

2010

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

Carl A. Jorgensen

Michael J. Jenkins

Follow this and additional works at: <https://digitalcommons.usu.edu/barkbeetles>

 Part of the [Ecology and Evolutionary Biology Commons](#), [Entomology Commons](#), [Forest Biology Commons](#), [Forest Management Commons](#), and the [Wood Science and Pulp, Paper Technology Commons](#)

## Recommended Citation

Jorgensen, C.A. and M.J. Jenkins. 2010. Potential fire behavior in spruce beetle-induced tree mortality in Intermountain spruce-fir forests. Unpublished

This Article is brought to you for free and open access by the Quinney Natural Resources Research Library, S.J. and Jessie E. at DigitalCommons@USU. It has been accepted for inclusion in The Bark Beetles, Fuels, and Fire Bibliography by an authorized administrator of DigitalCommons@USU. For more information, please contact [dylan.burns@usu.edu](mailto:dylan.burns@usu.edu).



1 Potential fire behavior in spruce beetle-induced tree mortality in Intermountain spruce-fir  
2 forests

3  
4 Carl Arik Jorgensen<sup>a</sup> and Michael James Jenkins<sup>b</sup>

5  
6  
7 <sup>a</sup>USDA Forest Service, Westside Ranger District Caribou-Targhee National Forest  
8 Pocatello, Idaho 83204, USA.

9  
10 <sup>b</sup>Utah State University, Department of Wildland Resources, Logan, UT 84322-5230

11  
12  
13  
14 **Abstract**

15  
16 Spruce beetle- (*Dendroctonus rufipennis* Kirby [Coleoptera: Curculionidae])  
17 induced tree mortality can increase fire intensity and severity resulting from changes to  
18 surface and aerial fuels. From inventoried fuel complexes, custom fuel models were  
19 developed. The endemic bark beetle condition class had greater amounts of live,  
20 available canopy fuel and canopy bulk density than either the epidemic and post epidemic  
21 condition classes. Epidemic bark beetle condition classes had the highest amounts of  
22 needle litter and 1-hr time lag (0-0.64 cm diameter) fuel while the post-epidemic  
23 condition class had the highest amount live shrubs and non-woody plants. Fire behavior  
24 calculated with BehavePlus from the custom fuel models resulted in substantial  
25 differences in fire rates of spread and intensity for each spruce beetle condition class  
26 based on identical moisture scenarios and wind speeds. Rates of spread for epidemic and  
27 post-epidemic condition classes ranged between 2.0 – 2.9 and 3.0 – 4.5 times faster than  
28 the endemic condition class. Fireline intensities ranged from 4.1 – 5.0 times higher in the  
29 epidemic condition class and 6.6 – 8.8 times higher in the post-epidemic condition class  
30 compared to endemic condition class. An observed lack of overstory sheltering is  
31 attributed to increased fire behavior in epidemic and post epidemic condition classes and

32 has a dominating affect on fire behavior. Post-epidemic condition class rates of spread  
33 and fireline intensities at identical midflame wind speeds were 1.7 and 3.3 times higher,  
34 respectively, than endemic parameters. Relatively, higher rates of spread (4.4 times) and  
35 fireline intensities (8.5 times), were observed between endemic and post-epidemic  
36 condition classes when calculated with 6.1 m wind speed adjusted for canopy sheltering.  
37 Custom fuel models developed for epidemic and post-epidemic classes showed similar  
38 results to selected established fuel models; however, no single fuel model exactly  
39 predicted fireline intensity and rate of spread for each of the custom fuel models  
40 developed.

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

42

## 43 **Introduction**

44

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

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

66           Regardless, insect altered fuel complexes can affect fire behavior (Stocks 1987).  
67 Hopkins (1909) first linked spruce beetle mortality to increases in fire behavior.  
68 Overstory removal typical of widespread severe spruce beetle mortality can change  
69 microclimatic conditions through a combination of factors, including insolation, relative  
70 humidity, temperature, and increases in herbaceous material (Schulz 2003). Higher wind  
71 speeds in the surface fuels can potentially increase the rate of spread of surface fires  
72 (Albini and Baughman 1979, Rothermel 1983). Increased solar radiation resulting from  
73 overstory removal raises fuel temperatures and is also associated with increased fire  
74 behavior (Rothermel 1983, Rothermel et al. 1986, Byram and Jemison 1943). The  
75 increase in live surface fuels and downed woody debris will affect the total fuel load  
76 available for combustion and create undetermined fire behavior potential (Agee et al.  
77 2002, DeRose and Long 2007)

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

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

100

## 101   **Methods**

### 102   *Study Site Selection*

103

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

112 current and older spruce beetle-caused tree mortality and uninfested stands within close  
113 proximity.

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

126  
127 ***Data Collection***

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

133

134 *Stand Characteristics*

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

140 *Canopy Fuels*

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

145 *Surface and Ground Fuels*

146           Surface and ground fuels were inventoried on each plot utilizing methods  
147 described by Page and Jenkins (2007a) and Brown et al. (1982). In summary, four planar  
148 intercept transects 19.81 m long, were established in each cardinal direction from each  
149 plot center. These transects were used to tally downed woody fuels intersecting the  
150 transect plane by standard time-lag diameter based fuel size classifications of 1 hour (0.0-  
151 0.64 cm), 10 hour (0.64-2.54 cm), 100 hour (2.54-7.62 cm), and 1000 hour (>7.62 cm)  
152 fuel classes. The smallest pieces (1 hour and 10 hour) were tallied between 1.52 m and  
153 3.35 m. The 100 hour size class was tallied between 1.52 m and 6.40 m and the 1000  
154 hour size class was tallied between 1.52 m and 19.81 m.

155           Two fixed diameter micro-plots 1.83 m in diameter were established at 10.67 and  
156 19.81 m along each of the four transects (total of eight per plot) for quantifying fuel bed



157 intercept height, live/dead shrub and herbaceous cover and height as well as litter/duff  
158 biomass and depth. The data collected in each sub-plot included the percentage of both  
159 live and dead cover and average height for shrubs and herbaceous plants (forbs and  
160 grasses). Duff and litter depth, in addition to fuel intercept height, were measured at the  
161 center of each sub-plot. Fuel intercept height was determined by imposing a 0.3 m plane  
162 perpendicular to the fuel transect and measuring the highest downed woody particle  
163 intercepted by that plane (Brown 1974).

164

## 165 ***Data Analysis***

166

### 167 *Calculation of Stand Characteristics*

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

### 172 *Calculation of Canopy Fuels*

173 The data collected from sample trees were utilized to calculate the live available  
174 canopy fuel load, canopy base height and canopy bulk density. Live available canopy  
175 fuel load was determined from live crown biomass estimates using allometric equations,  
176 developed by Brown (1978), and based on tree species and crown class. These equations  
177 provided fuel estimates for live foliage and branchwood less than 0.65 cm. We  
178 incorporated all live foliage and 65% of the calculated branchwood in the live available  
179 canopy fuel load (Call and Albin 1997, Cruz et al. 2003). Mean canopy base height was  
180 calculated as a weight average using the number of trees ha<sup>-1</sup> represented by each

181 sampled tree, averaged over plots within a stand. Canopy bulk density for each plot was  
182 then calculated from the live available canopy fuel load divided by the canopy length (i.e.  
183 total tree height minus crown base height) of the randomly selected and measured tree on  
184 each plot.

#### 185 *Calculation of Surface and Ground Fuels*

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

#### 194 *Statistical Analysis*

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

201

202 ***Fuel Model Construction***

203

204 Custom fuel models for fire behavior predictions were created and analyzed for  
205 endemic, epidemic and post epidemic spruce beetle condition classes based on methods  
206 described by Page and Jenkins (2007b) and Burgan and Rothermel (1984). The custom  
207 fuel models are based on estimated summaries of litter, 1 hour, 10 hour, 100 hr time lag  
208 fuel weights and live shrub and live herbaceous fuel loads. These summaries are based  
209 on customized fuel model inputs described and required by BehavePlus (Andrews et al.  
210 2003). Shrub, herbaceous and fuel bulk height were averaged to represent the required  
211 surface fuel bed depth. The required 1 hr input was calculated from the combined litter  
212 and 1 hr time lag fuel biomass estimates. Input parameters from Anderson (1982)  
213 standard fuel model 10 were used as guidance to describe fuel complexes affected by  
214 bark beetle mortality. Specifically, heat content, surface area to volume ratios and  
215 moisture of extinction of live and dead fuel from standard fuel model 10 can parameterize  
216 the live and dead fuels present in sampled stands (Page and Jenkins 2007b). All input to  
217 the fuel models are listed in Tables 2, 3, and 4 along 90% confidence levels, and  
218 observed data ranges.

219

220 ***Surface Fire Behavior***

221

222 The estimations for surface fire behavior prediction using BehavePlus (v. 3.0.1)  
223 were calculated for maximum rate of spread and fireline intensity at the head of the  
224 surface fire (Andrews et al. 2003). The assumptions and limitations associated with the  
225 surface spread equation used in BehavePlus and the stylized fuel model used for  
226 predictions apply to all calculations. Limitations include a continuous and uniform fuel

227 bed in contact with the ground, no incorporation of woody pieces larger than 7.62 cm,  
228 predictions are limited to surface fire, during calculation no weather variables change,  
229 and no fire spotting is incorporated into rates of surface fire spread (Rothermel 1972).

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

249

250 ***Crown Fire Behavior***

251

252           Attributes of crown fire potential were also calculated with BehavePlus which is  
253 based on the Van Wagner (1977) crown fire initiation model and the Rothermel (1991)  
254 crown fire behavior model (Andrews et al. 2003). BehavePlus does not account for  
255 energy released during combustion of 1000 hr fuel in its surface fire module even though  
256 this can be influential for crown fire initiation (Rothermel 1991). The BURNUP program  
257 included in the First Order Fire Effects Model (FOFEM v. 5.21) is able to compute fuel  
258 consumption during flaming and smoldering combustion for 1-hr, 10-hr, 100-hr, 1000-hr  
259 sound and rotten material in addition to litter, duff, live herbaceous and live shrub  
260 biomass (Reinhardt et al. 1997). Combustion estimates were determined for specific fuel  
261 moisture (Table 5), relative humidity, and seasonal changes defined with in the FOFEM  
262 model (Reinhardt et al. 1997). The inventoried fuel complex was input into FOFEM to  
263 obtain the amount of fuel burned during flaming combustion. New fireline intensities  
264 were then calculated by inputting that amount of estimated fuel into the fire intensity  
265 equations presented in Byram (1959). These recalculated fireline intensities were then  
266 input into the crown fire module in BehavePlus to estimate crown fire potential in the  
267 absence of the surface fire module (Andrews et al. 2003). Only the estimated fuels  
268 consumed during flaming combustion were used to recalculate intensity. This method  
269 incorporates the large diameter fuels (> 7.52 cm) for intensity calculations but these fuels  
270 are assumed to have no effect on forward rate of spread in this method (Page and Jenkins  
271 2007b, Rothermel 1972).

272           Wind speeds, fuel moisture estimates, and re-calculated intensities were coupled  
273 in the BehavePlus crown fire module to provide estimates of critical crown fire rate of

274 spread, critical fireline intensity, whether or not active crowning and/or torching would  
275 occur, and what type of fire would burn. The Van Wagner (1977) crown fire initiation  
276 model uses canopy base height and foliar moisture content as predictors to crown fire  
277 initiation. The Rothermel (1991) crown fire spread model uses the canopy bulk density  
278 and wind speed to determine the critical rate of spread that a crown fire must maintain.  
279 Therefore, additional required inputs to the crown fire module are canopy bulk density,  
280 canopy base height, and crown foliar moisture content. Foliar moisture content was input  
281 as 100% for all crown fire prediction simulations.

282

### 283 *Fuel Model Comparisons*

284

285         The calculations from the custom fuel models were compared to calculations from  
286 the established fuel models under similar parameters (Anderson 1982, Scott and Burgan  
287 2005). All fuel model comparisons were estimated for normal summer fuel moisture  
288 conditions and the same range of midflame wind speeds. It is acknowledged that lack of  
289 canopy and vegetative sheltering, especially in bark beetle affected fuel complexes, can  
290 allow wind to have a dramatic effect on fire behavior (Page and Jenkins 2007b,  
291 Rothermel 1983, Albini and Baughman 1979). Therefore, identical midflame wind  
292 speeds were used for fire behavior comparison to remove the effect of canopy sheltering  
293 on the 6.1 m wind speeds and directly compare the single influence of fuel on the fire  
294 behavior between the custom fuel models and the established fuel models. However, the  
295 effect of solar radiation on fuels was maintained in shaded vs. unshaded moisture values  
296 within the custom fuel model calculations. Fuel models 8 and 10 (Anderson 1982) and  
297 other existing fuel models from Scott and Burgan (2005) were used as standard

298 comparisons to the custom fuel models developed as suggested by Burgan and Rothermel  
299 (1984).

300

## 301 **Results**

302

### 303 *Crown Fire Behavior*

304

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

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

322

323

324 *Surface Fire Behavior*

325           The calculated surface fire behavior for the spruce beetle condition classes is  
326 primarily described by Figures 1 and 2. The PEP class was generally characterized by  
327 faster rates of spread and higher fireline intensities than the En or epidemic (Ep) classes.  
328 The Ep class exhibits the next highest fire behavior characteristics summarized by faster  
329 rates of spread and higher fireline intensities than the En class but still lower than the PEP  
330 class. Fire behavior predictions for the En condition class gradually increased, but more  
331 dramatic fire behavior predictions were calculated in Ep and PEP condition classes with  
332 considerable increases due to high wind speeds resulting from unsheltered fuel due to  
333 lack of canopy.

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

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



346 combustion Table 7. The epidemic condition had the longest combustion duration and  
347 most fuel consumed during total combustion than any other spruce beetle condition class.

348

349 ***Fuel Model Comparisons***

350

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

360 The epidemic fuel model appears to be represented closely by a few of the  
361 established fuel models (Figure 4). Fuel model 10 exhibited very similar rates of spread  
362 results when compared to our fuel model. The timber-understory 2 (TU2), timber-  
363 understory 3 (TU3), timber understory 4(TU4) models over predicted rate of spread and  
364 both timber models (TL5 and TU5) under predicted the rate of spread compared to our  
365 custom model (Figure 4). Concerning fireline intensity in the epidemic areas, fuel model  
366 10 was also the closest established fuel model for comparison. Fuel model TU2 was  
367 equally close with an under prediction compared to our estimates. The TU3, TU4 and  
368 TU5 fuel models over predicted fireline intensity while fuel model TL5 under predicted  
369 both rates of spread and fireline intensity in the epidemic spruce beetle condition classes.

370 In post epidemic condition classes, rates of spread were well represented by fuel  
371 model 10 (Figure 5). Fuel models TU5 and Shrub 4 (SH4) were close representations at  
372 lower wind speeds but as wind speed increased, greater differences were observed with a  
373 reduction in rate of spread when compared to the post epidemic fuel model. Fuel model  
374 10 is nearly identical to our post epidemic calculations regarding rate of spread. Fuel  
375 models TU2, TU3, TU4 and Slash-Blowdown – 2 (SB2) appeared to over predict rate of  
376 spread as wind speeds increased. Concerning fireline intensity, fuel model 10 was again  
377 a near match with sampled post epidemic classes. SH4 and TU2 under predicted the  
378 fireline intensity while TU3, TU4, TU5 and SB2 over predicted the fireline intensity of  
379 the post epidemic spruce beetle condition classes.

380

### 381 **Discussion**

382

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

394 have complex and prolonged effects on the fire environment in spruce beetle-altered  
395 spruce-fir forests (Albini and Baughman 1979, Byram and Jemison 1943, Rothermel  
396 1983).

397

398 ***Crown Fire Behavior***

399

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

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

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

418 1992, Long 1994, Johnson et al. 2001, Arno 2000). These naturally developed fuels  
419 complexes, combined with advanced spruce and subalpine fir regeneration lowers live  
420 canopy base height in post-epidemic stands, can eventually provide a period of increased  
421 flammability. Regeneration will continue to grow if undisturbed, canopy bulk density  
422 will increase and limit the amount of live surface fuel in the stand, standing dead trees  
423 will remain in the canopy for long periods of time while gradually continuing to maintain  
424 levels of downed woody debris on the forest floor. Continuous aerial fuels including  
425 canopy snags, combined with abundant ladder fuels, may increase potential flammability  
426 in post-outbreak stands.

427         Our current understanding of crown fire behavior is limited and only a  
428 parameterization of input data and equations were used. Alexander and Cruz (2006)  
429 found that the Rothermel's (1991) crown fire prediction model, used in this analysis,  
430 under predicted crown fire behavior. By comparison, Alexander and Cruz (2006) showed  
431 the Cruz et al. (2005) crown fire prediction model to over predict potential crown fire  
432 behavior. No model is perfect and the comparison between Rothermel (1991) and Cruz  
433 et al. (2005) are made from data on different scales (Scott 2006). Cruz and Alexander  
434 (2010) reviewed studies that predicted crown fire potential and concluded there is a  
435 significant under prediction bias

436

### 437 *Surface Fire Behavior*

438

439         Greater rates of spread and fireline intensity were estimated for the post-epidemic  
440 spruce beetle condition class when 6.1 m wind adjustment factors were applied, due to  
441 canopy reduction, compared to the epidemic and endemic classes. Canopy reduction and

442 lack of overall sheltering from the overstory fuels influences fire behavior in bark beetle  
443 altered stands compared to fully sheltered stands (Page and Jenkins 2007b). When  
444 custom fuel model comparisons were made with identical midflame wind speeds, both  
445 post-epidemic and epidemic classes showed similar rates of spread and fireline  
446 intensities, but were still higher than endemic classes. Substantial differences between  
447 fuels in epidemic and post-epidemic condition classes (i.e. fine fuels and live woody fuel)  
448 have been observed, but differences in the behavior of surface fires were less definitive  
449 under identical conditions.

450       Due to the abundance of fine fuels, calculations for the epidemic condition class  
451 were still expected to produce higher rates of spread and fireline intensity compared to  
452 the endemic class, once overstory sheltering effects were removed. The post-epidemic  
453 fire behavior calculations contradicted initial expectations. Due to the abundance of live  
454 fuel woody fuel, we expected to see a decrease in fire behavior when comparing  
455 epidemic and post-epidemic stands. The presence of abundant live fuels with high fuel  
456 moisture content are often considered a heat sink (Rothermel 1983, Andrews 1986,  
457 Stocks 1987, Agee et al. 2002). However, our data indicate sequential increases in  
458 potential fire behavior between endemic, epidemic and post-epidemic classes following  
459 spruce beetle outbreaks in Intermountain spruce-fir forests regardless of the increase of  
460 overall live fuel. Increased live fuels in our custom fuel models are not adequately  
461 reflected as a potential heat sink in current fire behavior calculation models. Fire  
462 behavior prediction models such as BehavePlus are not currently designed to accurately  
463 incorporate live fuel in calculations (Weise et al. 2005, Sun et al. 2006). This leaves  
464 adjustment of user defined fuel model inputs such as fuel moisture of extinction, live fuel

465 moisture content, and live fuel heat content to obtain replicable results to what is  
466 observed in the field. Although currently established fuel models and fire behavior  
467 calculation models have been invaluable for decades, validation is important. Especially  
468 when compositions of live fuels from differing ecosystems and elevations reflect extreme  
469 variations of fire behavior potential under the same burning conditions (e.g. chaparral  
470 versus *Ribes* spp). Further research is needed to better parameterize fire prediction in  
471 fuel strata differing in type, arrangement, species and moisture content (Romme 1982,  
472 Swetnam and Baisan 1996, Scott and Reinhardt 2001, Riccardi et al. 2007, Sandberg et  
473 al. 2007).

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

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

499

#### 500 *Fuel Model Comparison*

501

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

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

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

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



**533 Conclusions**

534

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

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

552

553 **Literature Cited**

554

555

556 Agee, J.K., C.B. Wright, N. Williamson and M.H. Huff. 2002. Foliar moisture content  
557 of Pacific Northwest vegetation and its relation to wildland fire behavior. For.  
558 Ecol. Manage. 167:57–66.

559

560 Albini, F.A. and J.K. Brown. 1978. Predicting slash depth for fire modeling. US For.  
561 Serv. Res. Pap. INT-206. 24 p.

562

563 Albini, F.A. and R.G. Baughman. 1979. Estimating windspeeds for predicting wildland  
564 fire behavior. US For. Serv. Res. Pap. INT – 221. 12 p.

565

566 Alexander, M.E. and M.G. Cruz. 2006. Evaluating a model for predicting active crown  
567 fire rate of spread using wildfire observations. Can. J. For. Res. 36:3015-3028.

568

569 Anderson, H.E. 1982. Aids to determining fuel models for estimating fire behavior. US  
570 For. Serv. Gen. Tech. Rep. INT-GTR-122. 22 p.

571

572 Andrews, P.L. 1986. Behave fire behavior and fuel modeling subsystem: burn  
573 subsystem part 1. US For. Serv. Gen. Tech. Rep. INT-GTR-194. 130 p.

574

575 Andrews, P.L., C.D. Bevins, and R.C. Seli. 2003. BehavePlus fire modeling system  
576 version 2.0: User's guide. US For. Serv. Gen. Tech. Rep. RMRS-GTR-106. 132  
577 p.

578

579 Aplet, .G.H., R.D. Laven, and F.W. Smith. 1988. Patterns of community dynamics in  
580 Colorado Engelmann spruce-subalpine fir forests. Ecol. 69:312-319.

581

582 Arno, S.F. 2000. Fire in western forest ecosystems: effects of fire on flora. P. 97-120 in  
583 *Wildland Fire in Ecosystems*, Brown, J.K., and J. Kapler Smith. (eds.). US For.  
584 Serv. Gen. Tech. Rep. RMRS-GTR-42-vol. 2.

585

586 Baker, W.L, and T.T. Veblen. 1990. Spruce beetles and fires in the nineteenth-century  
587 subalpine forests of Western Colorado, USA. Arc. and Alp. Res. 22:65-80.

588

589 Bebi, P., D. Kulakowski, and T.T. Veblen. 2003. Interactions between fire and spruce  
590 beetles in a subalpine Rocky Mountain landscape. Ecol. 84:362-371.

591

592 Bentz, B.J. and A.S. Munson. 2000. Spruce beetle population suppression in northern  
593 Utah. West. J. Appl. For. 15(3): 122-28.

594

595 Berg, E. 2007. Characterizing and classifying complex fuels – A new approach. Can. J.  
596 For. Res. 37:2381-2382.

597

- 598 Bessie, W.C. and E.A. Johnson. 1995. The relative importance of fuels and weather on  
599 fire behavior in subalpine forests. *Ecol.* 76:747-762.  
600
- 601 Bigler, C., D. Kulakowski, and T.T. Veblen. 2005. Multiple disturbance interactions and  
602 drought influence fire severity in Rocky Mountain subalpine forests. *Ecol.*  
603 86:3018-3029.  
604
- 605 Brown, A.A., and K.P. Davis. 1973. *Forest fire: control and use*. 2nd Ed., McGraw-Hill,  
606 New York, NY, 686 p.  
607
- 608 Brown, J.K. 1974. Handbook for inventorying downed woody material. US For. Serv.  
609 Gen. Tech. Rep. INT-GTR-16. 24 p.  
610
- 611 Brown, J.K. 1978. Weight and density of crowns of Rocky Mountain conifers. US. For.  
612 Serv. Res. Pap. INT-197. 56 p.  
613
- 614 Brown, J.K., R.D. Overheu, and C.M. Johnston. 1982. Handbook for inventorying  
615 surface fuels and biomass in the interior West. US For. Serv. Gen. Tech. Rep.  
616 INT-GTR-129. 48 p.  
617
- 618 Burgan, R.E., and R.C. Rothermel. 1984. BEHAVE: Fire behavior prediction and fuel  
619 modeling system-FUEL subsystem. US For. Serv. Gen. Tech. Rep. INT-GTR-  
620 167. 126 p.  
621
- 622 Byram, G.M. 1959. Combustion of forest fuels. P. 61-89 in *Forest fire: Control and*  
623 *use*. 2nd ed., Davis, K.P. (ed.). McGraw-Hill, New York, NY.  
624
- 625 Byram, G.M., and G.M. Jemison. 1943. Solar radiation and forest fuel moisture. *J.*  
626 *Agric. Res.* 67: 149-176.  
627
- 628 Call, P.T. and F.A. Albini. 1997. Aerial and Surface fuel consumption in crown fires.  
629 *Int. J. Wild. Fire* 7:259-264.  
630
- 631 Cruz, M.G., M.E. Alexander, and R.H. Wakimoto. 2003. Assessing canopy fuel stratum  
632 characteristics in crown fire prone fuel types of western North America. *Int. J.*  
633 *Wild. Fire.* 12:39-50.  
634
- 635 Cruz, M.G., M.E. Alexander, and R.H. Wakimoto. 2005. Development and testing of  
636 models for predicting crown fire rate of spread in conifer forest stands. *Can. J.*  
637 *For. Res.* 35:1626-1639.  
638
- 639 Cruz, M.G. and M.E. Alexander. 2010. Assessing crown fire potential in coniferous  
640 forests of western North America: a critique of current approaches and recent  
641 simulation studies. *Int. J. Wildland Fire* 19: 377-398.  
642

- 643 DeRose, R.J. and J.N. Long. 2007. Disturbance, structure, and composition: spruce beetle  
644 and Engelmann spruce forest on the Markagunt Plateau, Utah. *For. Ecol.*  
645 *Manage.* 244:16-23.
- 646  
647 DeRose, R.J. and J.N. Long. 2009. Wildfire and spruce beetle outbreak: simulation of  
648 interacting disturbances in the central Rocky Mountains. *Ecosci.* 16:28-38.
- 649  
650 Hopkins, A.D. 1909. Practical information on the Scolytid beetles of North American  
651 forests. I. Bark beetles of the Genus *Dendroctonus*. US Bureau of Entomol.  
652 Bull. 83. U.S. Gov't Printing Office, Washington D.C.
- 653  
654 Jenkins, M.J., E. Hebertson, W. Page, and C.A. Jorgensen. 2008. Bark beetles, fuels,  
655 fires and implications for forest management in the Intermountain West. *For.*  
656 *Ecol. Manage.* 254:16-34.
- 657  
658 Jenkins, M. J., C. A. Dicus and E. G. Hebertson. 1998. Post-fire succession and  
659 disturbance interactions on an intermountain subalpine spruce/fir forest. P. 219-  
660 229 in *Proceedings, Symposium: Fire in Ecosystem Management: Shifting the*  
661 *paradigm from suppression to prescription*, Pruden, T. L. and L. A. Brennan,  
662 (eds.). Tall Timbers Fire Ecology Conference Proceedings, No. 20. Tall Timbers  
663 Research Station, Tallahassee, FL.
- 664  
665 Johnson, E.A. 1992. Fire and vegetation dynamics: studies from the North American  
666 boreal forests. Cambridge University Press, Cambridge, United Kingdom.
- 667  
668 Johnson, E.A., K. Miyanishi, and S.R.J. Bridge. 2001. Wildfire regime in the Boreal  
669 forest and the idea of suppression and fuel buildup. *Conserv. Bio.* 15:1554-1557.
- 670  
671 Jorgensen, C.A. and M.J. Jenkins. In Review. Fuel complex alterations associated with  
672 beetle-induced tree mortality in Intermountain spruce-fir forests. *For. Sci. (in*  
673 *review)*.
- 674  
675 Knight, D.H. 1987. Parasites, lightning, and the vegetation mosaic in wilderness  
676 landscapes. P. 59-83 in *Landscape heterogeneity and disturbance*, Turner, M.G.  
677 (ed.). Springer-Verlag, New York, NY.
- 678  
679 Kulakowski, D., T.T. Veblen, and P. Bebi. 2003. Effects of fire and spruce beetle  
680 outbreak legacies on the disturbance regime of a subalpine forest in Colorado. *J.*  
681 *Biogeogr.* 30:1445-1456.
- 682  
683 Kulakowski, D., and T.T. Veblen. 2007. Effect of prior disturbance on the extent and  
684 severity of wildfire in Colorado subalpine forests. *Ecol.* 88:759-769.
- 685 Long, J.N. 1994. The middle and Southern Rocky Mountain Region. Pp. 335-386 in  
686 *Regional silviculture of the United States*, 3rd ed., Barrett, J.W. (ed.). John Wiley  
687 and Sons, New York, NY.

- 688 Lertzman, K.P. and C.J. Krebs. 1991. Gap phase structure of a subalpine old-growth  
689 forest. *Can. J. For. Res.* 21:1730-1741.  
690
- 691 Lutes, D.C., R.E. Keane, J.F. Caratt. C.H. Key, N.C. Benson, S. Sutherland, and L.J.  
692 Gangi. 2006. FIREMON: Fire Effects monitoring and inventory system. US  
693 For. Serv. Gen. Tech Rep. RMRS-GTR-164-CD. 400 p.  
694
- 695 Ottmar, R.D., D.V. Sandberg, C.L. Riccardi, and S.J. Prichard. 2007. An overview of  
696 the Fuel Characteristic Classification System – Quantifying, classifying, and  
697 creating fuelbeds for resource planning. *Can. J. For. Res.* 37:2383-2393.  
698
- 699 Page, W.G. and M.J. Jenkins. 2007a. Mountain pine beetle induced changes to selected  
700 lodgepole pine fuel complexes within the Intermountain Region. *For. Sci.*  
701 53:507-518.  
702
- 703 Page, W.G. and M.J. Jenkins. 2007b. Predicted fire behavior in selected mountain pine  
704 beetle – infested lodgepole pine. *For. Sci.* 53:662-674.  
705
- 706 Pyne, S.J., P.L. Andrews, and R.D. Laven. 1996. Introduction to wildland fire. 2nd Ed.,  
707 John Wiley and Sons, New York, NY.  
708
- 709 Reinhardt, E.D., R.E. Keane, and J.K. Brown. 1997. First order fire effects model:  
710 FOFEM 4.0, user's guide. US For. Serv. Gen. Tech. Rep. INT-GTR-344. 65 p.  
711
- 712 Riccardi, C.L., R.D. Ottmar, D.V. Sandberg, A. Andreu, E. Elman, K. Kopper, and J.  
713 Long. 2007. The fuelbed: a key element of the Fuel Characteristic Classification  
714 System. *Can. J. For. Res.* 37:2394-2412.  
715
- 716 Romme, W.H. 1982. Fire and landscape diversity in subalpine forests of Yellowstone  
717 National Park. *Ecol. Monogr.* 52:199-221.  
718
- 719 Romme, W.H., and D.G. Despain. 1989. Historical perspective on the Yellowstone fires  
720 of 1988. *Biosci.* 39:695-699.  
721
- 722 Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland  
723 fuels. US For. Serv. Res. Pap. INT-115. 40 p.  
724
- 725 Rothermel, R.C. 1983. How to predict the spread and intensity of forest and range fires.  
726 US For. Serv. Gen. Tech. Rep. INT-GTR-143. 161 p.  
727
- 728 Rothermel, R.C. 1991. Predicting behavior and size of crown fires in the northern  
729 Rocky Mountains. US For. Serv. Res. Pap. INT-438. 46 p.  
730

- 731 Rothermel, R.C., R.A. Wilson Jr., G.A. Morris, and S.S. Sackett. 1986. Modeling  
732 moisture content of fine dead wildland fuels: Input to the BEHAVE fire  
733 prediction system. US For. Serv. Res. Pap. INT-359. 61 p.  
734
- 735 Sandberg, D.V., C.L. Riccardi, and M.D. Schaaf. 2007. Reformulation of Rothermel's  
736 wildland fire behaviour model for heterogeneous fuelbeds. Can. J. For. Res.  
737 37:2438-2455.  
738
- 739 SAS Institute Inc. 2005. SAS, version 9.1. Cary, NC.  
740
- 741 Schmid, J.M. and T.E. Hinds. 1974. Development of spruce/fir stands following spruce  
742 beetle outbreaks. US For. Serv. Res. Pap. RM-131. 16 p.  
743
- 744 Schulz, B. 2003. Changes in downed and dead woody material following a spruce beetle  
745 outbreak on the Kenai Peninsula, Alaska. US For. Serv. Res. Pap. PNW-RP-559.  
746 10 p.  
747
- 748 Scott, J.H. 2006. Comparison of crown fire modeling systems used in three fire  
749 management applications. US For. Serv. Res. Pap. RMRS-RP-58. 25p.  
750
- 751 Scott, J.H., and E.D. Reinhardt. 2001. Assessing crown fire potential by linking models  
752 of surface and crown fire behavior. US For. Serv. Res. Pap. RMRS-29. 59 p.  
753
- 754 Scott, J.H., and R.E. Burgan. 2005. Standard fire behavior fuel models: A  
755 comprehensive set for use with Rothermel's surface fire spread model. US For.  
756 Serv. Gen. Tech. Rep. RMRS-GTR-153. 72 p.  
757
- 758 Stocks, B.J. 1987. Fire potential in the spruce budworm-damaged forests of Ontario.  
759 For. Chron. 63:8-14.  
760
- 761 Stockstad, D.S. 1975. Spontaneous and piloted ignition of pine needles. US For. Serv.  
762 Res. Note INT-194. 14p.  
763
- 764 Sun, L., Z. Xiangyang, S. Mahalingam, D.R. Weise. 2006. Comparison of burning  
765 characteristics of live and dead chaparral fuels. Comb. and Flame. 144:349-359.  
766
- 767 Swetnam, T.W. and C.H. Baisan. 1996. Historical fire regime patterns in the  
768 southwestern United States since AD 1700. P. 11-32. in *Fire Effects in*  
769 *Southwestern Forests, Proc. of the Second La Mesa Fire Symposium*, Allen, C.D.  
770 (ed.). US For. Serv. Gen. Tech. Rep. RM-GTR-286. 216 p.  
771
- 772 Taylor, K. L., and R.W. Fonda. 1990. Woody fuel structure and fire in subalpine fir  
773 forests, Olympic National Park, Washington. Can. J. For. Res. 20:193-199.  
774

- 775 Turner, M.G, and W.H. Romme. 1994. Landscape dynamics in crown fire ecosystems.  
776 Landscape Ecol. 9:59-77.  
777
- 778 Van Wagner, C.E. 1977. Conditions for the start and spread of crown fire. Can. J. For.  
779 Res. 7: 23-34.  
780
- 781 Veblen, T.T. 1986a. Age and size structure of subalpine forests in the Colorado Front  
782 Range. Bull. Torrey Bot. Club. 113:225-240.  
783
- 784 Veblen, T.T. 1986b. Treefalls and the coexistence of conifers in subalpine forests of the  
785 Central Rockies. Ecol. 67:644-649  
786
- 787 Weise, D.R., Z. Xiangyang, S. Lulu, S. Mahalingam. 2005. Fire spread in chaparral. –  
788 ‘go or no-go’? Int. J. Wild. Fire. 14:99-106.  
789
- 790 Xanthopoulos, G., and R.H. Wakimoto. 1993. A time to ignition-temperature-moisture  
791 relationship for branches of three western conifers. Can. J. For. Res. 23:253-258.  
792  
793

794

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 <sup>2</sup> )	% Dead TPH	Mean % Older Dead <sup>†</sup> ES		% Rock Cover
		ES	SAF	AS			Standing	Fallen	
<b>Fishlake</b>									
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%
<b>Manti-LaSal</b>									
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.

<sup>†</sup>spruce killed > 4 years ago.

795

796

797



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 <sup>2</sup> /m <sup>3</sup> )	6562			
Live Herbaceous SAV Ratio (m <sup>2</sup> /m <sup>3</sup> )	4921			
Live Woody SAV Ratio (m <sup>2</sup> /m <sup>3</sup> )	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.

801

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

	<b>Epidemic</b>			
	<b>Average</b>	<b>Range</b>	<b>Lower 90% CL</b>	<b>Upper 90% CL</b>
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 <sup>2</sup> /m <sup>3</sup> )	6562			
Live Herbaceous SAV Ratio (m <sup>2</sup> /m <sup>3</sup> )	4921			
Live Woody SAV Ratio (m <sup>2</sup> /m <sup>3</sup> )	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

802

803

804

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 <sup>2</sup> /m <sup>3</sup> )	6562			
Live Herbaceous SAV Ratio (m <sup>2</sup> /m <sup>3</sup> )	4921			
Live Woody SAV Ratio (m <sup>2</sup> /m <sup>3</sup> )	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

805

806

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

	Normal		Drought		Extreme	
	Summer		Summer		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

807

808

809

810

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

	<b>Estimated Live ACFL (tonne/ha)</b>	<b>Estimated Live Foliage (tonne/ha)</b>	<b>Estimated Dead Foliage (tonne/ha)</b>	<b>Live CBD (kg/m<sup>3</sup>)</b>	<b>Live CBH (m)</b>	<b>Critical ROS (m/min)</b>	<b>Critical Fireline Intensity (kW/m)</b>
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

811

812

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

	<b>Total Fuel Consumed (tonne/ha)</b>	<b>Fuel Consumed (Flaming) (tonne/ha)</b>	<b>Duration (hour:min:sec)</b>	<b>Fuel Consumed (Smoldering) (tonne/ha)</b>	<b>Duration (hour:min:sec)</b>
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

813

814

815

816

817

818

819

820

821

822

823

824

825

826

827

828

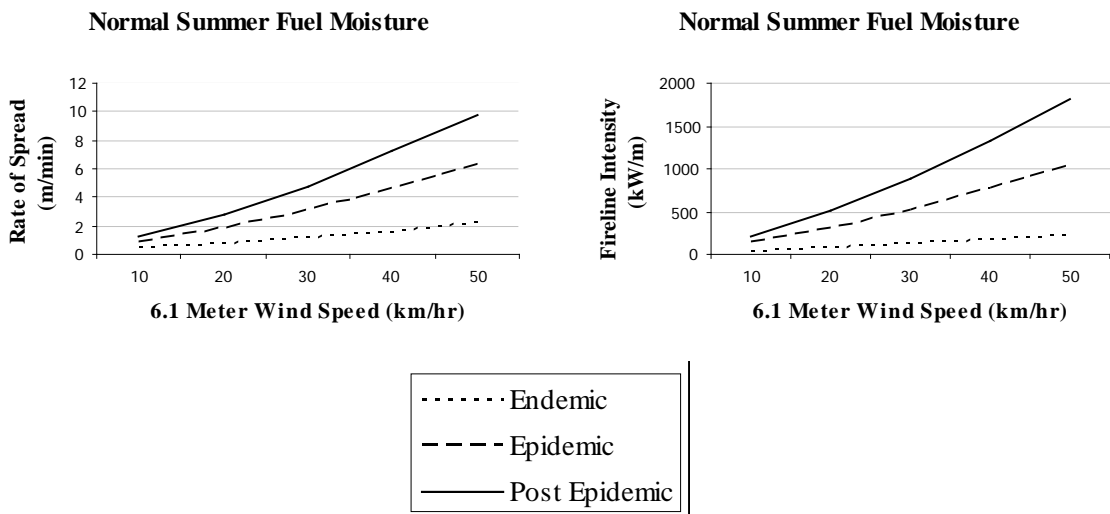
829

830

831

832

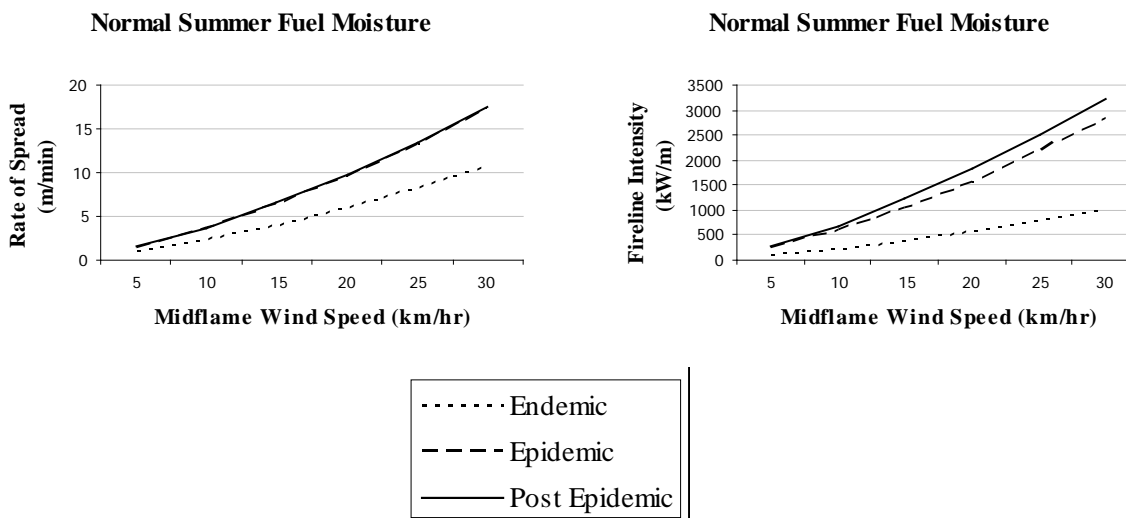
Figure 1. Fire behavior variables under normal summer fuel moisture conditions. Areas of endemic, epidemic and post epidemic beetle activity are compared to each other. Wind adjustment factors were 0.2 for endemic situations, 0.3 for epidemic, and 0.4 for post-epidemic situations to obtain midflame wind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



833

834

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.



835

836

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

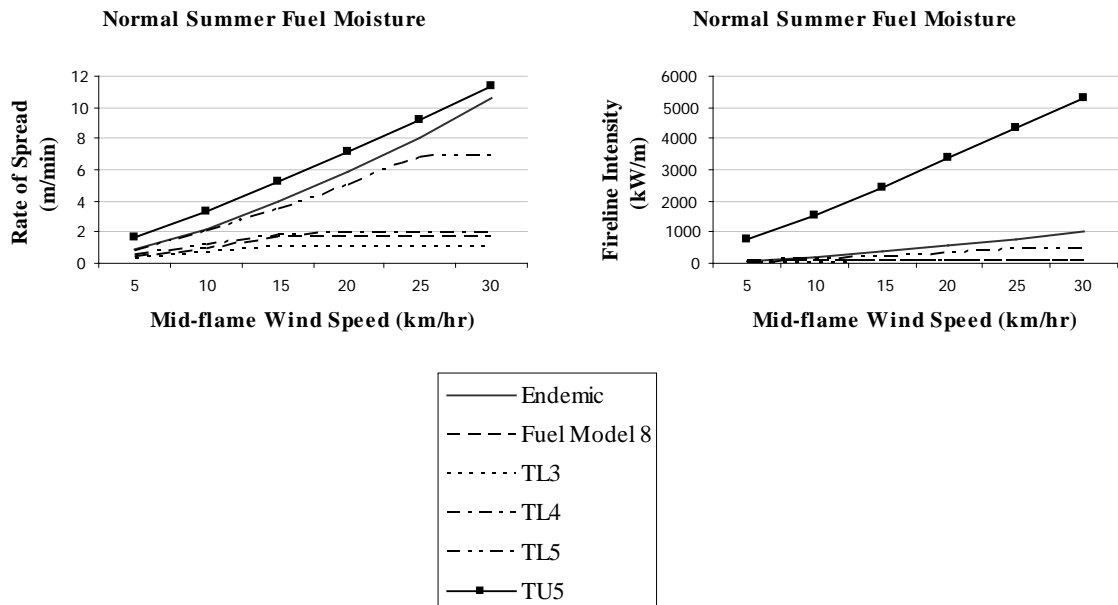
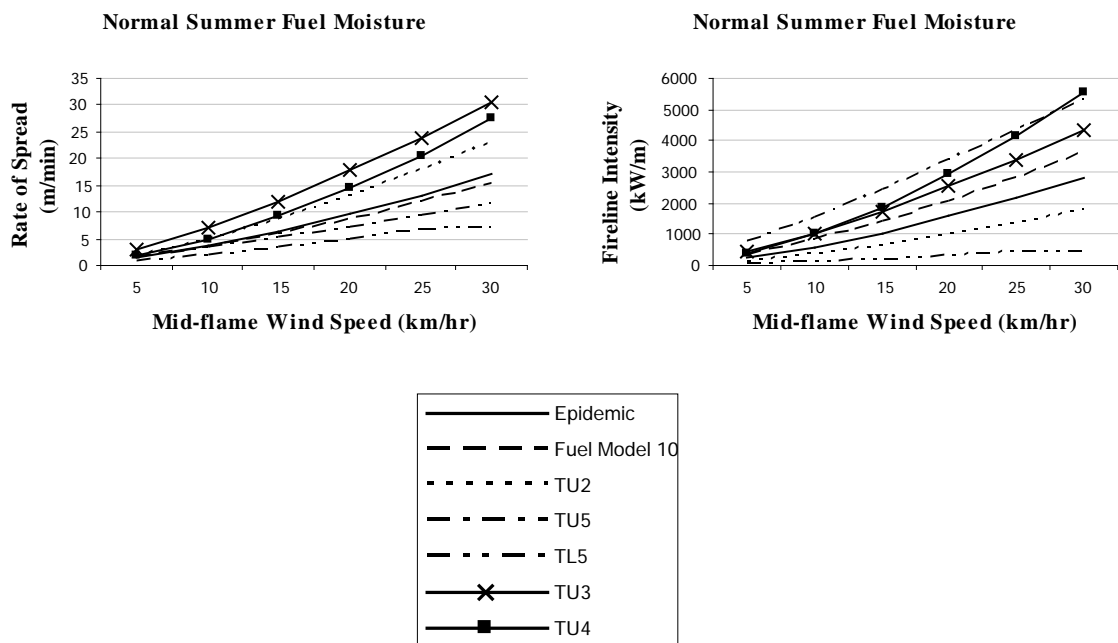
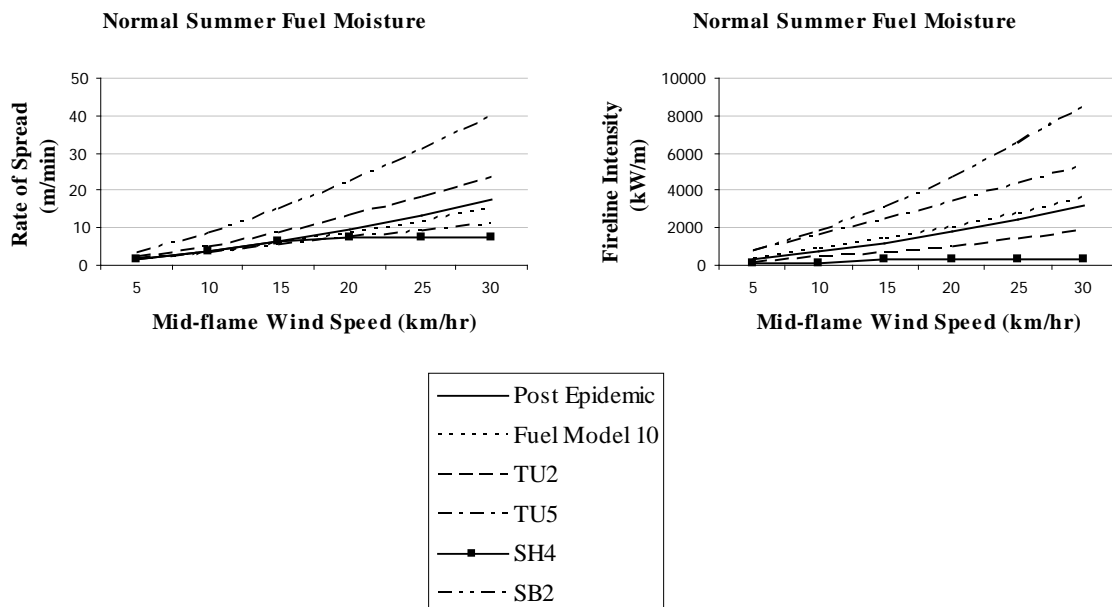


Figure 4. Rates of spread and fire line intensity comparisons for epidemic areas of beetle activity compared to established fuel models. Fire behavior variables are calculated with the same midflame windspeeds and under normal shaded fuel moisture conditions



840

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



841

842