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

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

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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⁻¹. 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⁻¹, 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⁻¹ estimated in post-epidemic stands was combined with the number of standing trees
171 ha⁻¹ from the variable radius plot to determine dead spruce trees ha⁻¹ 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⁻¹ 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 Albini 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*

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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

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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.

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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.

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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

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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

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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

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

	Estimated Live ACFL (tonne/ha)	Estimated Live Foliage (tonne/ha)	Estimated Dead Foliage (tonne/ha)	Live CBD (kg/m³)	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

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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

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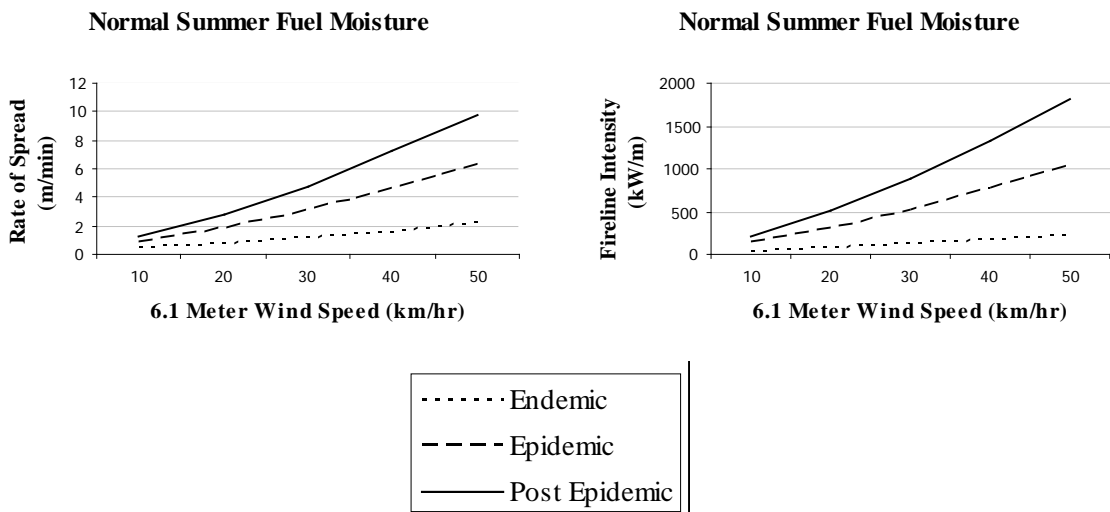
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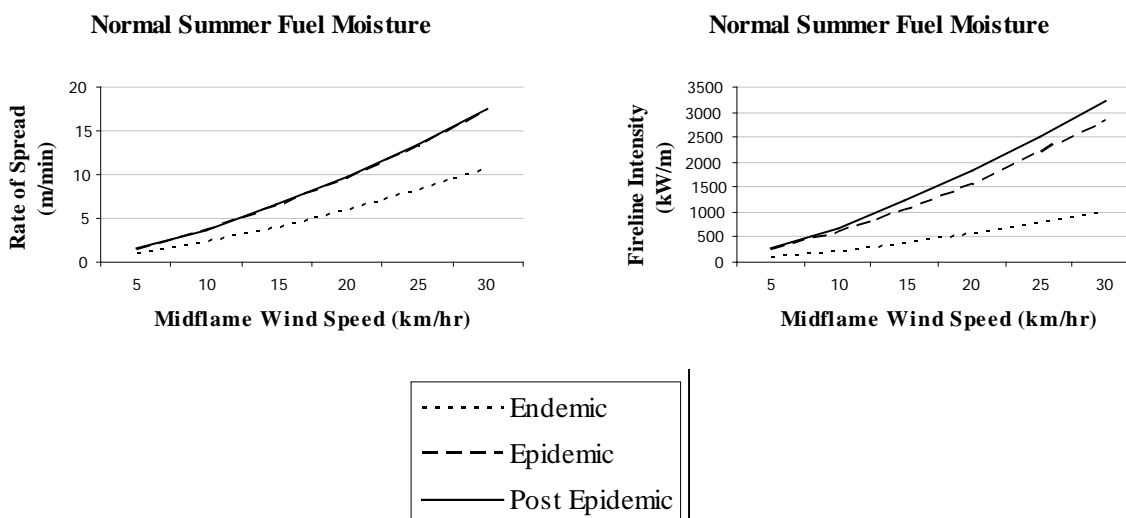
Figure 1. Fire behavior variables under normal summer fuel moisture conditions. Areas of endemic, epidemic and post epidemic beetle activity are compared to each other. Wind adjustment factors were 0.2 for endemic situations, 0.3 for epidemic, and 0.4 for post-epidemic situations to obtain midflame wind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



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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.



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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

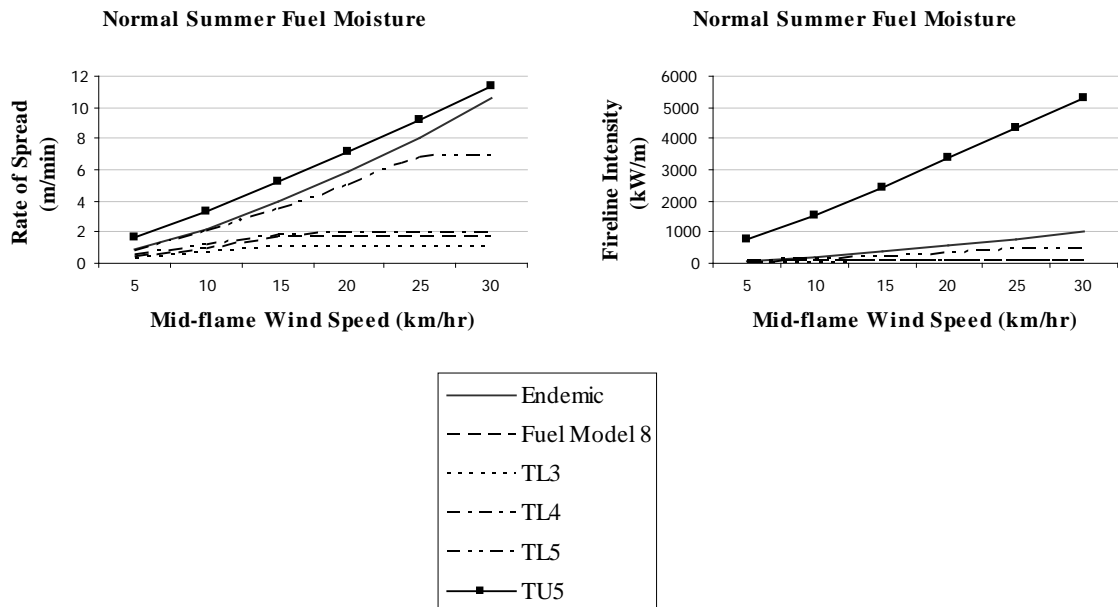
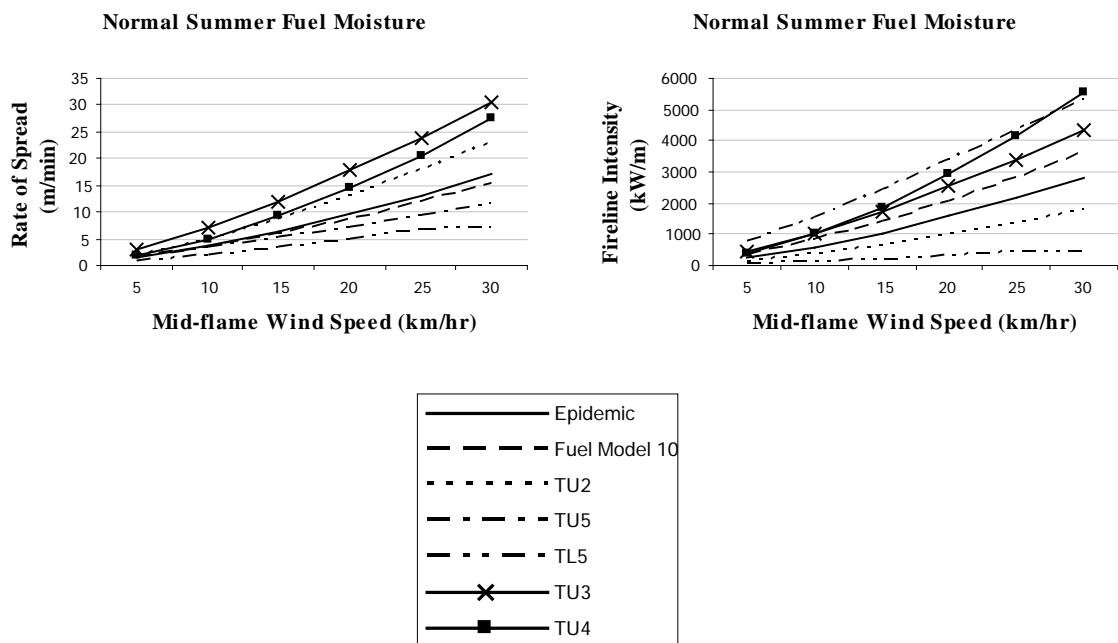
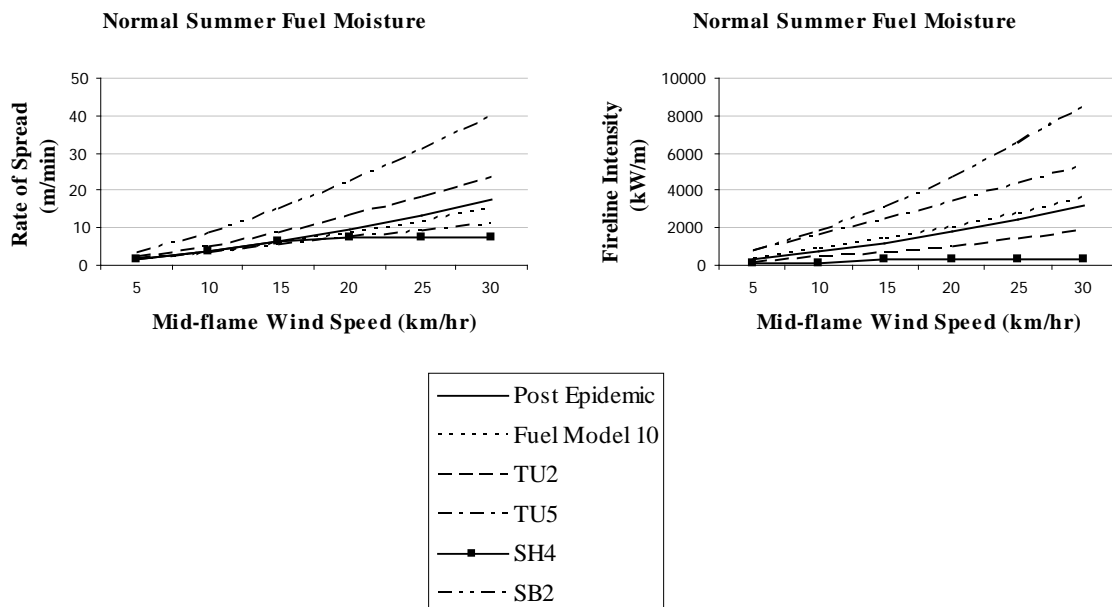


Figure 4. Rates of spread and fire line intensity comparisons for epidemic areas of beetle activity compared to established fuel models. Fire behavior variables are calculated with the same midflame windspeeds and under normal shaded fuel moisture conditions



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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



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