

Fuel and Fire Behavior in High-Elevation Five-Needle Pines Affected by Mountain Pine Beetle

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Extended Abstract

Abstract—Bark beetle-caused tree mortality in conifer forests affects the quantity and quality of forest fuels and has long been assumed to increase fire hazard and potential fire behavior. In reality, bark beetles and their effects on fuel accumulation and subsequent fire hazard have only recently been described. We have extensively sampled fuels in three conifer forest types (lodgepole pine, Engelmann spruce and Douglas-fir) and described bark beetle/fuels/fire interactions within the context of intermountain disturbance regimes. Our data sets were developed by measuring the forest biomass in stands with endemic, epidemic and post-epidemic bark beetle populations and comparing the quantity and quality of fuels present within each beetle population phase. Surface and canopy fuels data were used to create fuel models that are customized to represent the actual fuel conditions created by the bark beetles. Fire behavior predictions based on these custom fuel models showed that surface fire rate of spread and fireline intensities were higher in the current epidemic stands than in the endemic stands due to increased litter and fine fuel in all three forest types. Bark beetles selectively remove large diameter trees altering stand level canopy fuels and promoting release of herbaceous and shrub species which further affects fire potential. Bark beetle-caused tree mortality decreases vegetative sheltering which affects mid-flame wind speed and increases rate of fire spread. Passive crown fires are more likely in post-epidemic stands, but active crown fires are less likely due to decreased aerial fuel continuity. Intense surface fires are possible in post epidemic stands, but they are very much dependent on the rate at which dead trees fall.

Our present research will utilize this information in addition to spatial data to describe the influence of mountain pine beetle (MPB) on fuels and fire behavior in stands of high-elevation five-needle pines, including whitebark, limber, foxtail, Rocky Mountain bristlecone, and Great Basin bristlecone pine.

Introduction

Bark beetles in the genus *Dendroctonus* (Coleoptera: Curculionidae, Scolytinae) are native insects that play an important role in western North American coniferous forest ecosystems. At low population levels bark beetles infest large, old, often injured trees, thus recycling nutrients and creating openings for regeneration. When landscapes are composed of many susceptible host trees eruptive outbreaks are possible, especially during warm, dry periods which

weaken otherwise vigorous trees and decrease bark beetle development time. Episodic bark beetle outbreaks have been a common feature of coniferous forests at least since the last glacial retreat about 13,000 years ago. New evidence, however, supports the hypothesis that anthropogenic forcing of global temperatures has increased the vulnerability of whitebark pine to mountain pine beetle MPB (*D. ponderosae* Hopkins) attack and bark beetle population potential (Logan, these proceedings).

It is equally important to note, however, that bark beetle outbreaks are not possible without susceptible stands which are usually dense stands comprised of a large percentage (>60%) of mature, large diameter host trees. Changes to fuels complexes and fire behavior due to 20th century fire suppression and exclusion policies, livestock grazing and a more recent decrease in active timber management has created an abundance of large, old conifers in western North America. Baker (2009) suggested that the rash of large, human-caused wildfires in the late 1800s may have also contributed to susceptible landscapes. As a result, dramatic bark beetle outbreaks have occurred during the last 20-30 years involving spruce beetle (*D. rufipennis* Kirby) in Engelmann spruce, Douglas-fir beetle (*D. pseudotsugae* Hopkins) in Douglas-fir and mountain pine beetle in lodgepole pine (USDA 2009). Since about 2000 mountain pine beetle-caused tree mortality has increased in whitebark and limber pines and it is reasonable to assume that susceptible stands of other high-elevation, five-needle white pines are also at risk.

The scientific community, land managers, and the public at large have expressed concern that the widespread conifer mortality could increase wildfire occurrence and severity. Jenkins and others (2008) reviewed available literature on bark beetles, fuels and fires and described the changes to fuel bed characteristics and predicted fire behavior resulting from bark beetle activity. Other studies have elaborated the relationships for specific bark beetle/host systems including Douglas-fir in Utah (Hill and Jenkins, *in review*), lodgepole pine in Utah, southern Idaho (Page and Jenkins 2007a and b), Colorado (Klutsch and others 2009) and Wyoming (Simard and others 2011) and Engelmann spruce in Utah (Jorgensen and Jenkins 2011, Jorgensen and Jenkins, *in review*). From these papers it is possible to provide a general description of the effect of bark beetle activity on conifer fuels and the influence that an altered fuel complex has on fire

hazard and potential fire behavior. However, little research has been conducted to describe the relationship between bark beetle-caused tree mortality and wildfire in other forest systems, particularly for high-elevation five-needled pine species.

The purpose of this paper is to describe our current understanding of the influence of bark beetles on fuels and fire behavior in the conifers studied and how this may be related to high-elevation five-needle pine species and ecosystems.

Bark Beetle Effects on Fuel Bed Characteristics

The general changes in seven fuel bed characteristics over the course of a bark beetle rotation were described by Jenkins and others (2008). The bark beetle rotation begins when a stand becomes susceptible to bark beetle infestation and is capable of supporting an outbreak or epidemic. This bark beetle condition class is referred to as endemic and tree mortality is restricted to a few, weakened, or overmature individuals. During the endemic phase generally only one to several trees are attacked per hectare (Bentz and Munson 2000). Epidemics occur when otherwise healthy, but susceptible stands, are subjected to a period of short-term stress, such as drought. Under stressful conditions, aggressive bark beetle species, like MPB, can overcome host tree resistance resulting in rapidly increasing population numbers. During the epidemic phase 80 percent or more of susceptible trees are killed. The length of the epidemic phase varies with conifer species, but generally lasts 5 to 10 years and ending when most large diameter trees have been killed and bark beetle population levels decline. At this time, stands enter the post-epidemic phase which lasts for decades to centuries until small surviving or newly regenerated host trees again reach susceptible age and size.

Litter and Fine Woody Fuels

Significant increases in needle litter amount and depth, and increases in woody fuels less than 0.64 cm occur between the endemic and epidemic MPB phase in lodgepole pine (Page and Jenkins 2007a, Klutsch and others 2009). Figures 1a and 1b show similar changes in whitebark pine fuels in Wyoming. During outbreaks, the accumulation of these fuels occurs in pulses beneath the crowns of individual attacked trees. We expect that needle accumulation under high-elevation five-needle pines, especially foxtail and bristlecone species, will be greater than described for lodgepole pine since these species tend to retain a greater proportion of older needles. Increased duration of needle retention will also result in lesser litter amounts deposited in endemic stands of high-elevation five-needle pines, than in stands of lodgepole pine, or other pine species.

The rate of accumulation and spatial distribution of these fuels is dependent upon the arrangement of individual attacked trees within the stand and the number of

trees attacked each year. The rate of litter and fine woody fuel accumulation under an individual tree is also affected by crown condition as described later. Litter decomposes to duff within one to two years and results in a balance between litter accumulation and decomposition. Litter accumulation ceases when all needles have fallen off an individual attacked tree. Duff depth and amount increases to a maximum the year following the end of needle fall. Fine woody fuels will continue to accumulate as snow and wind break small twigs off standing snags. There is considerable variability in the accumulation of larger woody fuel and may continue for several decades into the post-epidemic phase. By the end of the epidemic phase, litter, fine woody fuel, and duff accumulations decrease and quickly return to endemic background levels.

Herbaceous and Shrub Fuels

The death of an overstory tree allows more available moisture and sunlight to reach both live and dead herbaceous and shrub fuels. The relative abundance and composition of herbaceous and shrub fuels very much depends on the biophysical environment and moisture regime, and spatial distribution and density of overstory trees. In general however, both fuel types increase dramatically in height and aerial coverage immediately following the death of the overstory tree (Figure 1c). Initially herbaceous fuels are most abundant, but are replaced by woody shrubs which will dominate well into the post-epidemic phase. Shrub abundance will begin to decrease as conifer cover increases reducing available moisture and sunlight beneath the developing canopy.

Coarse Woody Fuel and Fuel Bed Depth

Woody fuels larger than 0.64 cm in diameter do not increase significantly until well into the post-epidemic phase as large branches from standing snags fall to the forest floor. The fall rate for trees killed by bark beetles is not well known and varies considerably with topography (slope steepness, position, and aspect for example), soils, decay pathogens and exposure of the stand to wind. The accumulation of larger fuels increases woody fuel bed depth (Page and Jenkins 2007a, Jorgensen and Jenkins 2010). During the post-epidemic phase a balance between accumulation and decay is achieved as coarse woody debris decomposes. Deep winter snowpacks characteristic of high elevation pine sites mechanically compact fuels which decreases fuel bed depth during the post-epidemic phase.

Bark Beetle-Affected Surface and Canopy Fuel Matrices in High-Elevation, Five-Needle Pine Systems

Figure 2 describes the bark beetle-affected surface and canopy fuel matrices and the important variables affecting crown fire initiation and spread during the course of the bark beetle rotation in high-elevation five-needle pine species.



Figure 1. Bark beetle-affected crown and surface fuels characteristics of the endemic condition and green crown class (Fig. 1a), epidemic and green-infested and red crown classes (Fig. 1b) and post-epidemic and gray crown class (Fig. 1c) in whitebark pine in west-central Wyoming.

Surface Fuel Descriptors

Pine fuel zone (P_z)

P_z is best visualized as a circle of fuels lying under the drip line of an attacked tree. During the endemic phase fuel loads under high-elevation, five-needle pines are low (Figure 1a). During the time a tree is colonized by beetles there will be an increase in litter and fine woody fuel increasing for 1 to 4 years (Figure 1b). These fuels will then give way to forbs and shrubs (Figure 1c) into the post-epidemic phase. P_z will see an increase in coarse woody debris during the decades following tree death. The extent of stand or landscape level P_z will increase as slope angle increases which effectively decreases the distance between adjacent tree crowns.

Non-pine fuel matrix (NP_z)

NP_z is the area between the drip lines of adjacent trees and consists of dead and living shrubs, forbs, grasses, non-host trees and small host and the litter and down woody fuel they produce. The specific composition of the NP_z is highly variable with pine species, geographic location, elevation and plant community type.

Canopy Fuel Descriptors

Canopy fuel descriptors as used by Page and Jenkins (2007 a and b) and Scott and Reinhardt (2001) are based on stand characteristics, not individual trees. For purpose of illustration the following discussion describes canopy fuels based on individual tree crowns.

Crown width (CW)

CW is the greatest distance from one edge of the crown to the other. CW affects the size of P_z and the potential for adjacent trees to have overlapping P_z . CW also affects the potential for crown fire spread from tree to tree. The broad open crowns characteristic of high-elevation five-needle pines may increase the potential for active crown fire in high tree density stands.

Inter-crown Distance (ICD)

ICD is the distance from one tree crown to an adjacent tree crown. On average, ICD may be less in high-elevation five-needle pine stands when compared to stands of other pine species with similar basal areas due to the relatively broad architecture of trees.

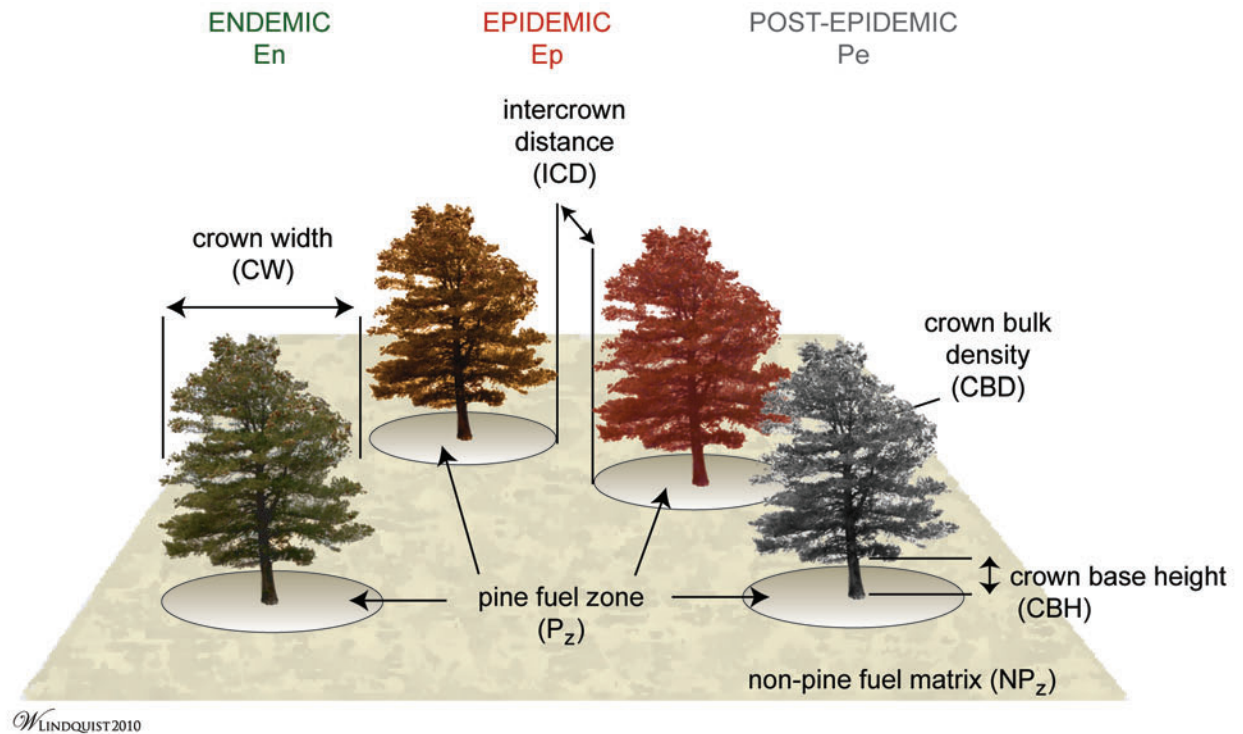


Figure 2. Bark beetle-affected surface and canopy fuel matrix and the important variables affecting crown fire initiation and spread during the course of the bark beetle rotation.

Crown base height (CBH)

CBH is the lowest live crown height in a stand at which there is a sufficient amount of forest canopy fuel to propagate fire vertically into the canopy (Scott and Reinhardt 2001). Bark beetles effectively increase CBH by causing needles to die and fall to the ground. As needles in the lower crown fall there is a substantial reduction in the potential for crown fire initiation. The presence of advanced regeneration, especially shade tolerant conifers, may lower average stand CBH.

Canopy bulk density (CBD)

CBD is the biomass of available canopy fuel per canopy unit volume. Available canopy fuel load (ACFL) is that which is consumed in the short duration flaming front of a crown fire and consists of live and dead foliage, 0 to 3 mm live branchwood, and 0 to 6 mm dead branchwood, plus any lichen and moss (Scott and Reinhardt 2001). Beginning the first season following bark beetle colonization, CBD and ACFL begins to decrease as needles die and fall to the forest floor. There is, in essence, a transfer of CBD to litter and fine woody fuel beneath the tree crown over the course of two to four years following colonization. CBD and ACFL values approach zero after all the needles have fallen from the tree.

Potential Changes to Bark Beetle-Affected Tree Crowns and Fuel Descriptors in High-Elevation, Five-Needle Pines

The characteristics of the crowns of individual attacked trees change during the period of bark beetle colonization, brood development, and adult emergence (Figures 1 a-c). For purposes of the following discussion, consider an otherwise healthy, susceptible pine host with a normal green crown (G). G will have typical CBD, ACFL and FMC_n (foliar moisture content). This tree is mass attacked by MPB at time zero during the flight period (July to August). It is assumed that this MPB population matures from eggs to adults in one year (although this may not be the case at high elevations and/or north latitudes). Eggs deposited by female beetles hatch and larvae develop to the overwintering stage (fourth instar) during the first season at zero plus four months ($0 + 4$). During the first season, the crown of the infested tree remains visibly green (G_i) with the only outward signs of successful attack being pitch tubes and boring dust present on the tree bole (Figure 1a). It is during this first season of beetle colonization that the development of the blue stain fungus also begins.

Blue stain is caused by a complex of fungi that are carried by bark beetles in their mycangia (specialized mouthpart



Figure 3. Bolts of mountain pine beetle-infested lodgepole pine in southwestern Montana showing characteristics of blue stain fungus infection in sapwood.

structures) and inoculated onto the sapwood surface (Figure 3). The fungi spread in the sapwood through living parenchyma cells and bordered pit pairs of dead, water conducting tracheid elements. The degree of blue stain development is dependent upon degree of host colonization, fungal pathogenicity, host resistance and the ability of the tree to compartmentalize the fungi. The amount of sapwood affected thus varies considerably, but in any case, the fungi will reduce water flow to the crown resulting in a net reduction in FMC_n . G_i will have normal CBD, ACFL, but may have lowering FMC_n due to initial blue stain development.

At the beginning of the second season (0+12 months), overwintering larvae resume development, pupate and new adults emerge from the brood tree to colonize another susceptible host. The tree crown will begin to fade from green to yellow (Y) (Figure 1b). Y trees have been infested for 12 months and will begin to show crown symptoms indicative of attack. FMC_n has been greatly reduced due to maximum blue stain development. CBD and ACFL remain normal.

By 0 + 16 months the crown will begin to turn red (R) (Figure 1b). Our preliminary observations of whitebark pine in Wyoming suggest that the R crown class can last up to 0 + 48 months. R needles begin to drop until all needles have fallen from the crown to the forest floor and the gray (GR) stage appears (Figure 1c). CBD and ACFL of R trees will decrease and approach, or become zero when the GR stage is entered.

Foliar Fuel Moisture Relationships

Live and dead FMC_n is an important parameter in crown fire initiation and spread. FMC_n is the amount of water in needles and very fine twigs on a dry weight basis. Figure 4 shows FMC_n relationships for G, G_i , Y, and R needles during the growing season. No specific FMC_n relationships have been established for high-elevation, five-needle pines. Figure 4 displays the FMC_n live, currently infested,

and older needles for eastern white pine (*P. strobus*) based on data reviewed by Keyes (2006). Fuel moisture values for R needles which follow trends of dead fuel moisture are also shown in Figure 4. FMC_n for R needles is affected by diurnal fluctuations in weather variables including precipitation, cloudiness, temperature, relative humidity and dew point. During wet conditions, R needle FMC_n values will approach 30%, but equilibrate within 0–2 hours when conditions become dry. We assume that the diurnal and seasonal weather-affected fluctuations will be at a greater range of moisture content during the cool, wet conditions of spring than the hot, dry summer months. Also displayed in Figure 4 is a hypothetical range of FMC_n for Y crown classes which we assume to lie between G and R crown classes. The actual values of FMC_n for Y crown classes will depend upon blue stain development, and is likely affected by diurnal and seasonal weather fluctuations especially as Y goes to R.

Volatile Compounds in Foliage

Plant terpenes are assumed to increase flammability of forest fuels, however, few studies have documented the effect in pine species (Ormeño and others 2008). It is unknown how much influence, if any, these compounds have on flammability. No previous work has been done on the possible changes to pine terpenes that may occur during the course of changes in pine foliage resulting from MPB activity as described above. We conducted very preliminary experiments collecting whitebark pine volatiles in situ from G, G_i , Y, and R-needled trees. The most common pine terpenes found in preliminary gas chromatograph analyses were alpha-pinene, beta-pinene, beta-myrcene, beta-phellandrene and 3-carene. The level of all compounds decreased from G to G_i to Y, but was elevated in R needles. An increase in flammable terpenes in R needles would be expected to increase surface rate of spread and crown fire potential. Ormeño and others

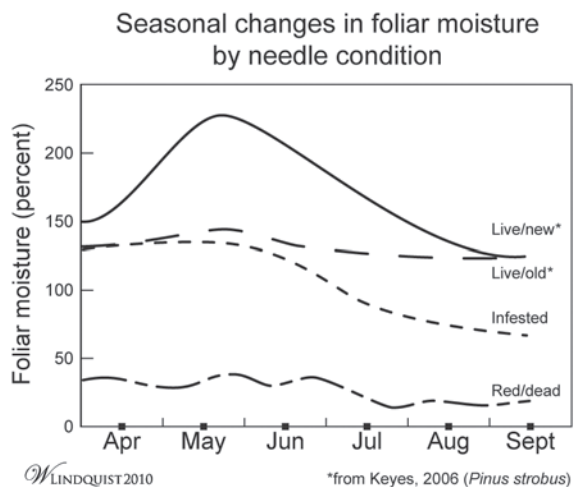


Figure 4. Seasonal changes in foliar moisture by needle condition. Live/new and live/old data are from Keyes (2006). Infested and red/dead needle condition represent suggested hypothetical values.

(2009) found increased terpene concentration and flammability in the litter of Mediterranean *Pinus* spp. studied. Mutch (1970) speculated that natural selection might favor increased flammability in certain fire regimes.

Effect of Bark Beetle-Altered Fuels on Fire Hazard and Potential Fire Behavior

Bark beetles are one of few native agents in nature capable of rapidly altering the quality of coniferous forest vegetation over large spatial scales. The effect of the altered fuel complex on the principle fire behavior descriptors including rate of spread, fireline intensity and flame length over the course of a bark beetle rotation was described by Jenkins and others (2008). There is also a dramatic increase in probability of ignition and potential for crown fire initiation and spread.

Surface Fire Ignition and Spread

The most important influence of bark beetle-caused tree mortality on fire behavior is the reduction in sheltering that occurs as crown bulk density decreases. The opened canopy allows for greater solar insolation and dryer fuels, and increased midflame wind speeds (Page and Jenkins 2007b). The combined effect of increased fine fuels with reduced FMC_n and increased windspeed during the epidemic phase is an increase in fireline intensity under moderate fire weather conditions (Page and Jenkins 2007b). The increase in the amount and depth of litter and fine woody fuel increases the probability of ignition under bark beetle-killed trees.

Coarse woody fuel accumulation and the increase in fuel bed depth that occur during the post-epidemic phase does not influence fire ignition or spread, but may add to surface fire energy release especially during periods of drought. The coarse woody fuel contained in standing snags may contribute to an increased period of flammability and fireline intensity when the site is shared with advanced regeneration in the decades following the outbreak.

In high elevation, five-needle pine stands, we expect that the fuel influence on surface fire behavior will be a function of the relative distribution of P_z and NP_z for a given species, plant community type and location. P_z will increase as pine species stand density increases and may compose 100% of the surface fuel matrix in very dense stands where P_z circles overlap.

Crown Fire Initiation and Spread

Factors affecting crown fire dynamics that are altered by bark beetle-caused tree mortality include CBH, ACFL, FMC_n and ICD. Crown fires are most dependent upon fire weather factors especially relative humidity, windspeed and weather influences on FMC_n . Crown fires are possible when CBH is sufficiently low for a surface fire of given intensity to ignite the foliage. Vertical fire spread within a tree crown is affected by CBD, ACFL and FMC_n . The initial process of crown fire initiation is also called passive crown fire. Active

crown fires occur when effective canopy windspeeds are sufficient to move the fire from one tree crown to another. Active crown fires can occur in connection with an intense surface fire (dependent) or rarely without interacting with the surface fire (independent). Active crown fires are affected by FMC_n , the presence of flammable volatile foliage organic compounds and ICD. The transition from R to GR trees early in the post-epidemic period may result in a short term reduction in the probability of active crown fire due to canopy thinning (Simard and others 2011).

Herbaceous and Shrub Fuels

The dramatic increase in shrubs and forbs during the epidemic and post-epidemic bark beetle phases was discussed above. Fire behavior prediction systems do not accurately handle inputs of live shrubs and forbs which occur under bark beetle-killed conifer stands. Intuition suggests that the shrub and forb layer acts as a “wet blanket” over the litter and fine woody fuels that accumulated prior to shrub and forb release. The high live fuel moisture contents of many shrubs and forbs functions as a heat sink tending to reduce the probability of ignition and surface fire spread rates expected from a “typical” conifer litter understory fuel model. The fact that this fuel bed is difficult to model is further complicated by the considerable variability in herbaceous plant and shrub composition and flammability.

Fire Behavior in High-Elevation, Five-Needle Pine Systems

High intensity, stand-replacing crown fires are a common feature of conifer forests in western North America, with or without bark beetle-altered canopy fuels. Real-time fire weather characterized by low relative humidity, high wind speeds, and low fuel moisture across live and dead fuel classes will dominate fire behavior regardless of fuel bed characteristics (Bessie and Johnson 1995). However, bark beetle-affected fuels may create conditions capable of producing high-intensity surface fires with the ability to transition to crown fires across a wider range of fire weather conditions. This is particularly true at higher elevations where narrow fire weather conditions exist due to a shorter snow free period, higher relative humidities, and lower temperatures.

The infinite array and complex assemblages of coniferous species, bark beetle-altered fuels condition classes, and the activity of other biotic and abiotic disturbance agents over complex terrain and large spatial and long temporal landscape scales also complicates potential fire behavior (Figure 5). Disturbance agents alter the landscape-scale fuel complex which may affect actual fire spread, severity and intensity within the affected landscape. The specific pattern and size of the affected area also has the ability to alter fire intensity and severity beyond the affected area.

The potential for crown fire in high-elevation, five-needle pines is greatest in mixed, transitional forests at lower elevations where they are a minor seral species in stands composed



Figure 5. Landscape view of a mixed conifer forest showing canopy fuels altered by mountain pine beetle and western spruce budworm near Butte, Montana.

of lodgepole pine, Douglas-fir and/or true firs (*Abies* spp.) and Engelmann spruce. In these forests, hazardous fuel pathways may have resulted from; 1) the suppression and exclusion of fire; 2) recent mountain pine beetle outbreaks that developed in pine types at lower elevations and spread up into pure five-needle pine stands; 3) bark beetle outbreaks triggered by drought in the numerous susceptible stands of Douglas-fir and Engelmann spruce; 4) vertical fuel ladders resulting from cyclic western spruce budworm, *Choristoneura occidentalis* Freeman (Lepidoptera: Tortricidae), outbreaks affecting true firs and Douglas-fir; and 5) other agents of disturbance including dwarf mistletoes (*Arceuthobium* spp.), root pathogens and rust fungi that are increasingly common in overmature conifer forests characteristic of the fire suppression era. The net result is a variably flammable, disturbance-altered complex of surface, ladder, and canopy fuels that may extend up in elevation to stands where high-elevation five-needle pines are a major seral or climax species.

In climax high-elevation, five-needle pine stands, surface and crown fire flammability are probably more closely governed by the mountain pine beetle-induced surface and canopy fuel changes described in this paper. Climax stands are generally fire-prone only during the period in the bark beetle rotation when green-infested, yellow and red crown classes share the canopy with green trees. As gray trees become dominant, shrubs and forbs increase, CBH increases in the absence of conifer reproduction, ACFL and CBD decrease and fire potential is reduced. Climax high-elevation, five-needle pine stands are most vulnerable to high intensity, high severity fires where extensive landscapes of disturbance-altered, mixed conifer fuels exist at lower elevations.

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