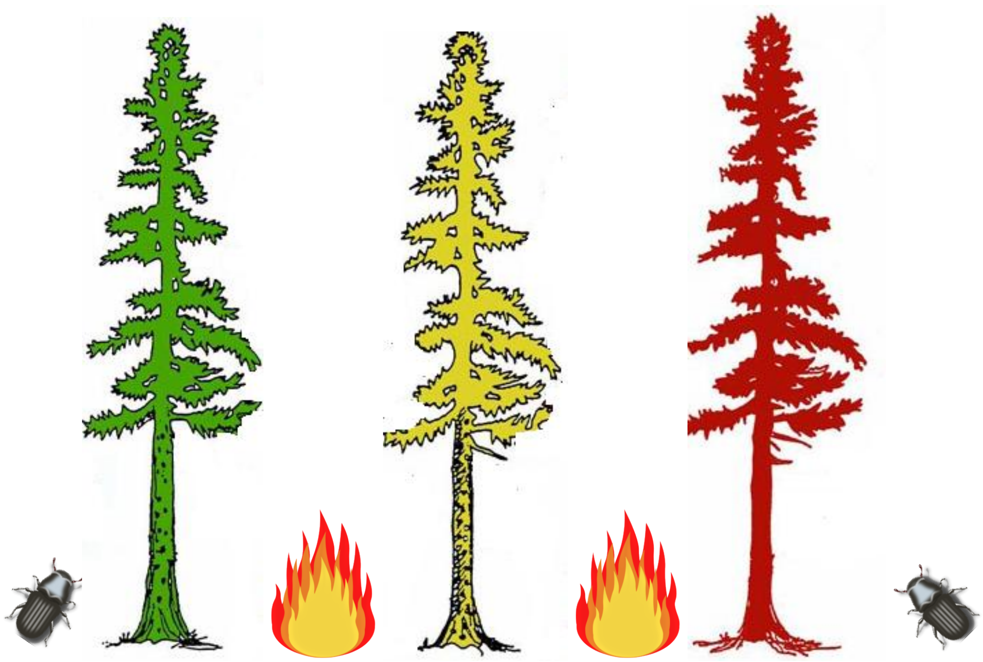
Fuel Dynamics and Potential Fire Behavior in Lodgepole Pine following Mountain Pine Beetle Epidemics in in south-central Oregon



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Abstract

Mountain pine beetle (*Dendroctonus ponderosae*, MPB), a bark beetle native to the western U.S., has caused vast areas of tree mortality across western North America over the last several decades. The majority of this mortality has been in lodgepole pine forests (*Pinus contorta*) and has raised concerns over the potential for extreme fire behavior across large landscapes as forest structure and fuels are altered following these MPB epidemics. Previous research has provided equivocal evidence concerning the influence of MPB on temporal and spatial effects to canopy and surface fuels and how these changes may consequently affect fire behavior. Recent research and synthesis efforts have begun to shed some light on the issues raised by managers, scientists, and the public in the wake of these epidemics. This study adds to the burgeoning body of research investigating the impacts of MPB epidemics; specifically, this project assessed changes in forest structure, surface fuels, and potential fire behavior following mountain pine beetle epidemics in south-central Oregon, where little work has been completed previously and potentially important ecological differences exist as compared to other lodgepole pine systems (e.g. Rocky Mountain lodgepole pine systems). It is important to consider the forest attributes, successional trends, and behavior of MPB when evaluating how fuels change over time following MPB mortality. Forests in the mature lodgepole pine type of the Deschutes and Fremont-Winema National Forests in south-central Oregon are generally low productivity, often single-species, uneven-aged stands, with a mixed severity fire regime. It has been informally noted by area entomologists that MPB activity tends to increase in those stands with a minimum of 100 trees per acre that are greater than 9 inches in diameter; MPB activity may last from a couple of years to a decade. They generally kill the largest trees, leaving primarily intermediate and suppressed trees that may additionally be infected with dwarf mistletoe. This study assessed changes in forest structure, surface fuels, and potential fire behavior following mountain pine beetle epidemics in south-central Oregon.

KEY FINDINGS:

- Our results support previous studies (Hicke et al. 2012) that have found that the influence of MPB on the subsequent organization of fuels changes with time since the beetle epidemic (TSB). In our study, these changes can be divided into four distinct stages based on the date of epidemic initiation:

  TSB1 – Overstory mortality stage (2-4 yrs post-initiation)
  TSB2 – Standing snag/Snagfall stage (5-13 yrs post-initiation)
  TBS3 – Regeneration stage (14-25 yrs post-initiation)
  TSB4 – Overstory densification stage (26-32 yrs post-initiation)

- Canopy bulk density declines significantly within the five years (TSB1) and slowly recovers over the following decades.
- Our data indicated that litter, 1-, and 10-hour fuel loads showed very little change throughout the chronosequence, whereas other models have found a peak within

the first 10 years and a subsequent decline to original levels over the following decades (Hicke et al. 2012).

- Our data indicate that 100-hr fuels slowly increase over time and continue climbing for decades, but the 1000-hr fuel loads begin to decrease by year 32 post-beetle in contrast to other studies that found both 100- and 1000-hr fuels continue to increase (Hicke et al. 2012).
- We found a lack of ladder fuels in the oldest time since beetle stage (TSB4), although our ladder fuels generally followed a similar trend to 100- and 1000-hour fuels in the Hicke et al. (2012).
- Modeled surface fire rates of spread and flame lengths were greatest in the standing snag/snagfall and regeneration stages (TSB2, TSB3). Rate of spread and flame length decreased in TSB4, in contrast to previously developed conceptual models (Hicke et al. 2012).
- Overall, our spatial fire behavior results indicate a current narrowing of fire behavior activity into moderate values for an area of the Fremont-Winema NF known as the Red Zone, currently comprised of fairly contiguous gray-stage lodgepole pine.
- Custom fuel models are not necessary for modeling fire behavior as standard fuel models adequately represent potential fire behavior. There may be more than one standard fuel model that captures expected fire behavior in a given stage.

Background and Purpose

Bark beetles (Coleoptera: Curculionidae, Subfamily Scolytinae) are important mortality agents in North America (Negron et al. 2008; Raffa et al. 2008). Recently, the mountain pine beetle (*Dendroctonus ponderosae*, MPB) has caused extensive lodgepole pine mortality in the western United States and Canada that has raised concern about potential fire behavior following this widespread mortality (Romme et al. 2006). Forest structure following mountain pine beetle infestation progresses through phases often referred to as “red”, “gray”, and “snagfall/regeneration or old” phases (Edburg et al. 2012; Hicke et al. 2012). The time necessary for a stand to progress through these phases varies across the species distribution (Jenkins et al. 2007; Hicke et al. 2012).

The MPB is a native insect present in most pine stands at endemic levels, although populations can quickly balloon when conditions are suitable as has been documented in south-central Oregon over the past 30 years. The peak occurred in 1986 when more than 1,000,000 infested acres were detected. MPB activity peaked again in 2008 to 2009, with over 400,000 infested acres detected. This extensive mortality from bark beetles, combined with future climate change effects (Littell et al. 2010), has raised questions about the potential for severe fire that are difficult to assess due to the lack of specific data concerning how MPB-caused mortality influences temporal and spatial aspects of fuels and in turn how these changes may affect fire behavior. This lack of data seriously limits the ability of fire managers to determine when and if fuels treatments will be effective and to provide for firefighter and public safety.

The *Pinus contorta* zone of south-central Oregon is a unique setting because *Pinus contorta* is an edaphic and topoedaphic climax occurring on both well-drained and poorly drained pumice soils, associated with broad depressions in the landscape where cold air pools (Franklin and Dyrness 1973). Cone serotiny is not common in lodgepole pine in central Oregon (Lotan and Critchfield 1990; Mowat 1960); therefore, the interaction of fire, bark beetles, and seed reproduction may be significantly different than in areas of the interior west where cone serotiny is high. In addition, lodgepole pine is a climax species in central Oregon and the fuel characteristics associated with vegetation development are unique compared to upper montane forests of the Rocky Mountains where spruce and fir are often the climax species.

We addressed the following questions specifically for the lodgepole pine forests of south-central Oregon: 1) How do fuel profiles (ground, surface, ladder and crown fuels) in lodgepole pine forests change over time in response to MPB epidemics in south-central Oregon? and 2) What are the effects of MPB epidemics on current and future fire behavior in lodgepole pine forests of south-central Oregon and how does fire behavior change over time following the epidemics?

To answer these questions we opted for a retrospective approach to better understand fuels following MPB epidemics in lodgepole pine vegetation types on the Deschutes and Fremont-Winema National Forests in order to reconstruct stand development and resultant ground, surface, ladder, and crown fuels. By developing a chronosequence covering a range of conditions we detected temporal changes in stand development and ground, surface, ladder, and crown fuels. To model and estimate the temporal and spatial change in potential fire behavior we selected several standard fuel models and developed custom fuel models based on our plot data to use in multiple fire behavior systems.

Study Description and Location

Our study area is located in the *Pinus contorta* zone (Franklin and Dyrness 1973) of central and south-central Oregon on the Deschutes and Fremont-Winema National Forests (Figure 1). Stand structure varies from low density, open stands in drier, lower productivity sites to closed canopy stands composed of larger diameter trees with prevalent conifer regeneration in moister, higher productivity sites (Mowat 1960). Fire history and fire regimes are not well studied and are best described as a mixed severity regime where crown fire is rare (Agee 1993; Gara et al. 1985; Geiszler et al. 1980). Much of the landscape has not experienced stand replacement fire since the 1920s, preceding MPB epidemics of recent records. Agee (1993) notes that litter is essentially non-existent in this type and shrubs and herbs are often too patchy to carry surface fire. Downed logs are often an important vector for fire spread, especially partially decayed logs. Fire return intervals have been estimated to range between 60-350 years for the lodgepole pine forest of the Fremont National Forest (Stuart 1983). Agee (1981) estimated fire return intervals further west within Crater Lake National Park at 60 years.

Additional fire history studies in similar forest types in California around Mt. Lassen have return intervals around 50 to 60 years (Bekker and Taylor 2001; Taylor and Solem 2001).

Elevation within the study area ranges from approximately 4,800 to 8,000 feet; temperatures range from an average daily minimum of 26° F to an average daily maximum of 81°. Annual precipitation, occurring mainly in the form of snow, amounts to 10 inches in the eastern portion of the study area, up to 111 inches at higher elevations (PRISM Climate Group, Oregon State University, 30-yr average for 1981-2010. http://prism.oregonstate.edu). Vegetation and environmental characteristics of the Lodgepole Pine Series Plant Associations of this region are described by Simpson (2008) and Volland (1985).

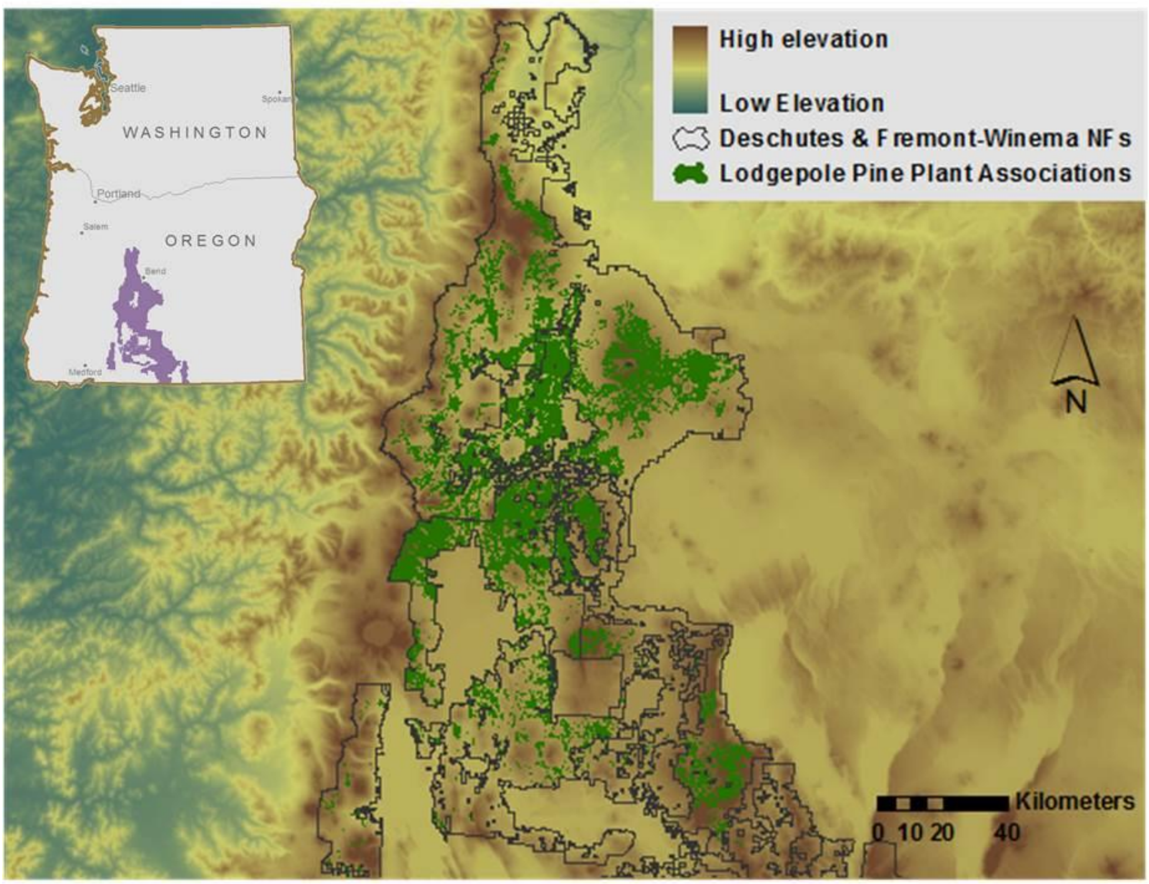

Figure 1. Climax lodgepole pine plant associations, derived from local plant association guides, within the Deschutes (northern) and Fremont-Winema (southern) forest boundaries

Methods

Sampling Design

We developed a 32-year chronosequence (1978-2010) to investigate the changes in fuel structure over time following mountain pine beetle disturbance. Using a combination of aerial detection survey (ADS) cumulative mortality data (McConnell et al. 2000) and previously developed plant associations for the area (Hopkins 1979; Simpson 2007; Volland 1985) we sampled areas of heavy tree mortality (> 30 trees per acre) across a productivity gradient (low, moderate, high) in climax lodgepole pine landscapes (Figure 2). Using the ADS data, we identified 19 separate years a MPB epidemic was initiated across enough stands to sample over the 32-year spectrum.

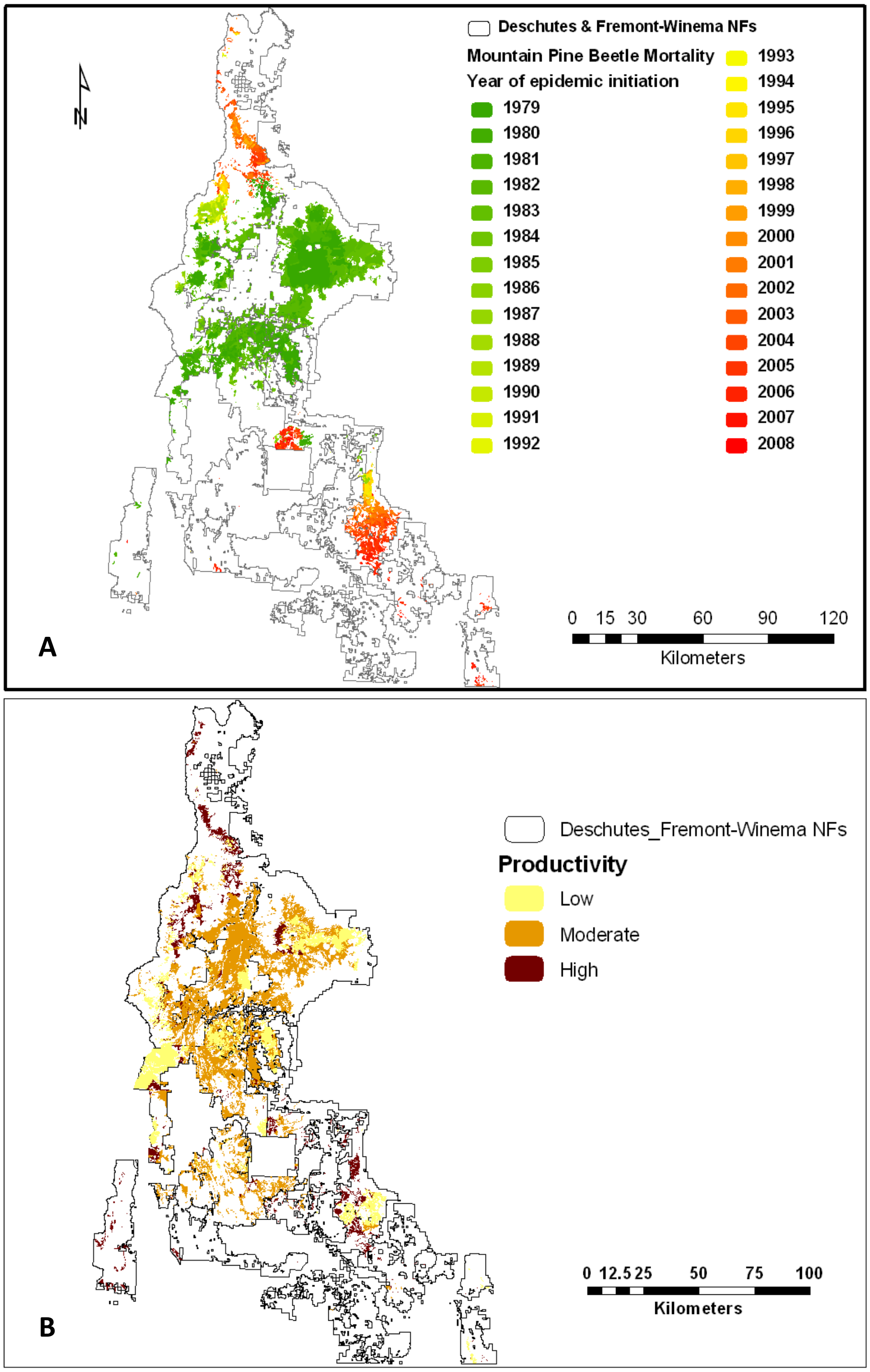

Figure 2. A) Year of mountain pine beetle epidemic initiation derived from ADS data (Aerial Detection Surveys, USFS Pacific Northwest Region; http://www.fs.usda.gov/detail/r6/forest-grasslandhealth/insects-diseases/?cid=stelprdb5286951) and B) productivity classifications from plant association guide data (Simpson 2008)

Within the 19 years of MPB epidemics, we sampled four replicates within each productivity class for a total of 12 plots per epidemic year (Figure 3). However, our total number of plots was limited to 213 as no suitable replacements could be established for 15 plots eliminated based on pre-established protocols (e.g., evidence of logging disturbance or fire, inaccurate plant association). Plots were selected using a spatially balanced random sampling algorithm (Stevens and Olsen 2004) in an R statistical software environment.

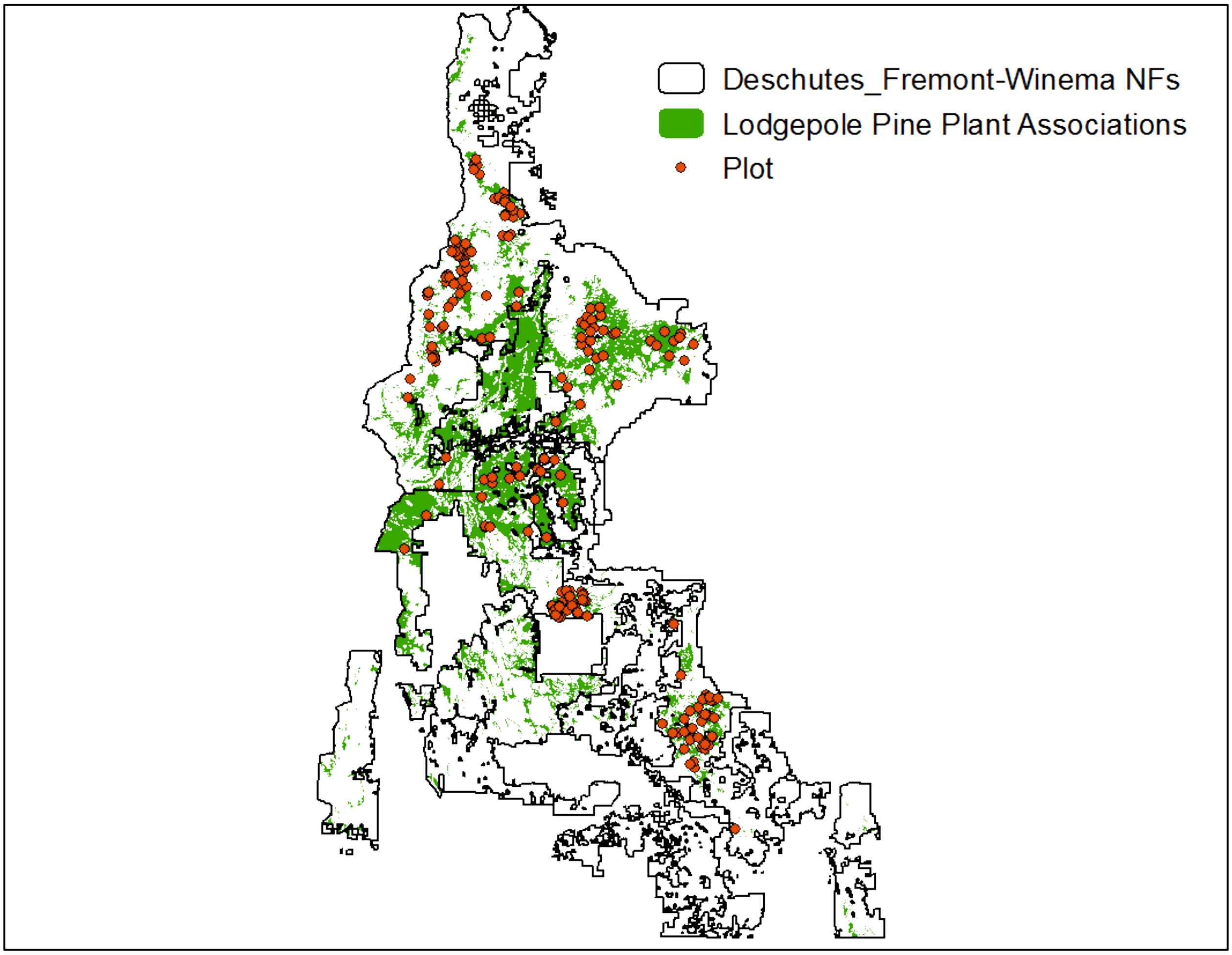

Figure 3. Randomly selected (spatially balanced) MPB epidemic chronosequence plot network within climax lodgepole plant associations on the Deschutes and Fremont-Winema National Forests

Field measurements

Sampling was conducted following the plot layout in Figure 4. A 29.27 ft (0.06 acres) radius central tree plot was established to measure diameter at breast height (DBH), tree height, and canopy base height of live and dead standing trees greater than 2 inches DBH. We assessed each live tree for mistletoe severity using the Dwarf Mistletoe Rating (DMR) system (Hawksworth 1977) and assigned a decay class to all dead trees measured. In four 10.5-ft radius subplots, we measured height and basal diameter and recorded species of all trees, saplings, and seedlings (less than 2 inches DBH). Within these subplots, shrubs were measured for several characteristics to determine biomass, including: basal diameter, height, crown width, and/or crown volume. Nested within each subplot was a 6.56 x 6.56 ft quadrat to measure percent ground cover (e.g., mineral soil, rock, vegetation) and percent cover of herbaceous vegetation by species.

Surface fuels were measured along four 82-ft transects in cardinal directions using the methods of Brown et al. (1982). At 32.8 ft and 65.6 ft along each transect, litter, duff, and surface fuel depths were measured. Canopy cover of the lower, middle, and upper canopy was assessed along the first 29.27 ft of the fuels transect; in addition, a convex densiometer was used at central tree plot center and subplot center following the methods of Strickler (1959). Along each transect from the central tree plot center, increment cores were taken to establish tree age for the first two live dominant or co-dominant trees. If no dominant or co-dominant trees were present in the central tree plot, trees were selected from the larger plot footprint or intermediate size class trees were selected. At the central tree plot center, a photograph was taken of surface fuels in each cardinal direction (i.e., along fuels transects) and one photograph was taken looking up into the canopy.

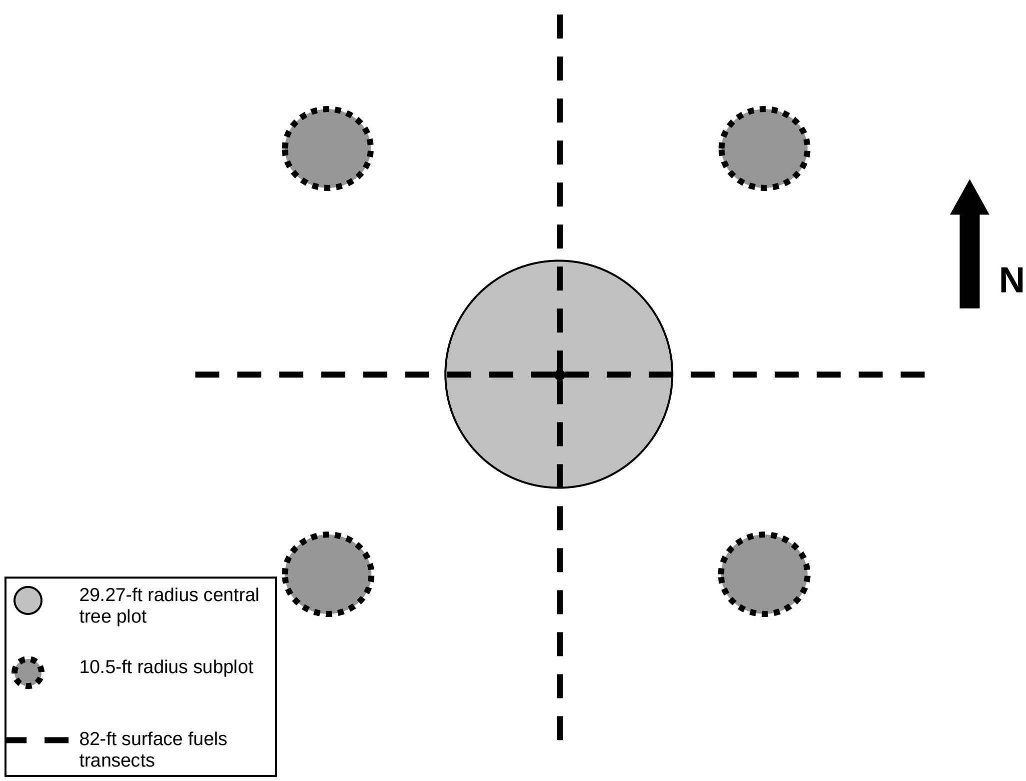

Figure 4. Diagram showing the plot design for sampling forest structure and the fuels complex following MPB epidemics

Data preparation

Counts of 1-, 10-, 100-, and 1000-hour fuels (0-0.25, 0.26-1.0, 1.1-3.0, and >3.0 inches, respectively) were converted from counts to tons per acre (Harmon and Sexton 1996; Harmon et al. 2008). Seedling/sapling and shrub counts were converted to biomass (tons/acre) using relationships of height or basal diameter and mass (Brown 1976; Ross and Walstad 1986; Means et al. 1994). Herbaceous cover estimates were converted to tons/acre using equations for the area in BIOPAK software (Means et al. 1994). Species for which no equations were available were estimated based on data from similar species. Biomass of duff and litter was calculated from depth measurements using conversion factors (Lutes et al. 2006). Canopy fuel parameters (canopy base height, canopy bulk density, and canopy height) were calculated using FuelCalc (Heward et al. 2013). Canopy bulk density was calculated using live green trees as well as red and brown trees with greater than 50 percent of needles remaining on the tree at the time of sampling based on ocular estimation. FuelCalc ratios for crown class were used as a proxy for trees with greater than 50 percent of needles remaining. Basal area (ft^2/acre) was calculated from DBH.

Fuels and Forest Structure MANVOA Analysis

To understand the changes in forest structure and fuels over time following mountain pine beetle epidemics we applied a multivariate approach. The fuels complex (both surface and crown) are comprised of several variables, all of which interact to influence fire behavior. As a multivariate circumstance it requires a multivariate statistical approach to better understand which fuels parameters are changing while truly accounting for interacting factors. We used Multivariate Analysis of Variance (MANOVA) to better determine which variables were most important in driving changes in the fuels complex that would in turn affect fire behavior. Surface fuel response variables examined included: 1-, 10-, 100-, and 1000-hr fuel loads; litter load; duff load; surface fuel bed depth; and herbaceous, woody shrub, live seedling, and live sapling biomass. Crown fuel response variables included: overstory canopy cover, basal area of live trees, basal area of dead trees, canopy base height, canopy bulk density, and canopy height. After examining trends in fuels and forest structure over time, we constructed four distinct post-MPB initiation stages.

The distinctions between stages were signified by a large change in at least one variable that would influence fire behavior. These stages are described in detail in the results section. We used these stages and the fuels data from field plots associated with each stage in the MANOVA analysis following the methods outlined by Grice and Iwasaki (2007). The first and second discriminant function coefficients for each fuel variable were used to create two multivariate composites. These composites represent how the combination of dependent variables (i.e., fuels) discriminates between the various stages of the post-MPB environment. The two fuels strata (surface and crown) were analyzed separately (i.e., composites developed and analyzed separately for surface and crown) given the nature of fire behavior models separating the spread of surface fire and crown fire. These composites were then analyzed in an ANOVA (Analysis of Variance) to identify covariates and significant changes in fuels over time. Covariates included the proportion of mountain pine beetle mortality (low, moderate, high) derived from ADS data and productivity (low, moderate, high). In addition, we performed univariate ANOVA to obtain estimates of fuel parameters and standard errors for each of the fuel variables.

Forest Structure Analysis

In order to evaluate potential fire behavior in stands affected by MPB, custom fuel models were built in BehavePlus v. 5.0.5 for each post-epidemic stage. As stand conditions can be quite variable following MPB disturbance, numerous simulations were completed to better capture the inherent heterogeneity in forested stand conditions. Fire behavior outputs from the custom fuel models were compared with outputs from standard fuel models (Scott and Burgan 2005). Results from the BehavePlus simulations informed changes to spatial landscape data for FlamMap analyses; the standard fuel models in the FlamMap landscape file were modified based on the BehavePlus simulations.

Fire and Weather Analysis

Weather and fire occurrence records were acquired and analyzed for the Fremont (FRF), Winema (WNF), and Deschutes (DEF) National Forests. In order to provide a framework for weather parameters to be used in point and spatial fire behavior analyses, it is often helpful to complete an analysis evaluating historical fire growth and fire behavior in relation to observed weather. Not only it is easy to identify record-setting years for fire occurrence, but it is also possible to examine the weather that coincided with large fire years.

This analysis couples weather station data and fire occurrence data from multiple sources. Fire occurrence data and daily weather observation data were downloaded from the Fire and Weather Data on the FAMWEB website (https://fam.nwcg.gov/fam-web) for the DEF, FRF, and the WNF and imported into FireFamilyPlus v. 4.1.0 (Bradshaw and Tirmenstein 2009). Hourly weather observations were downloaded from the Western Regional Climate Center (WRCC, http://www.raws.dri.edu) for each individual weather station and imported into FireFamilyPlus. Data from numerous RAWS (Remote Automated Weather Stations) were evaluated to determine which stations have adequate records and are representative of the areas previously impacted by MPB. Historical fire records were evaluated to identify years of high fire activity; in particular, 2002 and 2003 were busy fire seasons in the area. Historical weather records were evaluated to determine which weather station recorded weather and wind parameters associated with wildfire growth patterns and observed fire behavior during these years. The Hoyt Creek RAWS on the Fremont-Winema was the most representative of weather (wind speed and direction, temperature, and relative humidity) during months and years when large fires occurred. On the DEF, the Round Mountain RAWS had the best correlation with wind speed and direction and the Colgate RAWS tracked temperature and relative humidity reasonably well. Table 1 summarizes the fire weather used for fire behavior analyses. A full report of the fire weather analysis has been provided as a separate deliverable document to this report (Hollingsworth and Kurth 2012).

Fire Behavior Modeling

Two fire behavior systems were used. The first, BehavePlus, is a point fire behavior system that predicts fire behavior for a point in space. This system is often used to simulate fire behavior based on plot measurements. The second system is a geospatial fire behavior system known as FlamMap that predicts fire behavior on a larger scale, often defined as the landscape.

Table 1. Values used for moderate and dry fuel moisture conditions in fire behavior analyses. Weather data was obtained from the Colgate RAWS and wind records were derived from the Round Mountain RAWS for the period of May 1 to October 31, 1991-2011

Weather Parameter	Moderate Conditions		Dry Conditions	
	Value	Percentile	Value	Percentile
Max Temp.	88^{o} F	80	94^{o} F	93
Min RH	21%	45	12%	11
1-hr fuel moisture	3%	20	2%	3
10-hr fuel moisture	5%	29	3%	2
100-hr fuel moisture	9%	13	7%	2
Live herbaceous moisture	70%	-	50%	-
Live woody moisture	90%	-	80%	-
Wind Speed	7 mph	65	7 mph	65
	15 mph	98	15 mph	98

BehavePlus

Based on the fire and weather analysis, we calculated surface rate of spread, flame length, and type of fire (surface, torching, and crown) in BehavePlus 5.0.5 with different combinations of winds (moderate and high wind speeds) and live and dead fuel moisture (moderate and dry conditions). We built custom fire behavior fuel models representing approximately the 75th percentile for different measured variables from plot data and compared these outputs with outputs from nine standard timber and slash fuel models (Anderson 1982; Scott and Burgan 2005) provided by local fire managers (Table 2). We used a canopy fuel moisture value of 80% (lower end of recommended range for red stage) for TSB1, given previous research indicating lower needle moisture in beetle attacked/killed trees (Jolly et al. 2012). A foliar moisture content of 100% was used for TSB2-TSB4.

Table 2. Fuel models used for fire behavior analyses using BehavePlus. Surface fuel model numbers refer to standard fire behavior fuel models (Anderson 1982; Scott and Burgan 2005) and TSB refers to time since beetle

Stage	TSB1 (2-4 yrs)	TSB2 (5-13 yrs)	TSB3 (14-25 yrs)	TSB4 (26-32 yrs)
Surface Fuel Models	Custom 164 165 185	Custom 11 12 164 165 185 201 202	Custom 11 12 164 165 185 201 202	Custom 10 11 12 164 165 201 202

To compensate for an important limitation in the surface fire spread model (Rothermel 1972) that states fuels are homogeneous, input values for 1-hr fuel loading were decreased and the fuel bed depth and dead fuel moisture were increased within the custom fuel models. Each parameter was changed individually for the BehavePlus simulations using custom fuel models, keeping all other inputs constant in order to investigate the effect of changing parameters on predicted fire behavior. The BehavePlus simulations using standard fuel models were run using the same wind speed and live and dead fuel moisture conditions. These results were compiled to define an expected range of outputs for each fire behavior attribute.

FlamMap

FlamMap v. 5 was used to compare flame length and crown fire activity calculated from LANDFIRE data and LANDFIRE data modified based on our plot data. Dead fuel moisture values were conditioned for seven days for a period in 2002 immediately prior to the start of numerous long-term fire incidents on the Fremont-Winema NF; the weather and wind files for the Hoyt Creek RAWS were exported from FireFamilyPlus. Geospatial fire behavior analyses were performed in FlamMap to investigate potential landscape fire behavior in an area of newer MPB activity on the FRF. The "Red Zone" landscape on the Fremont-Winema National Forest is no longer red, but rather a large contiguous area of gray stage lodgepole pine stemming from widespread mortality due to a mountain pine beetle outbreak that occurred from approximately 2000 to present, with much of the mortality occurring prior to 2010. The Red Zone has been an area of concern for local managers due to safety concerns for the public and firefighters as well as expected coarse woody fuel loadings in the future as snags continue to fall. Managers have questioned where to locate potential future treatments to mitigate safety concerns and alleviate potential effects of post-frontal combustion in the jackstraw fuels.

Fuel moisture values were conditioned for seven days to account for the effects of topography and shading on dead fuel moisture values. Multiple FlamMap simulations were completed to evaluate the effect of wind direction, wind speed, and fuel moisture on predicted fire behavior. All scenarios used gridded winds calculated from WindNinja as embedded in FlamMap; gridded winds show a defined difference in wind velocity between valley bottoms and ridge tops as well as the topographic influences on wind direction. The results provided in this report are based on dry fuel moisture conditions with southwest winds at 15-mph.

Vegetation and fuels data necessary for spatial fire behavior analyses were acquired from the Landscape Fire and Resource Management Planning Tools Project, known as LANDFIRE (http://www.landfire.gov/, Rollins 2009). Using the LANDFIRE Data Acquisition Tool (LFDAT, Toney et al. 2012) in ArcMap 10.0, landscape data for the analysis areas were downloaded (standard fire behavior fuel models, canopy base height, canopy bulk density, canopy cover, canopy height, elevation, slope, and aspect).

FlamMap results from two different datasets were compared for the Red Zone: LANDFIRE Refresh 2008 data and LANDFIRE Refresh 2008 data modified based on results from the fuels and forest structure analysis and time since beetle initiation (TSB) calculated using the ADS cumulative mortality layer. To reflect the changes in fuels over time, the standard fire behavior fuel models, canopy base height, and canopy bulk density LANDFIRE layers were changed based on the fuels and forest structure analysis for each TSB stage. Table 3 indicates changes made depending upon the stage (since MPB initiation) a given pixel fell into (Figure 5). The Scott and Reinhardt (2001) method of crown fire calculation was used for all simulations.

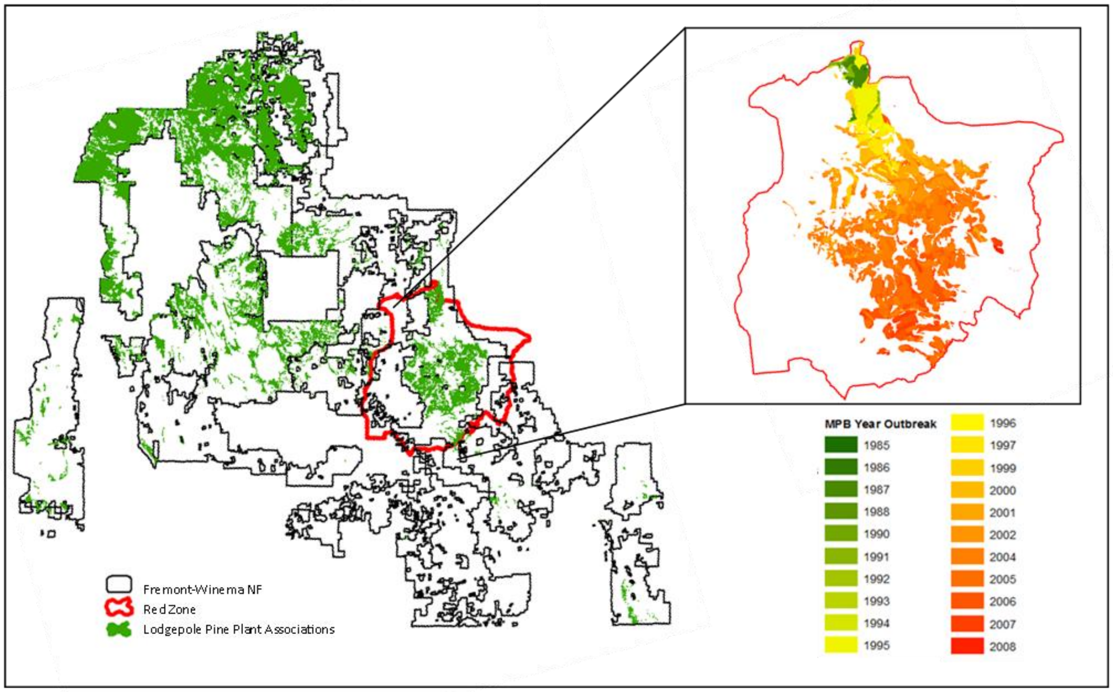

Figure5. Recent MPB activity within the Red Zone analysis area on the Fremont-Winema NF. Green on the large map indicates the Lodgepole Pine Plant Associations, while the yearly color codes are for the red zone only.

Table 3. Changes made to LANDFIRE data based on TSB stage for *FlamMap* spatial fire behavior analyses.

Stage	FBFM	CBD	CBH
TSB1	165 (TU5)	0.06	5.0
TSB2	202 (SB2)	0.03	7.0
TSB3	202 (SB2)	0.04	5.0
TSB4	202 (SB2)	0.05	6.0

Results

MANOVA Analysis

A Multivariate Analysis of Variance (MANOVA) conducted on fuels data from 2 to 32 years following infestation indicates that patterns in surface fuels are primarily driven by changes in 10- and 100-hr fine fuels, fuel bed depth, 1000-hr fuels, and to a small degree 1-hr fuels. Both multivariate discriminant functions included 100-hr, 1000-hr, and fuel bed depth as the strongest coefficients, while the second discriminant function also included 1- and 10-hr fuels as important coefficients. Crown fuel discriminant functions were dominated by either basal area of dead or live trees, overstory tree cover, canopy bulk density, canopy base height, and average stand height (Table 4). Larger values indicate stronger relationship in the discriminant function analyses.

The coefficients with larger magnitudes of strength were then used to create composite variables to test the significance of the multivariate fuels for surface and crown fuels separately. Composites for both surface and crown fuels were significantly different across stages of time since MPB.

Table 4. Discriminant function coefficients from MANOVA analysis of surface and crown fuel variables, * indicates coefficient used to develop a multivariate composite to test significance using ANOVA

Surface Fuel Variables	Standardized DF-1 Coefficients		Standardized DF-2 Coefficients
100-hr Fuel Load	0.69*	10-hr Fuel Load	-1.02*
Fuel Bed Depth	0.56*	100-hr Fuel Load	0.69*
1000-hr Fuel Load	0.46*	Fuel Bed Depth	0.56*
Herbaceous Load	-0.24	1000-hr Fuel Load	0.46*
Duff Load	-0.24	1-hr Fuel Load	0.39
Litter Load	-0.20	Duff Load	-0.24
1-hr Fuel Load	-0.038	Litter Load	-0.20
10-hr Fuel Load	0.033	Live Woody Load	-0.06
Live Woody Load	-0.06	Herbaceous Load	-0.024
Crown Fuel Variables			
Basal Area – Dead	-1.28	Canopy Bulk Density	1.5
Overstory Canopy Cover	0.29	Basal Area – Live	-1.21
Basal Area – Live	0.28	Canopy Height	0.65
Canopy Base Height	0.16	Overstory Canopy Cover	0.38
Canopy Height	0.09	Canopy Base Height	-0.19
Canopy Bulk Density	0.005	Basal Area – Dead	0.07

Fuels and Forest Structure

We assigned the plots to one of four post-initiation phases: overstory mortality (red), standing snag/snag-fall (gray), regeneration, and overstory densification. Surface and crown fuel parameters are discussed below for each phase. The canopy bulk density, herbaceous biomass, live woody biomass, 100- and 1000- hour fuel load, litter biomass, and fuelbed depth showed changes through the phases while other forest structure parameters measured were either highly variable or remained stable through all stages.

Time Since Beetle 1 (TSB1) – Overstory mortality phase (2-4 yrs post-initiation)

Often referred to as the red stage, this phase begins as a mix of recently killed (red needle), dead, and living (green) trees (Figure 6). The proportion of a stand affected by MPB varies greatly across the landscape and through time. The most apparent change during this phase is a nearly 50 percent decrease in canopy bulk density due to needle loss following mortality (Figure 7). Additionally, the 100-hr fuels may increase slightly as tree branches begin to fall. Loss of canopy allows more light to penetrate the canopy and may drive a slight increase in herbaceous biomass. Other fuel characteristics showed no consistent change during this phase.

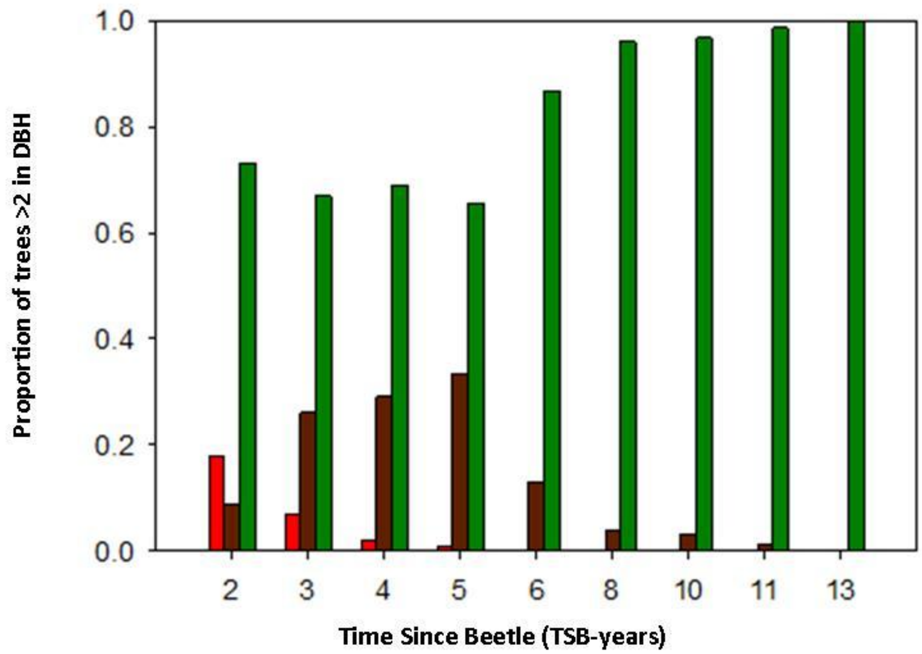

Figure 6. Patterns in forest structure and fuels across a 32-yr chronosequence following MPB epidemic initiation showing proportion of trees in the red (recently dead), brown (dead one or more years with more than 50% of the needles remaining), and green (currently live – may or may not have been attacked)

Time Since Beetle 2 (TSB2) – Standing Snag/Snag Fall phase (5-13 yrs post-initiation)

Often referred to as the gray stage, this period of time following MPB initiation is represented by gray standing snags that tend to fall slowly through this stage. A large pulse of snag fall occurs near the end of the stage and the beginning of the regeneration stage (approximately 13 yrs post-MPB). The 100- and 1000-hr fuel loads, litter mass, and live woody fuel loads increase while canopy base height and overstory canopy cover decrease through this stage (Figure 7).

Time Since Beetle 3 (TSB3) - Regeneration phase (14-25 yrs post-initiation)

The most noticeable changes in this stage are the increases in live woody fuels and fuel bed depth (Figure 7) resulting from a dramatic increase in the number of seedlings and saplings (regeneration) per acre. The 100-hr fuels remain high through this stage while 1000-hr fuels reach their maximum levels near the end of this stage (Figure 7).

Time Since Beetle 4 (TSB4) - Overstory densification phase (26-32 yrs post-initiation)

This stage is represented by a decrease in 1000-hr fuels and an increase in canopy bulk density, canopy cover and live tree basal area (Figure 7). Canopy bulk density and canopy base height values approach TSB1 values by year 32 of the chronosequence. Loads of 100-hr fuels and live woody fuel loads (Figure 7) remain similar to the previous stage. Overall, a densification of the overstory is apparent as seedlings and saplings that survived the MPB epidemic are now becoming the new overstory. Plant communities dominated by a shrub understory still have heavy shrub loads; however observations indicate that shrubs are declining in this stage. Lodgepole pine regeneration is still present and adding to consistent levels of live woody fuels.

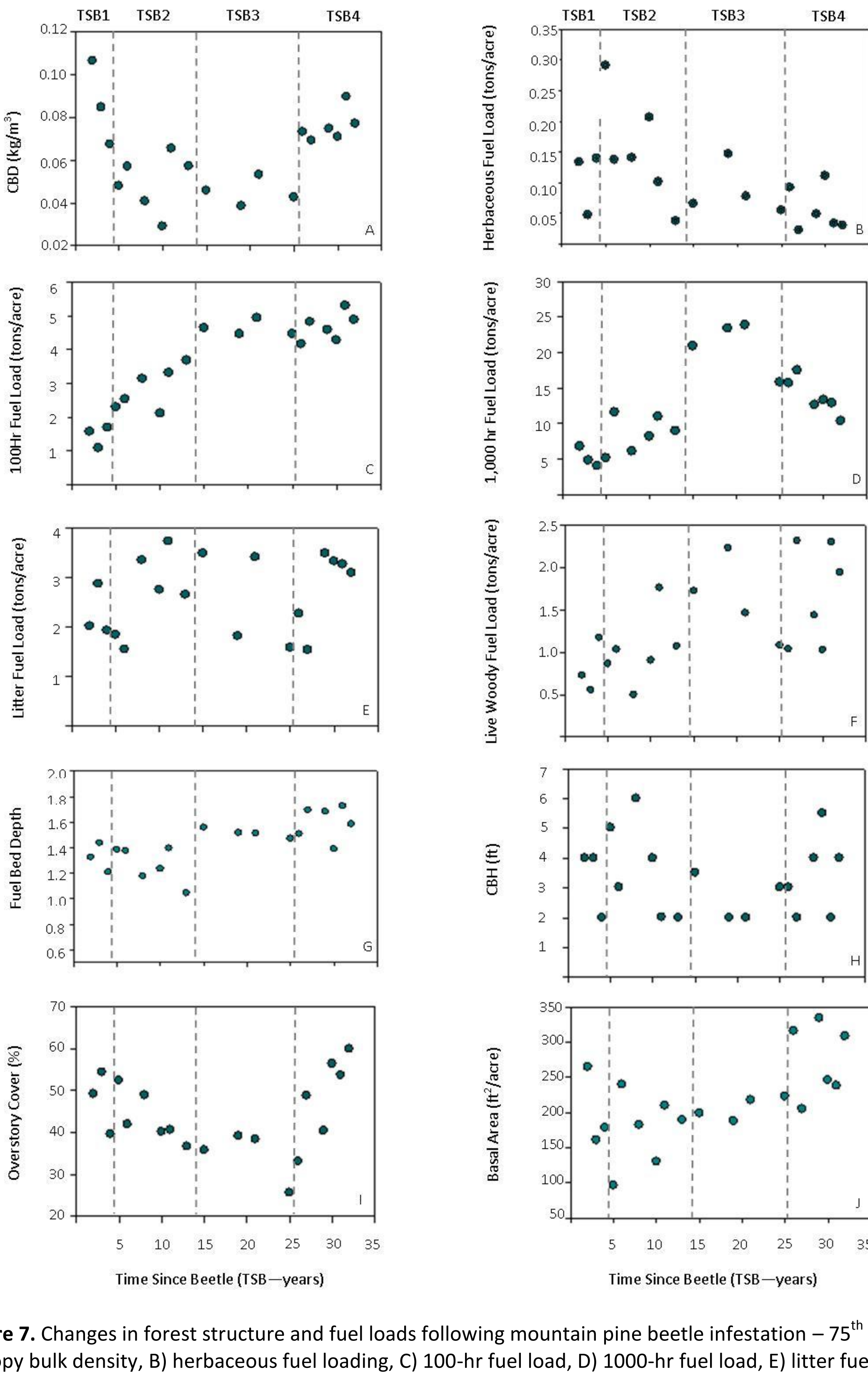

Figure 7. Changes in forest structure and fuel loads following mountain pine beetle infestation – 75th percentile A) canopy bulk density, B) herbaceous fuel loading, C) 100-hr fuel load, D) 1000-hr fuel load, E) litter fuel load, F) live woody fuel load, G) fuel bed depth, H) canopy base height, I) overstory cover and J) live tree basal area

Fire Behavior

BehavePlus

Custom fuel models were built for each stage based on the statistical analyses of the plot data. The custom fuel models allowed evaluation of the predicted fire behavior through time since beetle epidemic, but also to gauge the influence of fuel moisture conditions and varying wind speeds, and to compare with an array of standard fuel models.

Table 5. Simulated fire behavior for each time since beetle stage using custom fuel models

Time Since Beetle Stage	Fire Behavior	Moderate Conditions		Dry Conditions	
		7-mph Wind	15-mph Wind	7-mph Wind	15-mph Wind
TSB1	Surface Rate of Spread (ch/hr)	2.0	4.9	2.4	5.7
	Fireline Intensity (BTU/ft/s)	28	68	35	86
	Flame Length (ft)	2.1	3.1	2.3	3.5
	Type of Fire	surface	passive	surface	passive
TSB2	Surface Rate of Spread (ch/hr)	4.1	10.6	4.7	12.2
	Fireline Intensity (BTU/ft/s)	76	198	94	245
	Flame Length (ft)	3.3	5.1	3.6	5.7
	Type of Fire	passive	passive	passive	passive
TSB3	Surface Rate of Spread (ch/hr)	5.8	15.2	6.6	17.5
	Fireline Intensity (BTU/ft/s)	131	346	163	431
	Flame Length (ft)	4.2	6.6	4.7	7.3
	Type of Fire	passive	passive	passive	passive
TSB4	Surface Rate of Spread (ch/hr)	3.3	8.1	3.8	9.3
	Fireline Intensity (BTU/ft/s)	78	192	97	238
	Flame Length (ft)	3.3	5.0	3.7	5.6
	Type of Fire	passive	passive	passive	passive

Predicted fire behavior shows a progressive increase over time through TSB3 (14 – 25 yrs following infestation) and a decline thereafter (Table 5). The results are even more pronounced under dry fuel moisture conditions and high wind speeds (Figure 8).

While custom fuel models built from vegetation and fuels data gathered from plot data may seem to be more accurate than the standard fuel models in predicting fire behavior, this assumption may not necessarily be true. One notable difference is that there was not an herbaceous fuel load in any of the standard FBFM analyzed; there are very few timber fuel models that include both herbaceous and woody loads. Depending on the complexity of the understory, this may or may not be important. The fire spread models embedded in a system such as BehavePlus have numerous assumptions and limitations that should be considered.

Often the most limiting is the fact that the spread models are meant to be used in homogeneous fuels which is generally not the case in most forest types. Small changes in topography or surface fuels can affect microsite conditions which may affect how a fire would actually spread.

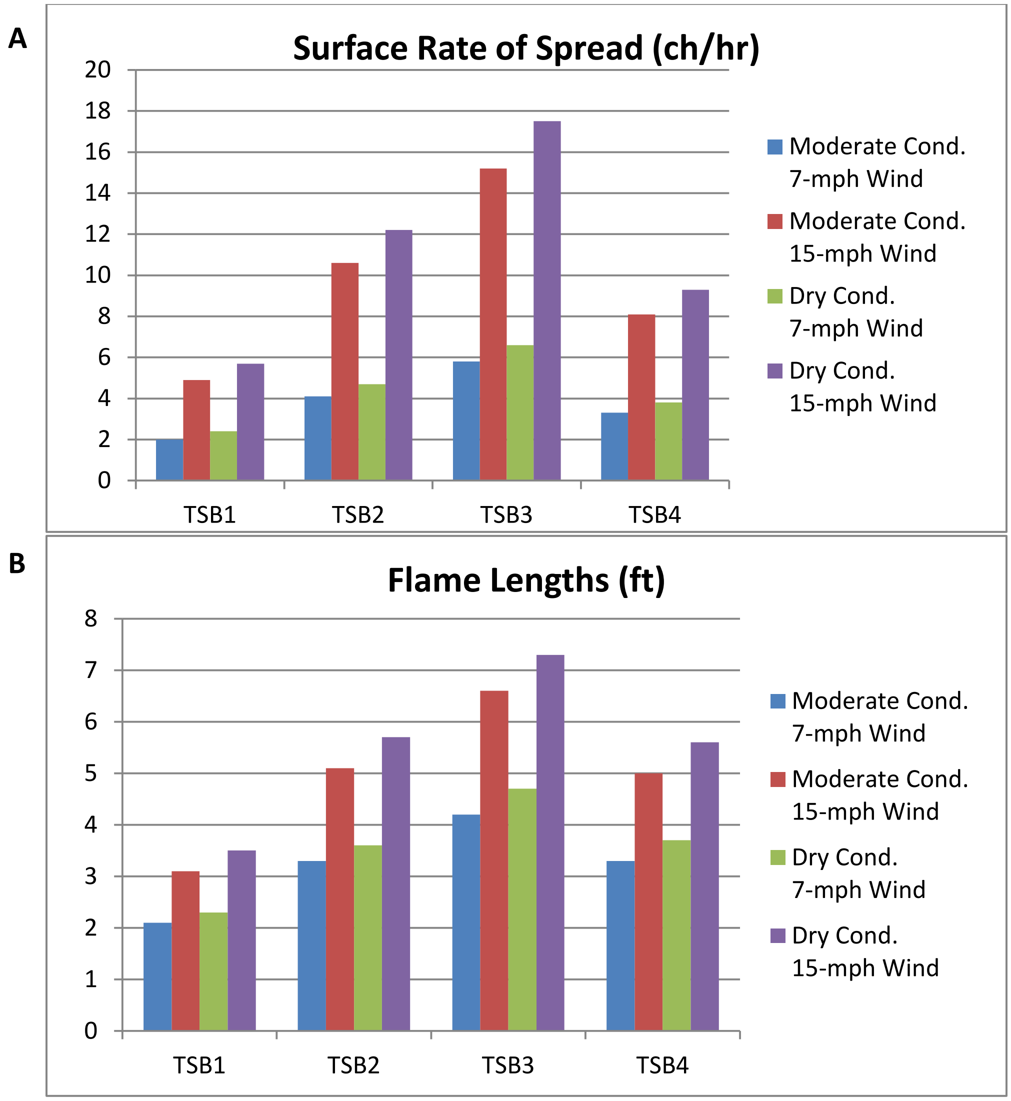

Figure 8. Comparison of simulated fire behavior between stages for A) rate of spread and B) flame lengths

One way to compensate for the inherent limitations within the fire spread models is to alter different input variables; this allows the expected variation in microsite conditions to be investigated as well as evaluating the sensitivity of the fire spread models to changes in inputs. For this example, the 1-hr fuel load was decreased or the fuel bed depth was increased for the custom fuel model created for each stage; all other inputs were kept the same. All new simulations used the dry fuel moisture conditions; the moderate fuel moisture conditions were added to define the range for each fire behavior attribute of interest (Table 6).

Table 6. Range in expected fire behavior based on varying some of the fuels inputs for the custom fuel models

Wind Speed	Fire Behavior Attribute	TSB1	TSB2	TSB3	TSB4
7-mph Wind	**Surface Rate of Spread (ch/hr)**	2 - 6	3 - 11	4 - 11	3 - 7
	Flame Length (ft)	2 - 4	3 - 7	3 - 6	3 - 5
	Type of Fire	Surface, Passive	Surface, Passive	Passive	Passive
15-mph Wind	**Surface Rate of Spread (ch/hr)**	4 - 15	8 - 29	11 - 29	8 - 17
	Flame Length (ft)	3 - 7	4 - 10	5 - 10	5 - 8
	Type of Fire	Passive	Passive	Passive	Passive

The output ranges for the custom fuel models were then compared with outputs from standard fuel models. To allow consistent comparisons, the same input data was used including wind adjustment factors, live and dead fuel moisture conditions, canopy base height, canopy bulk density, slope, and wind speed. Table 7 reports the results for surface rate of spread, flame length, and fire type (surface, passive, or active crown) for the different fuel moisture and wind speed scenarios. Below are results by TSB stage for custom and standard fire behavior fuel models. Comparisons of ranges in custom and standard FBFM are shown in Figure 9.

Table 7. Comparison of predicted fire behavior between standard fuel models and custom fuel models, the minimum and maximum values for each fire behavior output for the standard FBFM reflect moderate and dry fuel moisture conditions, respectively

TSB1

Wind	Fire Behavior Attribute	164	165	185	CUSTOM
7-mph Wind	Surface Rate of Spread (ch/hr)	4.7 – 5.6	4.7 – 5.6	2.2 – 2.5	1.8 – 5.9
	Flame Length (ft)	3.8 – 4.4	5.7 – 6.2	1.6 – 1.8	1.9 – 4.3
	Type of Fire	Passive	Passive	Surface	Surface, Passive
15-mph Wind	Surface Rate of Spread (ch/hr)	12.7 – 15.1	9.8 – 11.3	5.2 – 6.0	4.3 – 15
	Flame Length (ft)	6.1 – 6.9	8.0 – 8.8	2.4 – 2.7	2.8 – 6.6
	Type of Fire	Passive	Passive	Surface	Passive

TSB2/TSB3

Wind	Fire Behavior Attribute	11	12	164	165	185	201	202	CUSTOM
7-mph Wind	Surface Rate of Spread (ch/hr)	4.3 – 5.0	9.8 – 11.4	6.6 – 7.9	6.1 – 7.0	3.0 – 3.4	4.2 – 4.8	9.9 – 11.3	3.1 – 10.7
	Flame Length (ft)	3.1 – 3.5	7.5 – 8.5	4.5 – 5.1	6.4 – 7.0	1.9 – 2.1	2.7 – 3.0	5.4 – 5.9	2.7 – 6.5
	Type of Fire	Passive	Passive	Passive	Passive	Surface	Surface	Passive	Surface, Passive
15-mph Wind	Surface Rate of Spread (ch/hr)	9.3 – 10.9	20.7 – 24.2	19.4 – 23.0	13.3 – 15.3	7.5 – 8.6	10.4 – 11.9	26.4 – 30.1	8 – 28.8
	Flame Length (ft)	4.4 – 5.1	10.6 – 12.0	7.4 – 8.4	9.2 – 10.1	2.9 – 3.2	4.2 – 4.6	8.4 – 9.3	4.2 – 10.2
	Type of Fire	Passive	Passive	Passive	Passive	Surface, Passive	Passive	Passive	Passive

TSB4

Wind	Fire Behavior Attribute	10	11	12	164	165	201	202	CUSTOM
7-mph Wind	Surface Rate of Spread (ch/hr)	3. 8 – 4.5	3.3 – 3.9	7.6 – 8.8	4.7 – 5.6	4.7 – 5.4	3.1 – 3.6	7.2 – 8.2	3.2 – 6.7
	Flame Length (ft)	3.8 – 4.2	2.8 – 3.1	6.7 – 7.6	3.8 – 4.4	5.7 – 6.2	2.4 – 2.7	4.6 – 5.1	3.2 – 5.3
	Type of Fire	Passive	Surface, Passive	Passive	Passive	Passive	Surface	Passive	Passive
15-mph Wind	Surface Rate of Spread (ch/hr)	9.4 – 10.9	6.9 – 8.1	15.5 – 18.0	12.7 – 15.1	9.8 – 11.3	7.3 – 8.3	18.0 – 20.4	7.7 – 16.7
	Flame Length (ft)	5.7 – 6.3	3.9 – 4.4	9.3 – 10.5	6.1 – 6.9	8.0 – 8.8	3.5 – 3.9	7.1 – 7.8	4.8 – 8.2
	Type of Fire	Passive	Passive	Passive	Passive	Passive	Passive	Passive	Passive

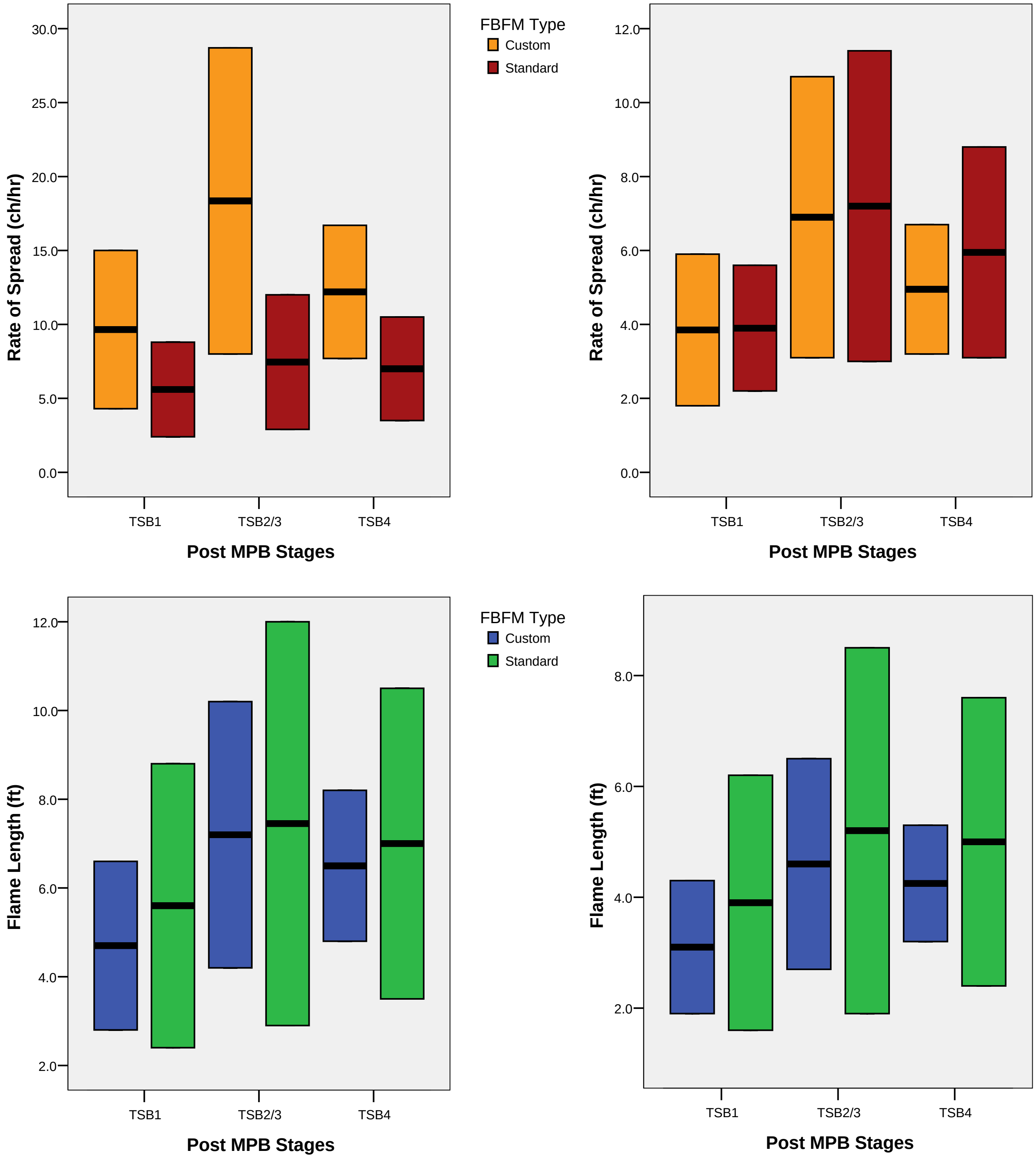

Figure 9. Surface rate of spread and flame length comparisons between custom and standard fire behavior fuel models in BehavePlus. Custom fuel models ranges are derived from decreasing 1-hr fuel loading and increasing fuel bed depth and dead fuel moisture

FlamMap

Figures 10 and 11 illustrate the change in both flame length and crown fire activity across the Red Zone landscape on the Fremont-Winema NF after accounting for changes in fuels incurred by recent mountain pine beetle epidemics. Table 8 shows the change in predicted flame lengths and type of fire between LANDFIRE data and the modified LANDFIRE data updated for MPB activity. The amount of area in the Red Zone experiencing moderate to high flame (4 to 11 feet) lengths was increased, while the minimum (<4 feet) and maximum flame length ranges (>11 ft) decreased (Table 8). The modified LANDFIRE data indicates the landscape area experiencing passive crown fire (torching) increased by approximately 31% compared to the base LANDFIRE simulations (Table 8) and was accompanied by a decrease in acres of surface fire and active crown fire.

Overall, these results indicate a narrowing of fire behavior activity into moderate values across this MPB-influenced landscape. These findings match the results from the point-based analysis using *BehavePlus*, given the lack of active crown fire and high incidence of passive crown fire.

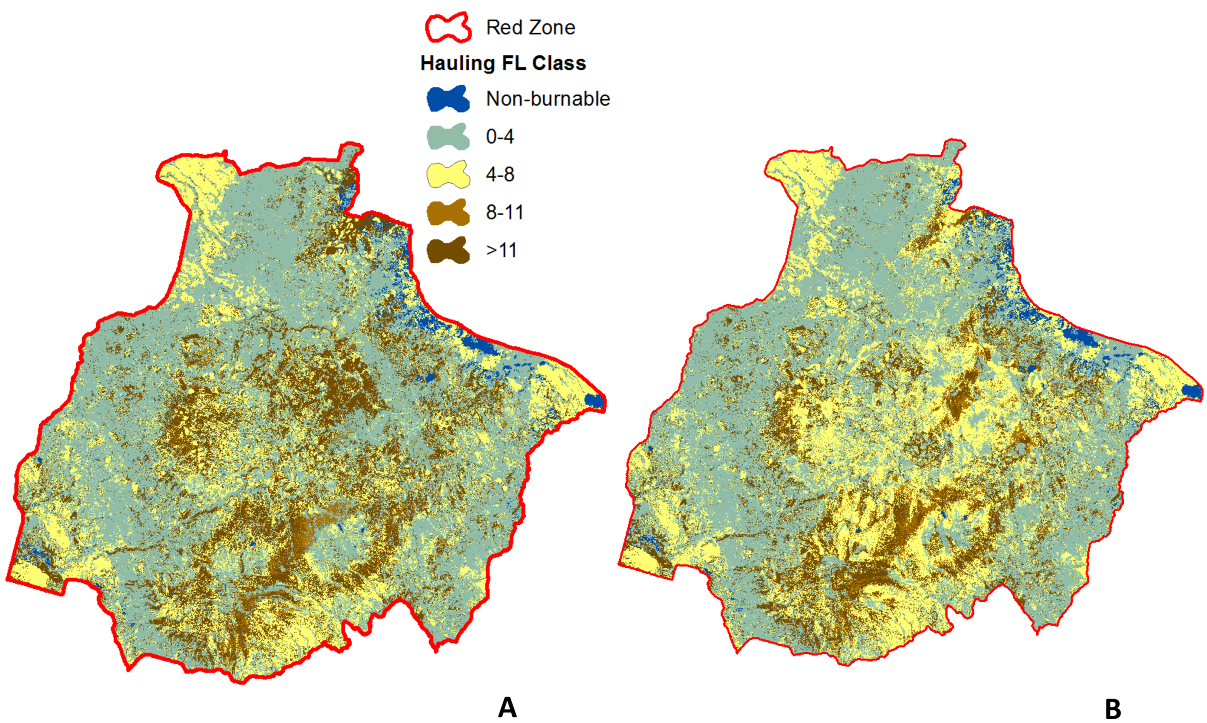

Figure 10. Comparison of flame length classes for A) LANDFIRE data and B) modified LANDFIRE data updated for MPB activity

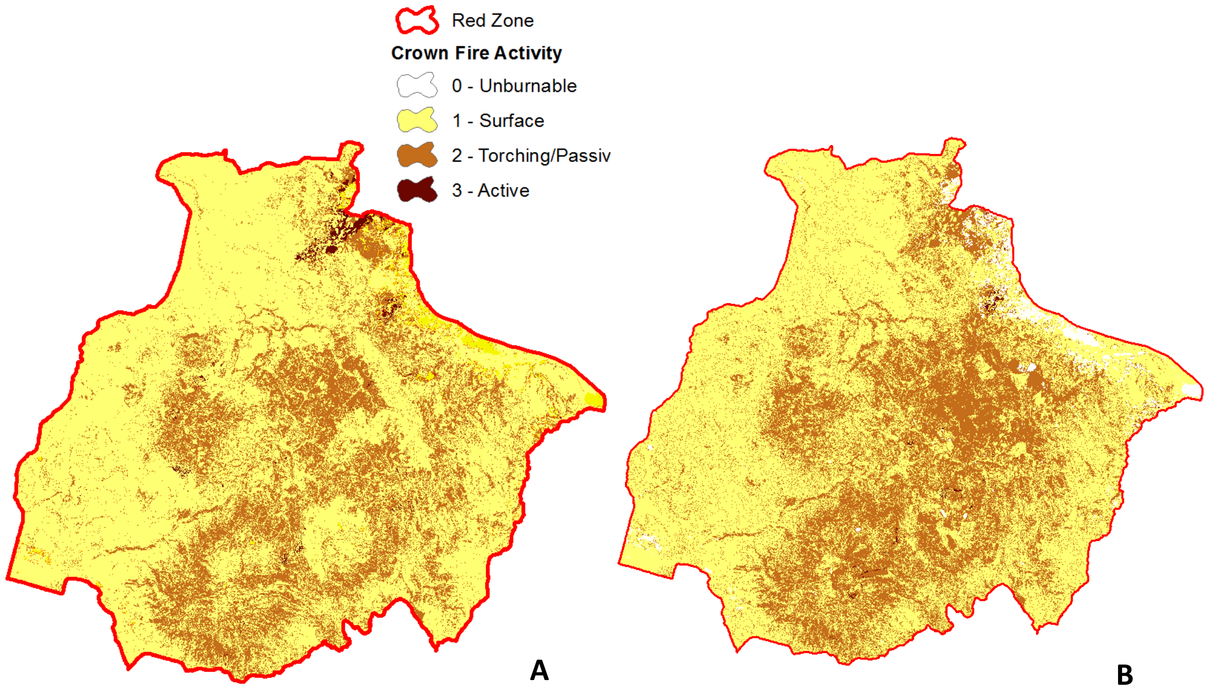

Figure 11. Illustration of change in area consisting of different crown fire activities for A) LANDFIRE data and B) modified LANDFIRE data updated for MPB activity

Table 8. Acres per flame length and fire type class for LANDFIRE data and Modified LANDFIRE data updated for MPB activity in the Red Zone

Flame Length (ft)	LANDFIRE (ac)	Modified LANDFIRE (ac)
0 – 4	172,994	165,720
4 – 8	75,305	97,829
8 – 11	10,266	5,594
>11	68,203	47,173
Fire Type	**LANDFIRE (ac)**	**Modified LANDFIRE (ac)**
Surface	240,309	215,156
Passive	84,031	110,519
Active	2,427	642

Discussion

Mountain pine beetle epidemics in lodgepole pine forests can leave vast acreages of forest with dead lodgepole pine (Raffa et al. 2008) and the past 30 years on the Deschutes and Fremont-Winema National Forests can serve as an example of the scale of these disturbances. There have been two distinct peaks in activity in the region, one occurring in the 1980s and the other more recently ramping up after 2000, persisting to this day at a distinctly lower level. Central Oregon lodgepole pine forests in this study are climax forests and develop multi-aged, single species stands. The MPB does not kill all trees and leaves a significant component of trees less than 9 inches in diameter. Local risk maps indicate there are lodgepole pine stands currently unaffected by MPB that are of a similar structure (approximately 100 trees per acre > 9 inches diameter) to those that have experienced epidemics during our chronosequence.

Our data indicate four distinct stages of stand structure and fuels organization over a 32 year period following MPB caused mortality events in south-central Oregon lodgepole pine forests. The potential for severe fire and crown fire were considered by several different analyses that inform this but are not direct measures of severity. Surface flame length and surface rate of spread were greatest in TSB2 and TSB3, and dropped off in TSB4. Active crown fire is rare, with passive crown fire or torching much more common as a result of the uniquely low density structure of these forests.

Hicke et al. (2012) synthesized the literature regarding the influence of bark beetles on fuels and potential fire behavior. These results suggest that generalizations are difficult to make, but that bark beetle outbreaks do affect fuels and fire behavior. We suggest that in the south-central Oregon lodgepole pine forests the MPB epidemics have a profound and measureable effect on fuels and potential fire behavior. Hicke et al. (2012) developed a generalized model for this influence which includes a 1-4 yr stage and 5-10 yr stage, and the subsequent decades stage. Alternatively, Hicke et al. (2012) notes four stages from previous studies, which overlap with these stages. Stages from previous studies (e.g., Simard et al. 2011) more closely match our stages, including a red phase (needles on), a gray phase (needles off), a snagfall phase which overlaps with a regrowth/understory development, and an old phase. The Hicke et al. (2012) model describes the pattern in change with time for fuels in four groups (canopy bulk density; litter, 1-, and 10- hr fuels; 100- and 1000-hr fuels; and ladder fuels) and fire potential/properties in three groups (torching potential, surface fire properties, and active crown fire potential).

Canopy bulk density declines significantly within five years and slowly recovers of the following decades, similar to our results (Figure 7). Litter, 1-, and 10-hour fuel loads peak within the first 10 years and decline to original levels over the following decades (Hicke et al. 2012), while our data indicated that these fuels showed very little change throughout the chronosequence (Figure 7). Hicke et al. (2012) suggest that 100- and 1000-hour fuels slowly increase with time and continue climbing for decades. However, our data indicate that -100-hr fuels clearly follow this trajectory, but the 1000-hr fuels begin to decrease by age 32 (Figure 7). Ladder fuels follow a similar trend to 100- and 1000-hour fuels in the Hicke et al. (2012) model, but we also found a lack of ladder fuels in the oldest time since beetle stage.

Lynch et al. (2006) studied the influence of MPB mortality events on the 1988 Yellowstone fires. Two MPB events had occurred in the area of the fire, one in 1972-1979 (16-yr TSB) and 1980-1983 (8-yr TSB). They used a spatial modeling technique to determine that there was no relationship between the fire and 8-yr TSB, but there was a significant correlation between the fire pattern and 16-yr TSB, with the caveat that drought and high winds were the key factor in the final fire sizes. This is an interesting finding in that 8-yr TSB would be a time when most snags are still standing and canopy bulk density is still low, while 16-yr TSB would be equivalent to our TSB3 stage, the stage with the highest predicted flame lengths and rate of spread.

Simard et al. (2011) asked the question, "Do mountain pine beetle outbreaks change the probability of active crown fire in lodgepole pine forests?". They focused their analysis on the red and gray stages (TSB1, TSB2 in our study). They found that the potential for active crown fire decreased due to the effect of tree mortality decreasing canopy bulk density. This is consistent with our results that indicate very low canopy bulk density in those stages. In our study, change in both flame length and crown fire activity across the Red Zone landscape were characterized after accounting for changes in fuels incurred by recent mountain pine beetle epidemics. The Red Zone at this time is mostly in the TSB2 (gray stage). We also found high potential for torching in all stages, implying that perhaps things are not quite as simple as Simard et al. suggest when evaluating a landscape.

Klutsch et al. (2011) used the Fire and Fuels Extension to the Forest Vegetation Simulator to determine potential fire behavior for Colorado lodgepole pine stands that had a mortality event seven years prior (TSB2 in our study) and those that had not experienced mortality from mountain pine beetle. Using 90th percentile weather conditions, their uninfected stands were more likely to exhibit crown fire than infested stands. This is in agreement with our TSB2 data as well as Simard et al. (2011) and Lynch et al. (2006). However, Klutsch et al. (2011) noted that in stands where crown fire was predicted there were more non-lodgepole pine trees, lower canopy base height, and more continuous canopy. They contend that in the lodgepole type, however, MPB does increase the intensity of surface fire behavior.

Jenkins et al. (2008) synthesized the influence of bark beetles (MPB, spruce beetle and Douglas-fir beetle) in the intermountain west and suggest that all these mortality agents produce similar patterns, especially since many stands are mixed-species stands, where mortality events take only one variety of tree. Page and Jenkins (2007a) examined changes to ground, surface, and aerial fuels during a current epidemic and at a site where beetles caused widespread mortality 20 years previous in a lodgepole pine type in the intermountain West. There were significant increases in fine surface fuels in recently infested stands; in the previously infested stand there were significant increases in down woody debris in all but the smallest size classes. They suggest that MPB activity caused a change in species composition (shift to fir from lodgepole pine) and a very different fuels complex that was dominated by large dead woody fuels and live surface fuels.

In their paper evaluating predicted fire behavior, Page and Jenkins (2007b) compared endemic, current epidemic, and post-epidemic MPB affected stands. For surface fires, both rates of spread and fireline intensities were higher in the current epidemic stands than in endemic stands due to increases in fine fuels, while in the post-epidemic stands the rates of fire spread and fireline intensities were higher than in the endemic stands due to decreased vegetative sheltering and the effect on midflame wind speed. Large diameter fuels also increased in post-epidemic stands and this increased potential total heat release and postfrontal combustion as well as potentially increasing resistance to fire control. Page and Jenkins also found that in post-epidemic stands, crown fires were more likely due to greater fireline intensities and lower canopy base heights, but the critical rate of spread needed to sustain an active crown fire was higher in the post-epidemic stands due to decreased aerial fuel continuity.

Management Implications

- Following a MPB epidemic in this region, structure of the forest changes such that fuel characteristics result in lower surface rate of spread and flame lengths in the years immediately following a MPB epidemic, but after 6-10 years, the surface rate of spread and flame length increase until about 28-30 years, when they decline again.
- Using the data and results of this study, managers on the Deschutes and Fremont-Winema National Forests can plan forest and fire management activities to achieve desired conditions based on the current condition as well as trajectory through time following pine beetle infestations. Plot data and the modified landscape data are available for analysis in various ecological modeling systems to assess wildlife, vegetation and fire management options.
- Our results indicate that custom fuel models are not necessary for modeling fire behavior as standard fuel models adequately represent potential fire behavior.

There may be more than one standard fuel model that captures expected fire behavior in a given stage.

- Modeled fire behavior characteristics such as surface rate of spread and flame length can help set priorities for locations and timing of fuel treatments and forest restoration. They can also provide a framework for assessing firefighter safety during periods of potentially extreme fire behavior.
- Fuels treatments and restoration may be most appropriate within 5-13 years following beetle initiation, prior to the majority of snags falling because this is before the peak surface fire behavior potential. Surface fire rate of spread and flame length are greatest after all the fuels have come to the ground at about 12 years and after conifer regeneration and shrubs have responded to change in available nutrients to create more surface fuels.
- Opportunities for using prescribed fire to treat fuels decrease in TSB3 when flame lengths and rates of spread are greatest.
- Dwarf mistletoe functions at the stand level to decrease canopy base height and increase the potential for torching in central Oregon. This may contribute to the complexity of the fire behavior.

Deliverables Table

Deliverable Type	Description	Delivery Dates
Refereed Publications	Two refereed publications are envisioned, and will be submitted to journals in 2014.	2014
Technology Transfer	Deschutes National Forest, Bend, OR, June 27, 2013. Fremont-Winema National Forest, Lakeview, OR, June 26, 2013. **Mountain Pine Beetle Influence on Fuels and Fire Behavior** A workshop summarizing a recent Joint Fire Science project on the Fremont-Winema and Deschutes National Forests entitled "Temporal dynamics of ground, surface, ladder, and crown fuels and their potential effects on fire behavior, following *Dendroctonus ponderosae* epidemics in the *Pinus contorta* zone of south-central Oregon". Presentations (followed by a field trip) by Travis Woolley, Stephen Fitzgerald, and Dave Shaw from OSU, and Andy Eglitis, LaWen Hollingsworth, and Laurie Kurth from the USFS.	2013
Technology Transfer	A field/photo guide for fuel loadings, structure, and predicted fire behavior following MPB epidemics in south-central Oregon is in draft form and will be delivered to the Deschutes and Fremont-Winema NF. We anticipate this publication by OSU Extension within the next year.	2014
Dataset	We received an additional JFSP grant to formally archive the dataset from the project. Our completion date is scheduled for June 30, 2014.	June, 2014
Fuel model inputs and modeling results	Custom fuel model inputs and all modeling results will be summarized and transferred to the federal cooperator.	June, 2014
Annual Progress and Final report(s)	Annual reports were submitted as well as this final report of findings to JFSP and the federal cooperator.	2010, 2011, 2012, and 2013

Deliverable Type	Description	Delivery Dates
Scientific Conferences	***Presentations*** **Fifth International Fire Ecology and Management Congress, Portland, Oregon, December 3-7, 2012.** a) Woolley (presenter), Hollingsworth, Shaw and Fitzgerald. Looking beyond red crowns: Canopy and surface fuels in lodgepole pine forests following mountain pine beetle epidemics in south-central Oregon. b) Woolley, Hollingsworth (presenter), Shaw, and Fitzgerald. Potential fire behavior in post-MPB lodgepole pine forests in south-central Oregon: Comparisons and lessons among BehavePlus, FCCS, and FlamMap. **Fourth Fire Behavior and Fuels Conference, Raleigh, NC, February 18-22, 2013.** a) Woolley (presenter), Hollingsworth, Shaw and Fitzgerald. Looking beyond red crowns: Canopy and surface fuels in lodgepole pine forests following mountain pine beetle epidemics in south-central Oregon b) Woolley, Hollingsworth (presenter), Shaw, and Fitzgerald. Potential fire behavior in post-MPB lodgepole pine forests in south-central Oregon: Comparisons and lessons among BehavePlus, FCCS, and FlamMap ***Posters*** May 9-12, 2011. North American Forest Insect Work Conference, Portland, OR. Mountain pine beetle and lodgepole pine in south-central Oregon: Fuel for fire??? Travis Woolley, David Shaw, Stephen Fitzgerald and Laurie	2012 - 2013

	Kurth. April 5-8. 2010. Western Forest Insect Work Conference. Flagstaff, Arizona. Poster: Woolley, T., D. Shaw, S. Fitzgerald, L. Kurth. Mt. Pine Beetle and Lodgepole Pine: Fuel for Fire?	
Leveraged Project	MS Thesis Agne, Michelle. 2013. Influence of dwarf mistletoe (*Arceuthobium americanum*) on stand structure, canopy fuels, and fire behavior in lodgepole pine (*Pinus contorta*) forests 21-28 years post-mountain pine beetle (*Dendroctonus ponderosae*) epidemic in central Oregon. Corvallis, OR: Oregon State University.	2013

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Appendix A. Additional leveraged project

Michelle Agne completed a MS thesis at OSU in September 2013 titled: Influence of Dwarf Mistletoe (*Arceuthobium americanum*) on Stand Structure, Canopy Fuels, and Fire Behavior in Lodgepole Pine (*Pinus contorta*) Forests 21-28 Years Post-Mountain Pine Beetle (*Dendroctonus ponderosae*) Epidemic in Central Oregon. This project used our plot system, data, and results.

Summary of the thesis findings:

- This thesis describes the combined influences of dwarf mistletoe and mountain pine beetle on stand structure, canopy fuels, and fire behavior in central Oregon lodgepole pine forests.
- We randomly selected and sampled 39 0.075-hectare plots within 13 stands in the Deschutes National Forest in central Oregon. The plots varied from 0 to 4 in average dwarf mistletoe rating (DMR) and all had experienced a mountain pine beetle mortality event 21 to 28 years prior to sampling (TSB3/TSB4). The 13 stands were chosen based on the JFSP plots from our original study. In addition, the surface fuels data from the JFSP project were used in the fire models.
- We compared stand density, stand basal area, canopy volume, proportion of the stand in dominant/codominant, intermediate, and suppressed cohorts, and average height and average diameter of each cohort, across the range of DMR. We found strong evidence of a decrease in canopy volume, suppressed cohort height, and dominant cohort diameter with increasing DMR. There was strong evidence that as DMR increases, proportion of the stand in the dominant/codominant cohort decreases, while proportion of the stand in the suppressed cohort increases. Structural differences associated with dwarf mistletoe create heterogeneity in this forest type and may have a significant influence on the productivity, resistance, and resilience of these stands. These findings show that it is imperative to incorporate dwarf mistletoe effects when studying stand productivity and ecosystem recovery processes.
- We then compared canopy base height, the fuel parameter that drives passive crown fire, and canopy bulk density, the fuel parameter that drives active crown fire, over the range of DMR to determine the effect of dwarf mistletoe on canopy fuels. We used BehavePlus to model passive crown fire and active crown fire in our plots. We found strong evidence of a decrease in canopy base height with increasing DMR. There was suggestive evidence of decrease in canopy bulk density with increasing DMR, after accounting for stand density. The results of the fire behavior modeling suggest that at low to moderate wind speeds, likelihood of passive crown fire increases with increased DMR. However, under more extreme weather (wind speeds >20 mph), the effect of dwarf mistletoe on passive crown fire potential was not shown to be important. The potential for active crown fire was extremely low in our plots, regardless of DMR. These findings show that dwarf mistletoe is having a significant effect on the potential for passive crown fire in lodgepole pine forests 21 to 28 years post-mountain pine beetle epidemic, and should be considered in future research regarding post-mountain pine beetle fuels and fire behavior.

Appendix B. Photos of the different stages

TSB1 – Overstory Mortality Stage (2-4 yrs)


TSB2 – Standing Snag/Snag Fall Stage (5-13 yrs)

TSB3 – Regeneration Stage (14-25 yrs)

TSB4 – Overstory Densification Stage (26-32 yrs)