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Potential Fire Behavior in Spruce Beetle-Induced Tree Mortality in Intermountain Spruce-Fir Forests

Carl A. Jorgensen

Michael J. Jenkins

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Carl Arik Jorgensen[a] and Michael James Jenkins[b]

[a]USDA Forest Service, Westside Ranger District Caribou-Targhee National Forest Pocatello, Idaho 83204, USA.

[b]Utah State University, Department of Wildland Resources, Logan, UT 84322-5230

Abstract

Spruce beetle- (*Dendroctonus rufipennis* Kirby [Coleoptera: Curculionidae]) induced tree mortality can increase fire intensity and severity resulting from changes to surface and aerial fuels. From inventoried fuel complexes, custom fuel models were developed. The endemic bark beetle condition class had greater amounts of live, available canopy fuel and canopy bulk density than either the epidemic and post epidemic condition classes. Epidemic bark beetle condition classes had the highest amounts of needle litter and1-hr time lag (0-0.64 cm diameter) fuel while the post-epidemic condition class had the highest amount live shrubs and non-woody plants. Fire behavior calculated with BehavePlus from the custom fuel models resulted in substantial differences in fire rates of spread and intensity for each spruce beetle condition class based on identical moisture scenarios and wind speeds. Rates of spread for epidemic and post-epidemic condition classes ranged between 2.0 – 2.9 and 3.0 – 4.5 times faster than the endemic condition class. Fireline intensities ranged from 4.1 – 5.0 times higher in the epidemic condition class and 6.6 – 8.8 times higher in the post-epidemic condition class compared to endemic condition class. An observed lack of overstory sheltering is attributed to increased fire behavior in epidemic and post epidemic condition classes and has a dominating affect on fire behavior. Post-epidemic condition class rates of spread and fireline intensities at identical midflame wind speeds were 1.7 and 3.3 times higher, respectively, than endemic parameters. Relatively, higher rates of spread (4.4 times) and fireline intensities (8.5 times), were observed between endemic and post-epidemic condition classes when calculated with 6.1 m wind speed adjusted for canopy sheltering. Custom fuel models developed for epidemic and post-epidemic classes showed similar results to selected established fuel models; however, no single fuel model exactly predicted fireline intensity and rate of spread for each of the custom fuel models developed.

Keywords: spruce beetle, Engelmann spruce, wildland fire, fire behavior

Introduction

Understanding fire behavior and its effects are vital to implementing suppression and prescribed burning tactics (Pyne et al. 1996). Fire behavior in a wildland setting is often dependant upon, and commonly a result of, complex interactions between weather, ignition, vegetation, fuel distribution, and topography (Turner and Romme 1994, Pyne et al. 1996, Bessie and Johnson 1995). Fuel is an essential part of the fire environment without which there is no substrate to support combustion and fire spread (Brown and Davis 1973, Pyne et al. 1996). Forest insect epidemics may play an important role in fire behavior by altering fuel complex characteristics (Arno 2000, Jenkins et al. 2008).

Historically it has been difficult to determine whether or not spruce beetle activity actually increases the susceptibility of subalpine forests to natural fires (Baker and Veblen 1990). Falling dead trees and other woody debris create a large fuel build up over time, but the overall fire danger seems to be exaggerated (Schmid and Hinds 1974, Bebi et al. 2003, Kulakowski et al. 2003). Mesic and moist understories of herbaceous material and shrubs, regardless of the amounts of fuels following spruce beetle outbreak may inhibit fire behavior (Kulakowski et al. 2003). Precipitation associated with summer thunderstorms usually reduces fire probability by boosting the foliar moisture of understory plants and fuel moisture of downed, woody debris (Schmid and Hinds 1974). Landscape structure was determined to have greater influence on fire severity than do spruce beetle outbreaks (Bigler et al. 2005). Real time fire weather, drought, and ignition point have been shown to have greater influence on fire extent than pre-fire conditions of spruce beetle outbreak (Bigler et al. 2005, Kulakowski and Veblen 2007).

Regardless, insect altered fuel complexes can affect fire behavior (Stocks 1987). Hopkins (1909) first linked spruce beetle mortality to increases in fire behavior. Overstory removal typical of widespread severe spruce beetle mortality can change microclimatic conditions through a combination of factors, including insolation, relative humidity, temperature, and increases in herbaceous material (Schulz 2003). Higher wind speeds in the surface fuels can potentially increase the rate of spread of surface fires (Albini and Baughman 1979, Rothermel 1983). Increased solar radiation resulting from overstory removal raises fuel temperatures and is also associated with increased fire behavior (Rothermel 1983, Rothermel et al. 1986, Byram and Jemison 1943). The increase in live surface fuels and downed woody debris will affect the total fuel load available for combustion and create undetermined fire behavior potential (Agee et al. 2002, DeRose and Long 2007)

Fuel loads of special concern following spruce beetle outbreaks are needles and small twigs falling from the canopy which may support ignition through a surface fuel layer (Knight 1987). Stocks (1987) noted that fire behavior increased following a spruce budworm outbreak due to increased fine fuels resulting from canopy mortality. In contrast, increases in herbaceous and shrub components had a dampening effect on ignited experimental fires (Stocks 1987). Although increases in live fuels contribute significantly to overall fuel load (Jorgensen and Jenkins, in review), this possibly creates a scenario where fires can be suppressed by high fuel moisture content in understory plants. An increase in understory fuel moisture may hamper fire spread and shorten the fire season (Agee et al. 2002).

It is difficult to fully assess fire potential in spruce beetle altered stands (Schmid and Hinds 1974, Baker and Veblen 1990, Kulakowski et al. 2003). Past fire management has relied on stylized fuel models from other fuel complexes to describe potential fire behavior in these altered stands. The purpose of our study was to utilize inventoried fuel loads discussed in Jorgensen and Jenkins (in review) to compare fire behavior between endemic, epidemic and post-epidemic areas of spruce beetle infestations under varying wind speeds and moisture scenarios. BehavePlus version 3.0.1 was used to assess frontal fire behavior variables of fireline intensity and rate of spread and to calculate crown fire potential by incorporating the Van Wagner (1977) crown fire initiation model coupled with the Rothermel (1991) crown fire spread model. The First Order Fire Effects Model (FOFEM v. 5.21) (Reinhardt et al. 1997) was used to analyze the amount of fuel and time devoted to flaming combustion and smoldering combustion.

Methods

Study Site Selection

Stand and fuels data from Jorgensen and Jenkins (in review) were utilized for fuel modeling. Forest Health Monitoring aerial detection survey maps (ADS) were first used to locate spruce-fir forests in Utah that had experienced spruce-beetle outbreaks from the late 1980s to 2006. Polygons of current and older spruce beetle-caused tree mortality were identified. Spruce beetle-caused tree mortality occurring from 2001 to 2006 was considered current. Older spruce beetle-caused tree mortality occurred prior to 2001. The Fishlake and Manti-LaSal National Forests located in central and southeastern Utah, respectively, were selected as study areas both having spruce-fir forests with polygons of current and older spruce beetle-caused tree mortality and uninfested stands within close proximity.

Aerial photographs and 7.5-minute, United States Geological Survey (USGS) topographic maps were next used to delimit potential spruce-fir stands within spruce beetle-affected polygons and adjacent uninfested forests. All stands were then grouped into one of three spruce beetle classifications; endemic, epidemic, and post-epidemic. The endemic class was comprised of uninfested stands or those with less than one currently attacked tree ha-1. The epidemic class consisted of stands within ‘current’ polygons that had increasing numbers of infested trees and at least two pockets of five trees attacked during the past 5 years (Bentz and Munson 2000). The post-epidemic class consisted of stands with a minimum of 75% mortality of overstory trees greater than 12.7 cm diameter at breast height (dbh) and no current spruce beetle activity detected during the past 5 years. Fuels data was collected in these stands as described in Jorgensen and Jenkins (in review).

Data Collection

Plots were systematically established in each sample stand from a randomly selected starting point and spaced 100 by 150 meters apart. Depending on stand size, 16 to 27 plots were sampled in each stand. General information was collected from each plot center including aspect, slope elevation, percent canopy closure, and percent rock cover.

Stand Characteristics

A 20 BAF prism and a 12.7 cm diameter breast height (dbh) lower diameter limit were used to select live and dead trees in each plot for sampling purposes. Species, dbh, canopy dominance, and percentage of live and/or dead needles were determined for each sampled tree. Stand age was determined from ring counts of increment cores taken from a representative live tree at stump height (0.31 m) on each plot.

Canopy Fuels

Crown base height and tree height were measured directly from one randomly selected live tree on the variable radius plot. Crown base height was defined as the height that flames could carry upward into a tree's canopy, representing the interaction between surface and crown fuels (Scott and Reinhardt 2001).

Surface and Ground Fuels

Surface and ground fuels were inventoried on each plot utilizing methods described by Page and Jenkins (2007a) and Brown et al. (1982). In summary, four planar intercept transects 19.81 m long, were established in each cardinal direction from each plot center. These transects were used to tally downed woody fuels intersecting the transect plane by standard time-lag diameter based fuel size classifications of 1 hour (0.0-0.64 cm), 10 hour (0.64-2.54 cm), 100 hour (2.54-7.62 cm), and 1000 hour (>7.62 cm) fuel classes. The smallest pieces (1 hour and 10 hour) were tallied between 1.52 m and 3.35 m. The 100 hour size class was tallied between 1.52 m and 6.40 m and the 1000 hour size class was tallied between 1.52 m and 19.81 m.

Two fixed diameter micro-plots 1.83 m in diameter were established at 10.67 and 19.81 m along each of the four transects (total of eight per plot) for quantifying fuel bed intercept height, live/dead shrub and herbaceous cover and height as well as litter/duff biomass and depth. The data collected in each sub-plot included the percentage of both live and dead cover and average height for shrubs and herbaceous plants (forbs and grasses). Duff and litter depth, in addition to fuel intercept height, were measured at the center of each sub-plot. Fuel intercept height was determined by imposing a 0.3 m plane perpendicular to the fuel transect and measuring the highest downed woody particle intercepted by that plane (Brown 1974).

Data Analysis

Calculation of Stand Characteristics

Live and dead basal area, trees ha^{-1}, and quadratic mean diameter were calculated for each tree species sampled in the survey for each stand. The number of downed trees ha^{-1} estimated in post-epidemic stands was combined with the number of standing trees ha^{-1} from the variable radius plot to determine dead spruce trees ha^{-1} post-outbreak.

Calculation of Canopy Fuels

The data collected from sample trees were utilized to calculate the live available canopy fuel load, canopy base height and canopy bulk density. Live available canopy fuel load was determined from live crown biomass estimates using allometric equations, developed by Brown (1978), and based on tree species and crown class. These equations provided fuel estimates for live foliage and branchwood less than 0.65 cm. We incorporated all live foliage and 65% of the calculated branchwood in the live available canopy fuel load (Call and Albini 1997, Cruz et al. 2003). Mean canopy base height was calculated as a weight average using the number of trees ha^{-1} represented by each sampled tree, averaged over plots within a stand. Canopy bulk density for each plot was then calculated from the live available canopy fuel load divided by the canopy length (i.e. total tree height minus crown base height) of the randomly selected and measured tree on each plot.

Calculation of Surface and Ground Fuels

Surface and ground fuels were input into the fire effects monitoring and inventory protocol (FIREMON) version 2.1.1 to derive specific surface and ground fuel loads (Lutes et al. 2006). Total fuel load estimates for downed woody fuels, litter, and duff were estimated using methods described by Brown (1974) within the software. Weight estimates for dead and living surface vegetation were based on summarized bulk densities from a variety of applicable publications based on surface vegetation coverage and average height as described in Page and Jenkins (2007a). The methods we used to compute fuel bulk depth are described in Albini and Brown (1978).

Statistical Analysis

One-way ANOVA was used to assess differences in the various response metrics (i.e. fuel loads and parameters) associated with three levels (i.e., endemic, epidemic, and post-epidemic classes) of spruce beetle infestation and is summarized in Jorgensen and Jenkins (in review) using the MIXED procedure in SAS/STAT software, Version 9.1.3 of the SAS System for Windows. Descriptive statistics of sample stands are represented in Table 1.

Fuel Model Construction

Custom fuel models for fire behavior predictions were created and analyzed for endemic, epidemic and post epidemic spruce beetle condition classes based on methods described by Page and Jenkins (2007b) and Burgan and Rothermel (1984). The custom fuel models are based on estimated summaries of litter, 1 hour, 10 hour, 100 hr time lag fuel weights and live shrub and live herbaceous fuel loads. These summaries are based on customized fuel model inputs described and required by BehavePlus (Andrews et al. 2003). Shrub, herbaceous and fuel bulk height were averaged to represent the required surface fuel bed depth. The required 1 hr input was calculated from the combined litter and 1 hr time lag fuel biomass estimates. Input parameters from Anderson (1982) standard fuel model 10 were used as guidance to describe fuel complexes affected by bark beetle mortality. Specifically, heat content, surface area to volume ratios and moisture of extinction of live and dead fuel from standard fuel model 10 can parameterize the live and dead fuels present in sampled stands (Page and Jenkins 2007b). All input to the fuel models are listed in Tables 2, 3, and 4 along 90% confidence levels, and observed data ranges.

Surface Fire Behavior

The estimations for surface fire behavior prediction using BehavePlus (v. 3.0.1) were calculated for maximum rate of spread and fireline intensity at the head of the surface fire (Andrews et al. 2003). The assumptions and limitations associated with the surface spread equation used in BehavePlus and the stylized fuel model used for predictions apply to all calculations. Limitations include a continuous and uniform fuel bed in contact with the ground, no incorporation of woody pieces larger than 7.62 cm, predictions are limited to surface fire, during calculation no weather variables change, and no fire spotting is incorporated into rates of surface fire spread (Rothermel 1972).

Fire behavior variables can be greatly affected by fuel moisture content, wind speeds, and shelter from surrounding vegetation. For the BehavePlus analysis, surface fire behavior predictions are computed with varying levels of fuel moisture contents, wind speed scenarios, and sheltering, but held constant at a 0% slope. Fuel moisture inputs were taken from Page and Jenkins (2007b) (Table 5) which were adapted from Rothermel (1991) for normal, drought, and extreme drought summer fuel moisture conditions. All fire behavior calculations used shaded values except for the post-epidemic fire behavior predictions. Fine dead moisture tables from Rothermel (1983) were used to calculate a difference between shaded endemic and epidemic fuels in addition to unshaded post-epidemic fuels since the latter can exhibit lower fuel moisture content due to solar radiation (Byram and Jemison 1943). Wind speeds for the surface fire behavior were calculated at the 6.1 meter level with an adjustment factor assigned on presence/absence of canopy from the resulting spruce beetle mortality to calculate midflame wind speed. Endemic stands were assigned an adjustment factor of 0.2, while epidemic and post epidemic stands were assigned adjustment factors of 0.3 and 0.4 respectively, (Rothermel 1983), to illustrate the effect of wind in combination with reduced sheltering created by spruce beetle induced tree mortality. Endemic (42%), epidemic (34%) and post-epidemic (27%) canopy closure estimates were used to determine 6.1 m wind speed adjustment in each spruce beetle condition class.

Crown Fire Behavior

Attributes of crown fire potential were also calculated with BehavePlus which is based on the Van Wagner (1977) crown fire initiation model and the Rothermel (1991) crown fire behavior model (Andrews et al. 2003). BehavePlus does not account for energy released during combustion of 1000 hr fuel in its surface fire module even though this can be influential for crown fire initiation (Rothermel 1991). The BURNUP program included in the First Order Fire Effects Model (FOFEM v. 5.21) is able to compute fuel consumption during flaming and smoldering combustion for 1-hr, 10-hr, 100-hr, 1000-hr sound and rotten material in addition to litter, duff, live herbaceous and live shrub biomass (Reinhardt et al. 1997). Combustion estimates were determined for specific fuel moisture (Table 5), relative humidity, and seasonal changes defined with in the FOFEM model (Reinhardt et al. 1997). The inventoried fuel complex was input into FOFEM to obtain the amount of fuel burned during flaming combustion. New fireline intensities were then calculated by inputting that amount of estimated fuel into the fire intensity equations presented in Byram (1959). These recalculated fireline intensities were then input into the crown fire module in BehavePlus to estimate crown fire potential in the absence of the surface fire module (Andrews et al. 2003). Only the estimated fuels consumed during flaming combustion were used to recalculate intensity. This method incorporates the large diameter fuels (> 7.52 cm) for intensity calculations but these fuels are assumed to have no effect on forward rate of spread in this method (Page and Jenkins 2007b, Rothermel 1972).

Wind speeds, fuel moisture estimates, and re-calculated intensities were coupled in the BehavePlus crown fire module to provide estimates of critical crown fire rate of spread, critical fireline intensity, whether or not active crowning and/or torching would occur, and what type of fire would burn. The Van Wagner (1977) crown fire initiation model uses canopy base height and foliar moisture content as predictors to crown fire initiation. The Rothermel (1991) crown fire spread model uses the canopy bulk density and wind speed to determine the critical rate of spread that a crown fire must maintain. Therefore, additional required inputs to the crown fire module are canopy bulk density, canopy base height, and crown foliar moisture content. Foliar moisture content was input as 100% for all crown fire prediction simulations.

Fuel Model Comparisons

The calculations from the custom fuel models were compared to calculations from the established fuel models under similar parameters (Anderson 1982, Scott and Burgan 2005). All fuel model comparisons were estimated for normal summer fuel moisture conditions and the same range of midflame wind speeds. It is acknowledged that lack of canopy and vegetative sheltering, especially in bark beetle affected fuel complexes, can allow wind to have a dramatic effect on fire behavior (Page and Jenkins 2007b, Rothermel 1983, Albini and Baughman 1979). Therefore, identical midflame wind speeds were used for fire behavior comparison to remove the effect of canopy sheltering on the 6.1 m wind speeds and directly compare the single influence of fuel on the fire behavior between the custom fuel models and the established fuel models. However, the effect of solar radiation on fuels was maintained in shaded vs. unshaded moisture values within the custom fuel model calculations. Fuel models 8 and 10 (Anderson 1982) and other existing fuel models from Scott and Burgan (2005) were used as standard comparisons to the custom fuel models developed as suggested by Burgan and Rothermel (1984).

Results

Crown Fire Behavior

Critical rates of spread and critical fireline intensities for crown fires are summarized by Table 6. Post-epidemic (PEp) stands had the highest likelihood of torching under lower wind speeds due to the lowest canopy base height. However, canopy bulk density was not high enough to sustain a constant active crown fire except when winds reached 50 km/h after torching had commenced. BehavePlus predicted torching to occur in the PEp class under all fuel moisture scenarios where 6.1 meter winds occurred at 25 km/hr for normal summer fuel moistures and 20 km/hr under drought and extreme drought summer moisture conditions.

In the endemic stands (En), BehavePlus did not predict any situation that surface fire would transition into a passive or active crown fire. However, active crown fire could be sustained under the defined summer fuel moisture conditions if crowning was to initiate somewhere else and move into the stand due to sufficient crown bulk density. Under extreme drought summer fuel moisture conditions, BehavePlus predicted wind speeds of 30 km/hr would be sufficient to maintain an active crown fire once initiated. Wind speeds of 30 km/hr under drought summer fuel moisture conditions and 40 km/hr under normal summer fuel moisture conditions could also sustain active crown fire rate of spread with our described fuel parameters.

Surface Fire Behavior

The calculated surface fire behavior for the spruce beetle condition classes is primarily described by Figures1 and 2. The PEp class was generally characterized by faster rates of spread and higher fireline intensities than the En or epidemic (Ep) classes. The Ep class exhibits the next highest fire behavior characteristics summarized by faster rates of spread and higher fireline intensities than the En class but still lower than the PEp class. Fire behavior predictions for the En condition class gradually increased, but more dramatic fire behavior predictions were calculated in Ep and PEp condition classes with considerable increases due to high wind speeds resulting from unsheltered fuel due to lack of canopy.

When spruce beetle condition classes were compared with identical midflame wind speeds, Ep and PEp classes were identical for rates of spread and very similar with regards to fireline intensity (Figure 2). All moisture conditions (normal summer, drought summer, and extreme drought summer) show the same pattern, although specific outputs differ with increases in rates of spread and fireline intensities as fuel moisture values decrease.

Flaming and smoldering combustion were also calculated to be different between spruce beetle condition classes, but correlated with the predicted fire behavior calculated by BehavePlus. Epidemic and post epidemic classes with high concentrations of large diameter fuel loading had longer smoldering durations as well as greater fuel consumption (Table 7). The epidemic class experienced higher fine fuel loads and overall fuel loads which burned for longer durations of time expressed in the flaming combustion Table 7. The epidemic condition had the longest combustion duration and most fuel consumed during total combustion than any other spruce beetle condition class.

Fuel Model Comparisons

The closest comparison for our custom endemic fuel model was fuel model timber – litter 5 (TL5) and timber – understory 5 (TU5) when predicting rate of spread. Fuel model TL5 was the closest when predicting fireline intensity (Figure 5). The greatest difference was detected at higher wind speeds where fuel model TL5 began to plateau and TU5 continued to increase with the endemic fuel model (Figure 5). The timber – litter 3 (TL3), timber – litter 4 (TL4) fuel models and fuel model 8 greatly under-predicted the rates of spread and fireline intensity for the endemic areas sampled, especially at higher wind speeds. Differences between established fuel models and our custom fuel models are more evident at higher wind speeds.

The epidemic fuel model appears to be represented closely by a few of the established fuel models (Figure 4). Fuel model 10 exhibited very similar rates of spread results when compared to our fuel model. The timber-understory 2 (TU2), timber-understory 3 (TU3), timber understory 4(TU4) models over predicted rate of spread and both timber models (TL5 and TU5) under predicted the rate of spread compared to our custom model (Figure 4). Concerning fireline intensity in the epidemic areas, fuel model 10 was also the closest established fuel model for comparison. Fuel model TU2 was equally close with an under prediction compared to our estimates. The TU3, TU4 and TU5 fuel models over predicted fireline intensity while fuel model TL5 under predicted both rates of spread and fireline intensity in the epidemic spruce beetle condition classes.

In post epidemic condition classes, rates of spread were well represented by fuel model 10 (Figure 5). Fuel models TU5 and Shrub 4 (SH4) were close representations at lower wind speeds but as wind speed increased, greater differences were observed with a reduction in rate of spread when compared to the post epidemic fuel model. Fuel model 10 is nearly identical to our post epidemic calculations regarding rate of spread. Fuel models TU2, TU3, TU4 and Slash-Blowdown – 2 (SB2) appeared to over predict rate of spread as wind speeds increased. Concerning fireline intensity, fuel model 10 was again a near match with sampled post epidemic classes. SH4 and TU2 under predicted the fireline intensity while TU3, TU4, TU5 and SB2 over predicted the fireline intensity of the post epidemic spruce beetle condition classes.

Discussion

Widespread spruce beetle induced tree mortality has been considered to increase fire behavior in affected stands (Hopkins 1909). Jorgensen and Jenkins (in revision) documented fuel complex alteration following extensive spruce beetle-induced tree mortality. The specific effects of spruce beetle-induced changes to fuels on fire behavior in Intermountain spruce-fir forests have not been previously described from collected fuels data (Schmid and Hinds 1974, Baker and Veblen 1990, Kulakowski et al. 2003). As the live canopy fuel load begins to deteriorate, the increasing dead fuel load in addition to the increasing live herbaceous and shrub components alter the overall fuel complex. As overstory sheltering decreases, more solar radiation and higher wind speeds are able to influence surface fuels (Albini and Baughman 1979). Increases in solar radiation and wind speeds, combined with increases of live and dead surface fuel, can have complex and prolonged effects on the fire environment in spruce beetle-altered spruce-fir forests (Albini and Baughman 1979, Byram and Jemison 1943, Rothermel 1983).

Crown Fire Behavior

Post-epidemic sites were characterized by low canopy base height and loss of canopy bulk density. This has resulted in predictions of more intense crown fire activity in the post-epidemic classes, due to torching, compared to the endemic class under the same weather parameters. In contrast, endemic areas had sufficient canopy bulk density to support active crown fire spread, however, canopy base heights were too high. Therefore, crown fires would not initiate unless it transitioned into an active crown fire outside the sample stand, and then moved into the described stands.

The potential for crown fire behavior within current epidemic stands is debatable. Dead needles can be ignited at lower temperatures than live foliage (Stockstad 1975, Xanthopoulos and Wakimoto 1993). High levels of tree mortality and dead canopy may increase crown fire potential due to a mixture of live and dead foliage in epidemic situations (Page and Jenkins 2007b). However, the moisture gradient of foliage from live to currently attacked to dead trees with foliage is not well understood. Any increase in the rate of needle cast could decrease the potential for crown fire behavior in spruce beetle-altered stands even though dead foliage ignites more easily than live. Therefore, crown fire behavior in the epidemic stands is currently difficult to predict.

Spruce-fir forests are generally susceptible to high-intensity, stand replacing fires attributed to naturally developing fuels complexes (Taylor and Fonda 1990, Johnson

1992, Long 1994, Johnson et al. 2001, Arno 2000). These naturally developed fuels complexes, combined with advanced spruce and subalpine fir regeneration lowers live canopy base height in post-epidemic stands, can eventually provide a period of increased flammability. Regeneration will continue to grow if undisturbed, canopy bulk density will increase and limit the amount of live surface fuel in the stand, standing dead trees will remain in the canopy for long periods of time while gradually continuing to maintain levels of downed woody debris on the forest floor. Continuous aerial fuels including canopy snags, combined with abundant ladder fuels, may increase potential flammability in post-outbreak stands.

Our current understanding of crown fire behavior is limited and only a parameterization of input data and equations were used. Alexander and Cruz (2006) found that the Rothermel's (1991) crown fire prediction model, used in this analysis, under predicted crown fire behavior. By comparison, Alexander and Cruz (2006) showed the Cruz et al. (2005) crown fire prediction model to over predict potential crown fire behavior. No model is perfect and the comparison between Rothermel (1991) and Cruz et al. (2005) are made from data on different scales (Scott 2006). Cruz and Alexander (2010) reviewed studies that predicted crown fire potential and concluded there is a significant under prediction bias

Surface Fire Behavior

Greater rates of spread and fireline intensity were estimated for the post-epidemic spruce beetle condition class when 6.1 m wind adjustment factors were applied, due to canopy reduction, compared to the epidemic and endemic classes. Canopy reduction and lack of overall sheltering from the overstory fuels influences fire behavior in bark beetle altered stands compared to fully sheltered stands (Page and Jenkins 2007b). When custom fuel model comparisons were made with identical midflame wind speeds, both post-epidemic and epidemic classes showed similar rates of spread and fireline intensities, but were still higher than endemic classes. Substantial differences between fuels in epidemic and post-epidemic condition classes (i.e. fine fuels and live woody fuel) have been observed, but differences in the behavior of surface fires were less definitive under identical conditions.

Due to the abundance of fine fuels, calculations for the epidemic condition class were still expected to produce higher rates of spread and fireline intensity compared to the endemic class, once overstory sheltering effects were removed. The post-epidemic fire behavior calculations contradicted initial expectations. Due to the abundance of live fuel woody fuel, we expected to see a decrease in fire behavior when comparing epidemic and post-epidemic stands. The presence of abundant live fuels with high fuel moisture content are often considered a heat sink (Rothermel 1983, Andrews 1986, Stocks 1987, Agee et al. 2002). However, our data indicate sequential increases in potential fire behavior between endemic, epidemic and post-epidemic classes following spruce beetle outbreaks in Intermountain spruce-fir forests regardless of the increase of overall live fuel. Increased live fuels in our custom fuel models are not adequately reflected as a potential heat sink in current fire behavior calculation models. Fire behavior prediction models such as BehavePlus are not currently designed to accurately incorporate live fuel in calculations (Weise et al. 2005, Sun et al. 2006). This leaves adjustment of user defined fuel model inputs such as fuel moisture of extinction, live fuel moisture content, and live fuel heat content to obtain replicable results to what is observed in the field. Although currently established fuel models and fire behavior calculation models have been invaluable for decades, validation is important. Especially when compositions of live fuels from differing ecosystems and elevations reflect extreme variations of fire behavior potential under the same burning conditions (e.g. chaparral versus *Ribes* spp). Further research is needed to better parameterize fire prediction in fuel strata differing in type, arrangement, species and moisture content (Romme 1982, Swetnam and Baisan 1996, Scott and Reinhardt 2001, Riccardi et al. 2007, Sandberg et al. 2007).

Current research in fire behavior modeling is attempting to estimate fire behavior in heterogeneous, but spatially explicit, wildland fuel beds, to provide more accurate fire behavior predictions for operational use, planning, and simulations (Berg 2007). . These methods are incorporating the input of fuel particles $\geq$ to 7.62 cm, types of litter and understory species composition, in addition to the input of fuel inventories instead of stylized fuel models (Sandberg et al. 2007, Ottmar et al. 2007, Riccardi et al. 2007). Input from researchers and land managers has been sought in model formulation and testing to improve fire behavior predictions (Berg 2007). This new concept in fuel modeling, The Fuel Characteristic Classification System (FCCS), is characterized by realistic multi-strata fuel beds that may better represent fuels than stylized fuel models. Our data provide detailed information describing fuel beds of spruce stands altered by differing levels of spruce beetle-induced tree mortality and may be useful in revised fuel bed characterization.

Wildfire occurrence is limited in stands that have been altered by extensive spruce beetle-induced tree mortality due to increases in live mesic understory plant biomass (Bebi et al. 2003, Kulakowski et al. 2003). Dead woody surface fuel and needle litter may be sheltered from solar radiation and wind on small scales by increased amount and height of live fuel biomass. Microclimate sheltering of litter and 1-hr fuels from wind and solar radiation by live surface fuel components, in addition to high levels of fuels moisture may make a less conducive environment for surface fire ignition. Other limitations could consist of the compaction of short needle litter, frequent monsoonal moisture events in the summer, and short snow free periods (Schmid and Hinds 1974, Albini and Brown 1978, Swetnam and Baisan 1996, Jenkins et al. 1998). Thus, surface fire ignition is potentially limited during summer months due to the abundant moist understory plant material produced following spruce beetle outbreaks.

Fuel Model Comparison

In endemic areas, no model closely predicted both rate of spread and intensity. Fuel model 10 was the most accurate fuel model considering fire behavior calculations for epidemic and post-epidemic stands. This model may represent the epidemic and post-epidemic areas well because of the large amounts of live fuel and increased fuel bed depth post-outbreak which are similar to the established fuel model. As the woody material increases following epidemics, especially litter fuel load, the predictions more closely represent those of fuel model 10. The increase of live fuels and litter in epidemic stands and live fuels in post-epidemic stands provide similar fire behavior calculations.

The differences between custom fuel models will be compounded as wind speed increases and overstory sheltering is reduced in epidemic and post-epidemic stands.

Wildfire is generally limited to stand replacing fire in subalpine forests, and weather is an important driving factor for wildfire occurrence and behavior (Romme and Despain 1989, Bebi et al. 2003, Kulakowski et al. 2003, Bigler et al. 2005). Fire weather conditions required for high intensity fires may not occur for hundreds of years following outbreaks (Romme and Despain 1989). However, the flammability created by fuels complexes alterations can persist for long periods of time as stand succession continues toward endemic conditions (Veblen 1986a, Veblen 1986b, Aplet et al. 1988, Lertzman and Krebs 1991, Jenkins et al. 1998, DeRose and Long 2007, DeRose and Long 2009). When dry weather and high fuel loads align with ignition, extreme fire behavior can be exhibited.

Limitations of the fire prediction model and fuel moisture data inputs used for live fuels are important for fire behavior analysis. Our calculations are based on previously defined fuel moisture scenarios developed by Rothermel (1991). The calculated fire behavior descriptions are also based on assumptions and limitations that are inherent to the fire prediction model. The main assumptions in the model used were a continuous and uniform fuel bed in contact with the ground, no incorporation of woody pieces larger than 7.62 cm, predictions limited to surface fire, weather variables unchanged during the calculation, and spotting is not incorporated into overall rate of spread (Rothermel 1972). Further research will be needed to determine if different compositions of live fuels burn differently and if increases in live surface fuel cover create sheltering for surface fuel, reducing overall ignition as opposed to expected flammability.

Conclusions

Stand mortality following spruce beetle epidemics has been shown to have a substantial impact on fuel complexes and fire behavior. Greater rates of spread and higher fireline intensities were predicted in epidemic and post-epidemic classes when compared to the endemic class. Changes to overstory sheltering of fuels also had an effect on the overall surface fire behavior. Post-epidemic conditions had the least amount of sheltering and highest calculations of fire behavior. Although, the epidemic and post-epidemic classes had substantially more live herbaceous or live shrub material, there did not appear to be any reduction in calculated fire behavior even though a conceptually large heat sink exists. When custom fuel models were compared at similar midflame wind speeds, differences were not as drastic once current epidemic conditions had been established compared to post-epidemic areas.

When the custom fuel models were compared to standard fuel models, it appears that fire behaviors in the post-epidemic and epidemic areas were closely predicted by the standard fuel model 10 in most cases. We conclude that other, similar fuel models can be used to calculate fire behavior in similar areas of epidemic and post-epidemic spruce beetle activity. However, no single standard fuel model precisely predicted the same intensities as were calculated with our custom fuel models.

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Table 1. The means calculated for selected attributes measured in stands in each spruce beetle condition class on both the Fishlake and Manti-LaSal study sites.

Class	Mean Age Live Trees (yr)	Live TPH (%)			Mean % Live BA (m^2)	% Dead TPH	Mean % Older Dead† ES		% Rock Cover
		ES	SAF	AS			Standing	Fallen	
Fishlake									
En	123	348.39 (64%)	139.22 (26%)	56.442 (10%)	84%	6%	6%	0%	20%
Ep	152	57.88 (28%)	148.99 (72%)	0 (0%)	13%	86%	26%	0%	23%
PEp	143	187.08 (79%)	48.4 (21%)	0 (0%)	17%	72%	65%	3%	14%
Manti-LaSal									
En	193	339.24 (72%)	132.45 (28%)	0 (0%)	82%	17%	17%	0%	10%
Ep	114	20.99 (15%)	120.47 (85%)	0 (0%)	27%	90%	79%	0%	6%
PEp	126	90.94 (40%)	138.36 (60%)	0 (0%)	25%	73%	55%	18%	21%

*En = Endemic; Ep = Epidemic; PEp = Post Epidemic; yrs = years; BA = mean basal area; yr = years; TPH = trees per hectare; ES = Engelmann spruce; SAF = subalpine fir; AS = aspen; QMD = quadratic mean diameter; cm = centimeters; Regen = regeneration.

†spruce killed > 4 years ago.

Table 2. Custom fuel model construction for endemic areas of spruce beetle activity including average fuel load, range of observations, in addition to lower and upper confidence limits. Other fuel model parameters are taken from fuel model 10.

	Endemic			
	Average	**Range**	**Lower 90% CL**	**Upper 90% CL**
1-HR Fuel Load (tonne/ha)	5.07	1.43-15.09	4.28	5.86
10-HR Fuel Load (tonne/ha)	2.69	0-7.11	2.31	3.06
100-HR (tonne/ha)	3.51	0-15.42	2.38	4.64
Live Herbaceous Fuel Load (tonne/ha) *	0.21	0-0.96	0.04	0.39
Live Woody Fuel Load (tonne/ha)	0.38	0-2.00	0.11	0.65
1 HR SAV Ratio (m^2/m^3)	6562			
Live Herbaceous SAV Ratio (m^2/m^3)	4921			
Live Woody SAV Ratio (m^2/m^3)	4921			
Fuel Bed Depth (m)	0.10	0.03-0.20	0.08	0.11
Dead Fuel Moisture of Extinction (%)	25			
Dead Fuel Heat Content (kJ/kg)	18622			
Live Fuel Heat Content (kJ/kg)	18622			

***** Indicates upper and lower confidence limits computed from transformed variable analyzed in Jorgensen and Jenkins (in review).
HR = hour; CL = confidence limit; ha = hectare; m = meter; SAV = surface area to volume; kj = kilojoule; kg = kilogram.

Table 3. Custom fuel model construction for epidemic areas of spruce beetle activity including average fuel load, range of observations, in addition to lower and upper confidence limits. Other fuel model parameters are taken from fuel model 10

	Epidemic			
	Average	**Range**	**Lower 90% CL**	**Upper 90% CL**
1-HR Fuel Load (tonne/ha)	7.85	.94-21.65	7.07	8.64
10-HR Fuel Load (tonne/ha)	2.82	0-8.54	2.45	3.19
100-HR (tonne/ha)	5.58	0-18.83	4.45	6.71
Live Herbaceous Fuel Load (tonne/ha) *	0.74	0.02-2.91	0.57	0.91
Live Woody Fuel Load (tonne/ha)	0.69	0-3.74	0.42	0.96
1 HR SAV Ratio (m^2/m^3)	6562			
Live Herbaceous SAV Ratio (m^2/m^3)	4921			
Live Woody SAV Ratio (m^2/m^3)	4921			
Fuel Bed Depth (m)	0.16	0.05-0.32	0.14	0.17
Dead Fuel Moisture of Extinction (%)	25			
Dead Fuel Heat Content (kJ/kg)	18622			
Live Fuel Heat Content (kJ/kg)	18622			

***** Indicates upper and lower confidence limits computed from transformed variable analyzed in Jorgensen and Jenkins (in review).

HR = hour; CL = confidence limit; ha = hectare; m = meter; SAV = surface area to volume; kj = kilojoule; kg = kilogram

Table 4. Custom fuel model construction for post-epidemic areas of spruce beetle activity including average fuel load, range of observations, in addition to lower and upper confidence limits. Other fuel model parameters are taken from fuel model 10.

	PEp			
	Average	**Range**	**Lower 90% CL**	**Upper 90% CL**
1-HR Fuel Load (tonne/ha)	5.00	0.67-27.12	4.22	5.79
10-HR Fuel Load (tonne/ha)	3.15	0-9.12	2.77	3.52
100-HR (tonne/ha)	5.42	0-17.93	4.29	6.55
Live Herbaceous Fuel Load (tonne/ha) *	0.80	0.02-3.50	0.63	0.98
Live Woody Fuel Load (tonne/ha)	1.70	0.04-4.91	1.43	1.97
1 HR SAV Ratio (m^2/m^3)	6562			
Live Herbaceous SAV Ratio (m^2/m^3)	4921			
Live Woody SAV Ratio (m^2/m^3)	4921			
Fuel Bed Depth (m)	0.22	0.06-0.40	0.20	0.23
Dead Fuel Moisture of Extinction (%)	25			
Dead Fuel Heat Content (kJ/kg)	18622			
Live Fuel Heat Content (kJ/kg)	18622			

***** Indicates upper and lower confidence limits computed from transformed variable analyzed in Jorgensen and Jenkins (in review).
HR = hour; CL = confidence limit; ha = hectare; m = meter; SAV = surface area to volume; kj = kilojoule; kg = kilogram

Table 5. Fuel moistures used for fire behavior calculation. Taken from Page and Jenkins (2007b), adapted from Rothermel (1991).

	Normal Summer		**Drought Summer**		**Extreme Drought Summer**	
	Shaded	**Unshaded**	**Shaded**	**Unshaded**	**Shaded**	**Unshaded**
1 HR	6	4	4	3	3	2
10 HR	8	6	5	4	4	3
100 HR	10	8	7	6	6	5
1000 HR	13	11	9	8	8	7
Live	117	117	78	78	70	70

Table 6. Canopy parameters with associated estimated critical rate of spread (ROS) and critical fireline intensity for En and PEp spruce beetle condition classes.

	Live ACFL (tonne/ha)	Estimated Live Foliage (tonne/ha)	Estimated Dead Foliage (tonne/ha)	Live CBD (kg/m^3)	Live CBH (m)	Critical ROS (m/min)	Critical Fireline Intensity (kW/m)
En	22.59	16.43	0.13	0.160	6.61	18.7	2848
Ep	4.73	3.48	1.43	0.030	2.91	-	-
PEp	6.61	4.87	0.19	0.060	3.37	50.0	1037

ha = hectare; kg = kilogram; m = meter; min = minute; kW = kilowatt; ACFL = available canopy fuel load; CBD = canopy bulk density; CBH = canopy base height; ROS = rate of spread

Table 7. Total fuel consumed during flaming and smoldering combustion. Combustion duration for both types of combustion are included in seconds

	Total Fuel Consumed (tonne/ha)	Fuel Consumed (Flaming) (tonne/ha)	Duration (hour:min:sec)	Fuel Consumed (Smoldering) (tonne/ha)	Duration (hour:min:sec)
En	58.87	7.33	0:02:00	51.54	1:11:45
Ep	78.68	12.67	0:02:45	66.00	1:23:00
PEp	71.53	10.00	0:02:30	61.56	1:19:15

ha = hectare; min = minute; sec = second

Figure 1. Fire behavior variables under normal summer fuel moisture conditions. Areas of endemic, epidemic and post epidemic beetle activity are compared to each other. Wind adjustment factors were 0.2 for endemic situations, 0.3 for epidemic, and 0.4 for post-epidemic situations to obtain midflame wind speeds based on vegetation sheltering. Fuel moistures were assigned as shaded for endemic and epidemic fuels and unshaded for post-epidemic fuels

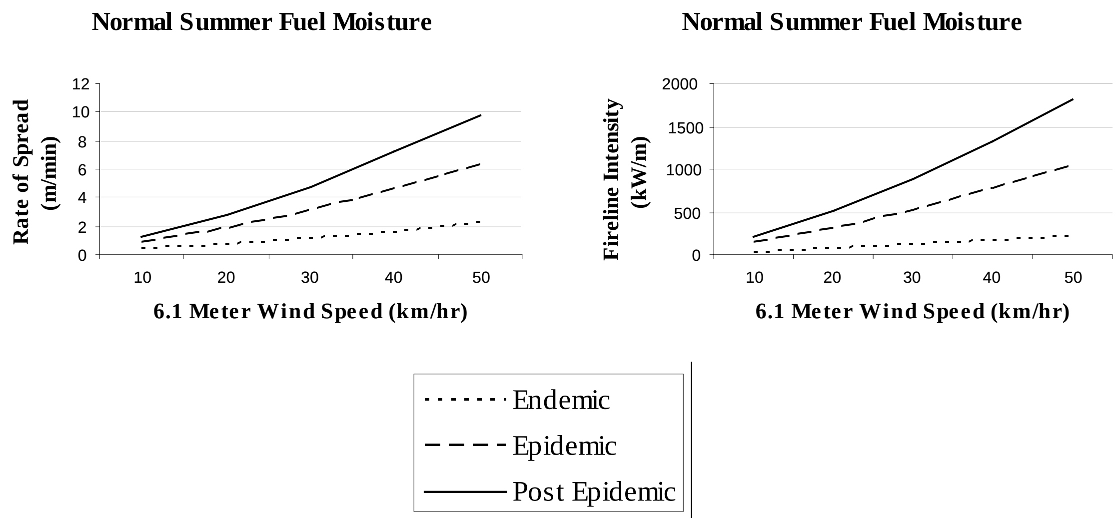

Figure 2. Fire behavior variables estimated under identical midflame wind speeds. All calculations are based on normal summer fuel moistures. Fuel moistures were assigned as shaded for endemic and epidemic fuels and unshaded for post epidemic fuels.

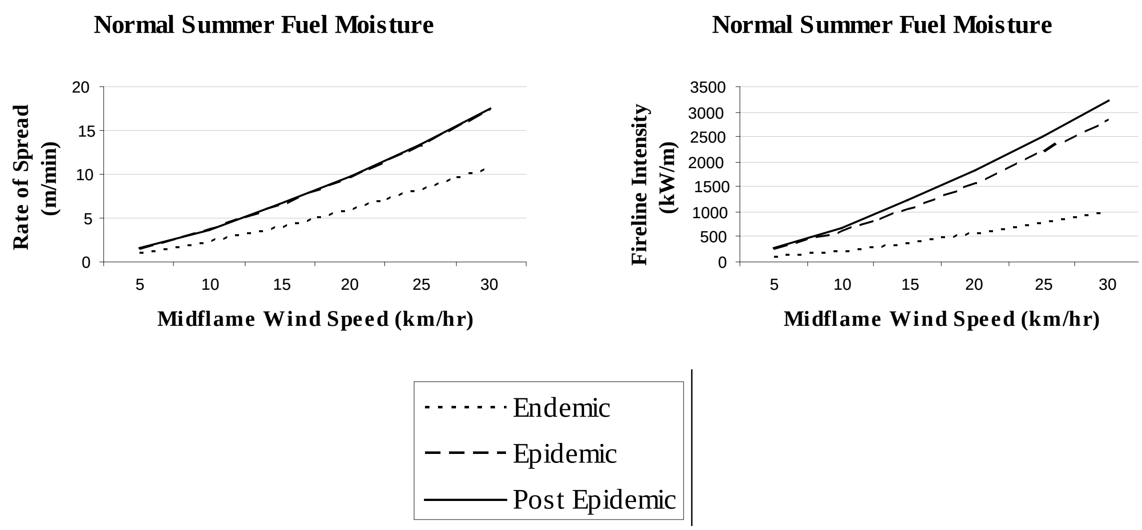

Figure 3. Rates of spread and fire line intensity comparisons for endemic areas of beetle activity compared to established fuel models. Fire behavior variables are calculated with the same midflame windspeeds and under normal shaded fuel moisture conditions

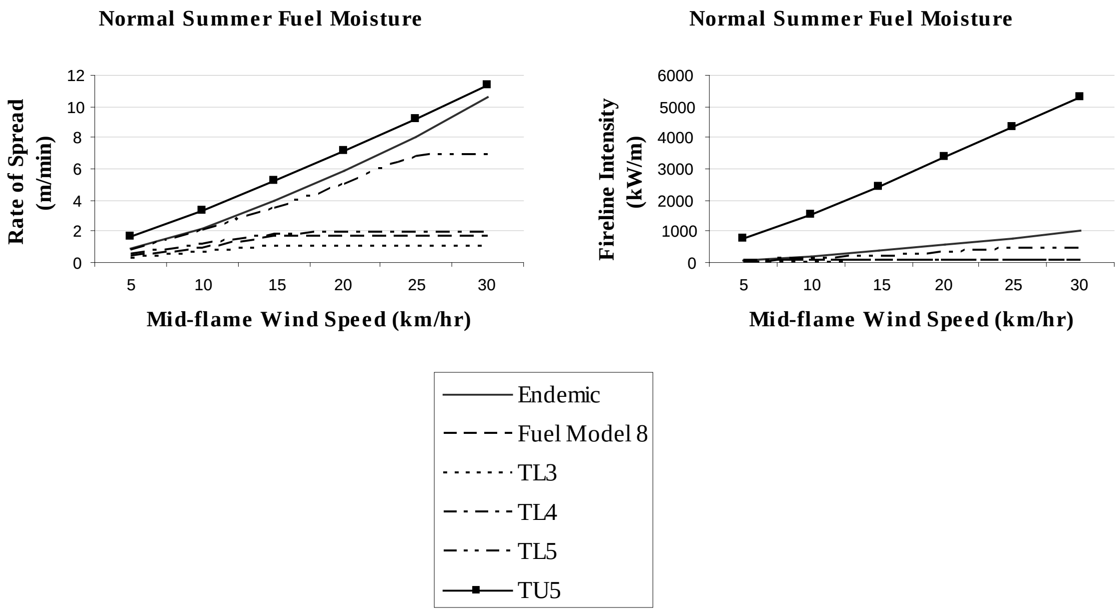

Figure 4. Rates of spread and fire line intensity comparisons for epidemic areas of beetle activity compared to established fuel models. Fire behavior variables are calculated with the same midflame windspeeds and under normal shaded fuel moisture conditions

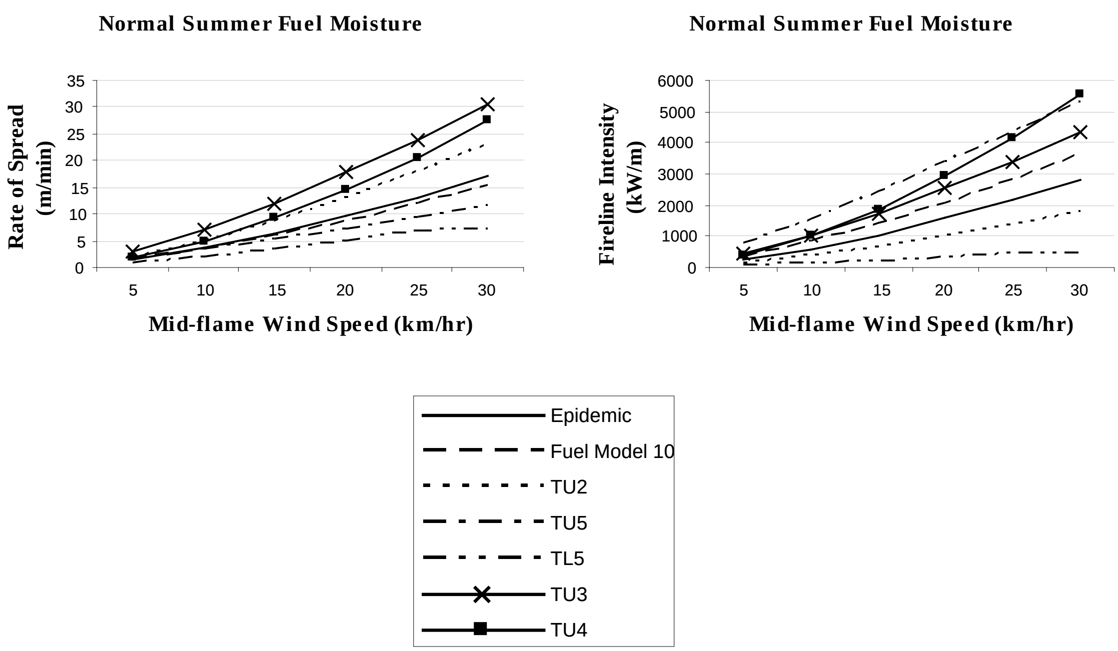

Figure 5. Rates of spread and fire line intensity comparisons for post-epidemic areas of beetle activity compared to established fuel models. Fire behavior variables are calculated with the same midflame wind speeds and under normal un-shaded fuel moisture conditions