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The Effects of Spruce Beetle (Coleoptera: Curculionidae: Scolytinae) on Fuels and Fire in Intermountain Spruce-Fir Forests

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THE EFFECTS OF SPRUCE BEETLE (COLEOPTERA: CURCULIONIDAE:

SCOLYTINAE) ON FUELS AND FIRE IN INTERMOUNTAIN

SPRUCE-FIR FORESTS

by

Carl Arik Jorgensen

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ABSTRACT

The Effects of Spruce Beetle (Coleoptera: Curculionidae:

Scolytinae) on Fuels and Fire in Intermountain

Spruce-Fir Forests

by

Carl Arik Jorgensen, Master of Science

Utah State University, 2010

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In spruce-fir forests, there are many biotic and abiotic disturbances that can alter

stand structure and composition. Many of these disturbances can produce high

percentages of tree mortality at different scales. Spruce beetle has been considered a

devastating disturbance agent, capable of creating high levels of mortality that will alter

fuel complexes that may affect fire behavior. For comparison, stand data were gathered

in endemic (near Loa and Moab, UT), epidemic (near Loa and Fairview, UT), and post-

epidemic (near Salina and Loa, UT) condition classes of spruce beetle activity.

Generally, fine fuels were higher during the epidemic and returned to background levels

during post-epidemic conditions. Also, herbaceous and shrub components increase

following outbreak situations with an initial pulse of herbaceous material during

epidemics followed by the expansion of shrub material in post-epidemic areas. Fuel bed

bulk depth, large diameter woody material, sound and rotten, and duff did not

significantly differ between spruce beetle condition classes. Available live canopy

fuel, canopy bulk density, and canopy base height were significantly reduced from

endemic when compared to epidemic and post-epidemic condition classes. The fuel

complex alterations resulted in changes to calculated surface and crown fire behavior.

Crown base height decreased in post-epidemic classes, which allowed for easier crown

fire initiation. Due to large gaps in canopy continuity, no active crown fire was initiated.

In endemic situations, canopy bulk density was adequate to maintain active crown fire

runs, but crown base height was too high to initiate crown fire. Surface fire, estimated

from the custom fuel models following fuel complex alterations, showed that fireline

intensity and rates of spread were greater in post-epidemic areas, but mostly due to

reduced overstory sheltering. When custom fuel models were compared with similar

mid-flame wind speeds, epidemic and post-epidemic fire behavior predictions were

similar, indicating that reduced sheltering was more dominant than the influence of the

fuels complex or solar radiation. When custom fuel models were compared with

established fuel models, none predicted the same fire behavior outputs.

(109 pages)

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<div align="right">C. Arik Jorgensen</div>

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INTRODUCTION AND LITERATURE REVIEW

Introduction

The two most important agents of disturbance that drive vegetation dynamics in
Intermountain spruce-fir forests are fire and spruce beetle, *Dendroctonus rufipennis*
Kirby (Coleoptera: Curculionidae: Scolytinae) (Alexander 1987, Baker and Veblen
1990, Jenkins et al. 1998, Peet 2000, Schulz 2003). Fire has an important role in the
establishment of stands (Veblen et al. 1994, Jenkins et al. 1998, Arno 2000). The high-
intensity fires that occur in spruce-fir forests expose mineral soil and create seedbeds
conducive to the germination and growth of spruce and fir seedlings (Taylor and Fonda
1990, Johnson 1992, Arno 2000, Peet 2000, Johnson et al. 2001, Sibold et al. 2006). In
the long period of time between stand replacing fires, spruce beetle outbreaks typically
drive stand dynamics (Schmid and Hinds 1974, Alexander 1987, Baker and Veblen 1990,
Jenkins et al. 1998, McCullough et al. 1998, Parrish et al. 1999, Derose and Long 2007).

Endemic spruce beetle populations typically infest recently fallen host material
and kill weakened trees to account for the majority of annual spruce beetle-induced tree
mortality (Schmid and Frye 1977). Spruce beetle outbreaks can result in large amounts
of tree mortality over extensive areas in relatively short periods of time (Massey and
Wygant 1954, Schmid and Frye 1977, Dymerski et al. 2001, Keyes et al. 2003, Matthews
et al. 2005, Derose and Long 2007). A large concern with widespread outbreaks is that
the resulting tree mortality contributes to increases in fuel loads and consequently
increased potential for extreme fire behavior (Schmid and Frye 1977, Baker and Veblen

1990, Schulz 2003, DeRose and Long 2007, DeRose and Long 2009). Wildfire intensity, rate of spread, severity, and occurrence have been thought to increase because of spruce beetle-induced tree mortality (Hopkins 1909, Massey and Wygant 1954, Schmid and Frye 1977, Schulz 2003). However, associations between spruce beetle-induced tree mortality fuels and fire are not well understood (Jenkins et al. 2008).

For example, fuels monitoring research following spruce beetle outbreaks in white spruce (*Picea glauca* [Moench] Voss), Sitka spruce (*Picea sitchensis [Bong] Carr.),* and Lutz spruce (*Picea x lutzii Little)* forests in Alaska, in addition to Engelmann spruce forests in Northwestern Colorado suggests that large amounts of downed woody debris often accumulate following spruce beetle outbreaks (Cahill 1977, Schulz 2003). In spite of increased amounts of downed woody debris however, severe fires have only occurred in spruce-beetle affected areas during drought years when fuel moistures are low, and where forest structure and composition had a greater impact on fire severity than spruce beetle-caused tree mortality (Bigler et al. 2005). Although DeRose and Long (2009) suggested that post-outbreak stand conditions can greatly influence crown fire potential, Bebi et al. (2003) observed no increase in natural fire density following the 1940's spruce beetle outbreak in Colorado.

The objectives of this study are to:

1) Characterize and determine how fuels complexes between stands with endemic populations of spruce beetle, stands experiencing current outbreaks and stands with older spruce beetle-induced tree mortality differ with one-way ANOVA.

2) Create custom fuel models to estimate fire behavior in stands with endemic, epidemic, and post-epidemic spruce beetle populations to determine if differences in associated fuel complexes affect subsequent fire behavior.

3) Compare our custom fuel models to existing fuel models currently used for fire planning and suppression activities.

By quantifying and comparing fuel complex changes with subsequent model predicted changes in fire behavior resulting from spruce beetle-induced tree mortality, we can address the effects of spruce beetle activity on fuel accumulation and fire behavior in Intermountain spruce-fir forests. Land managers, researchers, and fire planners will be able to use this information to better assess spruce beetle-induced tree mortality and the fuels complex associated with this mortality in addition to predicting fire behavior resulting from the altered fuel complexes.

Literature Review

Spruce-fir Forests

Engelmann spruce (*Picea engelmannii* Parry ex. Engelm) and subalpine fir (*Abies lasiocarpa* var *latifolia*) forests comprise a major vegetative cover type in the Intermountain subalpine zone of North America. Elevations for these tree species typically range between 2500m to 3100m above sea level, depending on latitude, available moisture and temperature (Peet 1981, Long 1994). These trees occupy sites with average precipitation above 61 cm a year and are most often associated with moist sites (Alexander 1987, Peet 2000). In western North America, Engelmann spruce and subalpine fir forests extend as far south as Arizona (Oosting and Reid 1952), encompassing nine states and two Canadian provinces (Fowells 1965). These trees also comprise a major component of what is commonly known as timberline forest (Fowells 1965, Peet 1981, Long 1994). These forests are considered a southern extension/modification of northern boreal forests due to their floristics and structure (Peet 2000).

Forest composition is remarkably consistent throughout the Rocky Mountains (Peet 2000). In the Intermountain region, Engelmann spruce is most commonly intermixed with subalpine fir, although pure stands of each species can be found (Alexander 1980, Alexander 1987, Peet 2000). Other common tree associates are lodgepole pine (*Pinus contorta* Dougl. ex. Loud), quaking aspen (*Populus tremuloides* Michx), interior Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), blue spruce (*Picea*

pungens Engelm.), limber pine (*Pinus flexillas* James), and whitebark pine (*Pinus albicaulis* Engelm.) (Fowells 1965, Peet 1981, Bradley et al. 1992).

Undergrowth is often sparse in climax spruce-fir stands while seral stands are often rich in herbaceous growth (Yeager and Riordan 1953, Bradley et al. 1992). Common shrub components of seral stands can consist of *Vaccinium* spp., *Ribes* spp., buffaloberry (*Shepherdia* spp.), serviceberry (*Amelenchier* spp.), and elderberry (*Sambucus* spp.) intermixed with herbaceous components such as monkshood (*Aconitum columbianum)*, blue bells (*Mertensia* spp.), and arnica(*Arnica* spp.) (Fowells 1965, Youngblood and Mauk 1985, Peet 2000).

Site differences and disturbance histories often affect stand structures and development patterns in spruce-fir forests making them difficult to characterize (Rebertus et al. 1992, Peet 2000). Descriptions of stand structure and development of various spruce-fir forests in the Western United States are given by Oliver (1981), Alexander (1987), Aplet et al. (1988), Rebertus et al. (1992), Long (1994), and Jenkins et al. (1998). The ratios of spruce and fir dominance through the stages of stand development often vary (Aplet et al. 1988). Engelmann spruce and subalpine fir can be pioneering species when adequate regeneration requirements are met (Peet 1981, Aplet et al. 1988, Jenkins et al. 1998). However, their shade tolerance allows them to more typically exist as climax communities that succeed seral species in the absence of stand replacing disturbance (Oosting and Reid 1952, Fowells 1965, Alexander 1987, Veblen et al 1989, Jenkins et al. 1998). Although mature stands contain both species, the greater longevity of Engelmann spruce often counters the proliferation of subalpine fir, and allows Engelmann spruce to dominate the overstory and older age classes of trees. In contrast,

the shorter lived subalpine fir comprises the majority of the understory regeneration (Oosting and Reid 1952, Veblen 1986b).

The recruitment of understory cohorts can be variable and is often characterized by cycles of suppression and release (Veblen 1986b, Lertzman and Krebs 1991, DeRose and Long 2007). Release occurs with small scale disturbances such as when individual trees succumb to endemic levels of insects and diseases as stands age (Oosting and Reid 1952, Veblen 1986b, Aplet et al. 1988). Other examples of small scale disturbances include surface fires, lightning strikes, and avalanches (Schmid and Frye 1977, Oliver 1981, Aplet et al. 1988, Veblen et al. 1989, Veblen et al. 1991a, Sibold et al. 2006, Hebertson and Jenkins 2007). These disturbances create gaps in the overstory allowing for the continual recruitment of both species into the main canopy (Veblen 1986b). This variable recruitment explains why trees of similar size may be significantly different in age (Veblen 1986a, Alexander 1987).

In addition, larger disturbances also affect establishment of spruce and fir regeneration (Aplet et al. 1988, Veblen et al. 1991a). Crown fire and spruce beetle, *Dendroctonus rufipennis* Kirby (Coleoptera: Curculionidae), are the two primary large scale disturbances in spruce-fir forests (Massey and Wygant 1954, Oliver 1981). Fire will promote the establishment of tree regeneration with exposure of mineral soil while spruce beetle will promote growth of advance regeneration through increased nutrient availability (Oliver 1981, Veblen et al. 1989, Veblen et al. 1991a, Veblen et al. 1991b). Regardless of the scale, both large and small disturbances ultimately result in the development of climax spruce-fir forests when combined with adequate regeneration characteristics (Aplet et al. 1988, Jenkins et al. 1998, DeRose and Long 2007).

Spruce Beetle

The spruce beetle is a significant biotic disturbance agent in mature Engelmann spruce-dominated forests between major stand replacing fire events (Massey and Wygant 1954, Schmid and Frye 1977, Alexander 1987, Baker and Veblen 1990, Jenkins et al. 1998). Small clusters of beetles attacking single trees generally account for the most annual tree mortality (Schmid and Frye 1977). The spruce beetle will infest most species of spruce in North America, but its main host in the Intermountain West is Engelmann spruce (Massey and Wygant 1954, Schmid and Frye 1977). Under epidemic levels; however, the spruce beetle has been documented to attack lodgepole pine and blue spruce (Massey and Wygant 1954, McCambridge and Knight 1972, Schmid and Frye 1977, Wood 1982, Pureswaran and Borden 2003).

Like other *Dendroctonus* spp., spruce beetles inhabit the inner bark of host material and feed in the phloem tissue. The outer bark serves to protect all life stages from adverse environmental conditions and predators (Wood 1982, Raffa et al. 1993). Once eggs hatch, spruce beetle larvae generally require more than one year to mature (Massey and Wygant 1954, Furniss and Carolin 1977). Spruce beetle larvae are also relatively cold-hardy and may require cold temperatures for reproductive diapause (Hansen et al. 2001b). Rates of larval maturation can be affected by the timing of dispersal, temperature of the phloem, and direct solar radiation on the bark surface (Rudinsky 1962, Werner and Holsten 1985, Hansen et al. 2001a). These factors can influence spruce beetle outbreak dynamics by increasing the likelihood of univoltine versus semi-voltine broods (Werner and Holsten 1985, Hansen et al. 2001a, Hebertson and Jenkins 2008).

Extensive colonization and larval feeding within the inner bark tissues disrupts the transport of water and nutrients throughout the host tree and can cause tree death (Furniss and Carolin 1977, Wood 1982, Nebeker et al. 1993, Raffa et al. 1993). During infestation, spruce beetles introduce fungi that also colonize these same tissues altering the host tree's physiology that assists in overcoming host tree defenses (Christiansen et al. 1987, Nebeker et al. 1993). The most common fungi associated with the spruce beetles are *Leptographium abiethum* (Peck) and many species of yeasts (Davidson 1955, Six and Bentz 2003).

Host trees respond to spruce beetle attack by producing copious amounts of oleoresin to pitch out colonizing beetles (Rudinsky 1962). Pitch tubes present on tree boles are usually the first indication of beetle attack (Schmid and Frye 1977, Nebeker et al. 1993). Trees also produce secondary defense compounds that inhibit maturation of spruce beetle brood (Raffa and Berryman 1987, Paine et al. 1997). Spruce beetle can easily overcome the defenses of weakened trees; however, the infestation of healthy trees requires large densities of attacking beetles (Raffa and Berryman 1983). These 'mass attacks' effectively deplete defensive compounds and thereby improve the host for brood development (Raffa and Berryman 1983). Female beetles also use host defensive compounds to synthesize aggregation pheromones that attract additional cohorts to the host tree, and thus facilitate mass attack (Raffa and Berryman 1983).

Endemic spruce beetle populations typically infest freshly fallen trees that no longer produce secondary defensive compounds (Massey and Wygant 1954, Schmid and Amman 1992, Veblen et al. 1994, Lieutier 2002). During winter months, snow cover also insulates the overwintering brood from lethally cold temperatures and protects them

from predation by woodpeckers and squirrels (Knight 1958, Knight 1961, McCambridge and Knight 1972, Frye et al. 1974, Schmid 1981, Werner and Holsten 1985). Spruce beetles colonize the shaded undersides of downed host material for brood production while *Ips* spp. attack sides exposed to sunshine (Massey and Wygant 1954, Schmid and Frye 1977 Holsten et al 1999, Hebertson and Jenkins 2007).

Occasionally spruce beetle also attack diseased, damaged and otherwise stressed trees (Schmid and Frye 1977, Hard 1985, Nebeker et al. 1993). Sharpe et al. (1986) lists that drought, nutrient deficiency, and competition for sunlight of varying intensities can affect tree physiology through increased or decreased osmotic adjustment. Increasing osmotic adjustment increases solutes and nutrients in plant tissues making a suitable diet for invading beetles and diseases (Sharpe et al. 1986, Raffa et al 1993). Moderate stress situations increases solutes in plant tissues, which compensate for unfavorable growing conditions by increasing turgor pressure (Sharpe et al. 1986). Under severe stress the tree's ability to defend itself is decreased (Sharpe et al. 1986). Drought has been documented to coincide with many spruce beetle outbreaks in the Intermountain West (Hebertson and Jenkins 2008).

Disturbances such as blowdown, logging or snow avalanches that increase the amount of fresh host material can contribute to build-up of spruce beetle populations and the initiation of epidemics (Schmid and Frye 1977, Christiansen et al. 1987, Veblen et al. 1989, Long 1994, Jenkins et al. 1998, Wallen and Raffa 2004, Hebertson and Jenkins 2007). Historical records support the occurrence extensive spruce beetle disturbances during the late 1800's, 1940's, and late 1980's through the late 1990's (Miller 1970, Baker and Veblen 1990, Rebertus et al. 1992, Hebertson and Jenkins 2008).

Because endemic populations generally invade downed material and then shift to attacking stressed and finally healthy trees, outbreak dynamics suggest population expansion is a function of the depletion of "easy" food resources rather than an adaptation that enables them to attack healthy standing trees (Wallen and Raffa 2004). If beetle population dynamics during epidemics were adaptive then all three food resources would be simultaneously at risk for attack (Raffa 1988, Wallen and Raffa 2004).

Dense stands largely comprised of Engelmann spruce with mean diameters exceeding 40.6 cm diameter breast height (dbh) and growing on well-drained sites are most conducive to spruce beetle population expansion (Massey and Wygant 1954, Schmid and Hinds 1974, Schmid and Frye 1976). During the long interval between stand replacing fires, spruce beetle outbreaks play an important role in spruce-fir stand dynamics (Parrish et al. 1999). Removal of the mature spruce component shifts stand composition and structure to subalpine fir and younger age classes of trees, respectively (Schmid and Frye 1977, Veblen et al. 1991b, Jenkins et al. 1998). Depending on the extent and severity of tree mortality in the affected stands, domination by spruce may not return for hundreds of years (Schmid and Frye 1977, DeRose and Long 2007).

Following spruce beetle outbreaks, mature subalpine fir and dead spruce tend to dominate the canopy while suppressed trees of both species are released as the availability of nutrients and solar radiation increases (Miller 1970, Stocks 1987, Veblen et al. 1991b, Holsten et al. 1995). Subalpine fir dominance in a spruce-fir stand is a good indicator of past spruce beetle disturbance whereas the presence of lodgepole pine is more indicative of a past fire disturbance (Veblen et al. 1991b) As subalpine fir begin to

die and fall, they create canopy gaps and expose mineral soil that allow for the

establishment of spruce regeneration (Aplet et al. 1988).

Additional changes resulting from wide spread spruce beetle activity and

subsequent tree mortality include alterations and fluctuations concerning annual

watershed flows, timber productivity, maintenance of critical wildlife habitat, aesthetic

values, and recreational resources (Mitchell and Love 1973, Amman et al. 1977, Schmid

and Frye 1977, McGregor and Cole 1985, Holsten et al. 1999, Samman and Logan 2000).

Following spruce beetle outbreaks, the variability of other vegetation types including

shrubs and herbaceous species also increases across the landscape (Allen et al. 2006).

Spruce-Fir Forests – Fire and Fuels

Fire is largely responsible for stand establishment in Intermountain spruce-fir

forests (Long 1994, Jenkins et al. 1998, Peet 2000). However, the occurrence of high

intensity fires is often rare in the subalpine zone due to infrequent extreme burning

conditions (Long 1994). Higher elevation forests receive higher precipitation and are

characterized by cooler temperatures (Johnson 1979). Although relatively uncommon,

dry conditions combined with high numbers of lightning strikes can cause the ignition of

small fires every summer (Romme and Despain 1989, Nash and Johnson 1996).

Due to these infrequent burning conditions, fire return intervals for subalpine

areas have been reported to occur between every 50 to 130 years in the northern Rockies

and up to greater than 200 years in northwestern Colorado (Arno 1980, Veblen et al.

1994). Romme (1982) concluded that 300 plus years could elapse between major crown

fire disturbances in the subalpine Yellowstone area. Anthropomorphic influences can

greatly influence fire frequency and return intervals through increased ignitions and suppression at different periods of history in sub-alpine spruce-fir forests (Wadleigh and Jenkins 1996).

In addition to weather, fuels and topography are vital in the fire environment for sustained combustion (Knight 1987, Turner and Romme 1994, Pyne et al. 1996). Spatial arrangement, moisture content and types of fuel present will affect fire intensity and rate of spread on the landscape (Byram 1959a, Rothermel and Anderson 1966, Turner and Romme 1994, McCullough et al. 1998, Arno 2000). These same fire behavior characteristics are also affected by stand productivity which is positively correlated with the accumulation of biomass on the site (Brown and See 1981). In spruce-fir forests, large amounts of surface and ladder fuels, low crown base heights and small needles, in addition to dead and lichen covered branches promote stand replacing crown fire with high levels of tree mortality and fuel consumption (Bloomberg 1950, Taylor and Fonda 1990, Johnson 1992, Long 1994, Arno 2000). Very small amounts of acreages burned in subalpine forests are strictly influenced by surface fire alone (Sibold et al. 2006).

Types of Fuels and Their Effect on Fire Behavior

Ground fuels - Wildland fires are generally characterized by the fuel layers consumed. Layers include ground, surface, and crown fuels (Johnson 1992). Ground fuels consist of duff, organic soils, roots, and rotten woody debris (Rothermel 1983, Scott and Reinhardt 2001). Although ground fuels account for large amounts of total available fuel for consumption, they do not significantly contribute to fire spread (Van Wagner 1972). The transition from glowing combustion within the ground fuels to flaming

combustion in surface fuels can occur under dry windy conditions (Van Wagner 1972, Anderson 1974, Romme 1982, Schulz 2003).

Surface fuels - Surface fuels consist of needles, leaves, grass, downed woody debris, shrubs low brush and short trees (Brown et al. 1982). Dead woody fuels are inventoried in size classifications of 1 hour (0.0-.64cm), 10 hour (.64-2.54cm), 100 hour (2.54-7.62cm) and 1000 hour (>7.62cm) in a planar intercept method (Brown 1974). These are the standard time lag fuel size classes reflecting the approximate amount of time it takes for the moisture content in woody fuel particles to equilibrate with atmospheric and environmental moisture conditions (Brown 1970, Fosberg 1970, Brown et al. 1982). Total surface fuel loads not only incorporate the standard time lag fuels but also shrub and herbaceous biomass, the depth of ground fuels and the overall fuel bed (Brown 1976, Brown et al. 1982).

Surface fire behavior models depend on the parameterization and quantification of the fuel load for accurate estimates of fire behavior. The fire effects monitoring and inventory protocol (FIREMON, version 2.1.1) (Lutes et al. 2006) computes weight for downed woody debris following the techniques outlined by Brown (1974), Brown et al. (1982) and vegetation based on summarized bulk densities from a variety of applicable publications based on percent cover and height (Duncan Lutes, pers. comm., US Forest Service, Nov. 6, 2006) in (Page and Jenkins 2007a). Shrub weights can also be calculated based on shrub species basal area (Brown 1976). Surface fuel parameters can be designated by weight per unit area and input into Rothermel's (1972) surface fire spread equation, which is the basis for most current surface fire behavior models (Finney 1998, Andrews et al. 2003, Reinhardt et al. 2003).

Downed woody fuel particle size and density are the most critical factors determining fire spread and intensity in surface fuels (Graham et al. 2004). This is largely because high surface-to-volume ratios increase the rate at which moisture and heat are exchanged within the fuel (Edmonds et al. 2000). Small diameter fuels have the greatest effect on surface fire rate of spread but are generally compact and decompose quickly (Romme 1982, Pyne et al. 1996, Swetnam and Baisan 1996).

Larger woody fuels have a negligible effect on surface fire spread although they can burn vigorously with high levels of intensity for long periods of time (Rothermel 1972, Albini and Reinhardt 1995). The presence of these heavy fuels and downed logs combined with steep slopes can increase surface fire intensity and the probability of an active crown fire when sufficient canopy fuels exist (Byram 1959b, Rothermel 1991). Fire spread through both fine and large woody fuels is also influenced by the depth, continuity and chemistry of the fuel bed (Graham et al. 2004).

When discussing any fire behavior, it is important to remember the influence of fuel moisture. Fuel moisture can affect overall energy released by burning fuel components and increase the required energy absorbed to heat fuel components to combustion (Rothermel and Anderson 1966, Rothermel 1983). Living and dead fuel mixtures do not always behave in the same manner regarding overall moisture absorption, retention and depletion (Schroeder and Buck 1970). The heat capacity of dry plant material is estimated to be only one-third that of water, lowering ignition temperatures in dead fuels (Van Wagner 1977). Under seasonal drying weather conditions when both mature live and dead fuels are mixed, flammability may become severe or extreme, which can be compounded by drought (Schroeder and Buck 1970,

Brown and See 1981). In non-drought years, fire has been limited and extinguished by

high humidity observed on north slopes, high elevations, and diurnally with fuel moisture

recovery (Rothermel 1983, Rothermel 1991). Consequently, sufficient fuel moisture in

living material can produce adequate water vapor to inhibit ignition (Fons 1946).

Rothermel (1983) discussed that live fuel moisture, an expression of the amount of water

in a fuel (50-300 percent), reaching as low as 100 percent can contribute to fire spread;

keeping in mind that Agee et al. (2002) discusses mitigation of fire behavior by live

shrubs (125 percent) in late season subalpine areas of the Pacific Northwest.

   Canopy fuels and crown fire – Canopy fuels most commonly consist of live

foliage although crown fires have been shown to consume combinations of all needles as

well as needles and some branch material (Rothermel 1991, Call and Albini 1997, Cruz et

al. 2003). Approximately 65% of branch-wood less than 0.64 cm can completely be

consumed at 100% fuel moisture content within crown fires contributing to energy

release (Call and Albini 1997). An often overlooked component of the canopy fuels

complex in coniferous forest systems is the canopy volatiles. Volatiles in foliage can

greatly influence combustion in tree canopies (Susot 1980). Extractives may yield

flammable materials at lower temperatures that may ignite at lower temperatures than the

pyrolysis of plant cellulose materials (Van Wagner 1977). Exactly how extractives

influence fire behavior is difficult to measure and is different in every burning

environment and tree species (Van Wagner 1977, Susot 1980).

   Overall, canopy fuels can be parameterized by available canopy fuel load, canopy

bulk density and canopy base height (Cruz et al. 2003). Available canopy fuels consist of

live and dead foliage, lichens, moss, and small diameter live and dead branch wood,

which have a higher moisture content and lower bulk density than surface fuels (Scott and Reinhardt 2001). Canopy bulk density is the mass of available canopy fuel per unit of canopy volume (Scott and Reinhardt 2001). Canopy base height is the lowest portion of canopy fuel sufficient to propagate fire vertically into the tree crowns from surface fire (Scott and Reinhardt 2001). The best way to calculate these fuels is by applying actual foliage biomass equations to current inventoried stand structures, but methods have been developed to create these parameters from stand density estimates (Cruz et al. 2003).

The probability of crown fire initiation is often dependant on the height of the crown base, the intensity of the surface fire, continuity of fuel from surface to crown strata, wind and foliar moisture content of canopy fuels (Anderson 1974, Van Wagner 1977, Romme 1982, Scott and Reinhardt 2001, Schoennagal et al. 2004). Foliar moisture content is less influential on crown fire initiation than crown base height (Van Wagner 1977). Foliar moisture also affects the heat required for surface fires to ignite canopy fuels (Scott and Reinhardt 2001). Higher amounts of foliar moisture appear to be maintained in the current year's growth and upper tree crown which then decreases as new foliage ages and as canopy fuels are arranged down the tree bole towards the ground, respectively (Brown 1978, Agee et al. 2002).

Crown fire behavior and pattern is a function of time and landscape structure often reflected by combinations of wind, topography, climatic factors, relative humidity and vegetation biomass (Rothermel 1991, Turner and Romme 1994). Crown fire's high spread rates and resistance to control can lead to burning of large acreage and significant adverse effects to natural resources as well as residential and recreation development (Scott and Reinhardt 2001). A high rate of spread is usually accomplished by increased

radiant heat transfer, wind, short range spotting, high canopy bulk density and low foliar

moisture content (Van Wagner 1977, Scott and Reinhardt 2001). Continued spread will

occur until all of the readily available canopy fuels are consumed, or a lack of wind stalls

the forward heat transfer (Van Wagner 1993). Crown fire spread can be limited by

reducing available canopy fuels and canopy bulk density (Graham et al. 2004).

Passive, active and independent crown fires are the three different types of crown

fires discussed by Van Wagner (1977). Passive crown fire is a partial/intermittent

crowning or transition state between surface fire to active crown fire based on available

fuel in the canopy and intensity of the surface fire (Van Wagner 1993). No solid flame is

maintained in the canopy but individuals or small groups of trees will torch (Scott and

Reinhardt 2001). Active crown fire consistently consumes canopy fuels and is a

combination of surface and canopy combustion of the entire fuel complex (Scott and

Reinhardt 2001). Active crown fires depend on surface fire intensity, crown fire

initiation as well as continuous canopy bulk density in large enough quantities to promote

continued spread of the crown fire (Van Wagner 1977, Johnson 1992). Independent

crown fires, although probable but not common, may spread without influence from the

surface fire, often requiring combinations of high wind, steep slopes and low foliar

moisture content (Scott and Reinhardt 2001).

Rothermel (1991) distinguished between two types of intense wildland fire

scenarios, plume-dominated and wind driven active crown fires. Plume-dominated

crown fires are a sign of growing intensity where total energy output of the crown fire is

critical for building convection and increasing the size of the fire rather than relying on

the effects of wind to increase overall fire size (Byram 1959b). Wind-driven crown fires

occur when the wind increases and drives the crown fire overall rate of spread

(Rothermel 1991).

Other factors affecting fire behavior in spruce-fir forests – Regardless of the

kinds of fuels present, the natural structure of spruce-fir forests make them prone to high-

intensity fires (Johnson 1992, Taylor and Fonda 1990, Arno 2000, Peet 2000, Johnson et

al. 2001, Sibold et al. 2006). Stand replacing fires are also restricted to certain landscape

vegetation patterns, burning conditions, and topography. They tend to coincide only

every few hundred of years depending on the chance and sporadic occurrence of drought,

ignition and high winds (Arno 2000). Local weather patterns and long-term drought are

important factors to consider when predicting current and potential fire behavior in

subalpine spruce-fir forests as was previously discussed (Bigler et al. 2005).

For example, the 1988 Yellowstone fires were a product of a fuels complex that

had evolved to late successional stands following fires in the late 1700's that were similar

in size to the 1988 fires (Romme and Despain 1989). However, the extreme fire behavior

of the 1988 Yellowstone fires was driven by drought and high wind events coupled with

stand conditions that had existed since the 1930's (Romme and Despain 1989).

Reconstruction of historical fire events have shown that extreme fire weather

(high winds, high temperature, drought, and decreasing humidity) is generally a more

important factor in controlling fire rate of spread and intensity, with fuels playing a minor

role (Fryer and Johnson 1988, Romme and Despain 1989). Extreme fire conditions will

dictate fire behavior regardless of landscape pattern or fuel accumulation and are vital to

sustain crown fire development (Turner and Romme 1994, Bessie and Johnson 1995).

While under low to moderate fire conditions, spatial arrangement of fuel patches can

affect fire spread at the landscape level (Turner and Romme 1994). Under moderate and low risk weather conditions for fire, surface fuel loads have greater impact on crown fire initiation than crown fire spread (Bessie and Johnson 1995). Weather factors, specifically wind speed and relative humidity, were more influential than fuels in analyzed surface fire intensities (Bessie and Johnson 1995).

Spruce Beetle – Fuel – Fire Interactions

Intuitively, fire occurrence, behavior and effects would seem to increase following spruce beetle outbreaks (Hopkins 1909). However, there are few historical records that suggest spruce beetle activity increases the susceptibility of subalpine forests to natural fires (Schmid and Hinds 1974, Baker and Veblen 1990). Tree mortality associated with insect outbreaks may contribute to the fuel load requirements necessary to support fire (Arno 2000). For example, significant increases in various surface fuel components in white spruce (*Picea glauca* (Moench) Voss) and Engelmann spruce dominated stands resulting from spruce beetle-induced tree mortality have occurred in the past (Cahill 1977, Schulz 2003). In addition, observed surface fuels alterations created by other insect species such as the spruce budworm (*Choristoneura fumiferana* (Clemens)) (Stocks 1987) and mountain pine beetle (*Dendroctonus ponderosae* Hopkins) (Page and Jenkins 2007b) have also had effects on fire behavior.

Following spruce beetle outbreaks, increases in needles and small twigs that fall from the canopy create surface fuels that support ignition and form a continuous ignitable fuel layer necessary for fire spread (Rothermel 1972, Knight 1987). In spite of this, the frequency of lightning caused fires following spruce beetle outbreaks have not been

shown to increase (Bebi et al. 2003). Standing dead trees in spruce beetle killed forests

can exist for long periods of time (Mielke 1950). It is also assumed that the falling dead

trees and other woody debris create a large fuel build up of downed woody fuels over

time; however, the fire danger associated with these conditions may be exaggerated

(Schmid and Hinds 1974, Kulakowski et al. 2003). Even when long standing snags are

considered as potential lightning rods, following precipitation usually reduces fire

probability by boosting the foliar moisture of an already mesic understory regardless of

the amounts of dead fuel (Schmid and Hinds 1974, Kulakowski et al. 2003). Extreme fire

rate of spread and intensity increases in stands altered by spruce beetle activity due to

advanced regeneration promoting active crown fire initiation (DeRose and Long 2009).

Overstory removal may change microclimatic conditions leading to less shade,

drier conditions, and more herbaceous material (Schulz 2003). Stocks (1987) noted that

fire intensity increased following a spruce budworm outbreak due to increases in fine

fuels resulting from canopy mortality. Herbaceous and shrub components on the forest

floor have been documented to increase following spruce beetle outbreaks , but had a

dampening effects on experimental fires (Yeager and Riordan 1953, Schmid and Hinds

1974, Stocks 1987). An increase in understory plants can increase fuel loads, but if high

fuel moisture can be maintained, then it will hamper fire spread and intensity while

shortening the fire season with high moistures lasting conceptually into October

(Rothermel 1983, Agee et al. 2002). The removal of overstory shelter will often account

for higher wind speeds at the ground surface and increase surface fire intensity and rates

of spread (Albini and Baughman 1979, Rothermel 1983, Page and Jenkins 2007b).

Increased solar radiation contacting fuels because of the lack of overstory raises fuel

temperature and is associated with increased fire intensity and rates of spread (Byram and

Jemison 1943, Rothermel 1983).

Insect and fire interactions may affect many aspects of forest structure and overall

productivity in subalpine forests, but are poorly understood (McCullough et al. 1998,

Jenkins et al. 2008). Landscape structure in addition to real time fire weather, drought,

and point of ignition are more influential than pre-fire conditions of spruce beetle-

induced tree mortality on fire extent (Bigler et al. 2005, Kulakowski and Veblen 2007).

During long fire-free periods, spruce beetle outbreaks and wind events promote younger

forests that further limit outbreak potential and fire behavior (Veblen et al. 1994, Parrish

et al. 1999). This suggests that past disturbances can influence present disturbance

interactions and resulting vegetative patterns across the landscape (McCambridge and

Knight 1972, Despain and Sellers 1977, Schmid and Amman 1992, Kulakowski et al.

2003, Jenkins et al. 2008).

Literature Cited

Agee, J.K., C.B. Wright, N. Williamson and M.H. Huff. 2002. Foliar moisture content of Pacific Northwest vegetation and its relation to wildland fire behavior. For. Ecol. Manage. 167:57–66. 10 p.

Albini, F.A., and E.D. Reinhardt. 1995. Modeling ignition and burning rate of large woody natural fuels Int. J. Wild. Fire 5:81-91.

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

Allen, J.L. S. Wesser, C.J. Markon, and K.C. Winterberger. 2006. Stand and landscape level effects of a major outbreak of spruce beetles on forest vegetation in the Copper River Basin, Alaska. For. Ecol. Manage. 227: 257–266.

Alexander, R.R. 1980. Engelmann spruce-subalpine fir. P. 206 in *Forest cover types of the United States and Canada*, Eyre, F.A., (ed). Society of American Foresters, Washington, DC

Alexander, R.R. 1987. *Ecology, silviculture and management of the Engelmann spruce-subalpine fir type in the central and southern Rocky Mountains*. US For. Ser. Agr. Hand. 659. 144 p.

Amman, G.D., M.D. McGregor, D.B. Cahill, and W.H. Klein. 1977. *Guidelines for reducing losses of lodgepole pine to the mountain pine beetle in the Rocky Mountains*. US For. Serv. Gen. Tech. Rep. INT-36. 22 p.

Anderson, H.E. 1974. *Appraising forest fuels: A concept*. US For. Serv. Res. Note. INT – 187. 10 p

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

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

Arno, S.F. 1980. Forest fire history in the Northern Rockies. J. For. 78:460-465.

Arno, S.F. 2000. Fire in western forest ecosystems: effects of fire on flora. P. 97-120 in *Wildland fire in ecosystems*, Brown, J.K., and J. K. Smith (eds.). US For. Serv. Gen. Tech. Rep. RMRS-GTR-42-vol. 2. 257 p.

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

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

Bessie, W.C., and E.A. Johnson. 1995. The relative importance of fuels and weather on fire behavior in subalpine forests. Ecol. 76:747-762.

Bigler, C., D. Kulakowski, and T.T. Veblen. 2005. Multiple disturbance interactions and drought influence fire severity in Rocky Mountain subalpine forests. Ecol. 86:3018-3029

Bloomberg, W.J. 1950. Fire and spruce. For. Chon. 26:157-161

Bradley, A.F., N.V. Noste, and W.C. Fischer. 1992. *Fire ecology of forests and woodlands in Utah*. US For. Serv. Gen. Tech. Rep. INT-GTR-290. 92 p.

Brown, J.K. 1970. Ratios of surface area to volume for common fine fuels. For. Sci. 16:101-105.

Brown, J.K. 1974. *Handbook for inventorying downed woody material*. US For. Serv. Gen. Tech. Rep. INT-GTR-16. 24 p.

Brown, J.K. 1976. Estimating shrub biomass from basal stem diameters. Can J. For. Res. 6:153-158.

Brown, J.K. 1978. *Weight and density of crowns of Rocky Mountain conifers*. US. For. Serv. Res. Pap. INT-197. 56 p.

Brown, J.K., and T.E. See. 1981. *Downed dead woody fuel and biomass in the Northern Rocky Mountains*. US For. Serv. Gen Tech. Rep. INT-GTR-117. 48 p.

Brown, J.K., R.D. Overheu, and C.M. Johnston. 1982. *Handbook for inventorying surface fuels and biomass in the interior West*. US For. Serv. Gen. Tech. Rep. INT-GTR-129. 48 p.

Byram, G.M. 1959a. Combustion of forest fuels. P. 61-89 in *Forest fire: Control and use*, 2nd ed., Davis, K.P. (ed.). McGraw-Hill, New York, NY. 686 p.

Byram, G.M. 1959b. Forest fire behavior. P. 90-123 in *Forest fire: Control and use*, 2nd ed., Davis, K.P. (ed.). McGraw-Hill, New York, NY. 686 p.

Byram, G.M., and G.M. Jemison. 1943. Solar radiation and forest fuel moisture. J. Agric. Res. 38:639-640.

Cahill, D.B. 1977. *Net impact of spruce beetle outbreak on White River National Forest, 1939-1951*. US For. Serv., Rocky Mtn Res. Sta., Reg. Rep.

Call, P.T., and F.A. Albini. 1997. Aerial and surface fuel consumption in crown fires. Int. J. Wild. Fire 7:259-264.

Christiansen, E. R.H. Waring, and A.A. Berryman. 1987. Resistance of conifers to bark beetle attack-searching for general relationships. For. Ecol. Manage. 22:89-106.

Cruz, M.G., M.E. Alexander, and R.H. Wakimoto. 2003. Assessing canopy fuel stratum characteristics in crown fire prone fuel types of western North America. Int. J. Wild. Fire. 12:39-50.

Davidson, R.W. 1955. Wood-staining fungi associated with bark beetles in Engelmann spruce in Colorado. Mycologia 47:58-67.

DeRose, R.J., and J.N. Long. 2007. Disturbance, structure, and composition: Spruce beetle and Engelmann spruce forest on the Markagunt Plateau, Utah. For. Ecol. Manage. 244:16-23.

DeRose, R.J. and J.N. Long. 2009. Wildfire and spruce beetle outbreak: Simulation of interacting disturbances in the central Rocky Mountains. Ecosci. 16:28-38.

Despain, D.G. and R.E. Sellers. 1977. Natural fire in Yellowstone National Park. W. Wildlands 4:20-24

Dymerski, A.D., J.A. Anhold, and A.S. Munson. 2001. Spruce beetle (Dendroctonus rufipennis) outbreak in Engelmann spruce (Picea engelmannii) in central Utah, 1986-1998. West. Nor. Am. Nat. 61:19-24.

Edmonds, R.L., J.K. Agee, and R.I. Gara. 2000. *Forest health and protection*. McGraw Hill, New York, NY. 630 p.

Finney, M.A. 1998. *FARSITE: Fire Area Simulator-model development and evaluation*. US For. Serv. Res. Pap. RMRS-RP-4. 47 p.

Fons, W.L. 1946. Analysis of fire spread in light forest fuels. J. Agric. Res. 72:93-121.

Fosberg, M.A. 1970. Drying rates of heartwood below fiber saturation. For. Sci. 16:57-63.

Fowells, H.A. 1965. *Silvics of forest trees of the United States*. USDA Agric. Handb. 271. Washington, DC. 762 p.

Frye, R.H., H.W. Flake, C.J. Germain. 1974. Spruce beetle mortality resulting from record low temperatures in Arizona. Environ. Entomol. 3:752-754.

Fryer, G.I. and E.A. Johnson. 1988. Reconstructing fire behavior and effects in a subalpine forest. J. Appl. Ecol. 25:1063-1072.

Furniss, R.L. and V.M. Carolin. 1977. *Western Forest insects*. US For. Serv. Misc. Publ. No. 1339. Washington, DC. 654 p.

Graham, R.T., S.M. McCaffrey, and T.B. Jain. 2004. *Science basis for changing forest structure to modify wildfire behavior and severity*. US For. Serv. Gen. Tech. Rep. RMRS-GTR-120. 43p.

Hansen, E.M., B.J. Bentz, and D.L. Turner. 2001a. Temperature-based model for predicting univoltine brood proportions in spruce beetle (Coleoptera: Scolytidae). Can. Entomol. 133:827-841.

Hansen, E.M., B.J. Bentz, and D.L. Turner. 2001b. Physiological bsis for flexible voltinism in the spruce beetle (Coleoptera: Scolytidae). Can. Entomol. 133:805-817.

Hard, J.S. 1985. Spruce beetles attack slowly growing spruce. For. Sci. 31:839-850.

Hebertson, E.G., and M.J. Jenkins. 2007. The influence of fallen tree timing on spruce beetle brood production. West. Nor. Am. Nat. 67:452-460.

Hebertson, E.G., and M.J. Jenkins. 2008. Climate factors associated with historic spruce beetle (Coleoptera: Curculionidae) outbreaks in Utah and Colorado. Environ. Entomol. 37:281-292.

Holsten, E.H., R.A. Werner, and R.L. DeVelice. 1995. Effects of a spruce beetle (Coleoptera: Scolytidae) outbreak and fire on Lutz spruce in Alaska. Environ. Entomol. 24:1539-1547.

Holsten, E.H., R.W. Their, A.S. Munson and K.E. Gibson. 1999. The spruce beetle. Forest Insect and Disease Leaflet 127. US For. Serv. For. Insect and Disease Leaflet 127. Washington, DC. 12 p.

Hopkins, A.D. 1909. *Practical information on the Scolytid beetles of North American forests. I. Bark beetles of the Genus Dendroctonus*. US Bureau of Entomol. Bull. 83. U.S. Gov't Printing Office, Washington, DC. 169 p.

Jenkins, M.J., C.A. Dicus, and E.G. Hebertson. 1998. Post-fire succession and disturbance interactions on an intermountain subalpine spruce-fir forest. P. 219-229 in *Proceedings, Symposium: Fire in Ecosystem Management: Shifting the paradigm from suppression to prescription*, Pruden, T. L., and L. A. Brennan, (eds.). Tall Timbers Fire Ecology Conference Proceedings, No. 20. Tall Timbers Research Station, Tallahassee, FL. 460 p.

Jenkins, M.J., E. Hebertson, W. Page, and C.A. Jorgensen. 2008. Bark beetles, fuels, fires and implications for forest management in the Intermountain West. For. Ecol. Manage. 254:16-34.

Johnson, E.A. 1979. Fire recurrence in the subarctic and its implications for vegetation composition. Can. J. Bot. 57:1374-1379.

Johnson, E.A. 1992. *Fire and vegetation dynamics: studies from the North American boreal forests*. Cambridge University Press, Cambridge, United Kingdom. 129 p.

Johnson, E.A., K. Miyanishi, and S.R.J. Bridge. 2001. Wildfire regime in the Boreal forest and the idea of suppression and fuel buildup. Conserv. Bio. 15:1554-1557.

Keyes, C., P. Rogers, L. LaMadeleine, V. Applegate, and D. Atkins. 2003. Utah Forest Health Report: A Baseline Assessment 1999–2001. US For. Serv., RMRS/State of Utah, Dept. of Nat. Res., Salt Lake City, UT, 45 p.

Knight, D.H. 1987. Parasites, lightning, and the vegetation mosaic in wilderness landscapes. P. 59-83 in *Landscape heterogeneity and disturbance*, Turner, M.G. (ed.). Springer-Verlag, New York, NY. 239 p.

Knight, F.B. 1958. The effects of woodpeckers on populations on the Engelmann spruce beetle. J. of Econ. Entomol. 51:603-607.

Knight, F.B. 1961. Variations in the life history of the Engelmann spruce beetle. Annals of the Entomol. Soc. of Am. 54:209-214.

Kulakowski, D., T.T. Veblen, and P. Bebi. 2003. Effects of fire and spruce beetle outbreak legacies on the disturbance regime of a subalpine forest in Colorado. J. Biogeogr. 30:1445-1456.

Kulakowski, D., and T.T. Veblen. 2007. Effect of prior disturbance on the extent and severity of wildfire in Colorado subalpine forests. Ecol. 88:759-769.

Lertzman, K.P., and C.J. Krebs. 1991. Gap phase structure of a subalpine old-growth forest. Can. J. For. Res. 21:1730-1741

Lieutier, F. 2002. Mechanisms of resistance in conifers and bark beetle attack strategies. P. 31-78 in *Mechanisms and development of resistance in trees and insects*, Wagner, M.R., K.M. Clancy, F. Lieutier, and T.D. Paine (eds.). Kluwer Academic Publishers, The Netherlands. 332 p.

Long, J.N. 1994. The middle and Southern Rocky Mountain Region. Pages 335-386 in *Regional silviculture of the United States*, *3rd ed.*, Barrett, J.W. (ed.). John Wiley and Sons, New York, NY 643 p.

Lutes, D.C., R.E. Keane, J.F. Caratt. C.H. Key, N.C. Benson, S. Sutherland, and L.J. Gangi. 2006. *FIREMON: Fire effects monitoring and inventory system*. US. For. Serv. Gen. Tech Rep. RMRS-GTR-164-CD. 400 p.

Massey, C. L. and N. D. Wygant. 1954. *Biology and control of the Engelmann spruce beetle in Colorado*. USDA Cir. No. 944. Washington, DC. 35 p.

Matthews, K., V. DeBlander, L. Pederson, P. Mocettini, and D. Halsey. 2005. *Forest insect and disease conditions report 2002-2004*. US For. Serv. For. Health Prot. Rep. R4-OFO-TR-05-12. 59 p.

McCullough, D.G., R.A. Werner, and D. Neumann. 1998. Fire and insects in northern and boreal forest ecosystems of North America. Annu. Rev. of Entomol. 43:107-127.

McCambridge, W.F., and F.B. Knight. 1972. Factors affecting spruce beetles during a small outbreak. Ecol. 53:830-839.

McGregor, M.K., and D.M. Cole. 1985. *Integrating management strategies for the mountain pine beetle with multiple-resource management of lodgepole pine forests*. US For. Serv. Gen. Tech. Rep. INT-174. 68 p.

Mielke, J.L. 1950. Rate of deterioration of beetle-killed Engelmann spruce. J. For. 48:882-888.

Miller, P.C. 1970. Age distributions of spruce and fir in beetle-killed forests on the White River Plateau, Colorado. Am. Mid. Nat. 83:206-212.

Mitchell, M.E., and L.D. Love. 1973. *An evaluation of a study on the effects on streamflow of the killing of spruce and pine by the Englemann spruce beetle*. Arizona Forestry Notes No. 9, Northern Arizona School of Forestry, Flagstaff, AZ. 20 p.

Nash, C.H., and E.A. Johnson. 1996. Synoptic climatology of lightning-caused forest fires in subalpine and boreal forests. Can. J. For. Res. 26:1859-1874.

Nebeker, T.E., J.D. Hodges, and C.A. Blanche. 1993. Host response to bark beetle and pathogen colonization. P. 157-173 in *Beetle-pathogen interactions in conifer forests*, Schowalter, T.D., and G.M. Filip (eds.). Academic Press, New York, NY. 252 p.

Oliver, C.D. 1981. Forest development in North America following major disturbances. For. Ecol. Manage. 3:153-168.

Oosting, H.J., and J.F. Reed. 1952. Virgin spruce-fir forest in the Medicine Bow Mountains, Wyoming. Ecol. Monogr. 22:69-91.

Page, W.G., and M.J. Jenkins. 2007a. Mountain pine beetle induced changes to selected lodgepole pine fuel complexes within the Intermountain Region. For. Sci. 53:507-518.

Page, W.G., and M.J. Jenkins. 2007b. Predicted fire behavior in selected mountain pine beetle – infested lodgepole pine. For. Sci. 53:662-674.

Paine, T.D., K.F. Raffa, and T.C. Harrington. 1997. Interactions among scolytid bark beetles, and live host conifers. Annu. Rev.of Entomol. 42:179-206.

Parrish, R., J.A. Antos, and M.J. Fortin. 1999. Stand development in an old-growth subalpine forest in southern interior British Columbia. Can. J. For. Res. 29:1347-1356.

Peet, R.K. 1981. Forest vegetation of the Colorado Front Range, composition and dynamics. Vegetatio 45:3-75.

Peet, R.K. 2000. Forests and meadows of the Rocky Mountains. P. 75-121 in *North American terrestrial vegetation*, Barbour, M.G., and W.D Billings (eds.). Cambridge University Press, New York, NY. 708 p.

Pureswaran, D.S. and J.H. Borden. 2003. Test of semiochemical mediated host specificity in four species of tree killing bark beetles (Coleoptera: Scolytidae). Environ. Enotmol. 32:964-969.

Pyne, S.J., P.L. Andrews, and R.D. Laven. 1996. *Introduction to wildland fire, 2nd ed.*, John Wiley and Sons, New York, NY. 769 p.

Raffa, K.F. 1988. Host orientation behavior of *Dendroctonus ponderosae*: Integration of token stimuli and host defenses. P. 368-390 in *Mechanisms of woody plant resistance to insects: Search for pattern*, Mattson, W., J. Levieux, and C. Bernard-Dagan (eds.). Springer-Verlag, New York, NY. 416 p.

Raffa, K.F., and A.A. Berryman. 1983. The role of host plant resistance in the colonization behavior and ecology of bark beetles (Coleoptera:Scolytidae). Ecol. Monogr. 53:27-49

Raffa, K.F., and A.A. Berryman. 1987. Interactive selective pressures in conifer-bark beetle systems: A basis for reciprocal adaptations. Am. Nat. 129:234-262.

Raffa, K.F., T.W. Phillips and S.M. Salom. 1993. Strategies and mechanisms of host colonization by bark beetles. P. 103-128 in *Beetle-pathogen interactions in conifer forests*, Schowalter, T.D., and G.M. Filip (eds.). Academic Press, New York, NY. 252 p.

Rebertus, A.J, T.T. Veblen, L.M. Roovers, and J.N. Mast. 1992. Structure and dynamics of old-growth Engelmann spruce-subalpine fir in Colorado. P. 139-151 in *Old-growth forests in the Southwest and Rocky Mountain Regions, Proc. of a Workshop*, Kaufmann, M.R., W.H. Moir, and R.L. Bassett (tech. coord.). US For. Serv. Gen. Tech. Rep. RM-GTR-213. 201 p.

Reinhardt, E.D, N.L. Crookston, and S.A. Rebain. 2003. *The fire and fuels extension to the forest vegetation simulator*. US For Serv. Gen. Tech Rep. RMRS-GTR-116. 209 p.

Romme, W.H. 1982. Fire and landscape diversity in subalpine forests of Yellowstone National Park. Ecol. Monogr. 52:199-221.

Romme, W.H., and D.G. Despain. 1989. Historical perspective on the Yellowstone fires of 1988. Biosci. 39: 695-699.

Rothermel, R.C. 1972. *A mathematical model for predicting fire spread in wildland fuels*. US For.Serv. Res. Pap. INT-115. 40 p.

Rothermel, R.C. 1983. *How to predict the spread and intensity of forest and range fires*. US For. Serv. Gen. Tech. Rep. INT-GTR-143. 161 p.

Rothermel, R.C. 1991. *Predicting behavior and size of crown fires in the northern Rocky Mountains*. US For. Serv. Res. Pap. INT-438. 46 p.

Rothermel, R.C., and H.E. Anderson. 1966. *Fire spread characteristics determined in the laboratory*. US For. Serv. Res. Pap. INT-30, 34 p.

Rudinsky, J.A. 1962. Ecology of Scolytidae. Annu. Rev. of Entomol. 7:327-348.

Samman, S., and J. Logan. 2000. *Assessment and response to bark beetle outbreaks in the Rocky Mountain area*. US For. Serv. Gen. Tech. Rep. RMRS-GTR-62. 55 p.

Schmid, J.M. 1981. *Spruce beetles in blowdown*. US For. Serv. Res. Note RM-411. 6 p.

Schmid, J.M., and R.H. Frye. 1976. *Stand ratings for spruce beetles*. US For. Serv. Res. Note RM-309. 4 p.

Schmid, J.M., and R.H. Frye. 1977. *Spruce beetles in the Rockies*. US For. Serv. Gen. Tech. Rep. GTR RM-49. 38 p.

Schmid, J.M., and T.E. Hinds. 1974. *Development of spruce-fir stands following spruce beetle outbreaks*. US For. Serv. Res. Pap. RM-131. 16 p.

Schmid, J.M., and G.D. Amman. 1992. Dendroctonus beetles and old-growth forests in the Rockies. P. 51-59 in *Old-growth forests in the Southwest and Rocky Mountain Regions, Proc. of a Workshop*, Kaufmann, M.R., W.H. Moir, and R.L. Bassett (tech. coord.). US For. Serv. Gen. Tech. Rep. RM-GTR-213. 201 p.

Schoennagal, T., T.T. Veblen, and W.H. Romme. 2004. The interaction of fire, fuels and climate across Rocky Mountain forests. Biosci. 54:661-676.

Schroeder, M., and C.C. Buck. 1970. *Fire weather*. USDA Agric. Handb. 360. 229 p.

Schulz, B. 2003. *Changes in downed and dead woody material following a spruce beetle outbreak on the Kenai Peninsula, Alaska*. US For. Serv. Res. Pap. PNW-RP-559. 10 p.

Scott, J.H., and E.D. Reinhardt. 2001. *Assessing crown fire potential by linking models of surface and crown fire behavior*. US For. Serv. Res. Pap. RMRS-29. 59p.

Sharpe, P.J.H., R.J. Newton, and R.D. Spence. 1986. Forest pests: The role of phloem osmotic adjustment in the defensive response of conifers to bark beetle attack. P. 113-131 in *Stress physiology and forest productivity*, Hennessey, T.C., P.M. Dougherty, S.V. Kossuth, and J.D. Johnson (eds.). Dordrecht, Netherlands: Martinus Nijhoff Publishers. 239 p.

Sibold, J.S., T.T. Veblen, amd M.E. Gonzalaz. 2006. Spatial and temporal variation in historic fire regimes in subalpine forests across the Colorado Front Range in Rocky Mountain National Park, Colorado, USA. J. Biogeogr. 32:631-647.

Six, D.L., and B.J. Bentz. 2003. Fungi associated with the North American spruce beetle, Dendroctonus rufipennis. Can. J. For. Res. 33:1815-1820.

Stocks, B.J. 1987. Fire potential in the spruce budworm-damaged forests of Ontario. For. Chron. 63:8-14.

Susott, R.A. 1980. Thermal behavior of conifer needle extractives. For. Sci. 26:347-360.

Swetnam, T.W., and C.H. Baisan. 1996. Historical fire regime patterns in the southwestern United States since AD 1700. P. 11-32. in *Fire effects in southwestern forests, Proc. of the Second La Mesa Fire Symposium*, Allen, C.D. (ed.). US For. Serv. Gen. Tech. Rep. RM-GTR-286. 216 p.

Taylor, K. L., and R.W. Fonda. 1990. Woody fuel structure and fire in subalpine fir forests, Olympic National Park, Washington. Can. J. For. Res. 20:193-199.

Turner, M.G, and W.H. Romme. 1994. Landscape dynamics in crown fire ecosystems. Landscape Ecol. 9:59-77.

Van Wagner, C.E. 1972. Duff consumption by fire in eastern pine stands. Can. J. For. Res. 2:34-39.

Van Wagner, C.E. 1977. Conditions for the start and spread of crown fire. Can. J. For. Res. 7:23-34.

Van Wagner, C.E. 1993. Predictions of crown fire behavior in two stands of Jack Pine. Can. J. For. Res. 23:442-449.

Veblen, T.T., K.S. Hadley, M.S. Reid, and A.J. Rebertus. 1989. Blowdown and stand development in a Colorado subalpine forest. Can. J. For. Res. 19:1218-1225.

Veblen, T.T, K.S. Hadley, E.M. Nel, T. Kitsberger, M. Reid, and R. Villalba. 1994. Disturbance regime and disturbance interactions in the Rocky Mountain subalpine forest. J. Ecol. 82:125-135.

Veblen, T.T. 1986a. Age and size structure of subalpine forests in the Colorado Front Range. Bull. Torrey Bot. Club. 113:225-240.

Veblen, T.T. 1986b. Treefalls and the coexistence of conifers in subalpine forests of the Central Rockies. Ecol. 67:644-649

Veblen, T.T., K.S. Hadley, and M.S. Reid. 1991a. Disturbance and stand development of a Colorado subalpine forest. J. Biogeogr. 18:707-716.

Veblen, T.T., K.S. Hadley, M.S. Reid, and A.J. Rebertus. 1991b. The response of subalpine forests to spruce beetle outbreak in Colorado. Ecol. 72: 213-231

Wadleigh, L., and M.J. Jenkins. 1996. Fire frequency and the vegetative mosaic of a spruce-fir forest in Northern Utah. Great Bas. Nat. 56:28-37.

Wallen, K.F., and K.F. Raffa. 2004. Feedback between individual host selection behavior and population dynamics in an eruptive herbivore. Ecol. Mongr. 74:101-116.

Werner, R.A., and E.H. Holsten. 1985. Factors influencing generation times of spruce beetles in Alaska. Can. J. For. Res. 15:438-443.

Wood, S.L. 1982. *The bark and ambrosia beetles of North and Central Ame*rica (Coleoptera:Scolytidae). A Taxonomic Monograph. Great Bas. Nat. Mem. 6. 1359 p.

Yeager, L.E., and L.E. Riordan. 1953. Effects of beetle-killed timber on range and wildlife in Colorado. Trans. No. Am.Wildl. Conf. 18:596–616.

Youngblood, A.P., and R.W. Mauk. 1985. *Coniferous forest habitat types of central and southern Utah*. US For. Serv. Gen. Tech. Rep. INT-187. 89 p.

CHAPTER 2

FUEL COMPLEX ALTERATIONS ASSOCIATED WITH SPRUCE BEETLE-

INDUCED TREE MORTALITY IN INTERMOUNAIN

SPUCE-FIR FORESTS

Abstract

Extensive outbreaks of spruce beetle (*Dendroctonus rufipennis* Kirby
[Coleoptera: Curculionidae]), and resulting tree mortality has been assumed to increase
hazardous fuel loads and consequently influence fire behavior, occurrence, and effects.
However, little research has been done to quantify or qualify how spruce beetle-induced
tree mortality may alter fuel complexes during the course of an outbreak. The objective
of our research was to determine how fuel complexes differ between stands with 1)
endemic populations of spruce beetle, 2) stands experiencing current outbreaks and 3)
stands with post-outbreak spruce beetle-induced tree mortality. We measured ground,
surface and aerial fuels in spruce-fir stands assigned into one of three spruce beetle
condition classes; endemic, epidemic, or post-epidemic. These stands were located on
the Manti-LaSal and Fishlake National Forests in south central and southern Utah. We
used analysis of variance to compare mean differences in stand attributes and fuel
variables between the three spruce beetle condition classes. Mean amount of down,
woody, surface fuel (tonnes/ha) in 1hour and 100 hour size classes were significantly
greater in epidemic stands verses endemic and post-epidemic stands. Mean litter depth
and amount was also significantly greater in epidemic stands. Fuel heterogeneity across
the study area and within stands may explain why spruce beetle-induced tree mortality

did not result in significantly different amounts of other downed woody fuels measured.

A significant increase in live herbaceous material was detected in epidemic stands while

a significant increase in both live herbaceous and live shrub material was detected in

post-epidemic stands. Spruce-fir stands also had significantly less live aerial fuels

following outbreaks compared with endemic stands. This information can be used to

better understand fire ecology and spruce beetle outbreak relationships in spruce-fir

forests.

Introduction

Engelmann spruce (*Picea engelmannii* Parry ex Engelm) and subalpine fir (*Abies

lasiocarpa* var *latifolia* Nutt) forests are widely distributed in the subalpine zone of the

Intermountain West (Long 1994). Compared to lower elevation forest types, spruce-fir

forests have relatively long fire return intervals (Wadleigh and Jenkins 1996). In the

northern Rockies for example, fire return intervals were estimated at between 50-130

years (Arno 1980). Stand replacing crown fires occur more than every 200 and 300 years

in northwestern Colorado (Veblen et al. 1994) and the Yellowstone area, respectively

(Romme 1982).

The length of time between stand replacing fires is due to short snow-free periods

(approximately two months) and slow rates of decomposition that allow surface and

ground fuels to accumulate (Romme 1982, Veblen et al. 1994, Jenkins et al. 1998).

Insect epidemics, windstorms, or previous fire events can also contribute to increased fuel

loads (Arno 2000). Consequently, the fuels complexes that develop in maturing spruce-

fir forests become more conducive to crown-fire development when environmental

conditions are appropriate and are often regarded as a limiting factor for fire spread

(Johnson 1992, Arno 2000, Johnson et al. 2001).

In spruce-fir forests, spruce beetle (*Dendroctonus rufipennis* Kirby (Coleoptera:

Curculionidae)) epidemics result in the most significant amount of tree mortality between

stand replacing fire events (Baker and Veblen 1990, Veblen et al. 1991b, Veblen et al.

1994, Jenkins et al. 1998, Parish et al. 1999). Extensive spruce beetle epidemics have

been reported in the western United States since the mid 1880s (Hopkins 1909, Schmid

and Frye 1977, Baker and Veblen 1990, Rebertus et al. 1992, Hebertson and Jenkins

2008). Over the past two decades large areas, including nearly 36,000 ha between 2002

through 2004, of spruce-fir forests in central and southern Utah have been affected by

spruce beetle epidemics, with the insect often killing over 90% of spruce greater than 36

cm in diameter (Dymerski et al. 2001, Keyes et al. 2003, Matthews et al. 2005, DeRose

and Long 2007). The intensity and expanse of tree mortality has federal and state land

management agencies as well as private landowners concerned over the buildup of hazard

fuels and increased potential for extreme fire behavior. However, little research has been

done to quantify or qualify how spruce beetle-induced tree mortality actually alters fuel

complexes. Fuel complex alterations have been observed in other bark beetle outbreaks

such as mountain pine beetle (*Dendroctonus ponderosae* Hopkins, Coleoptera:

Curculionidae) in lodgepole pine (Stone and Wolfe 1996, Page and Jenkins 2007a) with

increases in litter, 1hour, and live fuel loads; and Douglas-fir beetle (*Dendroctonus*

pseudotsugae Hopkins, Coleoptera: Curculionidae) with live fuel load and cover

increasing following outbreaks (McMillin and Allen 2003).

The objective of this research was to determine how fuel complexes differ between stands with endemic populations of spruce beetle versus stands experiencing current outbreaks or those with older spruce beetle-induced tree mortality. Understanding specific changes in fuel complexes associated with spruce beetle-induced tree mortality can help land managers devise appropriate strategies for long term management of spruce-fir forests, hazardous fuel mitigation, and fire planning.

Methods

Study Site Selection

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

Aerial photographs and 7.5-minute, United States Geological Survey (USGS) topographic maps were next used to delimit potential spruce-fir stands within spruce beetle-affected polygons and adjacent uninfested forests. All stands were then grouped into one of three spruce beetle classifications; endemic, epidemic, and post-epidemic. The endemic class was comprised of uninfested stands or those with less than one

currently attacked tree ha-1. The epidemic class consisted of stands within 'current'

polygons that had increasing numbers of infested trees and at least two pockets of five

trees attacked during the past five years (Bentz and Munson 2000). The post-epidemic

class consisted of stands with a minimum of 75% mortality of overstory trees greater than

12.7 cm diameter at breast height (dbh) and no current spruce beetle activity detected

during the past five years. These classes were chosen to serve as substitutes for spruce

beetle outbreak conditions similar to time substitution experiments described by Pickett

(1989).

Specific criteria were then established to select potential stands within each spruce

beetle class to sample. This was done to ensure that mean differences in both surface

and aerial fuels could be attributed to spruce beetle class. These criteria were as follows:

1. All stands within and among spruce beetle classes had mean basal areas greater

   than 23 m2/ha, mean quadratic spruce diameters greater than 36 cm, and were

   composed of greater than 65% spruce. Both live and dead standing spruce trees

   were considered in determining the structure of post-epidemic stands.

2. All stands were located on sites with similar characteristics including slope,

   aspect, and habitat type.

3. None of the stands had been altered by other disturbances such as timber

   harvesting, snow avalanches, or blowdown.

4. Stands were accessible.

Every potential sample stand was then surveyed and mensuration data collected to

validate its spruce beetle classification and to ensure that the all above selection criteria

were satisfied. Stands that did not meet all selection criteria were eliminated from the

study. Two sample stands in each of the three spruce beetle condition classes were then

randomly selected from the remaining set of potential candidates on both the Fishlake

and Manti-LaSal National Forests.

From a randomly selected starting point, stand and fuels data were collected on plots

systematically established in each sample stand following a grid pattern with lines spaced

100.58 m by 150.48 m apart.

Data Collection

For sampling purposes, plots were systematically established in each sample stand

from a randomly selected starting point and spaced 100 meters by 150 meters apart.

Depending on stand size, 16 to 27 plots were sampled in each stand. From each plot

center, general information was collected for each plot including aspect, slope, elevation,

percent canopy closure and percent rock cover. All sample data were collected during

the summers of 2006 and 2007.

Stand characteristics – A 20 basal area factor (BAF) prism and a 12.7 cm dbh

lower diameter limit were used to select live and dead sample trees, regardless of species

in each plot for sampling purposes. Species, dbh, crown class, and percentage of live

and/or dead needles were determined for each tree. Each sample tree was also assigned a

condition of 1) healthy (i.e., no visible evidence of attack), 2) unhealthy (i.e., tree

damaged but able to survive), and 3) dead. Year of spruce beetle attack was also

determined for all sampled trees. Recently attacked trees were successfully infested or

killed within the last four years. Older attacked trees were attacked more than four years

ago or had died from other mortality agents. Attack dates were based on living beetle

development stages within the inner bark, the percentage of green versus fading foliage, fine twig loss, and bark deterioration. Stand age was determined from ring counts of increment cores taken from a representative live tree at stump height (0.30 m) on each plot.

Small tree regeneration (< 12.7 cm dbh and greater than 15.24 cm in height) was recorded by species and height class from 0.30 to 3.05 m in a 2.07 m fixed-radius plot (Brown et al. 1982). In post-epidemic stands an additional 8.02 m fixed-radius plot was used to tally stumps of spruce beetle-killed trees that fell since the initiation of the outbreak.

Fuel measurements – All fuels were inventoried on each plot utilizing methods described by Page and Jenkins (2007a) and Brown and others (1982).

Canopy fuels – Estimates of the percentage of live, dead and green-altered needles were made for all sampled trees. Green altered foliage refers to needles on currently attacked trees where live fuel moisture may differ from green needles on unattacked trees (Jenkins et al. 2008). Crown base height, crown width and tree height were measured directly from a representative live tree greater than 12.7 cm dbh. Crown base height was defined as the height in which flame could carry upward into a tree's canopy, representing the interaction between surface and crown fuels (Scott and Reinhardt 2001).

Surface and ground fuels – Four planar intercept transects 19.81 m long, were established in each cardinal direction from plot center and were used to tally downed woody fuels intersecting the transect plane. A go-no-go gauge was used to measure standard time lag diameter-based fuel size classifications of 1 hour (0.0-0.64 cm), 10 hour (0.65-2.54 cm), 100 hour (2.55-7.62 cm), and 1000 hour (>7.62 cm). The smallest pieces

(1 hour and 10 hour) were tallied between 1.52 m and 3.35 m. The 100 hour size class was tallied between 1.52 m and 6.40 m and the 1000 hour size class was tallied between 1.52 m and 19.81 m.

Two fixed-diameter micro-plots 1.83 m in diameter were established at 10.67 and 19.81 m along each of the four transects (total of eight per plot) for quantifying fuel bed intercept height, live/dead shrub and herbaceous cover and height as well as litter/duff biomass and depth. The data collected in each micro plot included the percentage of both live and dead cover and average height for shrubs and herbaceous plants (forbs and grasses). Duff and litter depth in addition to fuel intercept height was measured at the center of each micro-plot. Fuel intercept height was determined by imposing a 0.30 m plane perpendicular to the fuel transect and measuring the highest downed woody particle intercepted by that plane (Brown 1974).

Data Analysis

Summary of stand characteristics – Live and dead basal area, trees ha^{-1}, and quadratic mean diameter (qmd) were calculated for each tree species sampled in the survey. The number of downed trees ha^{-1} estimated in post-epidemic stands was combined with the number of standing dead trees ha^{-1} from the variable-radius plot to determine dead spruce trees ha^{-1} post-outbreak. Tree regeneration heights, stems ha^{-1}, and the amount of oven dried fuel biomass ha^{-1}, estimated from Appendix D of Brown et al. (1982) were also calculated.

Summary of canopy fuels – Data collected from sample trees were utilized to calculate the live, available canopy fuel load, canopy base height and canopy bulk

density. Live, available canopy fuel load was determined from live crown biomass

estimates using allometric equations developed by Brown (1978) based on tree species

and crown class. These equations provide fuel estimates for live foliage and branch

wood less than 0.65 cm. Call and Albini (1997) determined that all live foliage and 65%

of 1-h fuels in the tree crown would be consumed at 100% moisture content in a crown

fire. We, therefore, added 65% of the 1-h fuels into the live crown weight to determine

available canopy fuel load (Call and Albini 1997, Cruz et al. 2003). Mean canopy base

height was calculated as a weight average using the number of trees ha^{-1} represented by

each sampled tree, average over plots within a stand. Canopy bulk density for each plot

was then calculated from the live, available canopy fuel load divided by the canopy

length (i.e., total tree height minus crown base height) of the randomly selected and

measured tree on each plot (Keane et al. 1998).

To calculate suspended canopy foliage weight, foliage was separated into live,

dead, and green-altered foliage on sampled trees using a procedure similar to Page and

Jenkins (2007a). Live foliage was classified as green needles remaining on healthy and

unhealthy trees. Green, altered foliage was approximated for recently infested trees

having more than 90% green needles remaining. Dead foliage was derived from infested

trees with less than 90% green needles remaining and/or foliage fading from green to

yellow or red in coloration.

Calculation of surface and ground fuels – Surface and ground fuels were input

into the fire effects monitoring and inventory protocol (FIREMON), version 2.1.1 to

derive specific surface and ground fuel loads (Lutes et al. 2006). Total fuel load

estimates for downed woody fuels, litter, and duff were estimated using methods

described by Brown (1974) within the software. Weight estimates for dead and living

surface vegetation were based on summarized bulk densities based on surface vegetation

coverage and average height as described in Page and Jenkins (2007a). The methods we

used to compute fuel bulk depth are described in Albini and Brown (1978).

Statistical analysis – Fuel variables/parameters were averaged over plots to

calculate stand means in each spruce beetle condition class. These estimated stand means

(comprising the fundamental replicating unit) were then used to assess if stand level fuel

complexes differ between endemic, epidemic and post-epidemic classes of spruce beetle

outbreaks in a completely randomized design.

The majority of the data were determined to be normally distributed (PROC

UNIVARIATE) (SAS Institute Inc 2005). However, live Engelmann spruce trees ha^{-1}

were square root transformed while live subalpine fir trees ha^{-1}, live herbaceous cover

and biomass were log-transformed prior to analysis to better meet assumptions of

normality and homoscedasticity. All other variables were analyzed on the original scale.

One-way ANOVA was used to assess differences in the various response metrics

(i.e., fuel loads and parameters) associated with three levels (i.e. endemic, epidemic, and

post-epidemic classes) of spruce beetle infestation.   The data analyses were generated

using the MIXED procedure in SAS/STAT software, Version 9.1.3 of the SAS System

for Windows (SAS Institute Inc 2005).

Results

A summary of stand attributes for sampled stands in each spruce beetle

classification is given in Table 2.1. Numbers of live Engelmann spruce differed

significantly between the three bark beetle condition classes. Endemic stands had

significantly greater numbers of live Engelmann spruce followed by post-epidemic stands

and epidemic.

All sampled epidemic and post-epidemic classes had significantly higher numbers

of dead Engelmann spruce trees ha-1, lower live basal area, and lower live spruce qmd,

compared to the endemic class. Low numbers of spruce trees had fallen since the

beginning of spruce beetle activity in the post-epidemic stands (Table 2.1). Only 11% of

the spruce trees killed in post-epidemic stands had fallen since outbreak initiation.

Table 2.1. The means calculated for selected attributes measured in stands compared between spruce beetle condition classes on the Manti-LaSal and Fishlake National Forests.

Fuel Type	Beetle Condition	Mean	S.E.	*Num df*	*Den df*	*F*	*P*	Estimate	*df*	*t-value*	*P*
Age (yr)	En	158	35.16					En vs Ep	9	1.94	0.08
	Ep	133	19.19	2	9	2.35	0.15	Ep vs PEp	9	-0.13	0.90
	PEp	134	8.44					En vs PEp	9	1.81	0.10
Live ES TPha	En	340	4.58					En vs Ep	9	10.29	<0.01
	Ep	39	18.44	2	9	53.16	<0.01	Ep vs PEp	9	-4.61	0.00
	PEp	139	48.07					En vs PEp	9	5.68	0.00
Live SAF TPha	En	136	3.38					En vs Ep	9	0.06	0.95
	Ep	135	14.26	2	9	3.30	0.08	Ep vs PEp	9	2.20	0.06
	PEp	93	44.98					En vs PEp	9	2.25	0.05
Live BA (m^2)	En	44	5.88					En vs Ep	9	29.07	<0.01
	Ep	8	1.67	2	9	536.96	<0.01	Ep vs PEp	9	-1.44	0.18
	PEp	10	1.44					En vs PEp	9	27.63	<0.01
ES qmd (cm)	En	38	4.51					En vs Ep	9	20.8	<0.01
	Ep	5	0.30	2	9	223.72	<0.01	Ep vs PEp	9	-7.07	<0.01
	PEp	16	4.58					En vs PEp	9	13.73	<0.01
Dead ES TPha	En	45	23.10					En vs Ep	9	-8.28	<0.01
	Ep	273	74.05	2	9	70.37	<0.01	Ep vs PEp	9	-3.22	0.01
	PEp	361	110.32					En vs PEp	9	-11.50	<0.01

*En = Endemic; Ep = Epidemic; PEp = Post-Epidemic; yr = years; BA = mean basal area; TPha = trees ha⁻1; ES = Engelmann spruce; SAF = subalpine fir; QMD = quadratic mean diameter.

<u>Surface and Ground Fuels</u>

The effect of bark beetle condition class on surface and ground fuels is given in Table 2.2 and shown graphically in Figure 2.1. The epidemic condition class generally had the greatest amount of surface and ground fuels, although fuel bulk depth was highest in the post-epidemic class. Only the mean differences in litter amount and depth were significant. Mean amounts of 10 hour time lag fuels did not differ significantly between the three outbreak condition classes, but the amount of these fuels did increase from endemic to epidemic classes and from epidemic to post-epidemic classes. Epidemic and post-epidemic classes had significantly more 100 hour time lag woody fuels than the endemic class. Stands in all three condition classes had similar amounts of rotten 1000 hour time lag fuels.

The amount, height, and coverage of live herbaceous plants was significantly greater in epidemic and post-epidemic classes compared to endemic class, while significantly more dead herbaceous plant materials occurred in post-epidemic class than the other two classes (Table 2.3). The analysis of live shrub measures yielded similar significant results, except dead shrub cover and biomass did not differ significantly among the three condition classes (Table 2.4).

Table 2.2. Summary of downed woody fuel data compared between spruce beetle condition classes on the Manti-LaSal and Fishlake National Forests.

Fuel Type	Beetle Condition	Mean	S.E.	Num df	Den df	F	P	Estimate	df	t-value	P
1-Hr (tonnes/ha)	En	1.05	0.06					En vs Ep	9	-1.86	0.10
	Ep	1.25	0.25	2	9	2.34	0.15	Ep vs PEp	9	1.88	0.09
	PEp	1.05	0.32					En vs PEp	9	0.02	0.99
10-Hr (tonnes/ha)	En	2.69	0.17					En vs Ep	9	-0.47	0.65
	Ep	2.82	0.57	2	9	1.35	0.31	Ep vs PEp	9	-1.13	0.29
	PEp	3.15	0.50					En vs PEp	9	-1.60	0.14
100-Hr (tonnes/ha)	En	3.51	0.16					En vs Ep	9	-2.38	0.04
	Ep	5.58	2.08	2	9	3.50	0.08	Ep vs PEp	9	0.19	0.85
	PEp	5.42	0.11					En vs PEp	9	-2.19	0.06
1000-Hr-Sound (tonnes/ha)	En	25.46	3.24					En vs Ep	9	-0.33	0.75
	Ep	27.79	1.19	2	9	0.34	0.72	Ep vs PEp	9	-0.49	0.64
	PEp	31.22	1.66					En vs PEp	9	-0.82	0.43
1000-Hr-Rotten (tonnes/ha)	En	17.01	1.34					En vs Ep	9	-1.46	0.18
	Ep	25.39	1.57	2	9	1.13	0.36	Ep vs PEp	9	1.03	0.33
	PEp	19.48	0.53					En vs PEp	9	-0.43	0.68
Duff (tonnes/ha)	En	30.44	1.91					En vs Ep	9	-1.46	0.18
	Ep	35.76	7.03	2	9	1.07	0.38	Ep vs PEp	9	0.70	0.50
	PEp	33.20	5.50					En vs PEp	9	-0.76	0.47
Litter (tonnes/ha)	En	4.02	2.01				<0.01	En vs Ep	9	-4.21	<0.01
	Ep	6.60	1.09	2	9	12.08		Ep vs PEp	9	4.31	<0.01
	PEp	3.95	0.37					En vs PEp	9	0.10	0.92
Fuel Bulk Depth (cm)	En	6.53	0.13					En vs Ep	9	-0.84	0.42
	Ep	7.27	1.93	2	9	3.52	0.07	Ep vs PEp	9	-1.76	0.11
	PEp	8.83	1.12					En vs PEp	9	-2.60	0.03
Duff Depth (cm)	En	3.45	0.22					En vs Ep	9	-1.45	0.18
	Ep	4.05	0.81	2	9	1.05	0.39	Ep vs PEp	9	0.72	0.49
	PEp	3.76	0.62					En vs PEp	9	-0.73	0.48
Litter Depth (cm)	En	0.91	0.45				<0.01	En vs Ep	9	-4.16	<0.01
	Ep	1.49	0.25	2	9	11.92		Ep vs PEp	9	4.30	<0.01
	PEp	0.89	0.09					En vs PEp	9	0.14	0.89

*En = Endemic; Ep = Epidemic; PEp = Post-Epidemic; ha = hectare; cm = centimeters

Surface Fuel Complex

Legend:
- Litter
- Duff (Divided by 10)
- 0-7.62 cm
- >7.62 cm (Divided by 10)
- Herbaceous Biomass
- Shrub Biomass
- Fuel Bulk Depth (cm)

X-axis: Spruce Beetle Activity Levels (Endemic, Epidemic, Post-epidemic)
Left Y-axis: Fuel Load (tonne/ha)
Right Y-axis: Bulk Depth (cm)
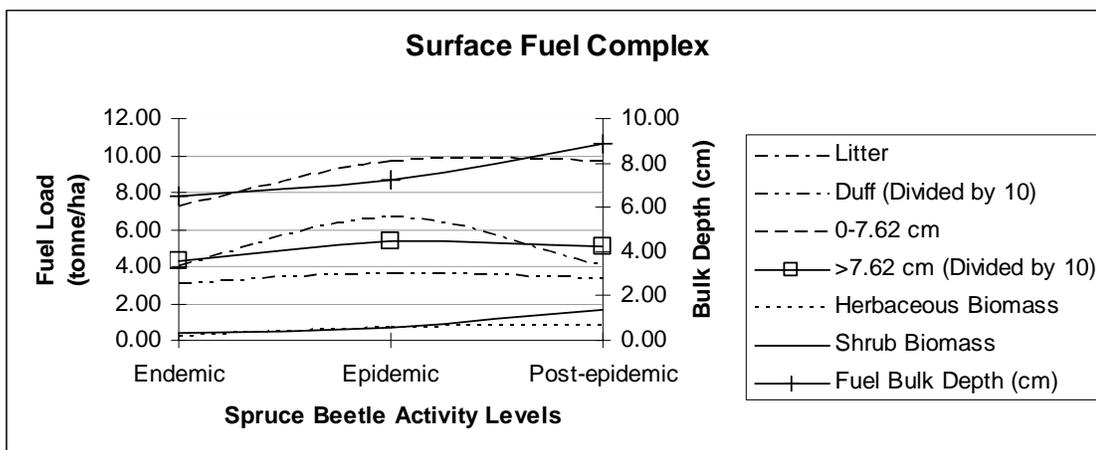
Figure 2.1. Summary of changes in surface fuel parameters during the course of the spruce beetle outbreak.

* cm = centimeters

Table 2.3. Summary of live herbaceous fuel data compared between spruce beetle condition classes on the Manti-LaSal and Fishlake National Forests.

Fuel Type	Beetle Condition	Mean	S.E.	Num df	Den df	F	P	Estimate	df	t-value	P
Live Herbaceous Cover (%)	En	16.00	1.95					En vs Ep	9	-4.91	<0.01
	Ep	30.65	9.91	2	9	15.77	<0.01	Ep vs PEp	9	0.09	0.93
	PEp	29.08	2.38					En vs PEp	9	-4.82	<0.01
Dead Herbaceous Cover (%)	En	1.05	0.40					En vs Ep	9	1.25	0.24
	Ep	0.72	0.35	2	9	14.76	<0.01	Ep vs PEp	9	-5.21	<0.01
	PEp	2.09	1.17					En vs PEp	9	-3.95	<0.01
Live Herbaceous (tonnes/ha)	En	0.21	0.02					En vs Ep	9	-5.82	<0.01
	Ep	0.74	0.39	2	9	27.88	<0.01	Ep vs PEp	9	-1.14	0.28
	PEp	0.80	0.03					En vs PEp	9	-6.96	<0.01
Dead Herbaceous (tonnes/ha)	En	0.01	0.003					En vs Ep	9	-0.34	0.74
	Ep	0.01	0.01	2	9	27.47	<0.01	Ep vs PEp	9	-6.24	<0.01
	PEp	0.04	0.02					En vs PEp	9	-6.58	<0.01
Herbaceous Height (m)	En	0.11	0.01					En vs Ep	9	-5.52	<0.01
	Ep	0.23	0.07	2	9	32.11	<0.01	Ep vs PEp	9	-2.27	0.05
	PEp	0.27	0.04					En vs PEp	9	-7.79	<0.01

*En = Endemic; Ep = Epidemic; PEp = Post-Epidemic; ha = hectare; m = meters

Table 2.4. Summary of live shrub data compared between spruce beetle condition classes on the Manti-LaSal and Fishlake National Forests.

Fuel Type	Beetle Condition	Mean	S.E.	*Num df*	*Den df*	*F*	*P*	Estimate	*df*	*t-value*	*P*
Live Shrub Cover (%)	En	7.03	1.29					En vs Ep	9	-1.32	0.22
	Ep	9.88	1.27	2	9	15.66	<0.01	Ep vs PEp	9	-4.05	<0.01
	PEp	18.61	0.84					En vs PEp	9	-5.37	<0.01
Dead Shrub Cover (%)	En	0.28	0.10					En vs Ep	9	-0.47	0.65
	Ep	0.36	0.10	2	9	0.66	0.54	Ep vs PEp	9	-0.67	0.52
	PEp	0.46	0.07					En vs PEp	9	-1.15	0.28
Live Shrub (tonnes/ha)	En	0.38	0.02					En vs Ep	9	-1.52	0.16
	Ep	0.69	0.13	2	9	22.31	<0.01	Ep vs PEp	9	-4.88	<0.01
	PEp	1.70	0.23					En vs PEp	9	-6.39	<0.01
Dead Shrub (tonnes/ha)	En	0.01	0.001					En vs Ep	9	-0.83	0.43
	Ep	0.02	0.01	2	9	0.91	0.44	Ep vs PEp	9	-0.50	0.63
	PEp	0.03	0.004					En vs PEp	9	-1.33	0.22
Shrub Height (m)	En	0.12	0.01					En vs Ep	9	-1.52	0.16
	Ep	0.17	0.02	2	9	15.01	<0.01	Ep vs PEp	9	-3.80	<0.01
	PEp	0.29	0.02					En vs PEp	9	-5.32	<0.01

*En = Endemic; Ep = Epidemic; PEp = Post-Epidemic; ha = hectare; m = meters

Comparison of Canopy Fuels

Stand canopies in the endemic class had significantly greater available fuel loads, bulk densities, and base heights (Table 2.5). The mean amount and kind of foliage significantly differed among the three condition classes (Figure 2.2). The mean amount of available live foliage was significantly greater in the endemic class compared to the epidemic and post-epidemic classes. The epidemic class had significantly more dead foliage and green altered by current spruce beetle attack than either the endemic or post-epidemic classes (Figure 2.2).

Table 2.5. Summary of live canopy fuel data compared between spruce beetle condition classes on the Manti-LaSal and Fishlake National Forests.

Fuel Type	Beetle Condition	Mean	S.E.	Num df	Den df	F	P	Estimate	df	t-value	P
Available Canopy Fuel Load (tonnes/ha)	En	22.59	2.44					En vs Ep	9	15.6	<0.01
	Ep	4.73	0.34	2	9	146.86	<0.01	Ep vs PEp	9	-1.64	0.13
	PEp	6.61	0.79					En vs PEp	9	13.95	<0.01
Canopy Bulk Density (kgs/m^3)	En	0.16	0.01					En vs Ep	9	10.21	<0.01
	Ep	0.03	0.01	2	9	56.04	<0.01	Ep vs PEp	9	-2.69	0.02
	PEp	0.06	0.001					En vs PEp	9	7.52	<0.01
Canopy Base Height (m)	En	6.61	1.45					En vs Ep	9	5.61	<0.01
	Ep	2.91	0.29	2	9	14.56	<0.01	Ep vs PEp	9	-0.19	0.56
	PEp	3.37	1.54					En vs PEp	9	5.42	<0.01

*df = degrees of freedom; Adj.= adjusted; En = Endemic; Ep = Epidemic; PEp = Post-Epidemic; ha = hectare; kgs/m^3 = kilograms per cubic meter; m = meters.
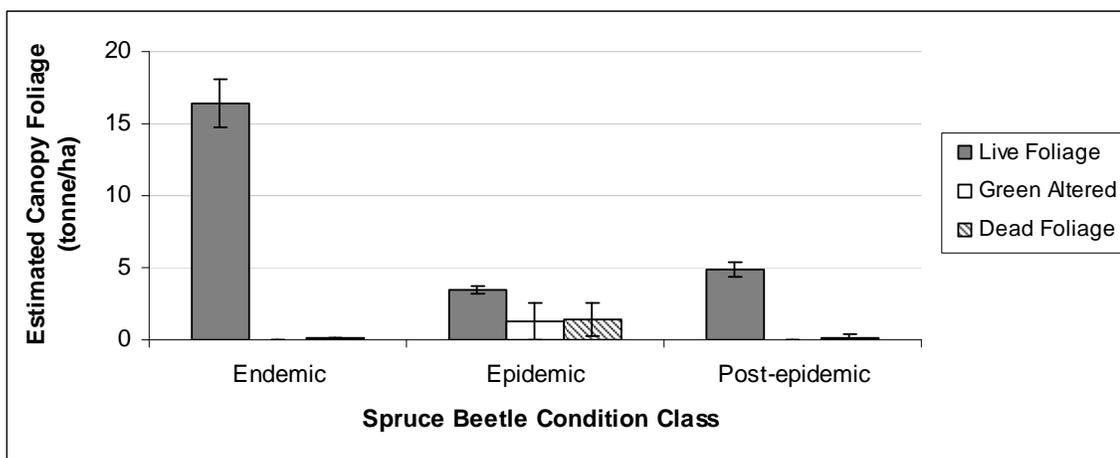
Figure 2.2. Mean amount (tonne/ha) and standard error of live, dead, and green altered foliage.
*ha = hectare.

Discussion

The results of our study revealed changes to stand conditions in spruce-fir forests during the course of spruce beetle outbreaks. The percentage of live overstory spruce decreased in epidemic and post-epidemic classes. A decrease in live basal area and average spruce diameters was also evident in epidemic and post-epidemic classes due to the high proportion of large diameter spruce that were killed by beetles.

We found that spruce beetle outbreaks in our study caused similar impacts to previous studies in the Rocky Mountains (Veblen et al. 1991b). The reduction in viable, natural seed sources and the lack of bare, mineral soil following beetle disturbance may deter the establishment of seedlings, requiring artificial regeneration of the site (Miller 1970).

We observed that stands in all three condition classes had advanced spruce and subalpine fir regeneration. Germinating seedlings were also observed in several stands. The presence of spruce seedlings and saplings in the understory suggests that this species may eventually dominate spruce beetle-affected stands again. Other studies have also shown that regeneration releases following spruce beetle outbreaks, although the return to Engelmann spruce-dominated forests depends upon the establishment of new seedlings (Whipple and Dix 1979, Aplet et al. 1988, Veblen et al. 1991b, Jenkins et al. 1998).

Canopy Fuels

Spruce beetle-induced tree morality altered the aerial fuels complexes in our study areas. We observed an overall reduction in the available fuel load, bulk density, and base height of live trees in the epidemic and post-epidemic class when compared to the endemic. Available fuels loads were approximately five and three times higher in the endemic class when compared to the epidemic and post-epidemic classes, respectively.

Initial decreases in live canopy fuels were largely due to the overall loss of foliage that occurred with the onset of tree mortality attributed to spruce beetle attack. Trees in the epidemic class had mixtures of live and dead needles although we did observe a rapid loss of needles from trees following bark beetle attack.

In epidemic and post-epidemic stands where the largest spruce were killed by beetles, smaller spruce and fir trees were tallied and comprised the live canopy fuel load (Table 2.5). This explains the difference in available canopy fuel loads, bulk density and crown base heights across the three beetle classes. Regeneration by species is not affected by beetle activity until well into the post-epidemic phase when conditions such as increases in available light, nutrients, water and mineral soil influence seedling establishment and growth (Aplet et al. 1988, Jenkins et al. 1998).

Surface and Ground Fuels

Changes in downed woody fuels, as well as herbaceous and shrub fuels, have been documented to increase following spruce beetle outbreaks in Alaska spruce-fir forests (Holsten et al. 1995, Schulz 2003, Boucher and Mead 2006) and forests in northwestern Colorado (Schmid and Hinds 1974, Veblen et al. 1991a, Veblen et al. 1991b). In our study however, we found the most significant differences in surface and ground fuels occurred within the litter component. There was 39 and 41% more litter in the epidemic class compared to the endemic and post-epidemic classes, respectively. The greater amount and depth of litter in the epidemic class likely resulted from the loss of needles from dead and dying trees.

The most notable change in fuel bed characteristics was in the herbaceous and shrub component. Both the epidemic and post-epidemic class had greater amounts, percent covers, and heights of live herbaceous and shrub fuels than the endemic class. Stands in the post-epidemic class had significantly more and taller shrubs than the

epidemic class. Dead fuels in all three condition classes were similar, except slightly

more dead herbaceous fuels occurred in the endemic class than the epidemic class.

The scarcity of understory vegetation we observed in the endemic class was

consistent with descriptions of undergrowth commonly observed in mature spruce-fir

forests (Bradley et al. 1992). The increases in both herbaceous and shrub fuels in

epidemic and post-epidemic classes were likely due to the increased availability of

sunlight, water, and nutrients as overstory spruce died (Yeagar and Riordan 1953,

Schmid and Hinds 1974, Veblen et al. 1991b).

Following spruce beetle outbreaks in Alaska, Schulz (2003) found that amount

and height of sound, woody, surface fuels increased. Cahill (1977) obtained similar

results from spruce-fir forests he studied on the White River Forest in western Colorado.

Our results however, indicated that spruce beetle condition class did not account for

much variation in down, woody fuel loads. Although the mean amounts of 1 hour time

lag fuels were not significantly different among the three classes, generally more of these

fuels were present in the epidemic class. This finding suggests that spruce beetle-killed

trees begin to shed small twigs in conjunction with or soon after needle loss. The post-

epidemic class had slightly more l hour time lag down woody fuels that the endemic class

perhaps because like litter, these fuels quickly decompose after falling to the forest floor

returning to approximate background levels.

We expected to observe more 10 hour and 100 hour time lag fuels in older spruce

beetle-affected stands as the larger branches of dead trees began to dry out and break.

We found that all three spruce beetle classes had comparable amounts of 10 hour time lag

fuels. The endemic class did have significantly less 100 hour time lag fuels than either of the two other classes.

Several studies indicate that 1000 hour time lag fuels increase as dead trees in post-epidemic stands begin to fall (Cahill 1977, Schulz 2003, DeRose and Long 2007). Jenkins et al. (2008) extrapolated from field data to estimate coarse, woody debris accumulation and decomposition over the course of a bark beetle rotation. Fall and decomposition rates for dead spruce however, are highly variable, and often influenced by site factors such as slope steepness, soil moisture, and the incidence of wood rotting fungi (Mielke 1950). Consequently, our ability to reliably detect spruce beetle-induced changes in these fuels may require a longer passage of time.

The deposition of woody fuels from spruce beetle-killed trees accounts for the significantly greater fuel bulk depth we observed in the post-epidemic class when compared to the endemic class. Fuel bulk depth is expected to increase over time dependent on fall rate and the balance between accumulation, compaction and decomposition.

Conclusion

In this study we quantified the changes to surface and aerial fuels that occur over the course of a spruce beetle outbreak in subalpine spruce-fir forests. We measured stand and fuel attributes on plots that had endemic, epidemic and post-epidemic spruce beetle populations. We found that during outbreak spruce stands undergo significant changes in structure, composition and fuel characteristics. As outbreaks develop spruce beetles systematically colonize and kill the largest trees first, resulting in an overall reduction in

stand diameter and basal area. The death of the large trees results in a flush of fine fuels, especially litter, during the first two seasons following tree death. Overstory beetle mortality opens the canopy allowing increases in live herbaceous fuels followed by live shrubs as stands move into the post-epidemic condition.   Fine and coarse woody fuels accumulate slowly over time, but did not increase significantly during the course of our study. We speculate that woody fuels will accumulate with time as wind and snow break up standing mortality and as dead trees fall. Deep winter snowpacks facilitate compaction of surface fuel and decomposition will offset some portion of accumulation as stands move farther into the post-epidemic condition.

   Bark beetle-induced overstory tree mortality results in canopy fuel changes as well.   The epidemic stage is likely the most flammable since crowns are composed of a combination of green, beetle-affected and dead needles with variable foliar moisture and terpene content decrease.   It is also during this period that surface fuel is most likely to support ignition and fire spread. In the late epidemic and early post-epidemic stage canopy bulk density, available fuel load and crown base height decrease and crown fire initiation is less likely. There will be a variable combination of spruce and fir poles, saplings and regeneration, standing dead snags and coarse woody surface fuel over the prolonged post-epidemic period.   Ultimately over decades-to-centuries stand structure, composition and fuel characteristics will transition from post-epidemic to endemic conditions suitable for another spruce beetle outbreak. Historic spruce beetle outbreaks have been documented (Hebertson and Jenkins 2008) and it seems likely that the cyclic pattern of beetles and fuels is a natural part of the subalpine spruce-fir landscape.

Literature Cited

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

Arno, S.F. 1980. Forest fire history in the Northern Rockies. J. For. 78:460-465.

Arno, S.F. 2000. Fire in western forest ecosystems: effects of fire on flora. P. 97-120 in *Wildland fire in ecosystems*, Brown, J.K., and J. K. Smith (eds.). US For. Serv. Gen. Tech. Rep. RMRS-GTR-42-vol. 2. 257 p.

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

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

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

Boucher, T.V., and B.R. Mead. 2006. Vegetation change and forest regeneration on the Kenai Peninsula, Alaska following a spruce beetle outbreak, 1987–2000. For. Ecol. Manage. 227:233–246.

Bradley, A.F., N.V. Noste, and W.C. Fischer. 1992. *Fire ecology of forests and woodlands in Utah*. US For. Serv. Gen. Tech. Rep. INT-GTR-290. 92 p.

Brown, J.K. 1974. *Handbook for inventorying downed woody material*. US For. Serv. Gen. Tech. Rep. INT-GTR-16. 24 p.

Brown, J.K. 1978. *Weight and density of crowns of Rocky Mountain conifers*. US. For. Serv. Res. Pap. INT-197. 56 p.

Brown, J.K., R.D. Overheu, and C.M. Johnston. 1982. *Handbook for inventorying surface fuels and biomass in the interior West*. US For. Serv. Gen. Tech. Rep. INT-GTR-129. 48 p.

Cahill, D.B. 1977. Net impact of spruce beetle outbreak on White River National Forest, 1939-1951. US For. Serv., Rocky Mtn Res. Sta., Reg. Rep.

Call, P.T., and F.A. Albini. 1997. Aerial and surface fuel consumption in crown fires. Int. J. Wild. Fire 7:259-264.

Cruz, M.G., M.E. Alexander, and R.H. Wakimoto. 2003. Assessing canopy fuel stratum characteristics in crown fire prone fuel types of western North America. Int. J. Wild. Fire 12:39-50.

DeRose, R.J. and J.N. Long. 2007. Disturbance, structure, and composition: spruce beetle and Engelmann spruce forest on the Markagunt Plateau, Utah. For. Ecol. Manage. 244:16-23.

Dymerski, A.D., J.A. Anhold, and A.S. Munson. 2001. Spruce beetle (*Dendroctonus rufipennis*) outbreak in Engelmann spruce (*Picea engelmannii*) in central Utah, 1986-1998. W. Nor. Am. Nat. 61:19-24.

Hebertson, E.G., and M.J. Jenkins. 2008. Climate factors associated with historic spruce beetle (Coleoptera: Curculionidae) outbreaks in Utah and Colorado. Environ. Entomol. 37:281-292.

Holsten, E.H., R.A. Werner, and R.L. DeVelice. 1995. Effects of a spruce beetle (Coleoptera: Scolytidae) outbreak and fire on Lutz spruce in Alaska. Environ. Entomol. 24:1539-1547.

Hopkins, A.D. 1909. *Practical information on the Scolytid beetles of North American forests. I. Bark beetles of the Genus Dendroctonus*. US Bureau of Entomol. Bull. 83. U.S. Gov't Printing Office, Washington, DC. 169 p.

Jenkins, M.J., C.A. Dicus, and E.G. Hebertson. 1998. Post-fire succession and disturbance interactions on an intermountain subalpine spruce-fir forest. P. 219-229 in *Proceedings, Symposium: Fire in Ecosystem Management: Shifting the paradigm from suppression to prescription*, Pruden, T. L., and L. A. Brennan, (eds.). Tall Timbers Fire Ecology Conference Proceedings, No. 20. Tall Timbers Research Station, Tallahassee, FL. 460 p.

Jenkins, M.J., E. Hebertson, W. Page, and C.A. Jorgensen. 2008. Bark beetles, fuels, fires and implications for forest management in the Intermountain West. For. Ecol. Manage. 254:16-34.

Johnson, E.A. 1992. *Fire and vegetation dynamics: studies from the North American boreal forests*. Cambridge University Press, Cambridge, United Kingdom. 129 p.

Johnson, E.A., K. Miyanishi, and S.R.J. Bridge. 2001. Wildfire regime in the Boreal forest and the idea of suppression and fuel buildup. Conserv. Bio. 15:1554-1557.

Keane, R.E., J.L. Garner, K.M. Schmidt, D.G. Long, J.P. Menakis, and M.A. Finney. 1998. *Development of input data layers for the FARSITE fire growth model for the Selway-Bitterroot Wilderness complex*. US For. Serv. Gen. Tech. Rep. Gen. Tech. Rep. RMRS-GTR-3. 66 p.

Keyes, C., P. Rogers, L. LaMadeleine, V. Applegate, and D. Atkins. 2003. *Utah Forest Health Report: A Baseline Assessment 1999–2001*. US For. Serv., Rocky Mountain Research Station/State of Utah, Dept. of Nat. Res., Salt Lake City, UT. 45 p.

Long, J.N. 1994. The middle and Southern Rocky Mountain Region. Pages 335-386 in *Regional silviculture of the United States*, *3rd ed.*, Barrett, J.W. (ed.). John Wiley and Sons, New York, NY. 643 p.

Lutes, D.C., R.E. Keane, J.F. Caratt. C.H. Key, N.C. Benson, S. Sutherland, and L.J. Gangi. 2006. *FIREMON: Fire effects monitoring and inventory system*. US. For. Serv. Gen. Tech Rep. RMRS-GTR-164-CD. 400 p.

Matthews, K., V. DeBlander, L. Pederson, P. Mocettini, and D. Halsey. 2005. *Forest insect and disease conditions report 2002-2004*. US For. Serv. For. Health Prot. Rep. R4-OFO-TR-05-12. 59 p.

McMillin, J.D., and K.K. Allen. 2003. Effects of Douglas-fir beetle (Coleoptera: Scolytidae) infestations on forest overstory and understory conditions in western Wyoming. W. No. Am. Nat. 63:498-506.

Mielke, J.L. 1950. Rate of deterioration of beetle-killed Engelmann spruce. J. For. 48:882-888.

Miller, P.C. 1970. Age distributions of spruce and fir in beetle-killed forests on the White River Plateau, Colorado. Am. Mid. Nat. 83:206-212.

Page, W.G., and M.J. Jenkins. 2007a. Mountain pine beetle induced changes to selected lodgepole pine fuel complexes within the Intermountain Region. For. Sci. 53:507-518.

Parish, R., J.A. Antos, and M.J. Fortin. 1999. Stand development in an old-growth subalpine forest in southern interior British Columbia. Can. J. For. Res. 29:1347-1356.

Pickett, S.T.A. 1989. Space-for-time substitution as an alternative to long-term studies. pg. 110-135 in *Long-term studies in ecology: Approaches and alternatives*, Likens, G.E. (ed.) Springer-Verlag, New York, NY. 214 p.

Rebertus, A.J, T.T. Veblen, L.M. Roovers, and J.N. Mast. 1992. Structure and dynamics of old-growth Engelmann spruce-subalpine fir in Colorado. P. 139-151 in *Old-growth forests in the Southwest and Rocky Mountain Regions, Proc. of a Workshop*, Kaufmann, M.R., W.H. Moir, and R.L. Bassett (tech. coord.). US For. Serv. Gen. Tech. Rep. RM-GTR-213. 201 p.

Romme, W.H. 1982. Fire and landscape diversity in subalpine forests of Yellowstone National Park. Ecol. Monogr. 52:199-221.

SAS Institute Inc. 2005. SAS, version 9.1. Cary, NC.

Schmid, J.M. and R.H. Frye. 1977. *Spruce beetles in the Rockies*. US For. Serv. Gen. Tech. Rep. GTR RM-49. 38 p.

Schmid, J.M. and T.E. Hinds. 1974. *Development of spruce/fir stands following spruce beetle outbreaks*. US For. Serv. Res. Pap. RM-131. 16 p.

Schulz, B. 2003. *Changes in downed and dead woody material following a spruce beetle outbreak on the Kenai Peninsula, Alaska*. US For. Serv. Res. Pap. PNW-RP-559. 10 p.

Scott, J.H., and E.D. Reinhardt. 2001. *Assessing crown fire potential by linking models of surface and crown fire behavior*. US For. Serv. Res. Pap. RMRS-29. 59 p.

Stone, W.E., and M.L. Wolfe. 1996. Response to understory vegetation to variable tree mortality following a mountain pine beetle epidemic in lodgepole pine stands in northern Utah. Vegetation 122:1-12.

Veblen, T.T., K.S. Hadley and M.S. Reid. 1991a. Disturbance and stand development of a Colorado subalpine forest. J. Biogeogr. 18:707-716.

Veblen, T.T., K.S. Hadley, M.S. Reid, and A.J. Rebertus. 1991b. The response of subalpine forests to spruce beetle outbreak in Colorado. Ecol. 72:213-231.

Veblen, T.T., K.S. Hadley, E.M. Nel, T. Kitsberger, M. Reid, and R. Villalba. 1994. Disturbance regime and disturbance interactions in the Rocky Mountain subalpine forest. J. Ecol. 82:125-135.

Wadleigh, L., and M.J. Jenkins 1996. Fire frequency and the vegetative mosaic of a spruce-fir forest in northern Utah. Great Basin Natur 56:28-37.

Whipple S.A., and R.L. Dix. 1979. Age structure and successional dynamics of a Colorado subalpine forest. Am. Mid. Nat. 101:142-158.

Yeager, L.E., and L.E. Riordan. 1953. Effects of beetle-killed timber on range and wildlife in Colorado. Trans. No. Am.Wildl. Conf. 18:596–616.

CHAPTER 3

POTENTIAL FIRE BEHAVIOR IN SPRUCE BEETLE-INDUCED

STAND MORTALITY IN INTERMOUNTAIN

SPRUCE-FIR FORESTS

Abstract

Spruce beetle (*Dendroctonus rufipennis*) induced tree mortality can increase fire intensity and severity resulting from changes to surface and aerial fuels. From inventoried fuel complexes, custom fuel models were developed. The endemic bark beetle condition class had greater amounts of live available canopy fuel and canopy bulk density than either the epidemic and post-epidemic condition classes. Epidemic bark beetle condition classes had the highest amounts of needle litter and1-hr time lag (0-0.64 cm diameter) fuel while the post-epidemic condition class had the highest amount live shrubs and non-woody plants. Fire behavior calculated with BehavePlus from the custom fuel models resulted in substantial differences in fire rates of spread and intensity for each spruce beetle condition class based on identical moisture scenarios and wind speeds. Rates of spread for epidemic and post-epidemic condition classes ranged between 2.0 – 2.9 and 3.0 – 4.5 times faster than the endemic condition class. Fireline intensities ranged from 4.1 – 5.0 times higher in the epidemic condition class and 6.6 – 8.8 times higher in the post-epidemic condition class compared to endemic condition class. An observed lack of overstory sheltering is attributed to increased fire behavior in epidemic and post-epidemic condition classes and has a dominating affect on fire behavior. Post-epidemic condition class rates of spread and fireline intensities at identical midflame

wind speeds were 1.7 and 3.3 times higher, respectively, than endemic parameters.

Relatively, higher rates of spread (4.4 times) and fireline intensities (8.5 times), were

observed between endemic and post-epidemic condition classes when calculated with 6.1

m wind speed adjusted for canopy sheltering. Custom fuel models developed for

epidemic and post-epidemic classes showed similar results to selected established fuel

models; however, no single fuel model exactly predicted fireline intensity and rate of

spread for each of the custom fuel models developed.

Introduction

Understanding fire behavior and its effects are vital to implementing suppression

and prescribed burning tactics (Pyne et al. 1996). Fire behavior in a wildland setting is

often dependant upon, and commonly a result of, complex interactions between weather,

ignition, vegetation, fuel distribution, and topography (Turner and Romme 1994, Bessie

and Johnson 1995, Pyne et al. 1996). Fuel is an essential part of the fire environment

without which there is no substrate to support combustion and fire spread (Brown and

Davis 1973, Pyne et al. 1996). Forest insect epidemics may play an important role in fire

behavior by altering fuel complex characteristics (Arno 2000, Jenkins et al. 2008).

Historically it has been difficult to determine whether or not spruce beetle activity

actually increases the susceptibility of subalpine forests to natural fires (Baker and

Veblen 1990). Falling dead trees and other woody debris create a large fuel build up over

time, but the overall fire danger seems to be exaggerated (Schmid and Hinds 1974, Bebi

et al. 2003, Kulakowski et al. 2003). Mesic and moist understories of herbaceous

material and shrubs, regardless of the amounts of fuels following spruce beetle outbreak

may inhibit fire behavior (Kulakowski et al. 2003). Precipitation associated with summer thunderstorms usually reduces fire probability by boosting the foliar moisture of understory plants and fuel moisture of downed woody debris (Schmid and Hinds 1974). Landscape structure was determined to have greater influence on fire severity than spruce beetle outbreaks (Bigler et al. 2005). Real time fire weather, drought, and ignition point have been shown to have greater influence on fire extent than pre-fire conditions of spruce beetle outbreak (Bigler et al. 2005, Kulakowski and Veblen 2007).

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

Fuel loads of special concern following spruce beetle outbreaks are needles and small twigs falling from the canopy which may support ignition through a surface fuel layer (Knight 1987). Stocks (1987) noted that fire behavior increased following a spruce budworm outbreak due to increased fine fuels resulting from canopy mortality. In

contrast, increases in herbaceous and shrub components had a dampening effect on ignited experimental fires (Stocks 1987). Although increases in live fuels contribute significantly to overall fuel load (Chapter 2), this possibly creates a scenario where fires can be suppressed by high fuel moisture content in understory plants. An increase in understory fuel moisture may hamper fire spread and shorten the fire season (Agee et al. 2002).

It is difficult to fully assess fire potential in spruce beetle altered stands (Schmid and Hinds 1974, Baker and Veblen 1990, Kulakowski et al. 2003). Past fire management has relied on stylized fuel models from other fuel complexes to describe potential fire behavior in these altered stands. The purpose of our study was to utilize inventoried fuel loads discussed in Chapter 2 to compare fire behavior between endemic, epidemic and post-epidemic areas of spruce beetle infestations under varying wind speeds and moisture scenarios. BehavePlus version 3.0.1 was used to assess frontal fire behavior variables of fireline intensity and rate of spread and to calculate crown fire potential by incorporating the Van Wagner (1977) crown fire initiation model coupled with the Rothermel (1991) crown fire spread model. The First Order Fire Effects Model (FOFEM v. 5.21) (Reinhardt et al. 1997) was be used to analyze the amount of fuel and time devoted to flaming combustion and smoldering combustion.

Methods

Study Site Selection

Stand and fuels data was utilized from Chapter 2 for fuel modeling. Forest Health Monitoring aerial detection survey maps (ADS) were first used to locate spruce-fir forests

in Utah that had experienced spruce-beetle outbreaks from the late 1980's to 2006. Polygons of current and older spruce beetle-caused tree mortality were identified. Spruce beetle-caused tree mortality occurring from 2001 to 2006 was considered current. Older spruce beetle-caused tree mortality occurred prior to 2001. The Fishlake and Manti-LaSal National Forests located in central and southeastern Utah, respectively, were selected as study areas both having spruce-fir forests with polygons of current and older spruce beetle-caused tree mortality and uninfested stands within close proximity.

Aerial photographs and 7.5-minute, United States Geological Survey (USGS) topographic maps were next used to delimit potential spruce-fir stands within spruce beetle-affected polygons and adjacent uninfested forests. All stands were then grouped into one of three spruce beetle classifications; endemic, epidemic, and post-epidemic. The endemic class was comprised of uninfested stands or those with less than one currently attacked tree ha-1. The epidemic class consisted of stands within 'current' polygons that had increasing numbers of infested trees and at least two pockets of five trees attacked during the past five years (Bentz and Munson 2000). The post-epidemic class consisted of stands with a minimum of 75% mortality of overstory trees greater than 12.7 cm diameter at breast height (dbh) and no current spruce beetle activity detected during the past five years. Fuels data was collected in these stands as described in Chapter 2.

Data Collection

Plots were systematically established in each sample stand from a randomly selected starting point and spaced 100 by 150 meters apart. Depending on stand size, 16

to 27 plots were sampled in each stand. General information was collected from each plot center including aspect, slope elevation, percent canopy closure, and percent rock cover.

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

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

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

Two fixed diameter micro-plots 1.83 m in diameter were established at 10.67 and

19.81 m along each of the four transects (total of eight per plot) for quantifying fuel bed

intercept height, live/dead shrub and herbaceous cover and height as well as litter/duff

biomass and depth. The data collected in each sub-plot included the percentage of both

live and dead cover and average height for shrubs and herbaceous plants (forbs and

grasses). Duff and litter depth, in addition to fuel intercept height, were measured at the

center of each sub-plot. Fuel intercept height was determined by imposing a 0.3 m plane

perpendicular to the fuel transect and measuring the highest downed woody particle

intercepted by that plane (Brown 1974).

Data Analysis

Calculation of stand characteristics - Live and dead basal area, trees ha^{-1}, and

quadratic mean diameter were calculated for each tree species sampled in the survey for

each stand. The number of downed trees ha^{-1} estimated in post-epidemic stands was

combined with the number of standing trees ha^{-1} from the variable radius plot to

determine dead spruce trees ha^{-1} post-outbreak.

Calculation of canopy fuels - The data collected from sample trees were utilized

to calculate the live available canopy fuel load, canopy base height and canopy bulk

density. Live available canopy fuel load was determined from live crown biomass

estimates using allometric equations, developed by Brown (1978), and based on tree

species and crown class. These equations provided fuel estimates for live foliage and

branchwood less than 0.65 cm. We incorporated all live foliage and 65 percent of the

calculated branchwood in the live available canopy fuel load (Call and Albini 1997, Cruz

et al. 2003). Mean canopy base height was calculated as a weight average using the number of trees ha^{-1} represented by each sampled tree, average over plots within a stand. Canopy bulk density for each plot was then calculated from the live available canopy fuel load divided by the canopy length (i.e. total tree height minus crown base height) of the randomly selected and measured tree on each plot.

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

Statistical analysis - One-way ANOVA was used to assess differences in the various response metrics (i.e. fuel loads and parameters) associated with three levels (i.e., endemic, epidemic, and post-epidemic classes) of spruce beetle infestation and is summarized in Chapter 2 using the MIXED procedure in SAS/STAT software, Version 9.1.3 of the SAS System for Windows. Descriptive statistics of sample stands are represented in Table 3.1.

Table 3.1. The means calculated for selected attributes measured in stands in each spruce beetle condition class in 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.
[†]spruce killed > 4 years ago.

Fuel Model Construction

Custom fuel models for fire behavior predictions were created and analyzed for

endemic, epidemic and post-epidemic spruce beetle condition classes based on methods

described by Page and Jenkins (2007b) and Burgan and Rothermel (1984). The custom

fuel models are based on estimated summaries of litter, 1 hour, 10 hour, 100 hr time lag

fuel weights and live shrub and live herbaceous fuel loads. These summaries are based

on customized fuel model inputs described and required by BehavePlus (Andrews et al.

2003). Shrub, herbaceous and fuel bulk height were averaged to represent the required

surface fuel bed depth. The required 1 hr input was calculated from the combined litter

and 1 hr time lag fuel biomass estimates. Input parameters from Anderson (1982)

standard fuel model 10 were used as guidance to describe fuel complexes affected by

bark beetle mortality. Specifically, heat content, surface area to volume ratios and

moisture of extinction of live and dead fuel from standard fuel model 10 can parameterize

the live and dead fuels present in sampled stands (Page and Jenkins 2007b). All input to

the fuel models are listed in Tables 3.2, 3.3, and 3.4 along 90% confidence levels, and

observed data ranges.

Table 3.2. 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			

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

Table 3.3. 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 | | | |
| | | | Lower | Upper |
	Average	Range	90% CL	90% CL
1-HR Fuel Load (tonne/ha)	7.85	0.94-21.65	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			

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

Surface Fire Behavior

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

Table 3.4. 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			

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

Fire behavior variables can be greatly affected by fuel moisture content, wind speeds, and shelter from surrounding vegetation. For the BehavePlus analysis, surface fire behavior predictions are computed with varying levels of fuel moisture contents, wind speed scenarios, and sheltering, but held constant at a 0% slope. Fuel moisture inputs were taken from Page and Jenkins (2007b) (Table 3.5), which were adapted from Rothermel (1991) for normal, drought, and extreme drought summer fuel moisture conditions. All fire behavior calculations used shaded values except for the post-epidemic fire behavior predictions. Fine dead moisture tables from Rothermel (1983) were used to calculate a difference between shaded endemic and epidemic fuels in addition to un-shaded post-epidemic fuels since the latter can exhibit lower fuel moisture content due to solar radiation (Byram and Jemison 1943). Wind speeds for the surface

fire behavior were calculated at the 6.1 meter level with an adjustment factor assigned on

presence/absence of canopy from the resulting spruce beetle mortality to calculate

midflame wind speed. Endemic stands were assigned an adjustment factor of 0.2, while

epidemic and post-epidemic stands were assigned adjustment factors of 0.3 and 0.4,

respectively (Rothermel 1983), to illustrate the effect of wind in combination with

reduced sheltering created by spruce beetle-induced tree mortality. Endemic (42%),

epidemic (34%) and post-epidemic (27%) canopy closure estimates were used to

determine 6.1 m wind speed adjustment in each spruce beetle condition class.

Table 3.5. Fuel moistures used for fire behavior calculation. Taken from Page and
Jenkins (2007b), adapted from Rothermel (1991).

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

Crown Fire Behavior

Attributes of crown fire potential were also calculated with BehavePlus which is

based off of the Van Wagner (1977) crown fire initiation model and the Rothermel

(1991) crown fire behavior model (Andrews et al. 2003). BehavePlus does not account

for energy released during combustion of 1000 hr fuel in its surface fire module even

though this can be influential for crown fire initiation (Rothermel 1991). The BURNUP

program included in the First Order Fire Effects Model (FOFEM v. 5.21) is able to

compute fuel consumption during flaming and smoldering combustion for 1-hr, 10-hr,

100-hr, 1000-hr sound and rotten material in addition to litter, duff, live herbaceous and live shrub biomass (Reinhardt et al. 1997). Combustion estimates were determined for specific fuel moisture (Table 3.5), relative humidity, and seasonal changes defined with in the FOFEM model (Reinhardt et al. 1997). The inventoried fuel complex was input into FOFEM to obtain the amount of fuel burned during flaming combustion. New fireline intensities were then calculated by inputting that amount of estimated fuel into the fire intensity equations presented in Byram (1959). These recalculated fireline intensities were then input into the crown fire module in BehavePlus to estimate crown fire potential in the absence of the surface fire module (Andrews et al. 2003). Only the estimated fuels consumed during flaming combustion were used to recalculate intensity. This method incorporates the large diameter fuels (> 7.52 cm) for intensity calculations but these fuels are assumed to have no effect on forward rate of spread in this method (Rothermel 1972, Page and Jenkins 2007b).

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

Fuel Model Comparisons

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

Results

Crown Fire Behavior

Critical rates of spread and critical fireline intensities for crown fires are summarized by Table 3.6. Post-epidemic (PEp) stands had the highest likelihood of torching under lower wind speeds due to the lowest canopy base height. However, canopy bulk density was not high enough to sustain a constant active crown fire except when winds reached 50 km/h after torching had commenced. BehavePlus predicted

torching to occur in the PEp class under all fuel moisture scenarios where 6.1 meter

winds occurred at 25 km/hr for normal summer fuel moistures and 20 km/hr under

drought and extreme drought summer moisture conditions.

Table 3.6. Canopy parameters with associated estimated critical rate of spread (ROS) and critical fireline intensity for En and PEp spruce beetle condition classes.

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

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

In the endemic stands (En), BehavePlus did not predict any situation that surface

fire would transition into a passive or active crown fire. However, active crown fire

could be sustained under the defined summer fuel moisture conditions if crowning was to

initiate somewhere else and move into the stand due to sufficient crown bulk density.

Under extreme drought summer fuel moisture conditions, BehavePlus predicted wind

speeds of 30 km/hr would be sufficient to maintain an active crown fire once initiated.

Wind speeds of 30 km/hr under drought summer fuel moisture conditions and 40 km/hr

under normal summer fuel moisture conditions could also sustain active crown fire rate

of spread with our described fuel parameters.

Surface Fire Behavior

The calculated surface fire behavior for the spruce beetle condition classes is primarily described by Figures 3.1 and 3.2. The PEp class was generally characterized by faster rates of spread and higher fireline intensities than the En or epidemic (Ep) classes. The Ep class exhibits the next highest fire behavior characteristics summarized by faster rates of spread and higher fireline intensities than the En class but still lower than the PEp class. Fire behavior predictions for the En condition class gradually increased but more dramatic fire behavior predictions were calculated in Ep and PEp condition classes with considerable increases due to high wind speeds resulting from un-sheltered fuel due to lack of canopy.

When spruce beetle condition classes were compared with identical midflame wind speeds, Ep and PEp classes were identical for rates of spread and very similar with regards to fireline intensity (Figure 3.2). All moisture conditions (normal summer, drought summer, and extreme drought summer) show the same pattern, although specific outputs differ with increases in rates of spread and fireline intensities as fuel moisture values decrease.

Flaming and smoldering combustion were also calculated to be different between spruce beetle condition classes, but correlated with the predicted fire behavior calculated by BehavePlus. Epidemic and post-epidemic classes with high concentrations of large diameter fuel loading had longer smoldering durations as well as greater fuel consumption (Table 3.7). The epidemic class experienced higher fine fuel loads and overall fuel loads which burned for longer durations of time expressed in the flaming

combustion Table 3.7. The epidemic condition had the longest combustion duration and

most fuel consumed during total combustion than any other spruce beetle condition class.
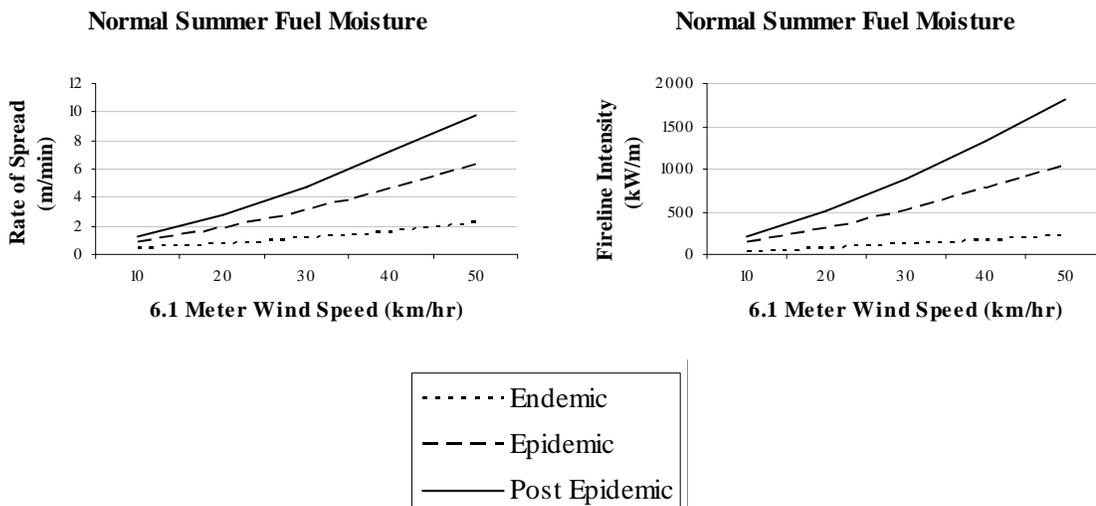

Figure 3.1. Fire behavior variables under normal summer fuel moisture conditions. Areas of endemic, epidemic and post-epidemic beetle activity are compared to each other. Wind adjustment factors were 0.2 for endemic situations, 0.3 for epidemic, and 0.4 for post-epidemic situations to obtain midflame wind speeds based on vegetation sheltering. Fuel moistures were assigned as shaded for endemic and epidemic fuels and un-shaded for post-epidemic fuels

Table 3.7. 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

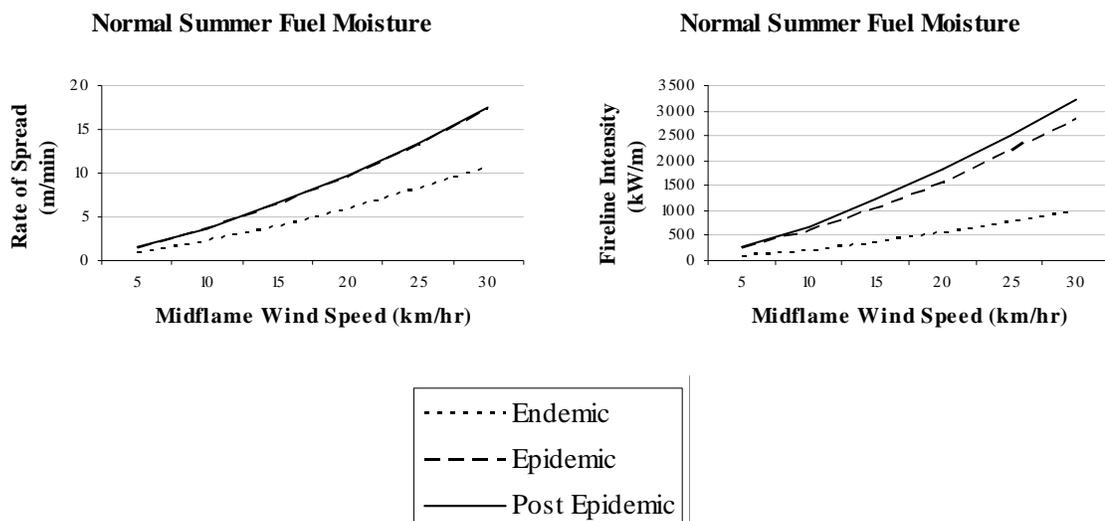**Normal Summer Fuel Moisture**   **Normal Summer Fuel Moisture**

Figure 3.2. 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 un-shaded for post-epidemic fuels.

Fuel Model Comparisons

The closest comparison for our custom endemic fuel model was fuel model timber – litter 5 (TL5) and timber – understory 5 (TU5) when predicting rate of spread. Fuel model TL5 was the closest when predicting fireline intensity (Figure 3.5). The greatest difference was detected at higher wind speeds where fuel model TL5 began to plateau and TU5 continued to increase with the endemic fuel model (Figure 3.5). The timber – litter 3 (TL3), timber – litter 4 (TL4) fuel models and fuel model 8 greatly under-predicted the rates of spread and fireline intensity for the endemic areas sampled, especially at higher wind speeds. Differences between established fuel models and our custom fuel models are more evident at higher wind speeds.
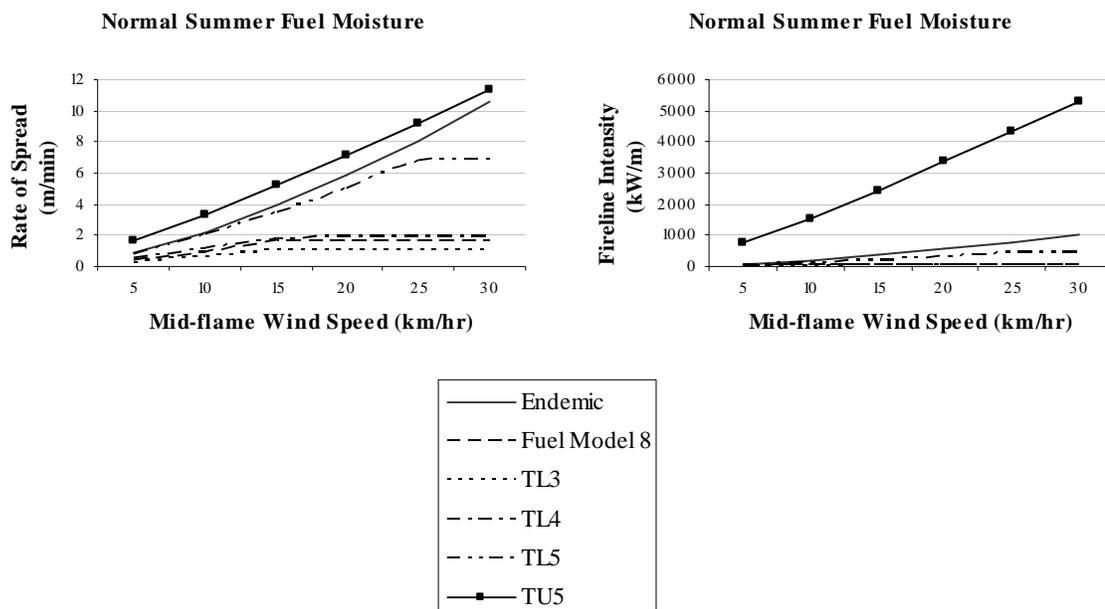
Normal Summer Fuel Moisture   **Normal Summer Fuel Moisture**

Figure 3.3. 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 wind speeds and under normal shaded fuel moisture conditions

The epidemic fuel model appears to be represented closely by a few of the established fuel models (Figure 3.4). Fuel model 10 exhibited very similar rates of spread results when compared to our fuel model. The timber-understory 2 (TU2), timber-understory 3 (TU3), timber understory 4(TU4) models over predicted rate of spread and both timber models (TL5 and TU5) under predicted the rate of spread compared to our custom model (Figure 3.4). Concerning fireline intensity in the epidemic areas, fuel model 10 was also the closest established fuel model for comparison. Fuel model TU2 was equally close with an under prediction compared to our estimates. The TU3, TU4 and TU5 fuel models over predicted fireline intensity while fuel model TL5 under predicted both rates of spread and fireline intensity in the epidemic spruce beetle condition classes.
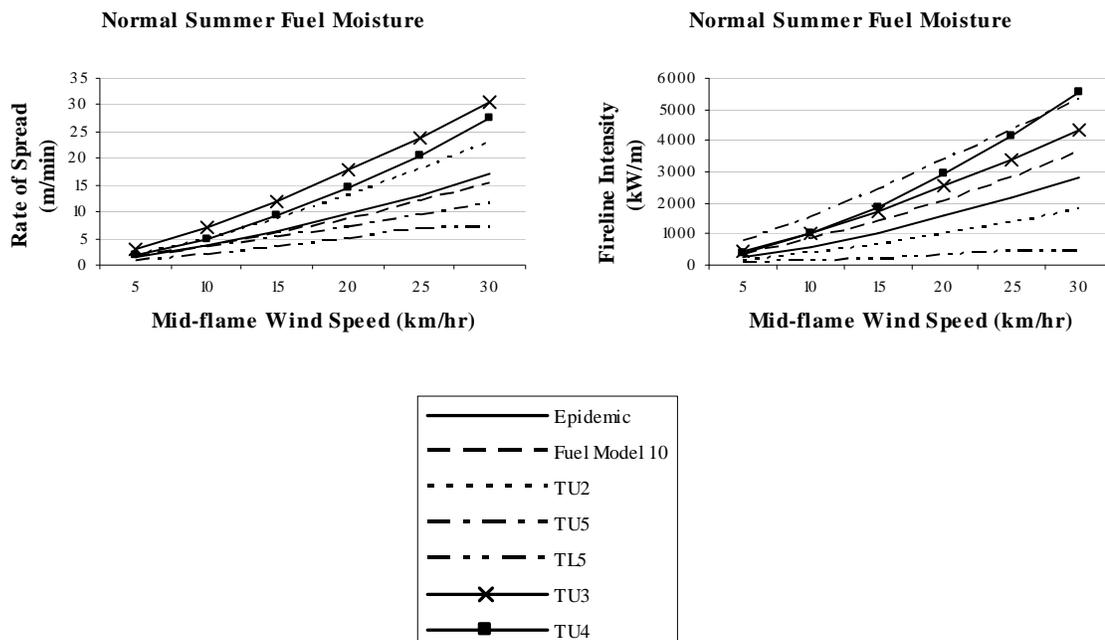
Normal Summer Fuel Moisture　　　　　　**Normal Summer Fuel Moisture**

Figure 3.4. 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 wind speeds and under normal shaded fuel moisture conditions.

In post-epidemic condition classes, rates of spread were well represented by fuel model 10 (Figure 5). Fuel models TU5 and Shrub 4 (SH4) were close representations at lower wind speeds but as wind speed increased, greater differences were observed with a reduction in rate of spread when compared to the post-epidemic fuel model. Fuel model 10 is nearly identical to our post-epidemic calculations regarding rate of spread. Fuel models TU2, TU3, TU4 and Slash-Blowdown – 2 (SB2) appeared to over predict rate of spread as wind speeds increased. Concerning fireline intensity, Fuel model 10 was again a near match with sampled post-epidemic classes. SH4 and TU2 under predicted the fireline intensity while TU3, TU4, TU5 and SB2 over predicted the fireline intensity of the post-epidemic spruce beetle condition classes.
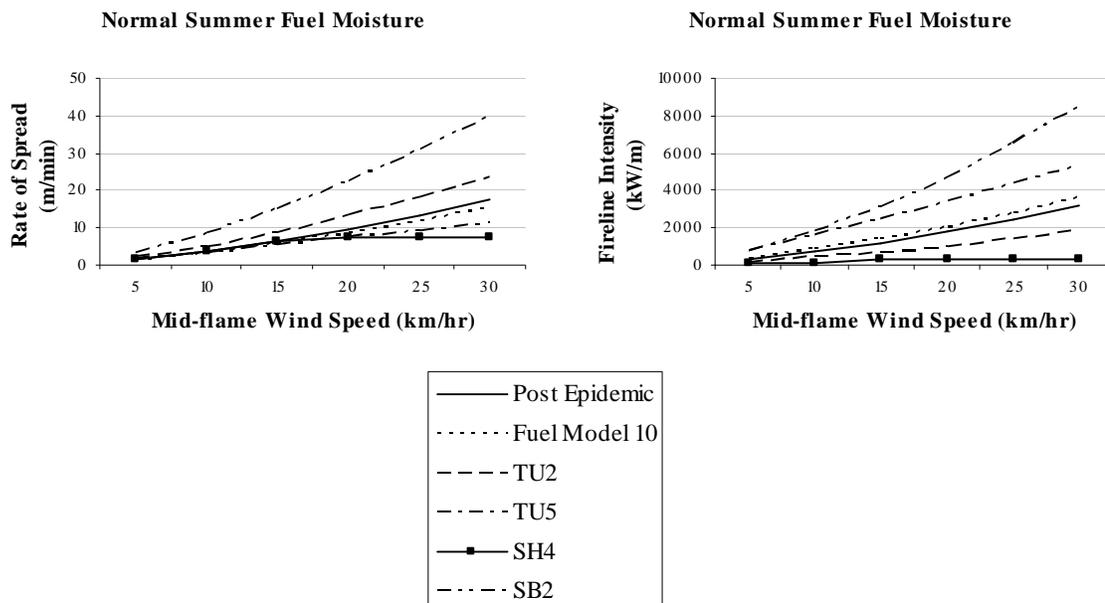
Figure 3.5. Rates of spread and fire line intensity comparisons for post-epidemic areas of beetle activity compared to established fuel models. Fire behavior variables are calculated with the same midflame wind speeds and under normal un-shaded fuel moisture conditions

Discussion

Widespread spruce beetle-induced tree mortality has been considered to increase fire behavior in affected stands (Hopkins 1909). Chapter 2 documented fuel complex alteration following extensive spruce beetle-induced tree mortality. The specific effects of spruce beetle-induced changes to fuels on fire behavior in Intermountain spruce-fir forests have not been previously described from collected fuels data (Schmid and Hinds 1974, Baker and Veblen 1990, Kulakowski et al. 2003). As the live canopy fuel load begins to deteriorate, the increasing dead fuel load in addition to the increasing live herbaceous and shrub components alter the overall fuel complex. As overstory sheltering decreases, more solar radiation and higher wind speeds are able to influence surface fuels (Albini and Baughman 1979). Increases in solar radiation and wind speeds, combined

with increases of live and dead surface fuel, can have complex and prolonged effects on the fire environment in spruce beetle-altered spruce-fir forests (Byram and Jemison 1943, Albini and Baughman 1979, Rothermel 1983).

Crown Fire Behavior

Post-epidemic sites were characterized by low canopy base height and loss of canopy bulk density (Chapter 2). This has resulted in predictions of more intense crown fire activity in the post-epidemic classes, due to torching, compared to the endemic class under the same weather parameters. In contrast, endemic areas had high enough canopy bulk density to support active crown fire spread. However, canopy base heights were not low enough in our sample stands for torching to initiate. Therefore, no crown fire would initiate unless it transitioned into an active crown fire outside the sample stand, and then moved into the described stands.

The potential for crown fire behavior within current epidemic stands is debatable. Dead needles can be ignited at lower temperatures than live foliage (Stockstad 1975, Xanthopoulos and Wakimoto 1993). High levels of tree mortality and dead canopy may increase crown fire potential due to a mixture of live and dead foliage in epidemic situations (Page and Jenkins 2007b). The moisture gradient of foliage from live to currently attacked and then to dead trees with foliage is unclear on crown fire behavior. Any increase in the rate of needle cast could decrease the potential for crown fire behavior in spruce beetle-altered stands even though dead foliage ignites easier than live. Therefore, crown fire behavior in the epidemic stands is currently difficult to predict.

Spruce-fir forests are generally susceptible to high-intensity stand replacing fires attributed to naturally developing fuels complexes (Taylor and Fonda 1990, Johnson 1992, Long 1994, Arno 2000, Johnson et al. 2001). These naturally developed fuels complexes, combined with increases in advance spruce and subalpine fir regeneration in addition to lower live canopy base height in post-epidemic stands, can eventually provide a period of increased flammability. Regeneration will continue to grow if un-disturbed, canopy bulk density will increase and limit the amount of live surface fuel in the stand, standing dead trees will remain in the canopy for long periods of time while gradually continue to maintain levels of downed woody debris on the forest floor. This scenario may provide for intense surface fires, continuous aerial fuels including remaining dead trees in the canopy, and an interface between with abundant ladder fuels developing in post-outbreak stands, thus increasing potential flammability in stands affect by spruce beetle-induced tree mortality.

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

Surface Fire Behavior

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

Due to the abundance of fine fuels, , calculations for the epidemic condition class were still expected to produce higher rates of spread and fireline intensity compared to the endemic class, once overstory sheltering effects were removed. The post-epidemic fire behavior calculations were contradictory to initial expectations. Due to the abundance of live fuel woody fuel, we expected to see a decrease in fire behavior when comparing epidemic and post-epidemic stands. Live fuels are often considered a heat sink when large amounts exist with adequate fuel moisture (Rothermel 1983, Andrews 1986, Stocks 1987, Agee et al. 2002). However, our data indicate sequential increases in potential fire behavior between endemic, epidemic and post-epidemic classes following spruce beetle outbreaks in Intermountain spruce-fir forests regardless of the increase of overall live fuel. Releases in live fuel are important to consider in contributions to

overall fuel load and as a potential heat sink when predicting fire behavior following spruce beetle activity.

Increased live fuels in our custom fuel models are not adequately reflected as a potential heat sink in current fire behavior calculation models. Fire behavior prediction models such as BehavePlus are not currently designed to accurately incorporate live fuel in calculations (Weise et al. 2005, Sun et al. 2006). This leaves adjustment of user defined fuel model inputs such as fuel moisture of extinction, live fuel moisture content, and live fuel heat content to obtain replicable results to what is observed in the field. Although currently established fuel models and fire behavior calculation models have been invaluable for past decades, evaluation is important to consider. Especially when compositions of live fuels from differing ecosystems and elevations reflect extreme variations of fire behavior potential under the same burning conditions (i.e. chaparral versus *Ribes* spp). Further research is needed to better parameterize fire prediction in differing fuel strata such as compositions of fuel mixtures regarding type, arrangement, species and moisture retention (Romme 1982, Swetnam and Baisan 1996, Scott and Reinhardt 2001, Riccardi et al. 2007, Sandberg et al. 2007).

Current research in fire behavior modeling is attempting to estimate fire behavior in heterogeneous, but spatially explicit wildland fuel beds. These methods are incorporating the input of fuel particles $\geq$ to 7.62 cm, types of litter and understory species composition, in addition to the input of fuel inventories instead of stylized fuel models (Ottmar et al. 2007, Riccardi et al. 2007, Sandberg et al. 2007). Input from researchers and land managers has been sought in model formulation and testing to improve fire behavior predictions (Berg 2007). This new concept in fuel modeling, The

Fuel Characteristic Classification System (FCCS), is characterized by realistic multi-strata fuel beds that may better represent fuels than stylized fuel models in response to demand from scientists and managers seeking more accurate fire behavior predictions for operational use, planning, and simulations (Berg 2007). Our data provide detailed information describing fuel beds of spruce stands altered by differing levels of spruce beetle-induced tree mortality and can be used in this new research.

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

Fuel Model Comparison

In endemic areas, no model closely predicted both rate of spread and intensity. Fuel model 10 was the most accurate fuel model considering fire behavior calculations for epidemic and post-epidemic stands. This model may represent the epidemic and post-

epidemic areas well because of the large amounts of live fuel and increased fuel bed depth post-outbreak which are similar to the established fuel model. As the woody material increases following epidemics, especially litter fuel load, the predictions more closely represent those of fuel model 10. The increase of live fuels and litter in epidemic stands and live fuels in post-epidemic stands provide similar fire behavior calculations. The differences existing between custom fuel models will compound as wind speed increases and the sheltering from overstory is reduced between endemic, epidemic and post-epidemic stands.

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

Limitations of the fire prediction model and fuel moisture data inputs used for live fuels are important for fire behavior analysis. Our calculations are based on previously defined fuel moisture scenarios developed by Rothermel (1991). The calculated fire behavior descriptions are also based on assumptions and limitations that are inherent to the fire prediction model. The main assumption in the model used were a continuous and

uniform fuel bed in contact with the ground, no incorporation of woody pieces larger than

7.62 cm, predictions limited to surface fire, weather variables un-changed during the

calculation, and spotting is not incorporated into overall rate of spread (Rothermel 1972).

Further research will be needed to determine if different compositions of live fuels burn

differently and if increases in live surface fuel cover create sheltering for surface fuel

reducing overall ignition as opposed to expected flammability.

Conclusion

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 behavior 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 calculated with our custom fuel models.

Literature Cited

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

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

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

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

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

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

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

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

Arno, S.F. 2000. Fire in western forest ecosystems: effects of fire on flora. P. 97-120 in *Wildland fire in ecosystems*, Brown, J.K., and J. K. Smith (eds.). US For. Serv. Gen. Tech. Rep. RMRS-GTR-42-vol. 2. 257 p.

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

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

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

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

Bessie, W.C., and E.A. Johnson. 1995. The relative importance of fuels and weather on fire behavior in subalpine forests. Ecol. 76:747-762.

Bigler, C., D. Kulakowski, and T.T. Veblen. 2005. Multiple disturbance interactions and drought influence fire severity in Rocky Mountain subalpine forests. Ecol. 86:3018-3029.

Brown, A.A., and K.P. Davis. 1973. *Forest fire: control and use. 2nd ed*., McGraw-Hill, New York, NY, 686 p.

Brown, J.K. 1974. *Handbook for inventorying downed woody material*. US For. Serv. Gen. Tech. Rep. INT-GTR-16. 24 p.

Brown, J.K. 1978. *Weight and density of crowns of Rocky Mountain conifers*. US. For. Serv. Res. Pap. INT-197. 56 p.

Brown, J.K., R.D. Overheu, and C.M. Johnston. 1982. *Handbook for inventorying surface fuels and biomass in the interior West*. US For. Serv. Gen. Tech. Rep. INT-GTR-129. 48 p.

Burgan, R.E., and R.C. Rothermel. 1984. *BEHAVE: Fire behavior prediction and fuel modeling system-FUEL subsystem*. US For. Serv. Gen. Tech. Rep. INT-GTR-167. 126 p.

Byram, G.M. 1959. Combustion of forest fuels. P. 61-89 in *Forest fire: Control and use*, 2nd ed., Davis, K.P. (ed.). McGraw-Hill, New York, NY. 686 p.

Byram, G.M., and G.M. Jemison. 1943. Solar radiation and forest fuel moisture. J. Agric. Res. 67: 149-176.

Call, P.T., and F.A. Albini. 1997. Aerial and Surface fuel consumption in crown fires. Int. J. Wild. Fire 7:259-264.

Cruz, M.G., M.E. Alexander, and R.H. Wakimoto. 2003. Assessing canopy fuel stratum characteristics in crown fire prone fuel types of western North America. Int. J. Wild. Fire. 12:39-50.

Cruz, M.G., M.E. Alexander, and R.H. Wakimoto. 2005. Development and testing of models for predicting crown fire rate of spread in conifer forest stands. Can. J. For. Res. 35:1626-1639.

DeRose, R.J., and J.N. Long. 2007. Disturbance, structure, and composition: spruce beetle and Engelmann spruce forest on the Markagunt Plateau, Utah. For. Ecol. Manage. 244:16-23.

DeRose, R.J., and J.N. Long. 2009. Wildfire and spruce beetle outbreak: simulation of interacting disturbances in the central Rocky Mountains. Ecosci. 16:28-38.

Hopkins, A.D. 1909. *Practical information on the Scolytid beetles of North American forests. I. Bark beetles of the Genus Dendroctonus*. US Bureau of Entomol. Bull. 83. U.S. Gov't Printing Office, Washington, DC. 169 p.

Jenkins, M.J., E. Hebertson, W. Page, and C.A. Jorgensen. 2008. Bark beetles, fuels, fires and implications for forest management in the Intermountain West. For. Ecol. Manage. 254:16-34.

Jenkins, M.J., C.A. Dicus, and E.G. Hebertson. 1998. Post-fire succession and disturbance interactions on an intermountain subalpine spruce-fir forest. P. 219-229 in *Proceedings, Symposium: Fire in Ecosystem Management: Shifting the paradigm from suppression to prescription*, Pruden, T. L., and L. A. Brennan, (eds.). Tall Timbers Fire Ecology Conference Proceedings, No. 20. Tall Timbers Research Station, Tallahassee, FL. 460 p.

Johnson, E.A. 1992. *Fire and vegetation dynamics: studies from the North American boreal forests*. Cambridge University Press, Cambridge, United Kingdom. 129 p.

Johnson, E.A., K. Miyanishi, and S.R.J. Bridge. 2001. Wildfire regime in the Boreal forest and the idea of suppression and fuel buildup. Conserv. Bio. 15:1554-1557.

Knight, D.H. 1987. Parasites, lightning, and the vegetation mosaic in wilderness landscapes. P. 59-83 in *Landscape heterogeneity and disturbance*, Turner, M.G. (ed.). Springer-Verlag, New York, NY. 239 p.

Kulakowski, D., T.T. Veblen, and P. Bebi. 2003. Effects of fire and spruce beetle outbreak legacies on the disturbance regime of a subalpine forest in Colorado. J. Biogeogr. 30:1445-1456.

Kulakowski, D., and T.T. Veblen. 2007. Effect of prior disturbance on the extent and severity of wildfire in Colorado subalpine forests. Ecol. 88:759-769.

Long, J.N. 1994. The middle and Southern Rocky Mountain Region. Pages 335-386 in *Regional silviculture of the United States*, *3rd ed*., Barrett, J.W. (ed.). John Wiley and Sons, New York, NY. 643 p.

Lertzman, K.P., and C.J. Krebs. 1991. Gap phase structure of a subalpine old-growth forest. Can. J. For. Res. 21:1730-1741.

Lutes, D.C., R.E. Keane, J.F. Caratt. C.H. Key, N.C. Benson, S. Sutherland, and L.J. Gangi. 2006. *FIREMON: Fire effects monitoring and inventory system*. US. For. Serv. Gen. Tech Rep. RMRS-GTR-164-CD. 400 p.

Ottmar, R.D., D.V. Sandberg, C.L. Riccardi, and S.J. Prichard. 2007. An overview of the Fuel Characteristic Classification System – Quantifying, classifying, and creating fuelbeds for resource planning. Can. J. For. Res. 37:2383-2393.

Page, W.G., and M.J. Jenkins. 2007a. Mountain pine beetle induced changes to selected lodgepole pine fuel complexes within the Intermountain Region. For. Sci. 53:507-518.

Page, W.G., and M.J. Jenkins. 2007b. Predicted fire behavior in selected mountain pine beetle – infested lodgepole pine. For. Sci. 53:662-674.

Pyne, S.J., P.L. Andrews, and R.D. Laven. 1996. *Introduction to wildland fire, 2nd ed.*, John Wiley and Sons, New York, NY. 769 p.

Reinhardt, E.D., R.E. Keane, and J.K. Brown. 1997. *First order fire effects model: FOFEM 4.0, user's guide*. US For. Serv. Gen. Tech. Rep. INT-GTR-344. 65 p.

Riccardi, C.L., R.D. Ottmar, D.V. Sandberg, A. Andreu, E. Elman, K. Kopper, and J. Long. 2007. The fuelbed: a key element of the Fuel Characteristic Classification System. Can. J. For. Res. 37:2394-2412.

Romme, W.H. 1982. Fire and landscape diversity in subalpine forests of Yellowstone National Park. Ecol. Monogr. 52:199-221.

Romme, W.H., and D.G. Despain. 1989. Historical perspective on the Yellowstone fires of 1988. Biosci. 39:695-699.

Rothermel, R.C. 1972. *A mathematical model for predicting fire spread in wildland fuel*s. US For. Serv. Res. Pap. INT-115. 40 p.

Rothermel, R.C. 1983. *How to predict the spread and intensity of forest and range fires*. US For. Serv. Gen. Tech. Rep. INT-GTR-143. 161 p.

Rothermel, R.C. 1991. *Predicting behavior and size of crown fires in the northern Rocky Mountains*. US For. Serv. Res. Pap. INT-438. 46 p.

Rothermel, R.C., R.A. Wilson Jr., G.A. Morris, and S.S. Sackett. 1986. *Modeling moisture content of fine dead wildland fuels: Input to the BEHAVE fire prediction system*. US For. Serv. Res. Pap. INT-359. 61 p.

Sandberg, D.V., C.L. Riccardi, and M.D. Schaaf. 2007. Reformulation of Rothermel's wildland fire behaviour model for heterogeneous fuelbeds. Can. J. For. Res. 37:2438-2455.

SAS Institute Inc. 2005. SAS, version 9.1. Cary, NC.

Schmid, J.M., and T.E. Hinds. 1974. *Development of spruce/fir stands following spruce beetle outbreaks*. US For. Serv. Res. Pap. RM-131. 16 p.

Schulz, B. 2003. *Changes in downed and dead woody material following a spruce beetle outbreak on the Kenai Peninsula, Alaska*. US For. Serv. Res. Pap. PNW-RP-559. 10 p.

Scott, J.H. 2006. *Comparison of crown fire modeling systems used in three fire management applications*. US For. Serv. Res. Pap. RMRS-RP-58. 25p.

Scott, J.H., and E.D. Reinhardt. 2001. *Assessing crown fire potential by linking models of surface and crown fire behavior*. US For. Serv. Res. Pap. RMRS-29. 59 p.

Scott, J.H., and R.E. Burgan. 2005. *Standard fire behavior fuel models: A comprehensive set for use with Rothermel's surface fire spread model*. US For. Serv. Gen. Tech. Rep. RMRS-GTR-153. 72 p.

Stocks, B.J. 1987. Fire potential in the spruce budworm-damaged forests of Ontario. For. Chron. 63:8-14.

Stockstad, D.S. 1975. *Spontaneous and piloted ignition of pine needles*. US For. Serv. Res. Note INT-194. 14p.

Sun, L., Z. Xiangyang, S. Mahalingam, and D.R. Weise. 2006. Comparison of burning characteristics of live and dead chaparral fuels. Comb. and Flame. 144:349-359.

Swetnam, T.W., and C.H. Baisan. 1996. Historical fire regime patterns in the southwestern United States since AD 1700. P. 11-32. in *Fire effects in southwestern forests, Proc. of the Second La Mesa Fire Symposium*, Allen, C.D. (ed.). US For. Serv. Gen. Tech. Rep. RM-GTR-286. 216 p.

Taylor, K. L., and R.W. Fonda. 1990. Woody fuel structure and fire in subalpine fir forests, Olympic National Park, Washington. Can. J. For. Res. 20:193-199.

Turner, M.G, and W.H. Romme. 1994. Landscape dynamics in crown fire ecosystems. Landscape Ecol. 9:59-77.

Van Wagner, C.E. 1977. Conditions for the start and spread of crown fire. Can. J. For. Res. 7: 23-34.

Veblen, T.T. 1986a. Age and size structure of subalpine forests in the Colorado Front Range. Bull. Torrey Bot. Club. 113:225-240.

Veblen, T.T. 1986b. Treefalls and the coexistence of conifers in subalpine forests of the Central Rockies. Ecol. 67:644-649

Weise, D.R., Z. Xiangyang, S. Lulu, and S. Mahalingam. 2005. Fire spread in chaparral. – 'go or no-go'? Int. J. Wild. Fire. 14:99-106.

Xanthopoulos, G., and R.H. Wakimoto. 1993. A time to ignition-temperature-moisture relationship for branches of three western conifers. Can. J. For. Res. 23:253-258.

CHAPTER 4

SUMMARY

Past and current research regarding fire and fuels in stands affected by spruce beetle-induced tree mortality has been summarized by Chapters I, II, and III of this document. Traditional concepts of fuel accumulation modeling and fire behavior calculation have been used to produce the results and conclusions summarized within the body of this thesis. Traditional ideology has conceptualized that alterations of the fuel complex following spruce beetle-induced tree mortality increases occurrence, behavior, and effects of wildland fire in spruce-fir forests. The objective of this study was to quantify specific changes to the fuel complex and predict fire behavior following fuel complex alterations.

Sampling began with 15 spruce-fir stands in central and southern Utah where endemic, epidemic and post-epidemic spruce beetle populations existed. Sample means from fuel load variables were then compared between these sampled endemic, epidemic and post-epidemic condition classes. The most noticeable changes to the fuel complex occurred in the live surface fuel components, fine downed woody debris, and the reduction of canopy fuel. Live overstory fuels, live available canopy fuel load (ACFL), live canopy bulk density (CBD), and live canopy base height (CBH) began declining during the onset of the spruce beetle outbreak and were lowest in epidemic and post-epidemic classes. Fine woody fuels (1 hr, 10 hr, and litter) were highest in the epidemic stands after deposition from the canopy on the forest floor and prior to decomposition. Duff and sound and rotten large diameter woody fuels were not found to be significantly

different between any condition classes of spruce beetle activity. The highest amount of live surface fuel (biomass and height) was in the epidemic and post-epidemic condition classes for shrubs and herbaceous components.

Surface fire behavior in each spruce beetle condition class was different and differed from established fuel models used in traditional fire behavior calculation. Post-epidemic classes displayed higher estimated rates of spread and fireline intensities despite the large amount of live herbaceous and shrub components of the surface fuel substrate. This has primarily been attributed to the lack of canopy sheltering on the surface fuels from wind and solar radiation, in addition to increases in overall surface fuel bed depth. When spruce beetle condition classes were compared with similar midflame wind speeds, both epidemic and post-epidemic classes yielded very similar results in rate of spread and intensity. Endemic areas had the lowest rates of spread and fireline intensities of all condition classes when compared using midflame and 6.1 m wind speeds. When the custom fuel models were compared to the established fuel models, no established model exactly reflected the custom fuel model results. Fuel model 10 was the closest comparison in both rates of spread and fireline intensity for epidemic and post-epidemic stands.

Probability of crown fire initiation was highest in post-epidemic condition classes due to low sampled canopy base height. However, active crown fire spread was limited due to low calculated canopy bulk density. Endemic classes had enough canopy bulk density to support active crown fire spread given the proper conditions, but the canopy base height was high enough that crown fire initiation was unlikely in the stands sampled and the weather parameters used. Calculated crown fire potential for post-epidemic areas

and endemic areas required knowledge of how the 1000 hr fuel contributed to overall intensity of the flaming front. Since there was no significant difference in 1000 hr fuel loads, the effect was marginal on crown fire behavior and initiation. Areas with high fine fuel loads experienced greater flaming combustion while areas with large diameter fuels and duff experienced greater smoldering combustion. The epidemic condition class produced greater flaming and smoldering combustion than either endemic or post-epidemic condition classes.

Understanding disturbance interactions in spruce-fir forests has been a recent focus of wildland ecology. Multiple studies have analyzed aspects of spruce beetle and fire disturbance interactions. Quantified fuel complexes and interpretations of potential fire behavior that this research describes should increase understanding of the effects of spruce beetle-induced tree mortality in spruce-fir forests. While no established fuel model reproduced our results exactly, it is important to remember that no model is an absolute representation of real time fire events. These fire behavior calculations are merely estimates given the current limitations of fire behavior prediction models. This research will support researchers, fire planners, and suppression operations in fuel complexes shaped by spruce beetle-induced tree mortality and its associated fire behavior. While acknowledging past research, this research will also add and promote future research into knowledge about disturbance interactions in spruce-fir forests.

APPENDICES

Appendix. Calculated rate of spread
and fireline intensity for figures in Chapter 3

A.1. Custom fuel model calculations with identical midflame wind speed and normal summer fuel moisture.

Midflame Wind Speed (km/hr)	Rate of Spread (m/min)			Fireline Intensity (kW/m)		
	Endemic	Epidemic	Post-Epidemic	Endemic	Epidemic	Post-Epidemic
5	0.9	1.4	1.5	84	238	284
10	2.2	3.6	3.7	207	588	695
15	3.9	6.3	6.5	365	1039	1214
20	5.9	9.6	9.8	551	1570	1817
25	8.1	13.2	13.4	762	2170	2492
30	10.6	17.2	17.4	994	2832	3231

A.2. Custom fuel model calculations with 6.1 meter wind speed and normal summer fuel moisture.

6.1 Meter Wind Speed (km/hr)	Rate of Spread (m/min)			Fireline Intensity (kW/m)		
	Endemic	Epidemic	Post-Epidemic	Endemic	Epidemic	Post-Epidemic
10	0.4	0.8	1.2	33	135	218
20	0.7	1.8	2.8	64	299	516
30	1.1	3.1	4.8	105	509	891
40	1.6	4.6	7.2	153	758	1328
50	2.2	6.3	9.8	207	1039	1817

A.3. Custom fuel model calculations with 6.1 meter wind speed and drought summer fuel moisture.

6.1 Meter Wind Speed (km/hr)	Rate of Spread (m/min)			Fireline Intensity (kW/m)		
	Endemic	Epidemic	Post-Epidemic	Endemic	Epidemic	Post-Epidemic
10	0.5	1.1	1.6	47	197	325
20	0.9	2.4	3.8	92	437	770
30	1.4	4.1	6.5	150	746	1330
40	2.1	6.1	9.8	218	1110	1981
50	2.8	8.3	13.3	295	1521	2710

A.4. Custom fuel model calculations with 6.1 meter wind speed and extreme drought summer fuel moisture.

6.1 Meter Wind Speed (km/hr)	Rate of Spread (m/min)			Fireline Intensity (kW/m)		
	Endemic	Epidemic	Post-Epidemic	Endemic	Epidemic	Post-Epidemic
10	0.5	1.2	1.8	57	236	396
20	1	2.7	4.3	110	523	938
30	1.6	4.6	7.5	180	893	1620
40	2.3	6.8	11.1	261	1328	2414
50	3.2	9.3	15.2	353	1820	3302