the lower levels of mortality are maintained for a longer period. The BO continues to drop to 38% at the end of the modeled timeframe, whereas the TB models a rapid increase from 36% to 57% from the 2013 to the 2015 timeframe, but drops back to 41% in 2015 before rising to 88% in the final FVS cycle. While there is little difference in response of the CTRL between 80 and 90 percentile plus fire weather, the effect of fuel treatments is reduced greatly under 90 percentile plus conditions at Ruby EU. TO treatment effect reduces percent BA mortality to near 85%, the percentage quickly rises to 94 percent, the same level as the TB treatment. Over the modeled timeframe the BO indicates the lowest level of mortality, but with mortality levels around 85% (Figures 34 and 35).

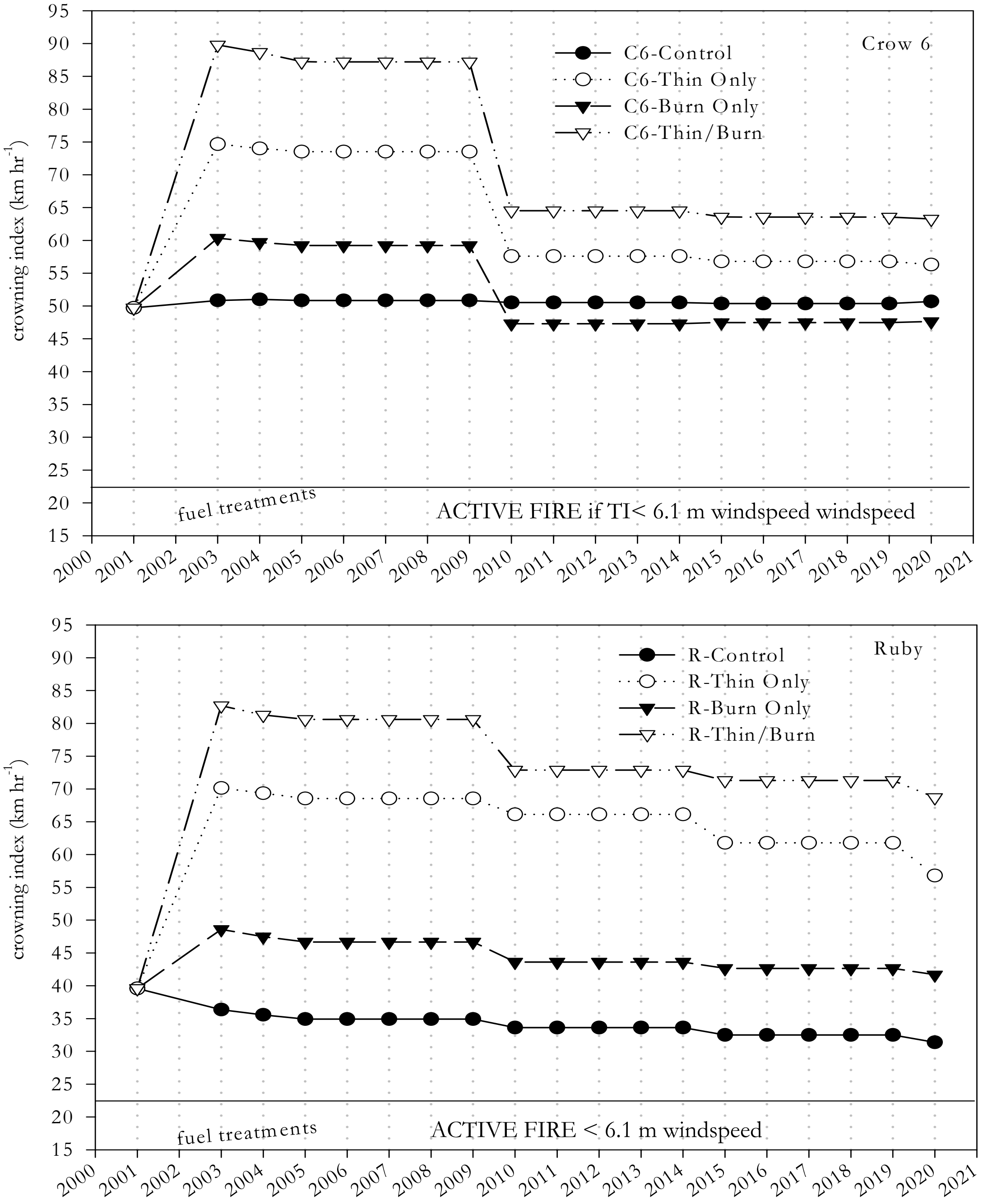
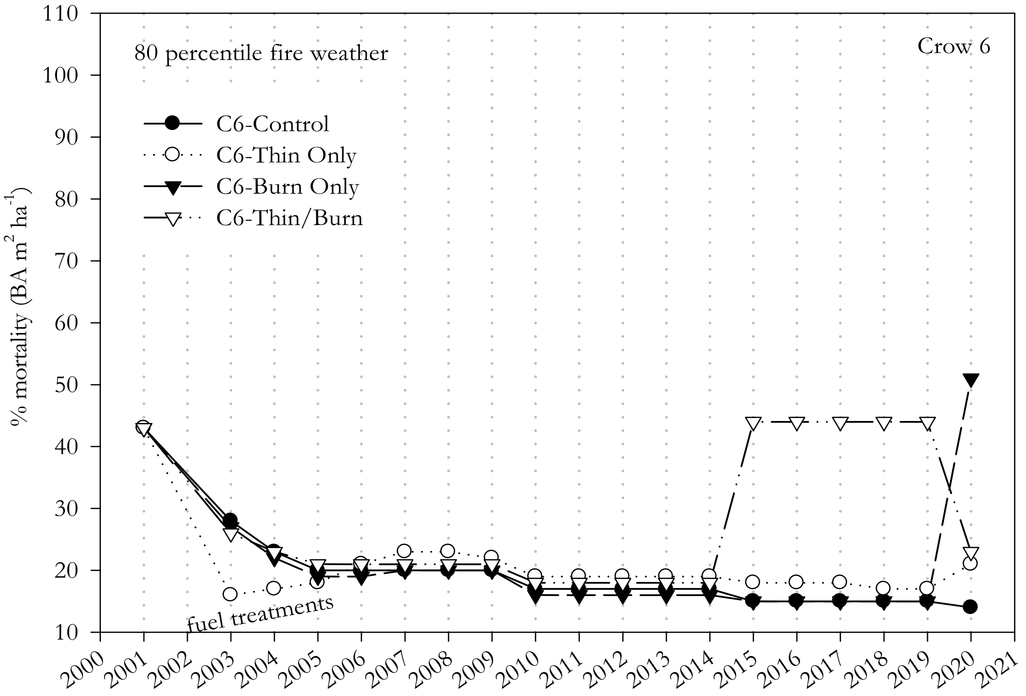


Figure 33: Crowning index (km hr^{1}) resulting from 90 percentile plus wildland fire modeled each year under four fuel treatment scenarios with FVS-FFE over a 19 year period for Crow 6 and Ruby EUs. Treatments applied in 2002 and initial effect displayed in 2003. Each year represents the potential hazard if a 90 percentile plus wildland fire occurred. Active fire behavior is modeled in FFE when the torching index AND crowning index is below the 6.1 m wind speed, 22.5 km hr^{1}· FVS cycle boundaries are set at 2001-05 and at 5 year intervals thereafter. Control and Thin Only are equal at Ruby, therefore Control not shown. FVS cycle boundaries are set at 2001-05 and at 5 year intervals thereafter.



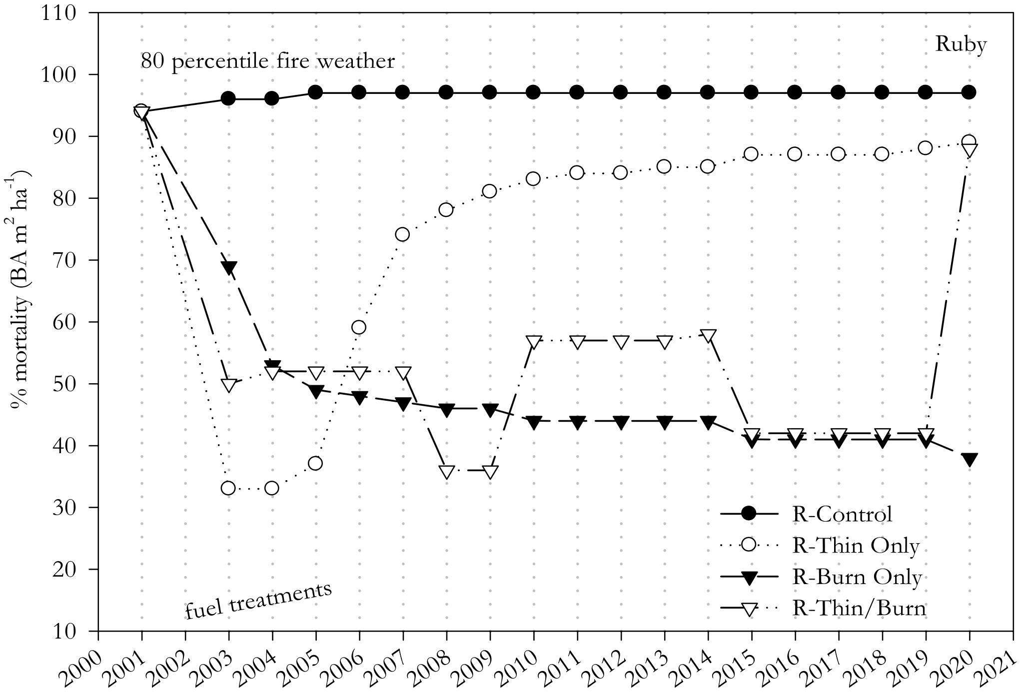
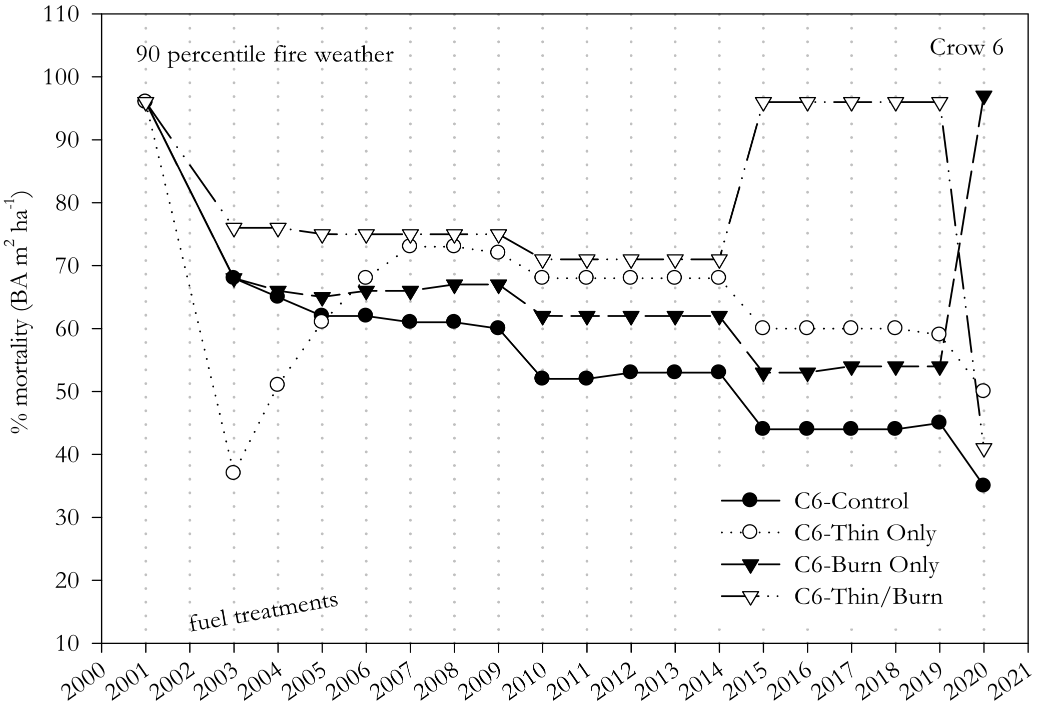


Figure 34: Potential percent basal area mortality resulting from 80 percentile wildland fire modeled each year under four fuel treatment scenarios with FVS-FFE over a 19 year period for Crow 6 and Ruby EUs. Treatments applied in 2002 and initial effect displayed in 2003. Each year represents the potential effect if an 80 percentile wildland fire occurred. FVS cycle boundaries are set at 2001-05 and at 5 year intervals thereafter.



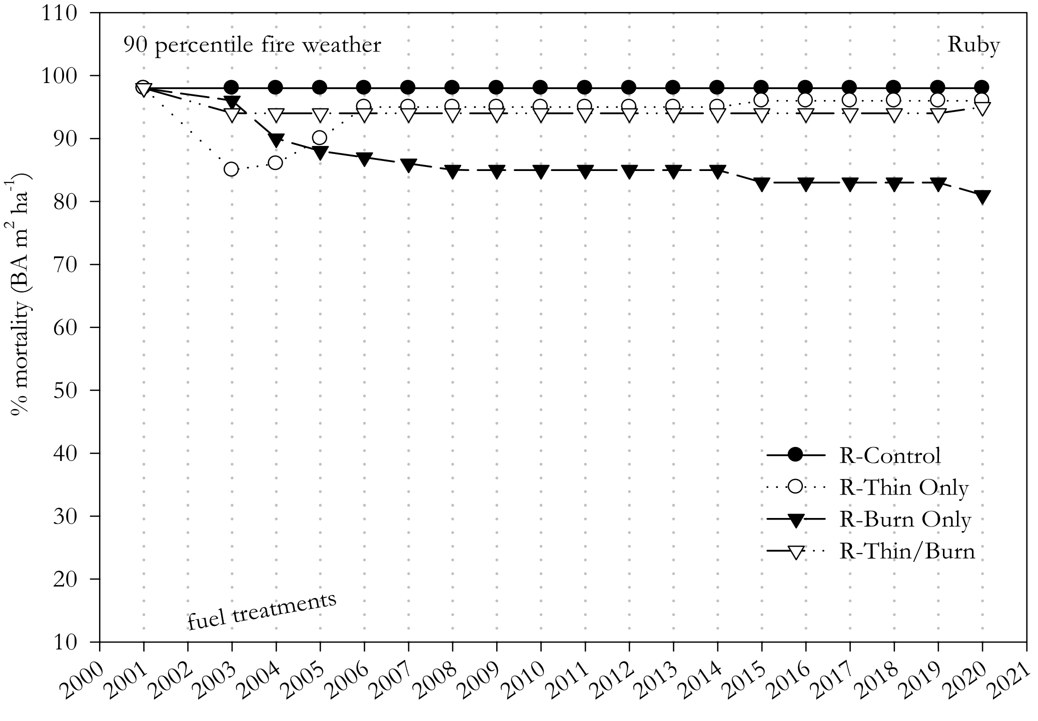


Figure 35: Potential percent basal area mortality resulting from 90 percentile plus wildland fire modeled each year under four fuel treatment scenarios with FVS-FFE over a 19 year period for Crow 6 and Ruby EUs. Treatments applied in 2002 and initial effect displayed in 2003. Each year represents the potential effect if an 90 percentile plus wildland fire occurred. FVS cycle boundaries are set at 2001-05 and at 5 year intervals thereafter.

DISCUSSION

Existing Wildland Fuel Conditions and Modeled Treatment Effect

Variability of Fuel Profile

Existing surface fuel variables in dry forests of the Wenatchee Mountains demonstrate high variation within stands, and moderate differences between stands, whereas canopy fuels attributes generally had higher variation between stands and less within. This general relationship is not too surprising considering that homogeneity of overstory vegetation is an important delineation criterion for identifying stand boundaries. Therefore, the within variability of overstory structure is reduced in the sampling process, whereas, a broader range of surface fuel conditions are included within a stand. It was not uncommon for surface fuel variables to be two standard deviations from the mean. These data indicate that surface fire behavior and severity within a stand could be quite variable at microsites. Indeed, fire behavior fuel models represented in each experimental unit range from five to seven; however, typically fire behavior fuel model 2 and 5 represent over 60% of the area in each EU (Figure 18). Fire behavior and effects models that report results based on mean level inputs. How much the variability matters is likely dependent on the scale at which any particular process or outcome operates—mean level fire intensity may have different effects on a given rare plant population than upper percentile conditions, but may have less effect on rate of fire spread. FVS-FFE does not compensate for within unit variability (mean surface fuel values are typically used as inputs); however, it does weight multiple fire behavior fuel models based on surface fuel components, as well as other fuel profile attributes, to calculate mean fire behavior and severity. Users do have the option to input any range of percentile fuel conditions to model fire behavior and effects or vary the size of the stand modeled to represent greater variability. The later might be conducted when producing output data to be used in FARSITE fire spread model. Ultimately, management objectives should determine choices.

Results indicate moderate levels of variability between experimental units as expected. The Kruskal-Wallis test statistic indicates at least one median difference between 12 EUs for each of the 18 fuel variables tested and that differences are not a coincidence. Furthermore, Dunn's post-hoc test indicates low to moderate numbers of significant median differences between EU pairwise comparisons of fuel variables tested (Table 24, Appendix E). Of 12 fuel variables tested, the greatest number of variables with significant differences found between any two EUs was seven, only occurring once, between Pendleton and Spromberg (Table 24). Out of 66 experimental pairwise comparisons, a significant median difference of two fuel variables was most common, with 17 pairs. Nine pairwise comparisons had no significant median fuel differences of the 12 fuel variables tested. Greatest overall differences appear to be between the groups of EUs Spromberg, Slawson, Ruby, Little Camas, and the group Crow 1, Crow 6, Pendleton (Table 24). These differences are likely explained by location of EUs in the gradient summarized in Table 13 and past management practices (Table 14). The first group located at the higher elevation range has a northern distribution and three of the four EUs were harvested in the 1970s. Whereas, the second group is located at a lower elevation range, has the southern most distribution and pre-commercial thins occurred in the 1970s.

Table 24. Summary of significant median differences of 12 fuel variables across 12 experimental units sampled.

EU	Crow 3	Crow 6	Little Camas	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
Crow 1	R,S,D,h,B	-	1,2,L,D,B	S,D,s	3,R,D,h,B	D,h,B	1,3,R,S,D,s	1,D	1,R,L,D,h,B	1,L,D,h,C,B	1,d,D,h,B
Crow 3	--	D,h	L	1,D	-	R,S,d	-	D	1,S,L	1	D,D
Crow 6	-	--	1,2,L,D,h,B	h,s	D,h	1,D,h,C,s	1,R,S,D	1,3,D,C	1,L,D,h,C,s	1,L.D,h,C,B	1,d,D,h
Little Camas	-		--	1,L,D,h	L	2,L	R,L,h	3,L,h,B	2,h	-	L,D
Pendleton	-	-	-	--	1,D,s	1,S,D	1,R,D	1,D	1,2,R,L,D	1,R,L,D,h,s,B	1,D,s
Poison	-	-	-	-	--	3,R	s	-	1,L	L,D	-
Ruby	-	-	-	-	-	--	R,S,	3,B	d,L	-	D
Sand 19	-	-	-	-	-	-	--	-	S,L	R,S,h,s	R,d,D
Sand 2	-	-		-	-		-	--	2,d,L	3,D,h,B	-
Slawson	-	-	-	-	-	-	-	-	--	H	d,L,D
Spromberg	-		-		-	-	-		-	--	d,L,D

1 = 1 hour timelag fuel, **2** = 10 hour timelag fuel, **3** = 100 hour timelag fuel, **S** = sound 1000+ hour timelag fuel, **R** = rotten1000+ hour timelag fuel, **d** = down dead wood depth, **L** = litter (Oi), **D** = duff (Oe), **h** = total herbaceous, **s** = total shrub, **C** = canopy closure, **B** = stand base height

Of the 12 fuel response variables tested, number of significant median pairwise differences varied by fuel variable (Table 24 and 25). Duff appears to be the most variable, with 36 out of 66 pairwise differences, and canopy closure appears the least, with five. Differences between one hour timelag fuel loading appears to be less across EUs than 10 and 100 timelag fuels.

Table 25. Number of significant pairwise median differences per fuel variable across 12 EUs.

fuel response variable	# pairwise differences
canopy closure	5
10 hour timelag	6
100 hour timelag	7
total shrub	8
down wood depth	9
rotten 1000+ hour	12
sound 1000+ hour	12
measured CBH	13
litter	23
total herb	23
1 hour timelag	25
duff	36

Differences of fuel response variables between treatments will influence fire behavior and severity as indicated by modeled results between Ruby and Crow 6 EUs. However, the magnitude of difference will be dependent on the combination of fuel variable differences that compose a given fuel profile, as well as physical attributes such as slope and fire weather. Pretreatment differences are great enough in some variables between EUs that consideration of differences will important in analyzing post treatment effects in the Fire and Fire Surrogate Treatments study.

Forest Floor

The litter fuel models developed to estimate mass with depth resulted in similar estimates in Douglas-fir and mixed results in ponderosa pine compared to other models reported in the literature. The general duff model developed slightly underestimated loading in comparison to results of other studies; however, the literature was lacking models developed in the East Cascades forests of ponderosa pine or Douglas-fir for comparison. Brown (1970) reported average ponderosa pine litter load values of 3.24 Mg ha^{-1} in the northern Rocky Mountains. Agee (1973) developed models in ponderosa pine and incense cedar (*Calocedrus decurrens [Torr.] Florin*) forest that predicted 7.83 Mg ha^{-1} for litter, 11.14 Mg ha^{-1} for duff, and a combined forest floor prediction of 10.25 Mg ha^{-1} for every centimeter of depth in the southern Sierra Nevada mountains of California. van Wagtendonk et al. (1998) developed models predicting 8.64 Mg ha^{-1} of litter and 13.19 Mg ha^{-1} of duff for Douglas-fir stands and in ponderosa pine stands 2.76 Mg ha^{-1} of litter and 14.02 Mg ha^{-1} of duff for every centimeter of depth in central Sierra Nevada. The prediction of the ponderosa pine litter model reported in this research is intermediate between these estimates. Differences in models may be attributed to differences in stand structure between the sites. In the Sierra Nevada of California van Wagtendonk et al. (1998) reported that depth mass predictions were strongly affected by stand structure and composition.

Even with the lack of fire these stands experienced over the last century, development of the duff layer is minimal. Duff development, or mean depth was greater in EUs dominated by ponderosa pine, Crow 1, Crow 6, and Pendleton units following relationships reported by Agee (1973) and van Wagtendonk et al. (1998). However, relative to other EUs, average percent slope of stands dominated by ponderosa pine is less, are at typically at lower elevations, and likely have lower annual precipitation which likely affect the amount of duff development and decomposition.

Large reductions in short-term litter and duff fuel loads were modeled in the burn treatments compared to the thin treatments (Figures 22 and 23). It was expected that there would be greater differences between the non-burn and burn treatments, and to a lesser degree between the TO and the CTRL litter in the short-term due to a pulse of foliage from thinned trees. While approximately 1.6 Mg ha^{-1} and 4.5 Mg ha^{-1} of foliage was contributed to the litter pool from activity fuels at Crow 6 and Ruby respectively (Table 20), it is not apparent in Figure 21, as there is a very rapid reduction in litter loads in all treatments, including the CTRL, in a five year period. It is difficult to determine the cause of this rapid decrease; it could one or a combination of three factors: 1.) the depth/mass model is over-predicting fuel load, 2.) the East Cascades variant of FFE decay rate is too rapid, or 3.) the EC variant is predicting too little litter fall. As FVS-FFE assumes that 100% of the current overstory tree foliage will fall within 4 and 5 years, and the depth/mass model is predicting loads that are similar to other reported results, it appears that a decay rate of 33% annually is too high. Preliminary results at the FFS site indicate litter decaying near 17 percent a year (George Scherer, Graduate Student, University of Washington, College of Forest Resources, Soils Lab, February 2005, written communication). In addition, it is likely that total contribution to the litter pool is underestimated, as the current model does not represent any litter that would accumulate from contributions from species other than trees, i.e. litter contributions from shrub and herbaceous species is not modeled in FVS-FFE. Underestimation of litter load in the CTRL and TO treatments would lead to an underestimation of fire behavior variables and effects under those treatments; however, it should not change relative differences between treatments.

Timelag Fuels

There is an initial rapid increase in the CTRL fine dead wood surface fuel that was not expected (Figure 21). This is a likely a result of rapid crown lifting and the movement of branch fuels to the surface profile. While there is not a direct measure of crown lift reported by FVS, summary of crown ratios from individual trees indicate a decrease in crown ratio, which would indicate a decrease in crown length. Crown lifting is modeled for every FVS cycle, of which there are four cycles in the first four years and every five years for the remaining time modeled. This should not affect the amount of material that is transferred to the surface profile as the amount of material calculated to fall each year is proportional to the time period. Mortality of trees is also a potential explanation of the rapid increase in fire dead wood fuel; however, mortality rates are low over the given time period. Furthermore, SDI (stand density index) is well below the level where mortality starts to occur at Crow 6, and just above at Ruby. As growth data was not collected for the site to, it remains unknown if the modeled growth rates are realistic.

It was expected that long-term response of fine dead surface fuels would include a gradual increase in loading and that relative differences from initial response would stay the same (Figure 21). While this trend occurred at Crow 6, except at the TO treatment, there was a relative decline in fine fuel loading at Ruby, except for the TO treatment where there was a rapid continual decline in loading (Figure 21). As discussed above, this trend can be attributed to the rate of tree growth in each of the treatments and corresponding rate at which crown lifting occurs. The intermediate TO only treatment has the highest initial loading because of the activity fuels; the relative decline in loading over time is attributed to reduced growth rates and corresponding reduced additions to fine surface fuels.

Herbaceous and Shrub Fuels

Estimated live and dead herbaceous load from field data collected was 1.12 Mg ha^{-1} at Crow 6 and 0.29 Mg ha^{-1} at Ruby. These values compare with an estimated starting live herbaceous load of 0.52 Mg ha^{-1} at both Crow 6 and Ruby, thus FEE under and over estimated starting herbaceous values compared to field models. Modeled shrub load from field data includes one hour equivalent live and 1-100 hour dead at 1.83 Mg ha^{-1} at Crow 6 and 2.09 Mg ha^{-1} at Ruby. This compares to FFE starting loads live shrub loads of 0.38 Mg ha^{-1} at Crow 6 and 1.08 Mg ha^{-1} at Ruby. In this instance, FFE underestimates shrub loading 2 to 5 times in comparison to field estimates. As shrub and herbaceous fuel loadings are not used to model fire behavior, the discrepancy does not affect treatment effect modeled in this research, but could contribute to real fire behavior differences.

Little difference of herbaceous or shrub fuel load was modeled in FFE between fuel treatments at Crow 6, but differences were pronounced at Ruby (Figures 24 and 25). This is not surprising, as the model interpolates between an “initiating” and “established” loading based on tree species and canopy cover. The spread of canopy cover between treatments at both EUs was not large, approximately 20% (Figure 27); however, Crow 6 is dominated by ponderosa pine and Ruby is dominated by Douglas-fir. Douglas-fir has broader span of modeled potential shrub loading between established and initiated (Table 7), and shrub loadings with dominant overstory of ponderosa pine are expected to decrease with a decrease in canopy cover explaining greater differences between the two EUs.

At Ruby, differences in treatments were expressed as greater loading of shrub and herbaceous fuels in the TB, little difference between the BO and the TO, and the CTRL the lowest (Figures 24 and 25). Minimal differences between TO and BO treatments can be explained by the built in assumption that directly relates understory fuel load to canopy cover without delay—understory response is dependent on overstory response, independent of treatment type. Understory consumption and direct response to fire is not modeled in FFE. Expectations of understory fuel load were not met at Crow 6, with little response in loading to treatments. Initial short-term expectation was a decrease in shrub and herbaceous loads in the burn treatments, with an increase in the TO. Shrub decreased slightly in response to all treatments and herbaceous loading increased slightly.

Canopy Fuels

It was expected that modeled canopy base height (CBH) would stay constant in the CTRL and intermediate TO, and increase in the BO and TB immediate post treatment. The intermediate TO treatment was not expected to increase CBH to a large degree as trees of small diameter—and height, were not removed. While the short-term effect of treatments followed expected trends at Ruby, the Crow 6 TO treatment CBH was increased to a slightly higher level than the BO treatment. At Crow 6, removal of intermediate size trees increased CBH as a small tree layer was predominately absent. Prescribed fire had little effect on CBH at Crow 6 as CBH was over 4 m pre-treatment, whereas at Ruby pre-treatment CBH was just over 1 m (Table 20, Figure 28). Greater treatment effect on CBH was modeled at the Ruby site, except there was little change between the CTRL and the TO treatment; however, this result is not surprising given the TO treatment only prescribed removal trees of intermediate size. Beyond relative short-term trends between treatments, CTRL CBH increased just over 4 m at Crow 6 in two FVS growth cycles (Figure 28). This is likely attributed to the change in crown ratio discussed above under timelag fuels, but it is not clear why there is a rapid change in crown ratios as tree height and diameter are increasing at moderate intervals. The CTRL CBH at Ruby does not follow this trend at Crow 6, as crown lift is masked by the differences in initiating structure between the two stands. Crow 6 has a very low density of trees below the 10-20 cm dbh size class, unlike Ruby, where there is a very high number of small diameter trees (Figures 6 and 7). Crown lift on small trees also occurs at a much slower rate.

The BO treatments increased CBH by over 6 m; however, by 2015 there is a pulse of regeneration in the TB treatment at Crow 6 and the CBH is reduced to under a meter, followed by BO at Crow 6, and TB at Ruby in 2020 (Figure 28 and 26). Rapid shifts in CBH can occur using the FFE method, using a volume of canopy material versus a mean stand height, but likely better portrays the relationship between CBH and passive crown fire. Long-term modeling of CBH is highly dependent on rate and amount of understory regeneration which can be difficult to predict (William E. Hartl, March 2003, written communication); however, is key to modeling the transition of surface fire to passive, and therefore the effectiveness and longevity of treatments. This research had limited information concerning regeneration to incorporate into the modeling. Lower or higher numbers and timing of regeneration would affect results.

Few surprises were observed in modeling effects of treatments on canopy bulk density, except that ten years after the BO treatment at Crow 6, canopy bulk density was modeled as greater than the CTRL (Table 20, Figure 29). This result is a product of the way regeneration was modeled, but does give pause to the possibility of a treatment increasing the vigor or increasing reproduction in a stand, and thus increasing mid-term CBD over a no treatment scenario; however, it is unlikely that regeneration and growth of trees in the study area would grow such that CBD would increase in a period of ten year. Nonetheless, no data was collected in the study area to analyze the response to thinning, and therefore is conjecture. It was expected that CBD would continue to increase in the CTRL at Crow 6, as it did at Ruby (Figure 29). In both of the stands modeled, reduction of CBD by the BO treatment was relatively less than the other treatments. The result is due to the real limitations of burning conditions allowed for implementing prescribed burns to obtain the level of mortality prescribed. Multiple entries with prescribed fire may be a solution; however, many managers still may not risk burning under more extreme conditions even with moderated fuel profile conditions.

Modeled Treatment Effect on Fire Behavior and Severity

Flame Length

FVS-FFE indicates initial short-term flame length and scorch height response between active treatments under 80 percentile weather conditions is the reverse from the trend expected; however, modeled differences between treatments at both EUs modeled are small (Figure 19). Nonetheless, active treatments at Ruby resulted in flame lengths that were near half that of the CTRL, but were just slightly less or greater at Crow 6. Simulated flame length increased in both fuel profile scenarios: from lowest to greatest in order of TO, BO, and TB (Figure 19). Intuitively one would expect as surface fuels are reduced flame length would decrease. Surface fuels increase as a result of the TO treatment and decrease in order of BO and TB treatments. Surface flame length response to treatments can be explained in terms of slope, fuel moisture, temperature, mid-flame windspeed as it relates to canopy cover, surface fuel loading, and the selection of fire behavior fuel models, of which the first three variables listed are held constant within each EU. TB treatment in both EUs had by far the greatest reduction in surface fuels (Table 19, Figures 21 and 21); it also reduced canopy cover by the greatest margin (Figure 27), which initiates greater mid-flame wind speeds which can increase flame length. A greater load of fine fuels does not automatically translate into longer flame lengths. For example, the TO treatment at both EUs has greater fine surface fuel loads than the BO; however, the flame length is less in the TO. The difference is not explained by mid-flame windspeed in this particular instance (Table 22), as is equal or greater in the TO, but is explained by the selection and weighted proportion of fire behavior fuel models selected (Table 26). Each FVS-FFE variant has defined parameters for determining which, and the percent weight, of the fuel models used for fire behavior calculations.

Table 26: Weighted percent of NFFL models selected by FFE to calculate 80 percentile wildland fire behavior and effects at two years post fuel treatments. Control, thin only, burn only, and thin and burn on Crow 6 and Ruby experimental units.

	Crow 6				Ruby			
	CTRL	TO	BO	TB	**CTRL**	TO	BO	TB
Fuel Models – 2 years post	6-65	11-35	6-89	2-62	10-83	11-53	5-84	5-58
	10-35	10-23	2-11	6-38	5-17	10-36	10-16	1-30
		6-23				12-11		10-12
		2-19						

The FFE East Cascade variant selects fire behavior fuel models based on surface and canopy fuel variables to calculate fire behavior, including: dominant tree species based on BA, quadratic mean diameter, canopy cover, fine and coarse fuel load, and activity fuels. Heavier fuel and logging slash type fire behavior fuel models are selected for the TO treatment, whereas the BO and TB are dominated by the shrub fuel model group at Ruby; however, at Crow 6 the grass fuel model group dominates. If a thin from below starting with the smallest trees would have been conducted or greater removal of BA, it is likely that fire behavior fuel models 12 or 13, medium and heavy logging slash, would have been allotted considerable weighting in the calculation of fire behavior in the thin treatments. Fire behavior increases considerably, perhaps times two, from Anderson's (1988) NFFL fuel models 11 to 12 and 13. Selection of fire behavior fuel models and allotted weight has a strong effect on modeled fire behavior. While the dynamic method moderates jumps in modeled fire behavior, it does not avoid the fact that the relationship between fuels and fire behavior is not based on continuous inputs and outputs. To date, fire behavior researchers have not resolved this issue. However, there are likely many relationships between fuels and fire behavior where discrete thresholds are real, resulting in rapid shifts in fire behavior.

It is often suggested in fire behavior models to adjust fire behavior parameters to meet fire behavior expectations (Burgan and Rothermel 1984, Finney 1997). The process of modeling will help managers gain insight into given fuel treatment scenarios, but if the user needs to adjust the model for outputs that are expected, the usefulness of the model is limited especially in the context of comparing short and long-term effects of treatment scenarios, and should be recognized.

Long-term trends (over 19-year period) followed similar response to short-term response at Crow 6 and Ruby; however, when percentile fire weather was increased from 80 to 90, differences between treatment effect and the control were large at Ruby. An increase in percentile fire weather, from 80 to 90, resulted in nearly doubling pretreatment flame length in both EUs; however, the treatment effect was much greater at Ruby. Relatively small changes in fire weather can have relatively large effect on fire behavior response to treatments depending on initial characteristics of the fuel profile.

Interestingly, while Crow 6 initial flame length under 90 percentile plus weather increased (Figure 31, year 2001) from the same period under 80 percentile weather (Figure 30), flame length drops from near three meters to around two meters for all the treatments including the control. It appears that the same trend occurs under 80 percentile fire weather conditions but is not apparent due to the magnitude of the response. It is likely that rapid decrease in flame length is related to the extremely rapid modeled decrease in litter fuels (Figure 22). From 2001 to 2003 litter load decreases by 10 Mg ha^{-1}; however, fine dead wood surface load increases 3.5 Mg ha^{-1} in the same period.

Passive and Active Crown Fire

Expectations of passive crown fire—the torching index, were met with mixed results (Figure 32). As slope and surface fuel moisture were held constant across the treatments, response should be explained in terms of surface fuels, wind reduction by canopy cover, and canopy base height. It was expected that the treatments that reduced ladder fuels, effectively increasing canopy base height, would increase the torching index, it was not expected that the burn only treatment would have a substantially greater effect than the intermediate thin and burn treatment. Furthermore, the importance of canopy cover in the context of canopy base height was underestimated, as is illustrated at Crow 6.

There is very little difference between treatment effects on canopy base height at Crow 6, canopy base height was high to begin with and rapidly increased across all treatments in the first few FVS cycles. Therefore the importance of canopy cover is elevated in respect to the treatments at Crow 6. Relative trends between the TI mirror trends of canopy cover. The control maintains the highest level of canopy cover, and maintains the highest TI (Figures 32 and 36). Higher densities of trees and related competition may also contribute to crown lifting, but crown lifting in FVS-FFE is only related to the rate of tree growth. The rapid increase in CBH is likely a artifact of the model and likely underestimates the torching hazard across all treatments at Crow 6. Tree regeneration was modeled in 2005, but is not indicated on the graph until 2010 and every five years after. The punctuated drop of TI in the thin burn treatment in 2015 and the burn only treatment in 2020 are related to rapid decreases in canopy base height that are caused by growth of understory regeneration.

The increase in CBH from 4 to 8 m in three years along with the abrupt leveling off of CBH mentioned above appears suspect. Little to no mortality was modeled in the stand during this period, thus not contributing to an increase in CBH. At year one, the SDI for the stand is 159, and FVS starts modeling mortality when SDI reaches 173 in year 2015. The required growth of trees to accomplish 1.3 m of crown lifting a year is on the border of realistic. However, growth data was not collected and thus growth rates can not be verified. If CBH increases are an overestimate, TI levels reported would be high, an overestimate as well.

While canopy base height at Crow 6 appears to relate to a drop in torching index in 2015 in the TB treatment and a radical drop in the BO treatment in 2020, and a rapid increase in the first few years including the CTRL, canopy base height differences are otherwise fairly flat over the modeled time period (Figure 28). Differences are explained by the amount of canopy removed by each of the treatments—surface wind speed likely increases as more tree canopy is removed, thus lowering the torching windspeed index; however, surface windspeed is not reported in FFE potential fire report. The windspeed reduction factor for calculating canopy fires is not as great as for surface fires (Scott and Reinhardt 2001). This would explain why the TB treatment indicates the lowest torching index up until the last year modeled.

The torching windspeed index at Ruby EU resulted in a very different response than at Crow 6. Ruby is multistoried stand with a starting canopy base height three times lower than that of Crow 6. It is also steeper. At Ruby, the intermediate TO treatment did nothing to increase the torching windspeed index—this is not surprising as trees in the lower layer, ladder fuels, were not reduced. At Crow 6 this result was not apparent, as there were very few ladder fuels. However, it is worth noting that the Ruby burn treatments that treated ladder fuels did increase the torching windspeed index to near the same levels at Crow 6. The BO had the greatest effect on torching windspeed index, as it reduced ladder fuels while maintaining high canopy cover; therefore likely not increasing surface wind speed.

While the results illustrate the importance of canopy cover's influence on wind reduction in developing treatments to reduce the incidence of torching, it also illustrates the importance of canopy base height. Even if canopy base is reduced with treatment, management needs to obtain information on regeneration response to the treatment for an understanding of the level of maintenance that would be required. This is a difficult component to predict or model. There are surprisingly few published studies on natural regeneration response to various treatments. Even with results from research to draw from, modeling regeneration response to various treatments would likely be difficult because of the number of variables likely to influence results. Likely variables include: availability, species, and timing of seed source or response to treatment (increaser or decreaser), degree of mineral soil disturbance by treatment, animal interaction, and weather variables such as timing and availability of moisture, first frost, and snow pack. Furthermore, decreasing canopy cover may have the dual effect of increasing mid-flame windspeeds, and increasing canopy base height over time due to understory plant response (McConnell and Smith 1970, Wienk et al. 2004).

If the objective in the Crow 6 EU is to increase the torching index windspeed, that is reduce the likelihood of passive crown fire in the stand, results indicate that no treatment has the greatest effect. This is only so because canopy base height (CBH) is high in the control and removing canopy cover increases mid-flame windspeeds and increases predicted fire hazard. Furthermore, treatments that reduce canopy cover are more likely to initiate regeneration of understory species, thus increasing CBH and increasing the potential of passive crown fire over the long-term. A different scenario is indicated at Ruby, where starting CBH is low. Without treating ladder fuels, reducing canopy cover will likely increase the probability of torching; however, when ladder fuels are treated, reduction of canopy cover may still matter. This point is illustrated between the TB and BO treatment at Ruby, where CBH was nearly equal between the two treatments, but canopy cover was just over 15% greater in the BO, resulting in lower torching index windspeeds in the TB (Figure 32).

Unlike the torching index windspeed, the crowning index windspeed response followed expectations in response to canopy bulk density reductions: reduced the greatest to least in the order of TB, TO, and BO treatments with relatively increasing crowning index windspeed with one exception (Figures 29 and 33). Approximately 10 years after the BO treatment at Crow 6, the potential for crowning is slightly higher than the CTRL. This is due to an initial decrease of trees from the BO treatment, and later recruitment of trees in 2010 increasing CBD. No recruitment of trees was modeled in the CTRL.

A requirement of active crown fire is that torching index is less the 6.1 m windspeed (22.5 km hr^{-1} in this research) AND that the crowning index is less than the 6.1 m windspeed (Figures 32 and 33). Therefore, fire hazard is very low at Crow 6 and Ruby, even in the CTRL. These treatment scenarios indicate that overemphasis or focus on reducing crown fire threat can obscure other real concerns. Just because active crown fire is not a great hazard, severity still can be high.

Basal Area Mortality

Treatment effect under 80 percentile fire weather at Crow 6 resulted in very little difference in basal area mortality, but mortality increased under 90 percentile plus fire weather following trends of scorch height or correlated flame length (Figures 31, 32, and 34 and 35). There is an initial sharp drop in the CTRL percent basal area mortality. This is related to a drop in flame length that is likely related to a drop in litter fuel loads (Figure 22). The TO treatment initially reported the lowest level of mortality between the treatments at both the EUs under 80 and 90 percentile plus weather conditions; however, the reduction in percent basal area mortality reverses the downward trend quickly and resumes near to greater levels of percent basal area mortality over time. These trends are opposite from those expected. It was expected that as stands grew and developed over time, the effect of treatments on fuel loading and structure would not be as apparent between stands, and therefore, the differences in percent basal area mortality would become less. This relationship did not hold true across all treatments as stands maintained unique fuel arrays over the time period modeled; however, overall differences were generally less in the last year modeled.

Fuel treatments at Crow 6 increased tree mortality, except for a brief period in the TO treatment under 90 percentile plus weather conditions; moreover, the level of mortality under 90 percentile plus weather conditions fuel treatments increased percent basal area tree mortality over the CTRL by a large margin. As canopy cover was decreased, mid-flame windspeed increased, flame length increased and the TI decreased. However, the CTRL at Ruby experienced near stand replacing results. Under 80 percentile weather conditions at Ruby, treatments had a large effect on basal area mortality. The intermediate TO treatment had the greatest initial effect on basal area mortality, reducing mortality from near 95% to 30% initially; however, percent mortality quickly rises to near CTRL levels (Figures 28, 29 and 34, Ruby) The decrease and increase of TO correspond to flame length patterns, which corresponds to CBH and CBD trends (Figure 30, Ruby). The same factors influence TB percent basal area treatment response; however, large fluctuations are occurring because canopy base height changes and decreases in flame length in 2008 and 2015 (Figures 28 and 30, Ruby). The BO treatment effect on had the greatest overall long-term effect on basal area mortality. This is because the BO treatment reduced and maintained canopy base height while maintaining the greatest cover of overstory effectively keeping mid-flame windspeeds low. Effectiveness of treatments in reducing basal area mortality was severely reduced under 90 percentile plus conditions. Thus indicating the need for managers to assess the level of risk they are willing to take and the need to develop prescriptions based on particular places and objectives.

As part of the National Fire and Fire Surrogates evaluation a success criteria was developed called the “80/80 rule” which states that, “Each non-control treatment shall be designed to achieve stand and fuel conditions such that, if impacted by a head fire under 80th percentile weather conditions, at least 80 percent of the basal area of overstory (dominant and codominant) trees will survive” (Agee et al. 2000b, p5). Fuel treatments as modeled in this research did not meet these expectations, except for a few years at Crow

6. If this sole criterion were used, it would indicate the need for more aggressive treatments, or the use of multiple fuel treatment entries.

Model Performance, Recommendations, Further Research

The modeled fuel dynamics of several variables give pause for discussion as they could influence reported fire behavior and effects results (Table 27). This discussion has more bearing on how closely the model may predict real differences on the ground, versus relative differences between treatments, as the same potential errors or assumptions are being applied to each of treatments compared.

The FFE modeled litter fuel loads drop precipitously over a short period as observed in the CTRL (Figure 22, Table 27). Field model estimates of litter were used as starting loads. If field model estimates are correct, FFE underestimates litter load over time. The potential explanation of why litter decreases at such a rate is discussed above under the heading Forest Floor. If litter is underestimated by the FFE model, underestimates of flame length in the non-burn treatments are likely, and perhaps in all treatments over the longer time period modeled.

Fine dead surface fuel increases substantially in the CTRL in the first four FVS cycles at Crow 6 (Figure 21, Table 27). Fine dead wood surface fuel load is dependent on tree death, growth and resulting crown lifting and rate of decay. Accumulation of fine surface fuels occurs through crown lifting and death of trees for each FVS growth cycle. CBH increases rapidly in the CTRL at Crow 6 indicating rapid crown lifting or reduction in crown ratio (Figure 28, Table 27). If CBH is overestimated at Crow 6, the torching index would likely be lower than results indicate. As tree growth occurs, a proportion of crown lift occurs resulting in transfer of fine dead wood material to the surface pool. If crown lifting is overestimated, so would the contribution to the surface fuel load having the effect of weighting the selection of fire behavior fuel models with greater fire intensity modeled; however, overall differences are likely to be less as overall fuel loads are likely underestimated (Table 27).

Table 27. Summary of FFE modeled fuel variable results of the CTRL from 2001 through 2005 that appear incorrect and could affect fire behavior and severity results beyond relative treatment differences. Values are the increase or decrease over the time period modeled.

	CBH (m) 2001-05	litter (Mg ha^{-1}) 2001-05	fine dead woody surface fuel (Mg ha^{-1}) 2001-05	modeled net fuel load difference (Mg ha^{-1})
Crow 6	4.8	-12.5	4.3	-10.1
Ruby	-	-15.0	4.0	-11.8

Selection of fire behavior fuel models in FFE is pivotal in estimating fire behavior and effects. While the user has the option to define which fire behavior fuel models, as well as a weighted percent, an improvement to the model would be to provide the user an over-ride of which fire behavior fuel models would be present for a given site over a given time period. For example, a proportion of fire behavior fuel model six was selected by FFE in this research which likely resulted in an over prediction of fire behavior and effects in some cases, as it is highly unlikely that fire behavior fuel model 6 would ever occur on these sites. Currently FFE allows the user to define the fire behavior fuel model for any time period, but does not allow the exclusion of a particular fire behavior fuel model in the weighting calculation.

As the FVS-FFE model is a set of instructions concerning a current state of knowledge of how fuels, fire, and weather interact, and its intended audience is managers, it is important that relationships – calculations, be as transparent and accessible as possible to the user. A user should be able to track all the related variables for a given output quickly. This entails knowing which variables are used to calculate a given metric and knowing which report to run. Ideally, variables used to calculate any given metric could be summarized in the same report. A simple summary, such as a lookup table or flow chart, for each metric with dependent variables would be useful.

FVS-FFE is a powerful and complex tool in testing assumptions in how fuel treatments may influence fire hazard reduction. Differentiating between model performance and preconceived expectations is difficult, but discrepancies can be identified, and ultimately should be resolved with empirical data.

Canopy base height is an important variable in predicting fire behavior. Research needs to be pursued to provide insight into the effect of overstory removal on canopy base height over longer periods of time. How do shrub, herbaceous fuels, and regeneration of understory trees respond to various fuel treatments? Are there certain parameters that would help predict responses? The inability to predict such responses will severely limit managers' ability to evaluate tradeoffs, plan projects, allocate resources, and obtain successful outcomes. The collection of baseline data along with the application of treatments at Fire and Fire Surrogate Treatments sites provides an opportunity to calibrate and improve fuel dynamic models in FVS-FFE.

Shrub and herbaceous fuel dynamics in FFE is superficial as the authors of FFE acknowledge. Efforts to dynamically model growth, death, and response to treatments of herbaceous and shrubs fuels are needed. Without such efforts, FVS-FFE will have no application in non-forested environments. Furthermore, shrub and herbaceous fuels do not directly influence fire behavior fuel model selection or fire behavior and effects as currently modeled in FFE except for as accounted for in the fire behavior fuel models. Moreover, shrub fire behavior fuel models often do not represent fuel and fire behavior relationships, such as the role of tall shrubs (measured over 4 m on some plots for this research) in reducing canopy base height. However, FVS-FFE does provide manual over-rides to change such relationships when observed.

Context of Fuel Treatments

Landscape Considerations

Further consideration beyond the type and effectiveness of fuel treatment at the stand or patch level is the size and context of the fuel treatment within a landscape; rarely will an individual stand perspective meet the objectives of the aggregate (Weatherspoon and Skinner 1996, Wilson and Baker 1998, Agee et al. 2000a, Finney 2001). FVS-FFE analysis is limited to stand by stand analysis; however, a program called INFORMS that uses FVS-FFE does allow for calculation of stand treatments across landscapes. INFORMS will generate outputs that will allow the user to use FARSITE (Finney 1997) which is more effective in modeling the effectiveness of fuel treatments in modifying fire behavior across a landscape (van Wagtendonk 1996, Stephens 1998). Furthermore, FVS-FFE does not model the affect of adjacent stands on fire behavior and severity; however, to the author's knowledge, none of the current fire models integrate adjacency—calculation of fire behavior and severity in each stand or pixel is independent of the next.

Fire Weather

This research modeled large differences in fire effects between 90 and 80 percentile wildland fire weather conditions. Percentile weather is based on relatively recent weather records. Climate change is a contemporary issue and how we calculate the probability and define extremes of weather data for modeling is an important consideration as it is the interplay of weather and fuels that will determine results of any given fire event. While climate change could ameliorate or intensify weather characteristics that drive fire behavior in North America, it is likely that extreme weather events will become more common and fire seasons will become longer (McKenzie et al. 2004). Given the need for long range planning of fuels and fuel treatments, managers might consider erring on the conservative side and modeling weather conditions that are more extreme.

Fire Hazard Reduction or Ecological Restoration?

The decision to implement fuel treatments by resource managers typically fall under two separate justifications that may be confused: one is the use of fuel treatments to modify fuel arrays with the intention of modifying fire behavior to reduce the direct fire hazard to human safety and specific human goods and services, and the second is the proposition of modifying fuels with the intent to restore proper process or function to proper place, otherwise, attempting ecological restoration/rehabilitation (Brown et al. 2004). In some ecosystems, especially ecologically systems that have a historically frequent fire interval and fire has been excluded, there is the opportunity for these two separate objectives to merge into a set of actions that are one and the same. However, there are many situations were the two are not compatible, and others where the distinctions are more subtle.

When ecological restoration is the goal, there is good reason to maintain a line of humility along the path. While science has discovered much about the function, composition, structure, processes, and variability of many ecological systems, there are many more opportunities for misinterpretation, blunder, and most importantly, to learn.

CONCLUSIONS AND RECOMMENDATIONS

This research modeling four fuel treatment scenarios in two fuel arrays indicates that the treatment of fuels can affect fire behavior and severity outcomes. However, the types of treatments have the potential to either increase or decrease intensity and severity.

Intermediate thin only had the short term effect of reducing flame lengths and associated mortality; however, the reduced short term flame length may be an artifact of the FFE model selection. Furthermore, the failure to increase canopy base height while simultaneously reducing canopy cover appears to reduce the effectiveness of the treatment over time. The thin and burn treatment was effective at increasing canopy base height overall, but at the cost of increasing mid-flame windspeeds, increasing flame length and tree mortality. The treatment was effective, but results were more erratic over the time period modeled. In addition, the thin and burn treatment had the greatest effect on reducing crown fire hazard; however, crown fire hazard was low to start. The burn only treatment effectively increased canopy base height while maintaining higher tree canopy cover resulting in lower mid-flame windspeeds and therefore having the greatest overall reduction of flame length and severity over the time period modeled. Results are very dependent on assumptions of the effect of treatments on tree regeneration, and natural tree regeneration is difficult to predict over longer periods of time.

Treatments had the effect of decreasing or increasing wildland fire behavior depending on the existing structure of the fuel profile, specific fire behavior variable of interest, time period and the extremity of wildland fire weather. Treatments at Crow 6 where canopy base height is high to begin with had little effect on flame length, increased the likelihood of passive crown fire, and decreased the potential for active crown fire. Whereas at Ruby, where starting canopy base height is low, treatments that effectively increased canopy base height decreased the potential for passive crown fire, reduced flame length, and decreased the potential for active crown fire. All treatments in both EU fuel profiles decreased the likelihood for active crown fire, but even the control in both units were under the threshold for active crown fire under 90 percentile plus fire weather conditions. However, treatments did have an effect on severity, but severity varied over the time period and percentile fire weather modeled. At Crow 6 treatments had little effect on percent basal area mortality under 80 percentile fire weather conditions, but overall increased percent basal area mortality under 90 percentile plus conditions. At Ruby all treatments had an effect on mortality, but the relative effectiveness of each treatment varied over time.

If the crowning index windspeed for an existing stand is higher than the extreme fire weather 6.1 m windspeed, treatments that reduce surface fuels and increase canopy base height are likely to have the greatest effect on fire intensity and severity. The reduction of canopy cover and how it influences mid-flame windspeed in the context of surface fuels and canopy base height is an important consideration. This recommendation assumes that independent crown fire is hypothetical, or at least crown fire hysteresis is rare, but if not assumed rare, the size of the treatment and its context to neighboring fuel profiles are all the more important.

These results stress the importance of developing prescriptions based on the existing vegetation fuel profile and specific desired objectives. Developing blanket fire hazard fuel prescriptions to influence fire behavior and severity and applying them across the landscape will likely come with mixed results. Furthermore, as discussed in the previous section, the context of stand or patch level treatments in the landscape will influence the effectiveness of treatments in reducing fire hazard and meeting other resource objectives.

Few studies compare fuel treatment longevity or long-term tradeoffs between treatments. Treatments that meet short-term objectives may have long-term effects that are counter to long-term objectives, such as positive response in understory regeneration decreasing canopy base height. Furthermore, fuels treatments will likely come with tradeoffs: reducing short-term hazard while increasing hazard for some period, requiring design and commitment to a monitoring and maintenance plan.

In summary:

- Assessment of initial fuel loading and structure is crucial to the development of fire hazard reduction prescriptions. Blanket fuel prescriptions will likely result in mixed success.
- Existing crown fire hazard should be assessed before prescriptions are written and not independent of torching hazard and surface fuel conditions.

- Canopy base height and surface fuel loading can not be ignored in hazardous fuels reduction projects. As ultimately passive and active fire hazard are dependent on these variables.
- Small changes in percentile fire weather conditions can make a large difference in the effectiveness of treatments.
- FVS-FFE is a complex and powerful set of models, it should be used carefully.
- When comparing treatment effect, fuel dynamic modeling issues are less of an issue than if one is going to use the results to form management prescriptions e.g., an underestimate of litter by the model could result in an underestimate of flame length prediction, but relative differences between treatments are likely the same.
- When using FVS-FFE defaults to model long-term trends, it is very important to review model assumptions about fuel dynamics and fire behavior model selection and weighting that directly are being used to calculate the variable of interest.
- Regeneration of tree species can have a large effect on resulting fire behavior modeled by FFE in subsequent decades.
- FVS-FFE is a stand or patch level tool. Effectiveness of hazard reduction at a stand level will rarely translate into hazard reduction effectiveness at the landscape level.

While there are limitations and issues involved with using fire behavior and effects models, conducting controlled experiments to measure the effect of fuel treatments on wildland fire behavior in dry type forests is not feasible. From a social and political standpoint, it would be nearly impossible to initiate an experimental prescribed fire in extreme fire weather conditions. From the experimental design perspective there are an immense number of variables to control for, mainly variables that can be grouped under the fire triangle: weather, topography, and fuel profile characteristics, each of which occur in practically innumerable combinations. There is also the difficulty of applying treatments in a consistent manner that have consistent effects, while conceptually it appears to be a straight forward, in practice it is a challenge. There are also issues of scale. Our understanding of the interaction of treatments on wildland fire behavior at the stand or community level will rarely translate processes occurring across a landscape. Even with the best ability to control such variables, there is the issue of how broad inferences can be made. Nonetheless, the issues that affect how we improve our knowledge of the human interaction with vegetation and how it affects wildland fire behavior, that is no reason not to learn from empirical and anecdotal experiences and events that can be used to refine the body of knowledge that is stored in fire behavior and effects models- our concept of how it all works. As more and more fuel treatments are applied and documented, there is a greater probability that wildland fire will occur in treated and non-treated stands. Qualitative and quantitative observations are essential to increase our understanding of this complex, relevant and interesting phenomenon.

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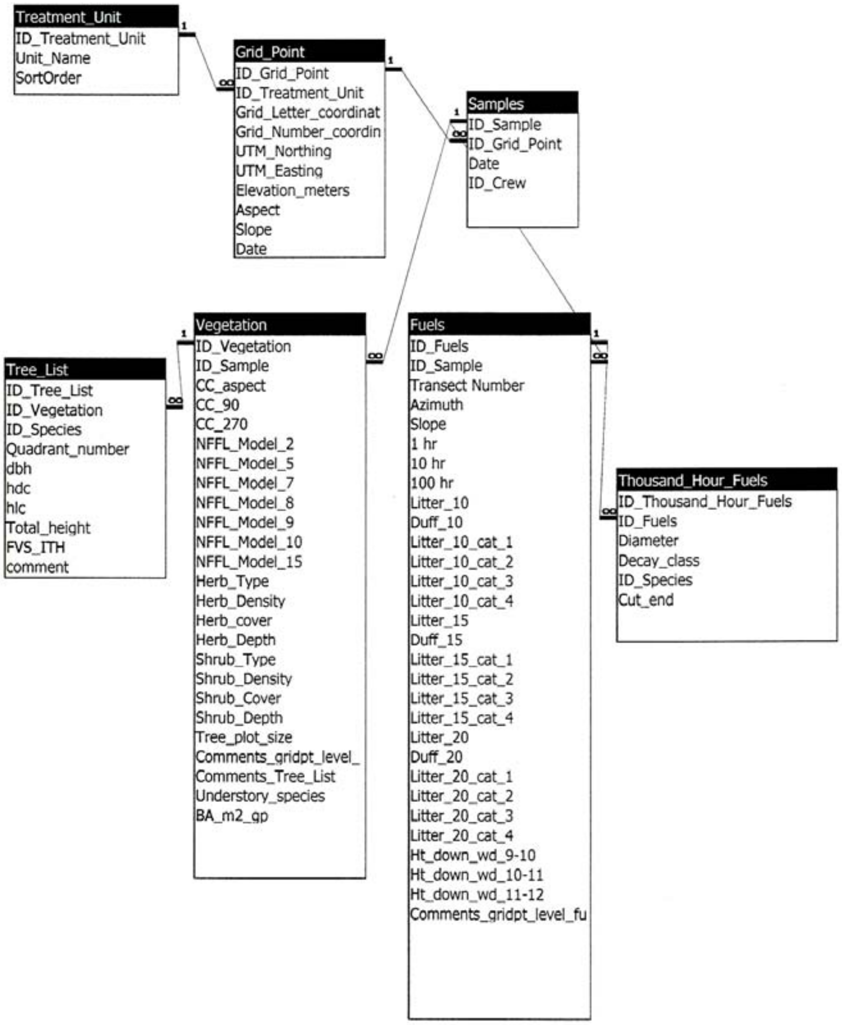
APPENDIX A: Relational database structure used for storing and formatting fuels data for analysis.

Relationships for fss_pretreatment_fuels_121703

Saturday, February 05, 2005



Treatment_Unit
ID_Treatment_Unit
Unit_Name
SortOrder

Grid_Point
ID_Grid_Point
ID_Treatment_Unit
Grid_Letter_coordinat
Grid_Number_coordin
UTM_Northing
UTM_Easting
Elevation_meters
Aspect
Slope
Date

Samples
ID_Sample
ID_Grid_Point
Date
ID_Crew

Tree_List
ID_Tree_List
ID_Vegetation
ID_Species
Quadrant_number
dbh
hdc
hlc
Total_height
FVS_ITH
comment

Vegetation
ID_Vegetation
ID_Sample
CC_aspect
CC_90
CC_270
NFFL_Model_2
NFFL_Model_5
NFFL_Model_7
NFFL_Model_8
NFFL_Model_9
NFFL_Model_10
NFFL_Model_15
Herb_Type
Herb_Density
Herb_cover
Herb_Depth
Shrub_Type
Shrub_Density
Shrub_Cover
Shrub_Depth
Tree_plot_size
Comments_gridpt_level_
Comments_Tree_List
Understory_species
BA_m2_gp

Fuels
ID_Fuels
ID_Sample
Transect Number
Azimuth
Slope
1 hr
10 hr
100 hr
Litter_10
Duff_10
Litter_10_cat_1
Litter_10_cat_2
Litter_10_cat_3
Litter_10_cat_4
Litter_15
Duff_15
Litter_15_cat_1
Litter_15_cat_2
Litter_15_cat_3
Litter_15_cat_4
Litter_20
Duff_20
Litter_20_cat_1
Litter_20_cat_2
Litter_20_cat_3
Litter_20_cat_4
Ht_down_wd_9-10
Ht_down_wd_10-11
Ht_down_wd_11-12
Comments_gridpt_level_fu

Thousand_Hour_Fuels
ID_Thousand_Hour_Fuels
ID_Fuels
Diameter
Decay_class
ID_Species
Cut_end

APPENDIX B: *Summary of pretreatment fuel variable results.*

EU	Crow 1	Crow 3	Crow 6	LC	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
canopy closure (%)												
mean	65	65	55	63	71	64	75	67	76	80	75	73
std. dev.	19	25	22	29	22	28	19	29	25	14	30	23
std. err.	3	5	4	5	4	5	3	5	5	3	5	4
min.	11	15	15	2	15	4	34	5	8	36	5	12
max.	85	94	85	100	98	95	97	95	97	93	100	94
count	33	30	35	31	35	29	31	31	30	30	36	31
canopy cover (%) FVS-FFE generated												
	35	41	41	36	36	44	52	47	55	53	55	59
canopy bulk density (kg m^{-3}) FVS-FFE generated												
	0.043	0.056	0.044	0.056	0.052	0.052	0.051	0.062	0.072	0.116	0.06	0.082
conifer density (trees ha^{-1})												
mean	304	340	287	656	431	468	703	363	603	1065	564	1000
std. dev.	195	254	176	447	389	369	471	414	493	986	450	1026
std. err.	33	46	30	80	66	67	86	74	90	180	75	184
min.	89	69	38	0	111	50	175	44	75	50	0	113
max.	1100	1300	900	2100	2300	1400	2300	1900	1900	4300	2200	4000
count	34	30	35	31	35	30	30	31	30	30	36	31
crown base height (m) based on individual tree measurements												
mean	6.2	4.1	5.1	3.4	4.3	4.9	3.4	4.3	6.4	3.5	2.5	4.1
std. dev.	1.8	2.2	1.6	3.1	1.9	4.1	2.4	2.3	3.6	1.7	1.9	3.0
std. err.	0.3	0.4	0.3	0.6	0.3	0.8	0.4	0.4	0.7	0.3	0.3	0.5
min.	2.7	1.3	2.6	0.1	0.1	0.2	0.4	1.3	1.1	0.7	0.0	0.1
max.	10.7	9.6	10.3	15.5	9.1	15.2	8.8	10.2	14.3	6.6	8.3	12.1
count	34.0	30.0	35.0	30.0	35.0	30.0	30.0	31.0	30.0	30.0	35.0	31.0
canopy base height (m) FVS-FFE generated												
	4.6	2.7	4.3	1.2	3	2.4	1.5	3	2.4	1.2	1.2	1.5

EU	Crow 1	Crow 3	Crow 6	LC	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
basal area (m^2 ha^{-1})												
mean	22.7	24.1	21.5	25.9	21.8	24.4	29.5	27.9	30.9	22.3	24.4	28.5
std. dev.	10.0	11.3	10.8	15.0	7.7	15.3	20.1	16.6	20.4	21.7	17.1	22.9
std. err.	1.7	2.1	1.8	2.7	1.3	2.8	3.6	3.0	3.7	4.0	2.8	4.1
min.	6.6	7.1	3.9	6.0	6.2	1.6	2.2	8.9	2.3	1.3	2.4	2.1
max.	58.6	58.6	64.4	66.7	33.1	57.4	84.7	98.0	76.8	105.8	81.7	95.4
count	34.0	30.0	35.0	32.0	35.0	30.0	31.0	31.0	30.0	30.0	36.0	31.0
herbaceous biomass (Mg ha^{-1})												
mean	1.2	0.4	1.1	0.1	0.5	0.3	0.3	0.5	0.6	0.5	0.1	0.3
std. dev.	0.8	0.4	0.7	0.1	0 .4	0.3	0.3	0.5	0.6	0.5	0.2	0.3
std. err.	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.1
min.	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
max.	3.1	1.6	2.6	0.6	1.2	1.0	1.2	2.1	2.1	2.1	0.6	1.0
count	34	30	34	31	35	30	30	31	30	29	36	31
shrub biomass (Mg ha^{-1}) includes live equivalent timelag 10hr and 100hr												
mean	6.3	6.3	3.3	2.5	2.0	8.8	3.8	2.3	5.7	4.3	5.8	5.8
std. dev.	7.7	13.1	3.9	4.3	4.7	12.8	5.4	7.9	9.0	9.5	6.7	11.1
std. err.	1.3	2.4	0.7	0.8	0.8	2.3	1.0	1.4	1.6	1.8	1.1	2.0
min.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
max.	33.7	56.1	15.7	20.2	19.6	44.9	19.6	43.5	29.1	39.3	30.9	56.1
count	34	30	34	31	35	30	30	31	30	29	36	31
dead woody fuel height (cm)												
mean	9.2	7.7	10.1	11.2	11.8	10.0	15.8	8.3	13.2	6.3	9.9	18.2
std. dev.	14.6	10.6	20.9	18.9	17.9	11.1	28.3	13.0	21.0	6.5	17.4	28.1
std. err.	1.7	1.4	2.5	2.4	2.1	1.4	3.6	1.6	2.7	0.8	2.0	3.6
min.	0.1	0.0	0.5	0.4	0.0	0.3	0.0	0.0	0.0	0.5	0.2	0.0
max.	86.3	59.7	130.7	107.0	111.7	56.7	200.0	95.0	120.3	38.7	129.3	170.0
count	70	58	69	63	71	59	62	62	60	59	72	61

EU	Crow 1	Crow 3	Crow 6	LC	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
forest floor depth (cm) litter + duff												
mean	5.6	5.0	5.6	2.9	6.5	4.7	5.2	4.4	4.2	3.1	4.7	4.3
std. dev.	3.0	2.7	2.9	2.3	3.1	2.9	4.1	2.7	2.2	1.8	4.0	2.3
std. err.	0.4	0.3	0.3	0.3	0.4	0.4	0.5	0.3	0.3	0.2	0.5	0.3
min.	1.1	0.3	0.3	0.2	1.2	0.1	0.1	0.0	0.2	0.7	0.1	0.2
max.	14.2	11.2	13.0	12.3	14.3	12.2	19.3	11.0	8.8	8.6	20.9	11.8
count	71	60	71	64	71	60	57	62	60	58	72	61
duff (Mg ha^{-1})												
mean	18.2	13.7	17.9	7.4	24.2	10.5	12.6	11.2	8.1	9.4	16.7	5.0
std. dev.	11.7	13.8	12.5	9.6	16.7	14.6	14.7	14.3	10.2	8.9	18.1	8.6
std. err.	1.4	1.8	1.5	1.2	2.0	1.9	1.9	1.8	1.3	1.2	2.1	1.1
min.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
max.	56.4	48.4	45.2	48.4	61.2	62.8	48.9	62.8	43.6	38.5	85.1	35.5
count	71	60	71	64	71	60	57	62	60	58	72	61
litter (Mg ha^{-1})												
mean	27.4	25.8	27.0	15.6	29.1	26.6	28.1	23.2	24.7	15.7	22.0	27.6
std. dev.	16.2	13.0	14.7	10.7	15.1	14.1	25.6	13.5	13.7	8.3	18.6	14.0
std. err.	1.9	1.7	1.7	1.3	1.8	1.8	3.4	1.7	1.8	1.1	2.2	1.8
min.	5.8	2.2	1.9	1.4	8.4	0.9	0.7	0.0	1.2	4.8	0.5	1.4
max.	79.2	60.3	61.5	53.1	91.7	62.8	140.0	65.2	55.5	47.1	97.0	85.7
count	71	60	71	64	71	60	57	62	60	58	72	61
forest floor (Mg ha^{-1}) litter + duff												
mean	45.6	39.5	43.1	23.0	53.3	37.0	40.7	34.4	32.8	25.1	38.7	32.6
std. dev.	23.9	22.5	21.4	18.7	25.5	24.4	32.1	22.8	17.7	14.9	33.1	17.8
std. err.	2.8	2.9	3.3	2.3	3.0	3.1	4.3	2.9	2.3	2.0	3.9	2.3
min.	8	2	3	1	8	1	1	0	1	5	0	1
max.	110.7	90.0	87.1	101.5	118.7	98.4	140.0	92.6	70.5	67.8	169.0	85.7
count	71	60	42	64	71	60	57	62	60	58	72	61

EU	Crow 1	Crow 3	Crow 6	LC	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
1 hour timelag dead wood (Mg ha^{-1})												
mean	0.3	0.7	0.3	1.9	0.3	1.5	1.5	1.6	1.7	1.3	1.4	1.7
std. dev.	0.3	0.9	0.4	3.3	0.5	2.2	2.2	1.7	2.4	0.8	1.3	2.9
std. err.	0.0	0.1	0.0	0.4	0.1	0.3	0.3	0.2	0.3	0.1	0.2	0.4
min.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
max.	2.1	3.7	2.1	19.5	2.7	9.3	9.3	7.9	13.1	3.4	7.2	18.6
count	72	60	71	64	71	60	60	62	60	60	72	61
10 hour timelag dead wood (Mg ha^{-1})												
mean	1.5	1.6	1.3	2.3	2.4	1.7	1.3	1.5	2.6	0.8	2.3	2.3
std. dev.	2.2	1.9	1.6	2.1	2.6	1.9	1.6	1.9	3.4	1.0	3.6	3.2
std. err.	0.3	0.2	0.2	0.3	0.3	0.2	0.2	0.2	0.4	0.1	0.4	0.4
min.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
max.	12.8	8.2	6.2	10.3	12.2	7.6	9.3	9.8	18.9	4.0	19.0	17.6
count	72.0	60.0	71.0	64.0	71.0	60.0	62.0	62.0	60.0	60.0	72.0	61.0
100 hour timelag dead wood (Mg ha^{-1})												
mean	5.7	2.8	4.4	6.4	5.2	3.0	6.6	2.0	4.0	4.2	6.9	5.0
std. dev.	6.1	5.0	4.9	8.4	7.6	5.7	11.5	4.0	6.3	5.9	10.0	9.2
std. err.	0.7	0.6	0.6	1.0	0.9	0.7	1.5	0.5	0.8	0.8	1.2	1.2
min.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
max.	22.3	27.4	24.6	38.5	43.0	24.6	83.4	17.7	41.8	29.0	57.5	39.8
count	72.0	60.0	71.0	64.0	71.0	60.0	62.0	62.0	60.0	60.0	72.0	61.0
sound 1000+ hour timelag dead wood (Mg ha^{-1}) decay class 1-3												
mean	11.9	6.7	8.8	11.6	16.5	5.1	17.1	3.0	6.8	8.1	12.3	17.7
std. dev.	14.0	18.9	15.6	19.1	26.6	9.3	32.0	13.9	11.7	25.7	29.0	38.9
std. err.	1.7	2.4	1.9	2.4	3.2	1.2	4.1	1.8	1.5	3.3	3.4	5.0
min.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
max.	60.5	119.0	92.6	87.3	140.9	35.0	173.3	106.3	51.4	186.9	190.3	193.9
count	71.0	60.0	71.0	64.0	71.0	60.0	62.0	62.0	60.0	60.0	72.0	61.0

EU	Crow 1	Crow 3	Crow 6	LC	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
rotten 1000+ hour timelag dead wood (Mg ha^{-1}) decay class 3-4												
mean	7.8	2.3	3.2	4.5	2.1	9.7	16.4	3.0	4.9	10.2	9.6	8.8
std. dev.	13.9	7.8	6.5	10.2	8.8	33.4	36.2	13.7	10.9	17.7	19.4	23.3
std. err.	1.6	1.0	0.8	1.3	1.0	4.3	4.6	1.7	1.4	2.3	2.3	3.0
min.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
max.	69.9	53.8	39.0	59.2	58.9	230.9	235.3	98.0	50.2	67.8	88.1	107.3
count	71.0	60.0	71.0	64.0	71.0	60.0	62.0	62.0	60.0	60.0	72.0	61.0

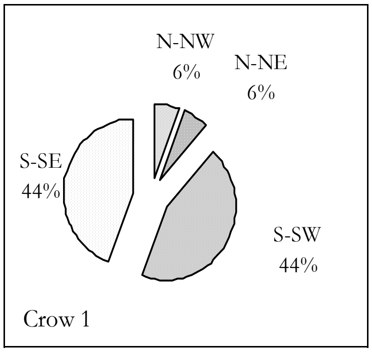
APPENDIX C: *Summary of plant species scientific name, common name, lifeform, and plant associations referenced in text.*

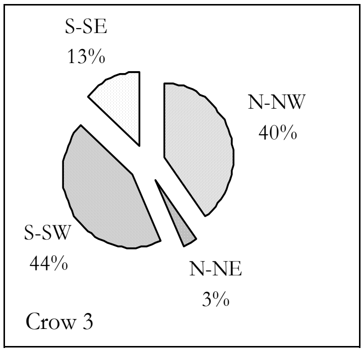
Scientific name[*]	Common name	Ecoclass code
Abies grandis (Dougl. ex D. Don) Lindl.	grand-firs	Tree
Larix occidentalis Nutt.	western larch	tree
Pinus ponderosa P.& C. Lawson	ponderosa pine	tree
Pseudotsuga menziesii (Mirbel) Franco	Douglas-fir	tree
Robinia pseudoacacia L.	black locust	tree
Acer glabrum Torr.	Rocky Mountain maple	tree/shrub
Acer macrophyllum Pursh	bigleaf maple	tree/shrub
Prunus emarginata (Dougl. ex Hook.) D. Dietr.	bitter cherry	tree/shrub
Prunus virginiana L	chokecherry	tree/shrub
Salix scouleriana Barratt ex Hook.	Scouler's willow	tree/shrub
Amelanchier alnifolia (Nutt.) Nutt. ex M. Roemer	Saskatoon serviceberry	shrub
Ceanothus sanguineus Pursh	redstem ceanothus	shrub
Ceanothus velutinus Dougl. ex Hook.	snowbrush ceanothus	shrub
Holodiscus discolor (Pursh) Maxim	ocenspray	shrub
Mahonia aquifolium (Pursh) Nutt.	hollyleaved barberry	shrub
Mahonia nervosa (Pursh) Nutt.	Cascade barberry, Cascade Oregon grape	shrub
Mahonia repens (Lindl.) G. Don	creeping barberry	shrub
Purshia tridentata (Pursh) DC.	antelope bitterbrush	shrub
Rosa spp. L.	rose	shrub
Spiraea betulifolia Pallas	white spirea, shiny-leaf spirea	shrub
Symphoricarpos albus (L.) Blake	common snowberry	shrub
Symphoricarpos oreophilus Gray	mountain snowberry	shrub
Bromus tectorum L.	cheatgrass	graminoid
Calamagrostis rubescens Buckl.	pinegrass	graminoid
Carex geyeri Boott	Geyer's sedge, elk sedge	graminoid
Pseudoroegneria spicata (Pursh) A. Löve ssp. Spicata	bluebunch wheatgrass	graminoid
Balsamorhiza sagittata (Pursh) Nutt.	arrowleaf balsamroot	forb

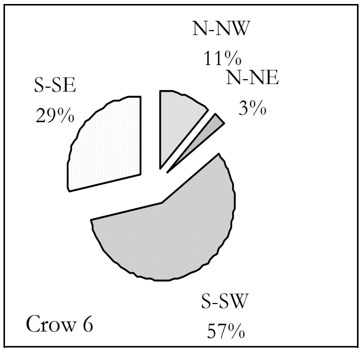
[*] Plant species nomenclature follows U.S. Department of Agriculture, Natural Resource Conservation Service (USDA 2002).

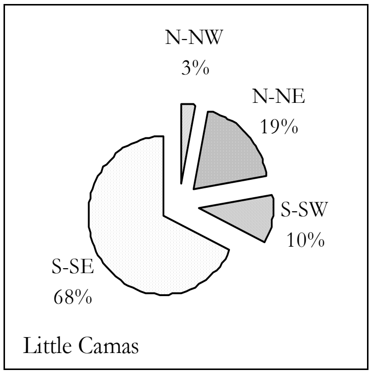
Scientific name*	Common name	Ecoclass code
Pinus ponderosa / Calamagrostis rubescens - Agropyron spectrum	Ponderosa pine/pinegrass-bluebunch wheatgrass	CPG231
Pseudotsuga menziesii / Spiraea betulifolia	Douglas-fir/shiny-leaf spirea	CDS640
Pseudotsuga menziesii / Symphoricarpos oreophilus	Douglas-fir/Mt. Snowberry	CDS632
Pseudotsuga menziesii / Symphoricarpos albus	Douglas-fir/common snowberry	CDS636
Pseudotsuga menziesii /Symphoricarpos albus / Calamagrostis rubescens	Douglas-fir/common snowberry/pinegrass	CDS638
Abies grandis/ Symphoricarpos albus / Calamagrostis rubescens	Grand fir/common snowberry/pinegrass	CWS336
Pseudotsuga menziesii / Carex geyeri	Douglas-fir/elk sedge	CDG132
Pseudotsuga menziesii / Calamagrostis rubescens	Douglas-fir/pinegrass	CDG131
Pseudotsuga menziesii / Spiraea betulifolia / Calamagrostis rubescens	Douglas-fir/shiny-leaf spirea/pinegrass	CDS638
Abies grandis / Berberis nervosa	Grand fir/Cascade Oregon grape	CWS225
*Plant species nomenclature follows Hitchcock and Cronquist (1974) as published in Lillybridge et al. (1995).		

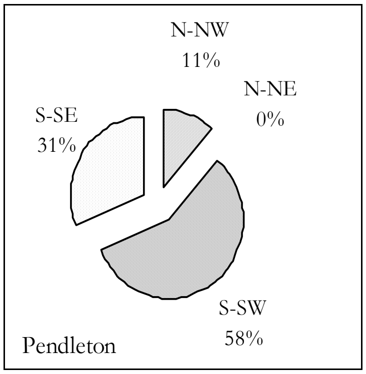
APPENDIX D: *Percent of cardinal directions representing aspect sampled at systematic grid points at each EU, samples range from 30 to 36.*

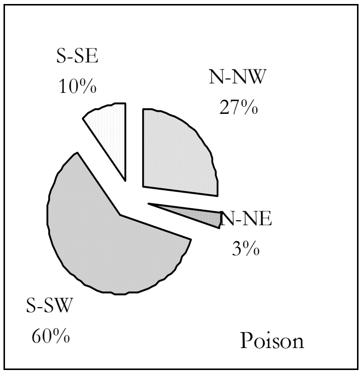

N-NW
6%
N-NE
6%
S-SE
44%
S-SW
44%
Crow 1

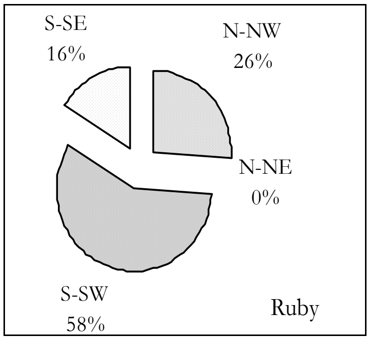

S-SE
13%
N-NW
40%
S-SW
44%
N-NE
3%
Crow 3

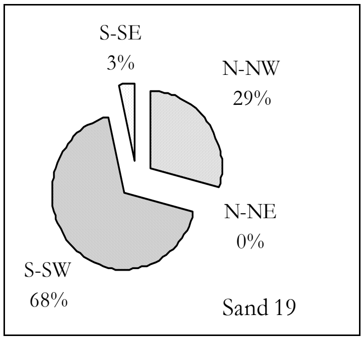

N-NW
11%
S-SE
29%
N-NE
3%
Crow 6
S-SW
57%

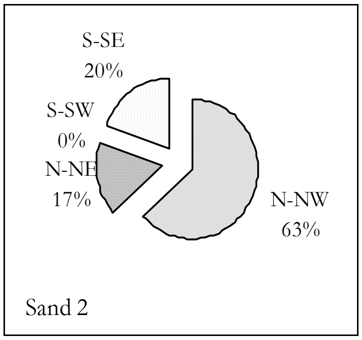

N-NW
3%
N-NE
19%
S-SW
10%
S-SE
68%
Little Camas

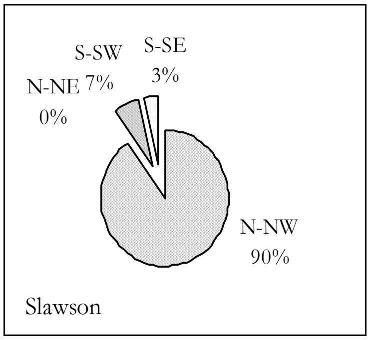

N-NW
11%
N-NE
0%
S-SE
31%
S-SW
58%
Pendleton

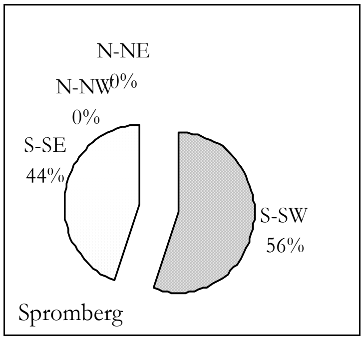

S-SE
10%
N-NW
27%
N-NE
3%
S-SW
60%
Poison

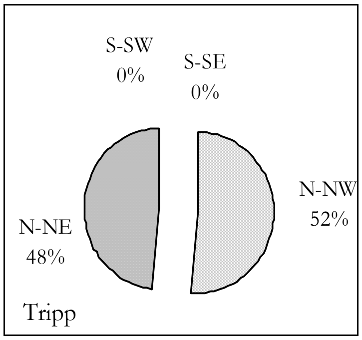

S-SE
16%
N-NW
26%
N-NE
0%
S-SW
58%
Ruby


S-SE
3%
N-NW
29%
N-NE
0%
S-SW
68%
Sand 19


S-SE
20%
S-SW
0%
N-NE
17%
N-NW
63%
Sand 2


S-SW
7%
S-SE
3%
N-NE
0%
N-NW
90%
Slawson


N-NE
0%
N-NW
0%
S-SE
44%
S-SW
56%
Spromberg


S-SW
0%
S-SE
0%
N-NW
52%
N-NE
48%
Tripp

APPENDIX E: *Summary of Dunn's post-hoc test indicating significant median differences between EUs for fuel variables* $\alpha < 0.05$.

canopy closure

EU	Crow 1	Crow 3	Crow 6	LC	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
Crow 1 <	--	-	-	-	-	-	-	-	-	-	0.05	-
Crow 3 <	-	--	-	-	-	-	-	-	-	-	-	-
Crow 6 <	-	-	--	-	-	-	0.05	-	0.01	0.01	0.001	-
Little Camas <	-	-	-	--	-	-	-	-	-	-	-	-
Pendleton <	-	-	-	-	--	-	-	-	-	-	-	-
Poison <	-	-	-	-	-	--	-	-	-	-	-	-
Ruby <	-	-	0.05	-	-	-	--	-	-	-	-	-
Sand 19 <	-	-	-	-	-	-	-	--	-	-	-	-
Sand 2 <	-	-	0.01	-	-	-	-	-	--	-	-	-
Slawson <	-	-	0.01	-	-	-	-	-	-	--	-	-
Spromberg <	0.05	-	0.001	-	-	-	-	-	-	-	--	-
Tripp <	-	-	-	-	-	-	-	-	-	-	-	--

Kruskal-Wallis Statistic KW = 41.916 (corrected for ties) The P value is < 0.0001.

stand canopy base height

EU	Crow 1	Crow 3	Crow 6	Little Camas	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
Crow 1 <	--	0.05	-	0.001	-	0.05	0.001	-	-	0.001	0.001	0.001
Crow 3 <	0.05	--	-	-	-	-	-	-	-	-	-	-
Crow 6 <	-	-	--	0.05	-	-	-	-	-	-	0.001	-
Little Camas<	0.001	-	0.05	--	-	-	-	-	0.01	-	-	-
Pendleton	-	-	-	-	--	-	-	-	-	-	0.05	-
Poison <	0.05	-	-	-	-	--	-	-	-	-	-	-
Ruby <	0.001	-	-	-	-	-	--	-	0.05	-	-	-
Sand 19 <	-	-	-	-	-	-	-	--	-	-	-	-
Sand 2 <	-	-	-	0.01	-	-	0.05	-	--	-	0.001	-
Slawson <	0.001	-	-	-	-	-	-	-	-	--	-	-
Spromberg	0.001	-	0.001	-	0.05	-	-	-	0.001	-	--	-
Tripp <	0.001	-	-	-	-	-	-	-	-	-	-	--

Kruskal-Wallis Statistic KW = 72.144 (corrected for ties) The P value is < 0.0001.

1 hour timelag fuels

EU	Crow 1	Crow 3	Crow 6	Little Camas	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
Crow 1 <	--	-	-	0.001	-	-	-	0.001	0.001	0.001	0.001	0.001
Crow 3 <	-	--	-	-	0.05	-	-	-	-	0.01	0.05	-
Crow 6 <	-	-	--	0.001	-	-	0.05	0.001	0.001	0.001	0.001	0.001
Little Camas<	0.001	-	0.001	--	0.001	-	-	-	-	-	-	-
Pendleton	-	0.05	-	0.001	--	0.01	0.001	0.001	0.001	0.001	0.001	0.001
Poison <	-	-	-	-	0.01	--	-	-	-	0.05	-	-
Ruby <	-	-	0.05	-	0.001	-	--	-	-	-	-	-
Sand 19 <	0.001	-	0.001	-	0.001	-	-	--	-	-	-	-
Sand 2 <	0.001	-	0.001	-	0.001	-	-	-	--	-	-	-
Slawson <	0.001	0.01	0.001	-	0.001	0.05	-	-	-	--	-	-
Spromberg	0.001	0.05	0.001	-	0.001	-	-	-	-	-	--	-
Tripp <	0.001	-	0.001	-	0.001	-	-	-	-	-	-	--

Kruskal-Wallis Statistic KW = 144.64 (corrected for ties). The P value is < 0.0001.

10 hour timelage fuels

EU	Crow 1	Crow 3	Crow 6	Little Camas	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
Crow 1 <	--	-	-	0.05	-	-	-	-	-	-	-	-
Crow 3 <	-	--	-	-	-	-	-	-	-	-	-	-
Crow 6 <	-	-	--	0.05	-	-	-	-	-	-	-	-
Little Camas <	0.05	-	0.05	--	-	-	0.05	-	-	0.001	-	-
Pendleton <	-	-	-	-	--	-	-	-	-	0.01	-	-
Poison <	-	-	-	-	-	--	-	-	-	-	-	-
Ruby <	-	-	-	0.05	-	-	--	-	-	-	-	-
Sand 19 <	-	-	-	-	-	-	-	--	-	-	-	-
Sand 2 <	-	-	-	-	-	-	-	-	--	0.01	-	-
Slawson <	-	-	-	0.001	0.01	-	-	-	0.01	--	-	-
Spromberg <	-	-	-	-	-	-	-	-	-	-	--	-
Tripp <	-	-	-	-	-	-	-	-	-	-	-	--

Kruskal-Wallis Statistic KW = 43.430 (corrected for ties). The P value is < 0.0001.

100 hour timelag fuels

EU	Crow 1	Crow 3	Crow 6	Little Camas	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
Crow 1 <	--	-	-	-	-	0.05	-	0.01	-	-	-	-
Crow 3 <	-	--	-	-	-	-	-	-	-	-	-	-
Crow 6 <	-	-	--	-	-	-	-	-	0.05	-	-	-
Little Camas <	-	-	-	--	-	-	-	-	0.01	-	-	-
Pendleton <	-	-	-	-	--	-	-	-	-	-	-	-
Poison <	0.05	-	-	-	-	--	0.05	-	-	-	-	-
Ruby <	-	-	-	-	-	0.05	--	-	0.01	-	-	-
Sand 19 <	0.01	-	-	-	-	-	-	--	-	-	-	-
Sand 2 <	-	-	0.05	0.01	-	-	0.01	-	--	-	0.01	-
Slawson <	-	-	-	-	-	-	-	-	-	--	-	-
Spromberg <	-	-	-	-	-	-	-	-	0.01	-	--	-
Tripp <	-	-	-	-	-	-	-	-	-	-	-	--

Kruskal-Wallis Statistic KW = 45.196 (corrected for ties). The P value is < 0.0001.

1000+ hour rotten timelag

EU	Crow 1	Crow 3	Crow 6	Little Camas	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
Crow 1 <	--	0.001	-	-	-	0.01	-	0.001	-	0.01	-	-
Crow 3 <	0.001	--	-	-	-	-	0.05	-	-	-	-	-
Crow 6 <	-	-	--	-	-	-	-	0.01	-	-	-	-
Little Camas<	-	-	-	--	-	-	-	0.001	-	-	-	-
Pendleton <	-	-	-	-	--	-	-	0.001	-	-	-	-
Poison <	0.01	-	-	-	-	--	0.05	-	-	-	-	-
Ruby <	-	0.05	-	-	-	0.05	--	0.001	-	-	-	-
Sand 19 <	0.001	-	0.001	0.001	0.001	0.001	-	--	-	-	0.05	0.05
Sand 2 <	-	-	-	-	-	-	-	-	--	-	-	-
Slawson <	0.01	-	-	-	-	-	-	-	-	--	-	-
Spromberg	-	-	-	-	-	-	-	0.05	-	-	--	-
Tripp <	-	-	-	-	-	-	-	0.05	-	-	-	--

Kruskal-Wallis Statistic KW = 65.509 (corrected for ties). The P value is < 0.0001.

1000+ hour sound timelag

EU	Crow 1	Crow 3	Crow 6	Little Camas	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
Crow 1 <	--	0.01	-	-	0.001	-	-	0.001	-	-	-	-
Crow 3 <	0.01	--	-	-	-	-	0.001	-	-	0.05	-	-
Crow 6 <	-	-	--	-	-	-	-	0.05	-	-	-	-
Little Camas	-	-	-	--	-	-	-	-	-	-	-	-
Pendleton <	0.001	-	-	-	--	-	0.001	-	-	0.01	0.05	-
Poison <	-	-	-	-	-	--	-	-	-	-	-	-
Ruby <	-	0.001	-	-	0.001	-	--	0.001	-	-	-	-
Sand 19 <	0.001	-	0.05	-	-	-	0.001	--	-	0.001	0.01	-
Sand 2 <	-	-	-	-	-	-	-	-	--	-	-	-
Slawson <	-	0.05	-	-	0.01	-	-	0.001	-	--	-	-
Spromberg <	-	-	-	-	0.05	-	-	0.01	-	-	--	-
Tripp <	-	-	-	-	-	-	-	-	-	-	-	--

Kruskal-Wallis Statistic KW = 65.121 (corrected for ties). The P value is < 0.0001.

down dead wood depth

EU	Crow 1	Crow 3	Crow 6	Little Camas	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
Crow 1 <	--	-	-	-	-	-	-	-	-	-	-	0.001
Crow 3 <	-	--	-	-	-	-	0.01	-	-	-	-	0.001
Crow 6 <	-	-	--	-	-	-	-	-	-	-	-	0.001
Little Camas	-	-	-	--	-	-	-	-	-	-	-	-
Pendleton <	-	-	-	-	--	-	-	-	-	-	-	-
Poison <	-	-	-	-	-	--	-	-	-	-	-	-
Ruby <	-	-	0.01	-	-	-	--	-	-	0.01	-	-
Sand 19 <	-	-	-	-	-	-	-	--	-	-	-	0.01
Sand 2 <	-	-	-	-	-	-	-	-	--	0.05	-	-
Slawson <	-	-	0.01	-	-	-	-	-	0.05	--	-	0.001
Spromberg <	-	-	-	-	-	-	-	-	-	-	--	0.05
Tripp <	0.001	0.001	0.001	-	-	-	-	0.01	-	0.001	0.05	--

Kruskal-Wallis Statistic KW = 63.119 (corrected for ties). The P value is < 0.0001.

litter (Oi) fuel loading

EU	Crow 1	Crow 3	Crow 6	Little Camas	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
Crow 1 <	--	-	-	0.001	-	-	-	-	-	0.001	0.01	-
Crow 3 <	-	--	-	0.001	-	-	-	-	-	0.001	-	-
Crow 6 <	-	-	--	0.001	-	-	-	-	-	0.001	0.001	-
LittleCamas<	0.001	0.001	0.001	--	0.001	0.001	0.01	0.001	0.001	-	-	0.001
Pendleton <	-	-	-	0.001	--	-	-	-	-	0.001	0.001	-
Poison <	-	-	-	0.001	-	--	-	-	-	0.001	0.05	-
Ruby <	-	-	-	0.01	-	-	--	-	-	0.01	-	-
Sand 19 <	-	-	-	0.001	-	-	-	--	-	0.01	-	-
Sand 2 <	-	-	-	0.001	-	-	-	-	--	0.001	-	-
Slawson <	0.001	0.001	0.001	-	0.001	0.001	0.01	0.01	0.001	--	-	0.001
Spromberg <	0.01	-	0.001	-	0.001	0.05	-	-	-	-	--	0.001
Tripp <	-	-	-	0.001	-	-	-	-	-	0.001	0.001	--

Kruskal-Wallis Statistic KW = 136.88 (corrected for ties). The P value is < 0.0001.

duff (Oe) fuel loading

EU	Crow 1	Crow 3	Crow 6	Little Camas	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
Crow 1 <	--	0.01	-	0.001	-	0.001	0.001	0.001	0.001	0.001	0.01	0.001
Crow 3 <	0.01	--	0.05	-	0.001	-	-	-	0.05	-	-	0.001
Crow 6 <	-	0.05	--	0.001	-	0.001	0.001	0.001	0.001	0.001	0.05	0.001
LittleCamas<	0.001	-	0.001	--	0.001	-	-	-	-	-	-	0.001
Pendleton <	-	0.001	-	0.001	--	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Poison <	0.001	-	0.001	-	0.001	--	-	-	-	-	0.05	-
Ruby <	0.001	-	0.001	-	0.001	-	--	-	-	-	-	0.001
Sand 19 <	0.001	-	0.001	-	0.001	-	-	--	-	-	-	0.01
Sand 2 <	0.001	0.05	0.001	-	0.001	-	-	-	--	-	0.01	-
Slawson <	0.001	-	0.001	-	0.001	-	-	-	-	--	-	0.001
Spromberg <	0.01	-	0.05	-	0.001	-	-	-	0.01	-	--	0.001
Tripp <	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.01	-	0.001	0.001	--

Kruskal-Wallis Statistic KW = 280.46 (corrected for ties). The P value is < 0.0001.

total herb fuel loading

EU	Crow 1	Crow 3	Crow 6	Little Camas	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
Crow 1 <	--	0.001	-	0.001	-	0.001	0.001	-	-	0.05	0.001	0.001
Crow 3 <	0.001	--	0.001	-	-	-	-	-	-	-	-	-
Crow 6 <	-	0.001	--	0.001	0.05	0.001	0.001	-	-	0.05	0.001	0.001
Little Camas	0.001	-	0.001	--	0.001	-	-	0.001	0.01	0.01	-	-
Pendleton	-	-	0.05	0.001	--	-	-	-	-	-	0.01	-
Poison <	0.001	-	0.001	-	-	--	-	-	-	-	-	-
Ruby <	0.001	-	0.001	-	-	-	--	-	-	-	-	-
Sand 19 <	-	-	-	0.001	-	-	-	--	-	-	0.01	-
Sand 2 <	-	-	-	0.01	-	-	-	-	--	-	0.05	-
Slawson <	0.05	-	0.05	0.01	-	-	-	-	-	--	0.05	-
Spromberg	0.001	-	0.001	-	0.01	-	-	0.01	0.05	0.05	--	-
Tripp <	0.001	-	0.001	-	-	-	-	-	-	-	-	--

Kruskal-Wallis Statistic KW = 125.95 (corrected for ties). The P value is < 0.0001.

total shrub fuel loading

EU	Crow 1	Crow 3	Crow 6	Little Camas	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
Crow 1 <	--	-	-	-	0.001	-	-	0.001	-	-	-	-
Crow 3 <	-	--	-	-	-	-	-	-	-	-	-	-
Crow 6 <	-	-	--	-	0.05	-	-	-	-	-	-	-
Little Camas	-	-	-	--	-	-	-	-	-	-	-	-
Pendleton <	0.001	-	0.05	-	--	0.001	-	-	-	-	0.001	0.05
Poison <	-	-	-	-	0.001	--	-	0.01	-	-	-	-
Ruby <	-	-	-	-	-	-	--	-	-	-	-	-
Sand 19 <	0.001	-	-	-	-	0.01	-	--	-	-	0.001	-
Sand 2 <	-	-	-	-	-	-	-	-	--	-	-	-
Slawson <	-	-	-	-	-	-	-	-	-	--	-	-
Spromberg <	-	-	-	-	0.001	-	-	0.001	-	-	--	-
Tripp <	-	-	-	-	0.05	-	-	-	-	-	-	--

Kruskal-Wallis Statistic KW = 53.942 (corrected for ties). The P value is < 0.0001.

1 hour timelag shrub loading

EU	Crow 1	Crow 3	Crow 6	Little Camas	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
Crow 1 <	--	-	-	-	0.001	-	-	0.001	-	-	-	-
Crow 3 <	-	--	-	-	-	-	-	-	-	-	-	-
Crow 6 <	-	-	--	-	0.05	-	-	-	-	-	-	-
Little Camas	-	-	-	--	-	-	-	-	-	-	-	-
Pendleton <	0.001	-	0.05	-	--	0.001	-	-	-	-	0.001	0.05
Poison <	-	-	-	-	0.001	--	-	0.01	-	-	-	-
Ruby <	-	-	-	-	-	-	--	-	-	-	-	-
Sand 19 <	0.001	-	-	-	-	0.01	-	--	-	-	0.001	-
Sand 2 <	-	-	-	-	-	-	-	-	--	-	-	-
Slawson <	-	-	-	-	-	-	-	-	-	--	-	-
Spromberg <	-	-	-	-	0.001	-	-	0.001	-	-	--	-
Tripp <	-	-	-	-	0.05	-	-	-	-	-	-	--

Kruskal-Wallis Statistic KW = 54.956 (corrected for ties). The P value is < 0.0001.

10 hour timelag shrub loading

EU	Crow 1	Crow 3	Crow 6	Little Camas	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
Crow 1 <	--	-	-	-	0.001	-	-	0.001	-	-	-	-
Crow 3 <	-	--	-	-	-	-	-	-	-	-	-	-
Crow 6 <	-	-	--	-	0.05	-	-	-	-	-	-	-
Little Camas	-	-	-	--	-	-	-	-	-	-	0.05	-
Pendleton <	0.001	-	0.05	-	--	0.001	-	-	-	-	0.001	-
Poison <	-	-	-	-	0.001	--	-	0.01	-	-	-	-
Ruby <	-	-	-	-	-	-	--	-	-	-	-	-
Sand 19 <	0.001	-	-	-	-	0.01	-	--	-	-	0.001	-
Sand 2 <	-	-	-	-	-	-	-	-	--	-	-	-
Slawson <	-	-	-	-	-	-	-	-	-	--	-	-
Spromberg <	-	-	-	0.05	0.001	-	-	0.001	-	-	--	-
Tripp <	-	-	-	-	-	-	-	-	-	-	-	--

Kruskal-Wallis Statistic KW = 54.956 (corrected for ties). The P value is < 0.0001.

100 hour timelag shrub loading

EU	Crow 1	Crow 3	Crow 6	Little Camas	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
Crow 1 <	--	-	-	0.001	0.001	-	-	0.001	-	0.001	-	-
Crow 3 <	-	--	-	-	-	-	-	-	-	-	-	-
Crow 6 <	-	-	--	0.01	0.01	-	-	0.05	-	0.05	-	-
Little Camas <	0.001	-	0.01	--	-	0.001	-	-	-	-	0.01	-
Pendleton <	0.001	-	0.01	-	--	0.001	-	-	-	-	0.001	-
Poison <	-	-	-	0.001	0.001	--	-	0.01	-	0.01	-	-
Ruby <	-	-	-	-	-	-	--	-	-	-	-	-
Sand 19 <	0.001	-	0.05	-	-	0.01	-	--	-	-	0.01	-
Sand 2 <	-	-	-	-	-	-	-	-	--	-	-	-
Slawson <	0.001	-	0.05	-	-	0.01	-	-	-	--	0.01	-
Spromberg<	-	-	-	0.01	0.001	-	-	0.01	-	0.01	--	-
Tripp <	-	-	-	-	-	-	-	-	-	-	-	--

Kruskal-Wallis Statistic KW = 75.647 (corrected for ties). The P value < 0.0001.

1 hour equivalent live herbaceous fuel loading

EU	Crow 1	Crow 3	Crow 6	Little Camas	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
Crow 1 <	--	0.001	-	0.001	-	0.001	0.001	-	-	0.05	0.001	0.001
Crow 3 <	0.001	--	0.001	-	-	-	-	-	-	-	-	-
Crow 6 <	-	0.001	--	0.001	0.05	0.001	0.001	-	-	0.05	0.001	0.001
LittleCamas<	0.001	-	0.001	--	0.001	-	-	0.001	0.01	0.01	-	-
Pendleton <	-	-	0.05	0.001	--	-	-	-	-	-	0.01	-
Poison <	0.001	-	0.001	-	-	--	-	-	-	-	-	-
Ruby <	0.001	-	0.001	-	-	-	--	-	-	-	-	-
Sand 19 <	-	-	-	0.001	-	-	-	--	-	-	0.01	-
Sand 2 <	-	-	-	0.01	-	-	-	-	--	-	0.05	-
Slawson <	0.05	-	0.05	0.01	-	-	-	-	-	--	0.05	-
Spromberg<	0.001	-	0.001	-	0.01	-	-	0.01	0.05	0.05	--	-
Tripp <	0.001	-	0.001	-	-	-	-	-	-	-	-	--

Kruskal-Wallis Statistic KW = 125.95, (corrected for ties) The P value is < 0.0001.

1 hour equivalent herbaceous live load is simply = 19*1hr dead herb load, thus this table is the same as 1hour herbaceous.

equivalent 1 hour live shrub loading

EU	Crow 1	Crow 3	Crow 6	Little Camas	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
Crow 1 <	--	-	-	-	0.001	-	-	0.001	-	-	-	-
Crow 3 <	-	--	-	-	-	-	-	-	-	-	-	-
Crow 6 <	-	-	--	-	0.05	-	-	-	-	-	-	-
Little Camas <	-	-	-	--	-	-	-	-	-	-	-	-
Pendleton <	0.001	-	0.05	-	--	0.001	-	-	-	-	0.001	0.05
Poison <	-	-	-	-	0.001	--	-	0.01	-	-	-	-
Ruby <	-	-	-	-	-	-	--	-	-	-	-	-
Sand 19 <	0.001	-	-	-	-	0.01	-	--	-	-	0.001	-
Sand 2 <	-	-	-	-	-	-	-	-	--	-	-	-
Slawson <	-	-	-	-	-	-	-	-	-	--	-	-
Spromberg <	-	-	-	-	0.001	-	-	0.001	-	-	--	-
Tripp <	-	-	-	-	0.05	-	-	-	-	-	-	--

Kruskal-Wallis Statistic KW = 53.613, (corrected for ties) The P value is < 0.0001.

equivalent 10hr live shrub loading

EU	Crow 1	Crow 3	Crow 6	Little Camas	Pendleton	Poison	Ruby	Sand 19	Sand 2	Slawson	Spromberg	Tripp
Crow 1 <	--	-	-	-	0.001	-	-	0.001	-	-	-	-
Crow 3 <	-	--	-	-	-	-	-	-	-	-	-	-
Crow 6 <	-	-	--	-	0.05	-	-	-	-	-	-	-
Little Camas <	-	-	-	--	-	-	-	-	-	-	0.05	-
Pendleton <	0.001	-	0.05	-	--	0.001	-	-	-	-	0.001	-
Poison <	-	-	-	-	0.001	--	-	0.01	-	-	-	-
Ruby <	-	-	-	-	-	-	--	-	-	-	-	-
Sand 19 <	0.001	-	-	-	-	0.01	-	--	-	-	0.001	-
Sand 2 <	-	-	-	-	-	-	-	-	--	-	-	-
Slawson <	-	-	-	-	-	-	-	-	-	--	-	-
Spromberg <	-	-	-	0.05	0.001	-	-	0.001	-	-	--	-
Tripp <	-	-	-	-	-	-	-	-	-	-	-	--

Kruskal-Wallis Statistic KW = 55.744, (corrected for ties) The P value is < 0.0001.