

THESIS

FUEL AND STAND CHARACTERISTICS IN PONDEROSA PINE INFESTED
WITH MOUNTAIN PINE BEETLE, *IPS* SPP., AND SOUTHWESTERN DWARF
MISTLETOE IN COLORADO'S NORTHERN FRONT RANGE

Submitted by

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY JENNIFER GENE KLUTSCH ENTITLED FUEL AND STAND CHARACTERISITICS IN PONDEROSA PINE INFESTED WITH MOUNTAIN PINE BEETLE, *IPS* SPP., AND SOUTHWESTERN DWARF MISTLETOE IN COLORADO'S NORTHERN FRONT RANGE BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

FUEL AND STAND CHARACTERISTICS IN PONDEROSA PINE INFESTED WITH MOUNTAIN PINE BEETLE, *IPS* SPP., AND SOUTHWESTERN DWARF MISTLETOE IN COLORADO'S NORTHERN FRONT RANGE

The effect of forest disturbances, such as bark beetles and dwarf mistletoes, on fuel dynamics is important for understanding forest dynamics and heterogeneity. Fuel loads and other fuel parameters were assessed in areas of ponderosa pine (*Pinus ponderosa* Laws.) infested with southwestern dwarf mistletoe (*Arceuthobium vaginatum* subsp. *cryptopodum* [Engelm.] Hawksworth & Weins), and in areas with endemic populations of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) (Coleoptera: Curculionidae, Scolytinae) and *Ips* spp. in the northern Front Range of Colorado. One hundred fifty plots, each 0.04 ha, were permanently established throughout the summers of 2005 and 2006. The study area was composed of ponderosa pine, with Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) comprising a large portion of small diameter trees. Adjusted means for coarse fuel loads were greater in areas with relatively high densities (stems/ha or basal area) of mountain pine beetle- and *Ips* spp.-induced mortality that was greater than about 4 years post-tree death when compared to areas without bark beetle-induced mortality, adjusting for southwestern dwarf mistletoe infestation severity and stand and site characteristics. More recent bark beetle-induced mortality was not associated with differences in fuel loads. Areas with ponderosa pine infested with southwestern dwarf mistletoe were associated with

different fuel arrangements and stand characteristics compared to areas with little to no infestation by southwestern dwarf mistletoe. Height to bottom of live crown was greater and percent live crown was less in plots with high severity of southwestern dwarf mistletoe infestation compared to plots without southwestern dwarf mistletoe-infested trees, adjusting for bark beetle-induced mortality. Together these biotic disturbances could have an affect on potential fire hazard by influencing the fuel amounts, fuel arrangements and stand densities.

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Chapter 1

Literature Review

Introduction

Wildfires, insects, and disease interact to maintain and drive forest ecosystems. The interaction between bark beetle (mountain pine beetle - *Dendroctonus ponderosae* Hopkins and *Ips* spp.) and southwestern dwarf mistletoe (*Arceuthobium vaginatum* subsp. *cryptopodum* (Engelm.) Hawksworth and Weins) infestations seem to vary and depend on stand structure, bark beetle populations, and host species composition. Many authors suggest that there is a change in dead fuels and fire hazard during and after bark beetle outbreaks (*Dendroctonus* spp.) or dwarf mistletoe (*Arceuthobium* spp.) infestations in pine forests (Dodge 1972, Alexander and Hawksworth 1975, Alexander and Hawksworth 1976, Gara et al. 1985, Schmid and Parker 1989, Harrington and Hawksworth 1990, Hessburg and Everett 1991, Schmid and Amman 1992, McCullough et al. 1998, Samman and Logan 2000, Lynch et al 2006). Beyond knowing that bark beetles and dwarf mistletoe infestations transform live trees into dead snags, information on the fire hazard associated with areas of infestation is generally not quantitative. Effects of these disturbance agents, and any interactions between them, should be further studied and acknowledged by researchers and forest managers due to the potential importance for both

ecological maintenance and also property destruction in the ever expanding wildland-urban interface (Jones 1974, Alexander & Hawksworth 1975, Castello et al. 1995, Conklin & Armstrong 2001).

Between elevations of 1700 and 2800 m in the northern Front Range of Colorado is the ponderosa pine forest type (Peet 1981, Veblen et al. 2000). At lower elevations, the ponderosa pine forests grades into grasslands while the upper margin of ponderosa pine forests become mixed with higher elevation species, such as *Pseudotsuga menziesii* (Mirbel) Franco, *Pinus flexilis* (James), *Pinus contorta* Dougl. ex Loud (Peet 1981). The site quality for growth of ponderosa pine tends to be poor, with many rocky outcrops and xeric environments (Morgen 1956, Peet 1981). Management through timber harvesting and prescribed fire has occurred throughout the northern Front Range of Colorado. Mountain pine beetle and *Ips* spp. are both native bark beetles that follow the distribution of ponderosa pine across North America (Furniss & Carolin 1977). The northern extent of southwestern dwarf mistletoe is within the study area of the Canyon Lakes Ranger District, CO (Merrill et al. 1987, Hawksworth & Weins 1996, Beam unpublished data).

This literature review covers fire in ponderosa pine forests, and biology and ecology of mountain pine beetle, *Ips* spp. and southwestern dwarf mistletoe. The objectives that are being addressed by both the chapter 1 and 2 involve 1) Determine the fire hazard associated with stands on ponderosa pine infested with mountain pine beetle, *Ips* spp. and southwestern dwarf mistletoe; 2) Identify

biological and ecological components of bark beetles and dwarf mistletoe that may alter forest structure.

1 Fire Ecology of ponderosa pine forests of Colorado's northern Front Range

Fire exclusion throughout the 20th century in the northern Front Range of Colorado has brought ponderosa pine forests to a stand structure that is thought to be outside the historical range of variability. Forest management objectives sometimes include the desire to return historical stand characteristics and processes to large portions of forest for the benefit of ecosystem biodiversity, resilience and the potential for decreased severity of extensive fires (Brown et al. 2000). Climate, disturbance regimes, tree regeneration, and other stand structural components make up the historical processes that shaped pre-Euro-American settlement forests. Because modern climate and biotic disturbance are not easily altered, managers have looked to historical fire regimes to achieve the goal of returning forests to historical densities and age structure as benchmarks for forest structure. Information on historical fire regimes and age structures have been used to plan and implement prescribed fire and mechanical thinning programs that are thought to mimic the conditions in which forests evolved.

Ponderosa pine occurs throughout the mid and lower elevations of the Front Range of the Rocky Mountains in Colorado (Peet 1981). There have been several fire regime studies conducted in the ponderosa pine of the northern and

central Front Range of Colorado. Some studies have looked at fire disturbance, while others have emphasized age structure and regeneration.

1.1 Studies on historical fire regimes

One of the earlier studies conducted was by Laven et al. (1980) was at a study site within the Cache la Poudre watershed, north of Rustic, CO. Laven et al. (1980) developed a site specific fire history and stand-age distribution within their 50 ha study area in ponderosa pine. The years sampled ranged from 1708 to 1973, and elevation of 2800 m. A mean interval between fires was used to describe fire history. The pre-Euro-American settlement mean fire interval was 66.0 years before 1840, which was derived from 6 sample trees (Laven et al. 1980). There was an increase in fire frequency during Euro-American settlement between 1840 and 1950, which has been subsequently documented by Veblen and others (2000). However, across the entire chronology (n=20 trees), the mean fire return interval was 45.8 years (Laven et al. 1980). Also, the fire size frequencies were calculated, with small fire frequencies equal to 20.9 years and large fire frequencies equal to 41.7 years (Laven et al. 1980). Through the stand-age analysis, it was concluded that tree regeneration was not correlated to fires in the past, but are instead related to something else like climate (Laven et al. 1980).

Another study by Brown et al. (2000) looked at stands from the Black Hills of South Dakota to southern Colorado. In Colorado's northern Front Range, the area of Lone Pine in the Arapaho-Roosevelt National Forest and Cache la

Poudre watershed was an old-growth ponderosa pine stand, not impacted by roads, logging, or human disturbance. The purpose of the study within this mixed conifer forest was to derive a comprehensive individual tree fire history for as far back as possible for the Lone Pine study site. The study sites ranged from 10 to 20 ha, had about 10 to 13 fire scarred trees, and were chosen for the high proportion of old-age fire-scarred trees or dead trees. Selection of fire scarred tree samples was biased towards dead trees to minimize impacts on live trees and extend fire chronologies as far back as possible.

Fire frequencies for the area near the sampled trees within the Lone Pine study area were considered to be within the historical range of variability (Brown et al. 2000). For the lower and upper elevation sample sites the median fire intervals were 80.5 and 117 years respectively, within the period of 1568 to 1887 (Brown et al. 2000). Brown et al. (2000) explained that there is “tentative evidence that crown fire may have been a component of the fire regime” and though there is no evidence there were frequent low intensity fires, the forest is considered to be generally open without an above average amount of dense stands.

The fire chronologies for the same Lone Pine site, plus two more within Larimer County using the median fire interval for the pre-Euro-American settlement period were developed by Brown & Shepperd (2001). The number of trees used ranged from 8 to 18 and the number of scars recorded ranged from 15 to 86. For the additional sites - one close and southwest of Lone Pine, the other further away and southeast of Lone Pine - the numbers of fire intervals

recorded were 8 and 14, and the median fire intervals were 29.5 and 16.0 years. With these additional study sites, the variability of the area and trees that recorded fires increased dramatically. These 4 sites also varied in elevation. The higher elevation sites had lower fire frequencies while the lower elevation sites had higher fire frequencies. At higher elevations, precipitation is higher and the temperature is cooler, reducing the ignition and spread probabilities for fires (Peet 1981, Brown & Shepperd 2001).

The objectives of Veblen et al. (2000) were to sample the elevational range of ponderosa pine (1830 to 2800 m) to look for influences of climate on fire regimes in the Central and Northern Front Range of Colorado and create climatically sensitive regional tree-ring chronologies. The research area included 41 sites and extended about 45 km north-south, with only the northern 4 sample sites being within the Canyon Lakes Ranger District. Location of sample sites was subjective, and constrained to areas with large trees and researcher access. At least 10 fire scars were sampled within a maximum sample radius of 200 m. Sample areas were categorized into elevation classes.

At the lowest elevations of the Veblen et al. (2000) sample sites, for the pre-Euro-American settlement period, the fire frequency was substantially higher than higher elevation forests. The conservative estimate for mean fire return interval ranged from 43.4 and 14.4 with higher elevations experiencing lower fire frequency and lower elevations experiencing higher fire frequency (Veblen et al. 2000). The authors attributed the high fire frequency at lower elevations to increased desiccation of fuel and herbaceous plant growth. Higher elevation

sample sites in pre-Euro-American settlement had a mixed severity fire regime, with a combination of low severity ground fires and high severity stand replacing fires (Veblen et al 2000).

Veblen et al. (2000) found a good correlation between climate and fire occurrence. Past climate was derived from instrumental and tree-ring proxy record. Fire occurrence is associated with not just drought but also wet periods. Following years with above average moisture during the spring to summer, there were more frequent widespread fires because of the potential buildup of fine fuels during high precipitation years, though increased ignitions due to lightening may have also contributed to greater fire frequency (Veblen et al. 2000).

Ponderosa pine forests in Rocky Mountain National Park and throughout the northern Front Range of Colorado experienced low, moderate, and severe fire events in pre-Euro-American settlement (Peet 1981, Brown et al. 1999, Kaufmann et al. 2000, Veblen et al. 2000, Ehle & Veblen 2003). Ehle & Veblen (2003) illustrated that high severity fires are an important part of the ecosystem and did occur within ponderosa pine forests in the northern Front Range of Colorado, though less frequently than low severity fires. The high severity fires were in mixed-conifer stands in higher elevations with low fire frequency (Brown et al. 1999, Kaufmann et al. 2000, Veblen et al. 2000, Ehle & Veblen 2003). These crown fires were at or right before the Euro-American settlement, but because fire suppression was not successfully implemented, the high severity fires were not due to unnatural causes (Ehle & Veblen 2003).

The northern Front Range of Colorado has a mixed severity fire regime in ponderosa pine stands with a combination of both low severity fires and stand replacing fires (Brown et al. 2000, Veblen et al. 2000, Ehle & Veblen 2003). Some study sites, for example Brown et al. (2000), could be considered within the historical range of variability. Others study sites, such as the sites including Rocky Mountain National Park could be considered outside the historical fire regimes (Veblen et al. 2000, Brown & Shepperd 2001, Ehle & Baker 2003). Studies on fire regimes are site specific and sometimes only reflect conditions that larger trees experienced during very specific climactic periods. However, information on the historical range of variability is helpful in understanding processes that shape and control ponderosa pine forests and can reflect how far current forests are from these controlling factors.

1.2 Uncertainties in fire history and management implications

There are limitations associated with the interpretation of historical fire records that have to be acknowledged for the appropriate use of this information. Studies on historical range of variability have the same inherent limitations, which include no modern calibration and assumptions about recorder trees (Baker & Ehle 2003). The ways that historical fires are recorded are limited because fire scars only record lower severity fires in previously scarred older trees. Fire scars, age structures, and photographs were used to reconstruct historical fire regimes and stand structures in the northern Front Range of Colorado (Laven et

al. 1980, Brown et al. 2000, Veblen et al. 2000, Brown & Shepperd 2001, Baker & Ehle 2003).

1.3 Fuels and fire behavior

Downed woody material is divided into size classes that represent the amount of estimated time to reach 63% equilibrium moisture content, assuming constant temperature and relative humidity (Brown 1978). The time lag size classes for the diameter of downed woody material are: 1 hour (< 0.6 cm), 10 hour ($0.6 - 2.5$ cm), 100 hour ($2.5 - 7.6$ cm), 1000 hour (> 7.6 cm) (Van Wagner 1968, Brown 1971, 1974). One, 10 and 100 hour fuel classes are considered fine fuel while 1000 hour fuel class is coarse fuel.

The amount of fuel, its distribution, type, and moisture content all effects fire intensity (McCullough 1998). Large fuel classes, along with compacted fuel such as the humus layer and duff fuels take a relatively longer time to dry out and are associated with increased fire intensity and smoke production (Johnson 1992, McCullough et al. 1998). Small fuel classes which are < 7.7 cm in diameter are associated with surface fires and dry out relatively quickly (Rothermel 1972, Johnson 1992). Fine fuels are also consumed during a crown fire as the fire spread upward through the understory and overstory latter fuels (Johnson 1992, Agee & Skinner 2005).

2 Mountain Pine Beetle and *Ips* spp.

Native bark beetles, mountain pine beetle (*Dendroctonus ponderosae* Hopkins) and *Ips* spp. attack ponderosa pine and other pines in Colorado (Schmid & Mata 1996). By tunneling under the bark of susceptible trees, adults deposit eggs along vertical galleries (Furniss & Carolin 1977). The eggs develop into larvae that tunnel horizontal feeding galleries under the bark, pupate and emerge as adults (Furniss & Carolin 1977). A tree with numerous bark beetle infestations will be girdled by galleries and also be killed by the introduction of blue stain fungi (*Ophiostoma* spp.) vectored by bark beetles (Furniss & Carolin 1977). Mountain pine beetle is a primary bark beetle that generally kills trees through mass attack, while *Ips* spp. are secondary and infest small diameter trees, branches, tops of trees, or trees stressed from pathogens or other bark beetle infestations (Furniss & Carolin 1977). The snags created by infestations of bark beetles are habitat for a multitude of insects, fungi, and vertebrates. Low winter temperatures along with biotic factors, such as limited host numbers, nematodes, woodpeckers, predacious and parasitic insects control populations of mountain pine beetle and *Ips* spp. (Furniss & Carolin 1977). Endemic populations of mountain pine beetle infest weaker and less vigorous trees, such as trees with root disease or damaged from lightening (Furniss & Carolin 1977, Schmid & Amman 1992, Eckberg et al. 1994, Schmid & Mata 1996, Negrón & Popp 2004). In epidemic populations, the discrimination toward certain trees is lessened and bark beetles infest trees regardless of health status (Furniss & Carolin 1977).

2.1 Stand conditions

Mountain pine beetle (*Dendroctonus ponderosae* Hopkins) epidemics have the potential to completely transform pine tree landscapes (Schmid & Amman 1992). Stand structure, species composition and successional trends can all be altered with high mortality due to bark beetle outbreaks (Schmid & Amman 1992, Keane et al. 1990). By selectively attacking larger diameter trees, mountain pine beetle (MPB) outbreaks can lower the mean diameter, stem density, and basal area (Amman 1977, Hessberg and Everett 1991, Schmid & Amman 1992). Outbreaks may also contribute to the acceleration of a non-host seral species. Lodgepole stands attacked by mountain pine beetle may be replaced by a climax mountain pine beetle resistant conifer species forest or if fire is present, an even-aged lodgepole pine forest (Amman 1977). According to Amman (1977), an even-aged lodgepole stand is conducive to future mountain pine beetle epidemics. Though the impacts from mountain pine beetle epidemics can be substantial, lower levels of tree mortality have lesser effects. Smaller outbreaks may only remove larger diameter trees and thus temporarily reduce stand density and contribute to stand uniformity which is more susceptible to future mountain pine beetle epidemics (Schmid & Amman 1992).

Previous mountain pine beetle outbreaks influence future epidemics by altering stand structure. Epidemic populations of mountain pine beetle can be historically evidenced though outbreaks are not continuous within a landscape (Schmid & Amman 1992). After an epidemic of mountain pine beetle, the size of the stand, the population numbers of mountain pine beetle during the last

outbreak, how the mountain pine beetle modified the stand structure and the rate at which the stand grows back into a susceptible condition will determine the next mountain pine beetle outbreak (Schmid & Amman 1992). For example, McCambridge and others (1982b) documented that 84% of the ponderosa pine basal area was killed by mountain pine beetle that reduced the basal area to 3.3 m²/ha. According to Schmid & Amman (1992), another outbreak would not be expected in this stand for 50 to 100 years. Whereas a stand that had experienced a smaller epidemic, where only 10 to 20% of the basal area was killed would be susceptible for another outbreak in 20 to 50 years (Schmid & Amman 1992).

A significant amount of mortality can be a result of a mountain pine beetle infestation. The current endemic population of mountain pine beetle in the northern Front Range of Colorado is infesting susceptible trees (Harris 2005). Stands with high stand density and a basal area > 17.1 m²/ha are considered at greater risk for infestation by mountain pine beetle (Negrón & Popp 2004). Also, trees that are more susceptible to infestation are dominant or codominant that have a diameter at breast height (1.37m, dbh) > 18.2 cm (Negrón & Popp 2004).

2.2 Fuels

Trees killed by bark beetles are considered dead woody fuels available for surface fires, but the potential effect on fire behavior depends on the position of the fuels. There is a potential of greater fuel loads available for a surface fire once these dead fuels fall to the ground, however the decay and compaction rate

of these fuels in Colorado's northern Front Range is unknown. According to many authors, bark beetle infestations increase fuel levels within forests which can create higher intensity and larger crowing fires (Wright 1974, Schmid & Amman 1992, Samman & Logan 2000). Bark beetle infestations distribute snags throughout the landscape that eventually fall to the ground and contribute to the fuel load which may increase the probability of natural ignition and crown fires (Hessburg & Everett 1991). The herbaceous vegetation in stands with trees killed by bark beetles is stimulated, except where seedlings were present prior to the bark beetle infestation (McCambridge et al. 1982a, Stone & Wolfe 1996, McMillin & Allen 2000, McMillin et al. 2003).

Fine fuels transformed from live to dead by bark beetle infestations may increase fire hazard (Schmid et al. 1985, Schmid & Parker 1989, Schmid & Amman 1992). This increased fire hazard due to twigs and needles will linger until 2 to 5 years after infestation, when the needles are lost from the tree (Schmid & Parker 1989, Schmid & Amman 1992). Though researchers state the importance of fine fuels from bark beetle-infested trees contributing to a greater fire risk, there is no quantitative data about the accumulation, composition, the amount of time fine fuels remain on trees, or how the deposition of these fine fuels on the forest floor contribute to fire behavior.

The placement of fuels is also a factor in fire spread. Bark beetle-killed trees stand for a varying period of time which benefit wildlife but may increase fire hazard by the accumulation of coarse woody material when they fall. The addition of these fuels to the overall downed woody fuel load is dependent on the

rate at which the bark beetle-killed trees fall to the ground. Studies on the natural falling rate of mountain pine beetle-killed trees show that time since infestation, tree size, soil conditions, and high wind events regulate the rate of fall of dead ponderosa pine (Keen 1955, Schmid et al. 1985). In Arapaho and Roosevelt National Forest, Schmid and others (1985) documented the natural falling rate of mountain pine beetle-killed ponderosa. Ponderosa pine in the study deteriorated slowly for 3 to 5 years after infestation, with the majority of trees falling between years 7 and 10. No trees fell in the first 2 years but during the 4th to 7th year, trees fell at rates of 3% to 17%. Wind was a significant factor in when and what direction trees fell. For the study, when winds exceeded 75 mph in the 5th year after infestation, up to 50% of the trees fell at one location (Schmid et al. 1985).

Accordingly, the potential fire hazard due to mountain pine beetle infestation has a temporal aspect. In Yellowstone National Park, Lynch and others (2006) investigated the spatial relationship between the 1988 fire and previous outbreaks of mountain pine beetle in lodgepole pine. They found that only areas with mountain pine beetle-induced mortality occurring 13 to 16 years before the fire had increased odds of 11% being burned by the 1988 fire; and a mountain pine beetle outbreak, 5 to 8 years before the fire, was not correlated with fire occurrence (Lynch et al 2006). The stand structure and vegetation response to the mountain pine beetle outbreak 13 to 16 years previous was attributed to the increased odds of being burned in the 1988 fire (Lynch et al. 2006).

3 Southwestern Dwarf mistletoe

Dwarf mistletoes (Viscaceae, *Arceuthobium* spp.) are obligate parasitic plants that infest conifer species in the Pinaceae family throughout North America, Asia, Europe, and Africa (Hawksworth & Wiens 1996, Geils et al. 2002). Abnormal shoot growth, reduced radial growth, persistence of infested branches, and reduced tree vigor are results of dwarf mistletoe infestations (Hawksworth 1961, Hawksworth & Wiens 1996). Plants act as sinks for carbohydrates and water (Hawksworth 1961, Hawksworth & Wiens 1996). Seeds are produced on female plants and forcibly ejected to spread to nearby hosts or within the same tree (Hawksworth 1961, Hinds et al. 1963, Hinds et al. 1965). In Colorado, ponderosa pine is the host for southwestern dwarf mistletoe that is spotty in distribution throughout the distribution of ponderosa pine. The northern limit of southwestern dwarf mistletoe is in the northern Front Range of Colorado (Merrill et al. 1987, Beam unpublished data).

Through fire exclusion and logging, stand characteristics and disturbance regimes of some area of ponderosa pine forests have changed (Alexander & Hawksworth 1975, Alexander & Hawksworth 1976, Brown et al. 1999, Kaufmann et al. 2000, Veblen et al. 2000). Dwarf mistletoe can be inhibited by wildfire by the fire killing host trees, or dwarf mistletoe can efficiently spread due to the thinning effect from partial burns (Alexander & Hawksworth 1975). Not only can dwarf mistletoe spread be influenced by stand structure and fire, but also fire behavior has the potential to be influenced by fuel levels and stand structure created by dwarf mistletoe infections.

The severity of dwarf mistletoe infestation are quantified using Hawksworth Dwarf Mistletoe Rating (dmr), where the tree crown is divided into thirds and each section assessed for percent of infested branches (Hawksworth 1977). If branches in each third of the tree have greater than 50% of the branches infected with dwarf mistletoe then the number 2 is recorded for that tree section. A number of 1 is given to tree sections with less than 50% of branches infected, and a 0 to tree sections without dwarf mistletoe infections. Each third is summed together for a total tree dmr that ranges from 0 to 6. For a stand rating of dwarf mistletoe severity, the dmr of each host tree is averaged.

3.1 Stand condition

Stand characteristics change throughout the development of dwarf mistletoe infections. Dwarf mistletoe and other slow moving and localized pathogens such as *Armillaria* root disease, mostly cause small scale mortality or gaps in mature forest canopies (Castello et al. 1995, Lundquist 1995, 2007). Harrington and Hawksworth (1990) reported a shift of average dbh, stand density and dmr from 1950 to 1982 in a ponderosa pine stand at the Grand Canyon. For trees greater than 3 inches dbh, stand density decreased from 29 trees per acre to 19 trees per acre. Also, the average dbh increased from 14.5 to 15.6 inches (Hawksworth 1977). Average dmr increased from 2.8 to 3.7 (on the 6-class scale) while the percentage of infected trees stayed the same at 80% (Hawksworth 1977, Harrington & Hawksworth 1990). In the 32 years between

measurements, there was a thinning of larger diameter trees and an increase in the dwarf mistletoe intensity but no further spread.

Forest stands infested with dwarf mistletoe experience differing degrees of damage ranging from decreased tree growth to mortality. The number of infections and their distribution within a tree determines the amount of damage and can be correlated with general stand conditions (Parmeter 1978). The ability of dwarf mistletoe to successfully infect a stand is dependent on the dynamics of the forest (Parmeter 1978). According to Beatty & Mathiasen (2003), the general rule-of-thumb of 1 dmr per decade describes the increase in intensity of dwarf mistletoe infections within a stand. Furthermore, Alexander & Hawksworth (1975) state that in a mature unburned lodgepole pine stand, the spread rate for dwarf mistletoe is relatively slow at about 1 to 2 feet per year. A complete life cycle for a female dwarf mistletoe plant, from initial establishment to the spreading of its first seeds is about 4 to 5 years (Beatty & Mathiasen 2003).

Along with altering forest communities, forest pathogens are responsible for changes of larger forest landscapes. Though abiotic disturbances receive more attention at the landscape scale, pathogens act as selective agents within a forest ecosystem that alter forest development (Castello et al. 1995). In Castello and others' (1995) review paper about influences put on and caused by forest pathogens, forest structure, composition, and conditions are discussed with forest pathogen examples. The interaction of lodgepole pine, dwarf mistletoe and fire is described. Dwarf mistletoe contributes to the structural heterogeneity within lodgepole pine forests that also enables it to spread efficiently. Spotty fires

also allow for unburned refugia of infected trees to remain and inoculate regeneration (Alexander & Hawksworth 1975). Also, fire perpetuates the susceptible lodgepole pine seral stage, not allowing the forest to develop to the resistant spruce and fir (Alexander & Hawksworth 1975, Castello et al. 1995). However, ponderosa pine is considered the climax forest for parts of the Colorado Front Range which prevents a comparison of successional control by dwarf mistletoe with lodgepole pine to the development and interaction of ponderosa pine with dwarf mistletoe and fire (Peet 1981).

3.2 Fuels

Few studies have investigated the fuel loading associated with dwarf mistletoe-infested trees (Koonce & Roth 1985, Harrington & Hawksworth 1990, Conklin & Armstrong 2001, Hoffman et al. 2007). Dwarf mistletoe induced mortality slowly contributes snags to stands which eventually fall to the ground to be incorporated into the dead and downed woody fuel available for surface fires. Within ponderosa pine forests infested with southwestern dwarf mistletoe, Hoffman and others (2007) demonstrated that in uniform stands in Arizona, the total fuel loading was at least four times greater in severely infested stands than in lightly or non-infested stands. The fine fuels, separated by fuel classes, (except 100 hour time lag fuel class), duff depth, fuel bed height, height to bottom of live crown and canopy fuel loading were not different between infestation classes for dwarf mistletoe infestation in the Hoffman and others (2007) study. From fire behavior models, torching index (the wind speed required for a surface

fire to burn into a crown) was different in plots with different infestation severities (Hoffman et al. 2007). The torching index was lower (representing increased fire hazard) in areas with $dmr > 4$ compared to areas without dwarf mistletoe infestation (Hoffman et al. 2007). Also, Hoffman and others (2007) found that there was a higher probability of active and passive crown fires in severely and moderately dwarf mistletoe-infested plots compared to plots without dwarf mistletoe infestation. The stands that Hoffman and others (2007) sampled were homogeneous in structure and species composition, thus surface and canopy fuel loading along with potential fire behavior are likely to be different in ponderosa pine forests with different structure and climate regimes.

Koonce & Roth (1985), in precommercial ponderosa pine stands in Oregon, showed greater fine fuels in plots with the highest severity of western dwarf mistletoe (*Arceuthobium campylopodum*) compared to plots without trees infested with dwarf mistletoe. In the sapling and small pole sized stands of ponderosa pine, there were significantly greater fine fuel loads in areas with high dwarf mistletoe infestations compared to plots with healthy trees (3.0 Mg/ha and 1.1 Mg/ha respectively). Correspondingly, 1000 hour fuel loads made up a significantly lower percentage of total fuel loading in plots with high dwarf mistletoe intensities compared to plots with healthy trees (Koonce & Roth 1985). Percent of aerial fuel loading of 100 hour time lag fuel class was greater in areas with $dmr > 4$ compared to areas with less dwarf mistletoe infestation severity (Koonce & Roth 1985).

For a prescribed burn in a ponderosa pine stand in the Grand Canyon area, Harrington and Hawksworth (1990) detailed the first year mortality of southwestern dwarf mistletoe infected trees after a fire. It was reported that the burning of heavy surface fuels resulted in most of the crown scorch recorded. Also, crowning fires occurred in an area of dense saplings with heavy surface fuels.

Harrington and Hawksworth (1990) found that the severity of southwestern dwarf mistletoe infection influenced the percentage of crown scorch on ponderosa pines. Trees with a lower percentage of scorch also had lower dwarf mistletoe infections while trees with the most scorch had high dwarf mistletoe ratings. Harrington and Hawksworth (1990) also found that infected trees had less distance between the forest floor and living crown, with average height to crown being 21% of tree height. For healthy trees, 38% of tree height was the average height to crown which allowed for less scorching of healthy trees. The increased portion of dwarf mistletoe infected crowns to be scorched was accounted to both the flammable witches' brooms and to lower crowns (Harrington & Hawksworth 1990).

First year mortality, after a prescribed burn, increased with greater crown scorch percentage, bole char, and dmr and lesser tree size (Harrington & Hawksworth 1990). The researchers developed a probability regression model that predicted that about two-thirds of healthy large trees would survive three-fourths of their crowns being scorched (Harrington & Hawksworth 1990). For trees severely infected with dwarf mistletoe, only about one-fourth would survive

the same level of crown scorch. The researchers explained the decreased probability of mortality of healthy trees compared to infected trees being less healthy and therefore any injury to its crown may be more lethal. Also similar crown scorch percentages for healthy and infected trees would consume greater absolute crown volume for infected trees due to greater crown length, and thus leave a relatively thin and unhealthy crown to support the infected tree (Harrington & Hawksworth 1990).

Researchers have stated that there are a greater amount of dead fuels on the forest floor and also greater stems and foliage near the ground in immature lodgepole pine infected with dwarf mistletoe as compared to uninfected stands (Hawksworth & Hinds 1964, Alexander & Hawksworth 1975). The vertical fuel continuity within these immature infected stands increases the possibility of crown fires (Alexander & Hawksworth 1975, Brown 1975). By trapping needles and fine twigs, witches' brooms within trees have increased fine fuels and are ideally situated in this vertical fuel continuum to allow for fire to burn out individual crowns (Alexander & Hawksworth 1975, Alexander & Hawksworth 1976).

Dwarf mistletoe infections have the potential to increase the flammability of ponderosa pine. Dead or resin soaked branches and stem cankers, spiked or dead tops, whole tree mortality and brooms within the tree could alter potential fire behavior (Alexander & Hawksworth 1975, Alexander & Hawksworth 1976, Conklin 2000). Also, dead, resinous branches that fall along the base of infected trees could add to the fuel load (Beatty & Mathiasen 2003). However, further

research is necessary to investigate the flammability of dwarf mistletoe infestation, these references do not include any quantitative data regarding these statements of increased fire hazards due to dwarf mistletoe.

4 Bark beetles and dwarf mistletoe

Mountain pine beetle, *Ips* spp. and southwestern dwarf mistletoe all infest ponderosa pine. In addition, studies have also shown that dwarf mistletoe and bark beetles interact by occurring in areas of similar stand structure, with dense stands that have a high proportion of host species (McCambridge et al 1982b, Maloney & Rizzo 2002, Beam unpublished data). Beam (unpublished data) identified that stands with dwarf mistletoe and bark beetles had greater density of ponderosa pine in the Canyon Lakes Ranger District, Colorado. Additionally, in a survey in ponderosa pine in the Colorado Front Range, the predisposition of dwarf mistletoe-infested trees to mountain pine beetle attack was assessed (Johnson et al. 1976). In one of 4 study areas, there was a significant trend for trees with severe dwarf mistletoe infestation to be attacked by mountain pine beetle (Johnson et al. 1976). In the northern Front Range of Colorado, McCambridge and others (1982b) found that a greater percentage of southwestern dwarf mistletoe-infested ponderosa pine were infested with mountain pine beetle as compared to trees not infested with dwarf mistletoe but killed by mountain pine beetle (30.8% and 20.5% respectively). The population of mountain pine beetle during the research were considered epidemic with large portions of ponderosa pine in the Front Range of Colorado being killed. The

researchers determined that ponderosa pine were more susceptible to mountain pine beetle infestation if the trees also have dwarf mistletoe infestations (McCambridge and others 1982b). Additionally, the trees surrounding these infested trees had a greater probability of being killed by mountain pine beetle due to their proximity to bark beetle population build-ups (McCambridge and others 1982b).

Studies have also shown that ponderosa pine infested with dwarf mistletoe is more susceptible to mountain pine beetle and *Ips* spp. attack (McCambridge et al. 1982b, Kenaley et al. 2006). During an *Ips* spp. outbreak in northern Arizona, ponderosa pine killed by *Ips* spp. had greater dwarf mistletoe infestation severities than trees not infested with dwarf mistletoe (Kenaley et al. 2006). Negrón & Wilson (2003) found that the infestation of piñon pine (*Pinus edulis* Englem) by piñon pine dwarf mistletoe (*Arceuthobium divaricatum* Engelmann) was a good predictor for piñon *Ips* (*Ips confusus* LeConte) infestation. The physiological changes due to dwarf mistletoe infestation such as declining host vigor, and redistribution of water and carbohydrates may not only change the susceptibility of trees to bark beetle infestations, but also be attractive for bark beetle infestation (Hawksworth 1961).

However, Maloney & Rizzo (2002) in their study site in mixed-conifer in the Sierra Nevada found no spatial relationship between the occurrence of dwarf mistletoe and bark beetles. The species the researchers were working with were white fir (*Abies concolor*) infested with *Arceuthobium abietinum* f. sp. *concoloris* and fir engraver beetle (*Scolytus ventralis* Leconte) and Jeffrey pine (*Pinus*

jeffreyi) infested with *Arceuthobium campylopodum* and Jeffrey pine beetle (*Dendroctonus jeffreyi* Hopkins). The severity of dwarf mistletoe infestations may not have been high enough to predispose attack by bark beetles infestation because trees are still relatively healthy (Maloney & Rizzo 2002).

The potential fire behavior under situations of both dwarf mistletoe infestation and bark beetle-induced mortality is unknown. Though dwarf mistletoe and bark beetles interact by being in similar stands, it is unclear how mortality due to both disturbances would influence fuel loading or surface and canopy fuel characteristics. Lundquist (2007) examined interactions of disturbances and showed the complex effects of multiple disturbances on fuel complexes in the Black Hills, SD. Mountain pine beetle-induced mortality had a null effect on the amount of fuels loads present, while other disturbances, most significantly root rot, were significantly correlated with fuel amounts.

5 Conclusions

The ponderosa pine in the Colorado Front Range have experienced both long term dwarf mistletoe (*Arceuthobium vaginatum* subsp. *cryptopodum* [Engelm.] Hawksworth and Weins) infections and periodic mountain pine beetle (*Dendroctonus ponderosae* Hopkins) outbreaks. Both prescribed and wildfires have also occurred in the Front Range. Throughout the literature, bark beetles and dwarf mistletoe are known to alter forest structure by creating snags and changing species composition. However, the influence on fire hazard of each disturbance agent and the interaction between dwarf mistletoe and mountain

pine beetle are generally not quantified. Also the spatial distributions of dwarf mistletoe, mountain pine beetle, and *Ips* spp. are not well understood.

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Chapter 2

Mountain pine beetle (*Dendroctonus ponderosae*), *Ips* beetles, and southwestern dwarf mistletoe (*Arceuthobium vaginatum* subsp. *cryptopodum*): effects on stand structure and fuel loading and arrangement in ponderosa pine (*Pinus ponderosa*) forests of the Northern Front Range of Colorado

Introduction

Forest disturbances, such as those caused by native bark beetles and dwarf mistletoes, are integral components of forest ecosystems. However, the effect on stand structure and fire and fuel dynamics by bark beetles and dwarf mistletoes is generally not known. Many authors have suggested there are relationships between fire hazard and bark beetle outbreaks (*Dendroctonus* spp.) or dwarf mistletoe (*Arceuthobium* spp.) infestations in forest ecosystems (Dodge 1972, Alexander and Hawksworth 1975, Alexander and Hawksworth 1976, Gara et al. 1985, Schmid and Parker 1989, Harrington and Hawksworth 1990, Hessburg and Everett 1991, Schmid and Amman 1992, McCullough et al. 1998, Samman and Logan 2000, Kulakowski et al. 2003, Lynch et al. 2006, Lundquist 2007, Hoffman et al. 2007). Yet there is little quantitative data that examines changes in fuel dynamics or fire hazard during or after bark beetle and dwarf mistletoe outbreaks in ponderosa pine forests. The purpose of this study was to examine fuel characteristics associated with ponderosa pine stands infested with southwestern dwarf mistletoe and bark beetles in Colorado's northern Front Range.

Ponderosa pine forests (*Pinus ponderosa* Laws.) of the northern Front Range of Colorado have experienced periodic infestations of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) (Coleoptera: Curculionidae, Scolytinae), *Ips* spp., and the southern portion of the study area has also

sustained infestations of southwestern dwarf mistletoe (*Arceuthobium vaginatum* subsp. *cryptopodum* [Engelm.] Hawksworth and Weins). Prescribed fires and wildfires have occurred in the ponderosa pine forests of the northern Front Range of Colorado – with an estimate of historical wildfire return intervals ranging from about 14 to 34 years, depending on elevation (Veblen et al. 2000). Wildfires have been of mixed severity, with both frequent surface fires and extensive stand-replacing crown fires being important elements in the ponderosa pine forests of Colorado's Front Range (Brown et al. 1999).

Interactions between abiotic and biotic disturbances are important for forest development, yet minimal attention has been paid to interactions that can control the direction of forest dynamics (Castello et al. 1995). To enable managers to make more informed decisions and improve our understanding of these ecological processes, the dynamics and interactions of pathogens, insects, and abiotic disturbances must be better understood and acknowledged (Jones 1974, Alexander & Hawksworth 1975, Castello et al. 1995, Conklin & Armstrong 2001).

Mountain pine beetle infestations can cause significant mortality in susceptible ponderosa pine forests. Populations of mountain pine beetle in the northern Front Range of Colorado have ranged from epidemic episodes (McCambridge et al. 1982b, Schmid & Mata 1996) to the current endemic level of mountain pine beetle infestation in ponderosa pine (Harris 2005, USDA and Colorado State Forest Service, 1996-2006 Aerial Detection Surveys <http://www.fs.fed.us/r2/resources/fhm/aerialsurvey/>). From a survey of randomly

placed plots in ponderosa pine forests in the Canyon Lakes Ranger District, CO conducted in 2005-2006, the average density of ponderosa pine infested with mountain pine beetle was 17.4 stems/ha (S.E.=2.3), occurring in 15% of surveyed areas (Russell Beam unpublished data, Colorado State University BSPM, Ft. Collins, CO 80523-1177). Current populations of mountain pine beetle are considered endemic because the amount of ponderosa pine being killed across the Canyon Lakes Ranger District, CO is not increasing and patch size of killed trees is generally small, ranging from 2 to 20 trees. Populations of mountain pine beetle within the last 10 to 20 years are dependent on tree characteristics and stand structure of ponderosa pine to successfully infest host trees (Sartwell & Stevens 1975, Schmid & Mata 1992, Negrón & Popp 2004). When not in epidemic numbers, mountain pine beetle infest vulnerable trees that are predisposed to attack. Conditions in Colorado that contribute to the susceptibility of a stand to infestation by mountain pine beetle include: high stand stocking > 17.1 m²/ha basal area, high ponderosa pine SDI (stand density index), and high quadratic mean diameter (Negrón & Popp 2004). For individual trees, the susceptibility of mountain pine beetle infestation increases for dominant and codominant trees with > 18.2 cm in diameter at breast height (1.37m, dbh) (Negrón & Popp 2004). Sartwell and Stevens (1975) note that in the Black Hills, SD, site conditions may influence susceptibility, with better quality growing sites supporting greater density stands, though they sustain less mountain pine beetle-killed trees. The generally poor growing conditions, due to rocky and shallow soil and relatively low precipitation, found in the northern Front Range of Colorado

may influence the susceptibility of ponderosa pine to mountain pine beetle infestation (Morgen 1956, Peet 1981, Negrón & Popp 2004). At epidemic populations, mountain pine beetle can infest and kill vast amounts of trees in a broader range of diameter classes and are less dependent on stocking levels.

Trees killed by bark beetles are considered dead woody fuels available for surface fires, but the potential effect on fire behavior depends on the position and spatial arrangement of the fuels. Once these dead fuels fall to the ground, there is a greater fuel load available for a surface fire. However, the decay and compaction rate of these fuels in Colorado's northern Front Range is unknown.

Surveys of the incidence of infestations by the parasitic plant southwestern dwarf mistletoe in the ponderosa pine of the northern Front Range of Colorado have shown that about 19 to 27% of surveyed areas within the extent of dwarf mistletoe have trees that are infested (Merrill et al. 1987, Russell Beam unpublished data, Colorado State University BSPM, Ft. Collins, CO 80523-1177). Many hypotheses have been suggested, but little quantitative data exists to support an interaction of dwarf mistletoe infestation and fire hazard. Dwarf mistletoe as a mortality agent of trees contributes snags to stands, which eventually fall to the ground and become woody material available for surface fires. Alexander & Hawksworth (1975) discuss possible effects of dwarf mistletoe infestation, such as increased dead fuels on the forest floor, as well as a greater amount of branches and foliage near the ground as compared to un-infested stands. By trapping needles and fine twigs, witches' brooms formed by dwarf mistletoe within trees could have a greater amount of fine fuels, and act as fire-

ladders, allowing a fire to carry from the surface to individual crowns (Brown 1974, Alexander & Hawksworth 1975, Alexander & Hawksworth 1976, Mooney et al. 2006). Also, dead or resin soaked branches and stem cankers, and spiked or dead tops created from dwarf mistletoe infestations were suggested to influence potential fire behavior (Hawksworth 1961, Alexander & Hawksworth 1975, Alexander & Hawksworth 1976, Tinnin et al. 1982, Conklin 2000, Geils et al. 2002, Beatty & Mathiasen 2003).

Few studies have investigated the fuel loading associated with dwarf mistletoe-infested trees (Koonce & Roth 1985, Harrington & Hawksworth 1990, Conklin & Armstrong 2001, Hoffman et al. 2007). Within ponderosa pine forests infested with southwestern dwarf mistletoe, Hoffman et al. (2007) found that in uniform stands in Arizona, the fuel loading was at least four times greater in severely infested stands than in lightly or non-infested stands. In precommercial ponderosa pine stands in Oregon, Koonce & Roth (1985) showed greater fine fuels in plots with the highest severity of dwarf mistletoe compared to plots without trees infested with dwarf mistletoe.

Fire exclusion and logging have changed the stand characteristics and disturbance regimes of ponderosa pine forests as compared to those of pre-Euro-American settlement times (Alexander & Hawksworth 1975, Alexander & Hawksworth 1976, Veblen et al. 2000). Researchers have hypothesized that dwarf mistletoe infestations in ponderosa pine stands were historically minimal in areas with periodic low intensity fires (Weaver 1951, Alexander & Hawksworth 1975, Hessburg & Everett 1991). Furthermore, when fire was excluded, damage

from dwarf mistletoe would be severe, resulting in the increase of witches' brooms and stand stagnation (Hessburg & Everett 1991). Partial fires allow for unburned refugia of infested trees to remain and inoculate regeneration (Alexander & Hawksworth 1975). Ponderosa pine forests, which have been historically heterogeneous, in the northern Front Range of Colorado have experienced changes in fire occurrence associated with greater influences of Euro-American presence, with a short period of increased fire occurrence during the mid-1880s leading to an increase in the number of dense stands present today (Kaufmann et al. 2000, Veblen et al. 2000).

Mountain pine beetle, *Ips* spp. and southwestern dwarf mistletoe all infest ponderosa pine. In addition, studies have shown that dwarf mistletoe and bark beetles interact by occurring in areas of similar stand structure, with dense stands that have a high proportion of host species (Hawksworth 1961, Beam unpublished data). The potential fire behavior under situations of both dwarf mistletoe infestation and bark beetle-induced mortality is unknown.

Surface fires burn the duff and litter layers along with fine and coarse wood fuel (Johnson 1992, McCullough et al. 1998). Crown fires, however, spread upward through the consumption of fine fuels in the canopy. Fire intensity is affected by fuel accumulation, distribution, type and moisture content (McCullough 1998). Fine fuels which are less than 7.6 cm in diameter, dry out very quickly and are a factor when predicting fire spread (Johnson 1992). The duff fuels, or humus layer, is more compact, and therefore takes longer to dry.

Coarse wood fuels along with the most compact duff layer take the longest to dry.

There are only a few qualitative studies available to draw upon in order to understand the specific effects of dwarf mistletoe and bark beetle infestation on fire hazard in ponderosa pine outside of the southwest. The purpose of this study was to contribute to the body of knowledge about the fuel amounts and possible fire hazard associated with ponderosa pine infested with southwestern dwarf mistletoe, mountain pine beetle, and (or) *Ips* spp. The objectives of this study were to: 1) Quantify dead downed wood fuel loads under areas infested with differing degrees of southwestern dwarf mistletoe and differing time since infestation of mountain pine beetle, and (or) *Ips* spp. in the Canyon Lakes Ranger District, CO; 2) Examine tree attributes, such as height to bottom of live crown and percent live crown, in relation to the infestations; and 3) Determine differences in pre-infestation stand structure of areas infested with bark beetles or dwarf mistletoe compared to stands without infested trees.

Materials and Methods

During the summers of 2005 and 2006, 150 fixed radius plots (0.04 ha) were permanently established within ponderosa pine forests of the Canyon Lakes Ranger District (CLRD), Roosevelt National Forest in Colorado's Northern Front Range. Dead downed wood fuel loads, understory, standard tree, and stand attributes, and disturbance agent severity and tree decay status were recorded. Plots were placed throughout the study area, in areas with ponderosa

pine not infested (baseline plots) and infested with southwestern dwarf mistletoe, mountain pine beetle, and (or) *Ips* spp. Plots established in 2005 were connected to a population survey of ponderosa pine (Russell Beam unpublished data, CSU BSPM, Ft. Collins, CO 80523-1177). Beam (unpublished data, unpublished data, CSU BSPM, Ft. Collins, CO 80523-1177) describes the methods for the population survey, where the ponderosa pine within the CLRD study area were randomly surveyed, by randomly selecting common vegetation unit ponderosa pine type polygons provided by the USDA Forest Service, for incidence and severity of southwestern dwarf mistletoe, MPB, *Ips* spp., as well as canopy cover. Fuel plots established in 2006 were placed in areas with southwestern dwarf mistletoe, MPB, and (or) *Ips* spp. and were not necessarily associated with the previous population survey areas.

Aspect, percent slope, slope position and configuration, stand structure, standard tree attributes, and disturbance severity were recorded in each plot. Slope position was categorized according to plot placement along the topographic landscape as valley or stream, bottom slope, lower slope, mid-slope, upper slope, or ridge or summit, all of which represent a general placement of the plot along a topographic landscape. Slope configuration describes the local topography of the plot and was categorized as: concave, convex, even or linear, undulating, and broken. Stand structure measurements included canopy closure estimates and number of vertical levels of tree heights within a plot. An open canopy was defined as having greater than a visually estimated 80% of the forest floor receiving sunlight, while a closed canopy as having less than 80% sunlight.

Stands were characterized as single storied, two-storied or multi-storied.

Standard tree measurements recorded in the plots included: tree species, tree height obtained from either inclinometer or handheld laser range finder, crown class (categorized as: open grown, dominant, co-dominant, intermediate, overtopped, suppressed, or understory), diameter at breast height (1.37 m, dbh), percent of live crown, and height to bottom of live crown. Average dbh and height, density (trees/ha), basal area (m^2/ha), and stand density index (SDI) were calculated for all trees combined within plots and for all ponderosa pine within plots (Long 1985). Finally, PRISM 800m resolution 30 year average (1971-2000) average annual temperature and precipitation data were assigned to all plots (The PRISM Group at Oregon State University 2006).

The dwarf mistletoe infection severity and tree degradation status of trees killed by bark beetles were assessed for every living and dead tree. The severity of dwarf mistletoe infection was quantified using the Hawksworth Dwarf Mistletoe Rating (dmr) with a scale of 0 to 6 (Hawksworth 1977). If trees exhibited external symptoms of bark beetle infestation, confirmation and identification of bark beetle presence were by examining galleries under the bark. The time since mortality based on amount of tree degradation was categorized into classes that ranged from 1 to 11, with 1 being a healthy tree and 11 being a mostly decayed log with few sections of bark or branches remaining. Modifications of tree degradation assessments and falling rates of dead trees by Keen (1929, 1955) and Schmid et al. (1985) were used to develop the time since tree mortality classes used in this study. Needle color and retention, bark retention, sound or rotten boles, and

whether the tree had fallen were criteria used to determine time since tree mortality due to bark beetle infestation. Recent tree mortality, where mortality was less than about 4 years since tree death, had a degradation status that ranged from all red needles present to < 10% red needles still remaining on tree. Old tree mortality, where mortality was greater than or equal to about 4 years since tree death, had a degradation status that ranged from all needles gone but some small twigs still present on trees to > 75% of bark missing and only large branches left on tree. To reconstruct stand structure before bark beetle or dwarf mistletoe infestation, trees that were currently dead, but were alive about 10 to 20 years previous (pre-infestation) were used in analysis with the assumption of no tree radial growth.

Within the 0.04 ha plots, three modified Brown's planar transects radiating from plot center, 120 degrees from each other were used to measure fuel levels (Van Wagner 1968, Brown 1971, 1974). Each 11.35 m fuel transect represented a plane that vertically extended to 2 m in height, where the counts of downed wood were recorded. Downed wood was characterized by size class that represent the amount of estimated time to reach 63% equilibrium moisture content, assuming constant temperature and relative humidity (Brown 1978). The standard time-lag classes for the diameter of downed woody material were: 1 hour (< 0.6 cm), 10 hour (0.6 - 2.5 cm), 100 hour (2.5 - 7.6 cm), and 1000 hour (> 7.6 cm). The 1 and 10 hour fuels were counted along the middle one meter of the 11.35 m transect; 100 hour along the middle 3 meters of the transect; and 1000 hour along the middle 9 m. The depths of duff and fuel bed were measured

at 3 points along each fuel transect, where duff was the decomposing organic layer above the mineral soil, and fuel bed was the vertical continuous available fuels from either woody or herbaceous components. The length along the transect covered by woody shrubs, grasses, and forbs was recorded. Within 2 m diameter circular plots placed in the center of the fuel transect, trees that were shorter than 1.37 m were assessed for species, tree status, height, height to bottom of live crown, DMR, and bark beetle presence.

Data Analysis. Tukey's multiple comparison procedure ($p=0.05$) was used to assess differences in adjusted mean amounts of fuel types in plots with southwestern dwarf mistletoe, mountain pine beetle, and (or) *Ips* spp. An analysis of covariance was performed as part of a model selection process where possible covariates were assessed by plotting and correlating residuals from models, taking into account the experimental design of canopy cover class with site and stand variables (Appendix I Table I-1) (SAS/STAT 9.1, GLM procedure).

Continuous variables for densities of mountain pine beetle-induced mortality, *Ips* spp.-induced mortality and dwarf mistletoe rating were tested for use as design components instead of the categorical design components that were used in the final analysis. Models with continuous design components showed no significant increase in amount of variability explained as compared to models with categorical design components. Through plotting residuals from the full model for each fuel type against each disturbance and drawing a smoothed regression line, some non-linearity of the data was identified. The cutoff between

high and low levels of mountain pine beetle- and *lps* spp.-induced mortality, and dwarf mistletoe rating were established through visually assessing the point where the slope of the smoothed regression line changed, and as a result, vary for different response variables. Two categories for dwarf mistletoe severity were used (absence of dwarf mistletoe or $dmr < 4$ and $dmr > 4$) as there was no significant difference in fuel amounts or arrangements in plots with the mean ponderosa pine $dmr < 4$ category compared to plots with the mean ponderosa pine $dmr = 0$ category.

To compare the density of trees pre-infestation (reconstructed trees) by either bark beetles or dwarf mistletoe to the density of live trees, a paired t-test was used, maintaining Type I error within species type using Bonferroni adjustment (SAS/STAT 9.1, MIXED procedure with repeated measures). The reconstructed tree density included trees that were live and less than about 20 years since death. The diameter distribution of reconstructed trees was compared to live trees in plots with trees of all infestation type using a chi-squared test. In plots with trees infested with dwarf mistletoe, the diameter distribution of dwarf mistletoe-infested trees was compared to trees not infested using a chi-squared test.

Results

Stand structure

The ponderosa pine stands within the study area had a large component of other tree species. In plots without trees that were infested with bark beetles

or dwarf mistletoe (baseline plots), ponderosa pine had a density of 416.5 stems/ha (S.E.=66.84) and 16.8 m²/ha (S.E.=1.65); and *Pseudotsuga menziesii* (Mirbel) Franco (Douglas-fir) accounted for the largest component of the non-host species with 105.3 stem/ha (S.E.=23.26) and 2.6 m²/ha (S.E.=0.82). *Juniperus scopulorum* Sarg., with a density of 63.1 stems/ha (S.E.=24.74) and 0.2 m²/ha (S.E.=0.08), made up the second largest component of non-host species in baseline plots. Other species, in decreasing order of prevalence included: *Pinus flexilis* (James), *Pinus contorta* Dougl. ex Loud. and *Populus tremuloides* Michx. In baseline plots, non-host species made up a greater proportion of the small tree component of the stand than did ponderosa pine ($p < 0.0001$ from a chi-squared test) (Fig. 1).

Density of tree regeneration was not different in plots with dwarf mistletoe infestation or bark beetle-induced mortality compared to plots without trees infested. The majority of tree regeneration was composed of non-host species, with the mean density of ponderosa pine regeneration being 398 seedlings/ha (S.E.=109) and for all species being 1862 seedlings/ha (S.E.=375).

Bark beetles altered stand structure in our plots by selectively infesting larger diameter ponderosa pine and reducing both the live tree basal area and density (Tables 1 & 2, Fig. 2D). Although the total tree density was different in reconstructed plots compared to live trees in plots with bark beetle-induced mortality, the density of ponderosa pine was not different, except in plots with trees that had both dwarf mistletoe and bark beetle infestations (Table 2). For

comparison, dwarf mistletoe infestation of trees did not alter the tree density, nor did it show to selectively infest a specific size class (Tables 1 & 2, Fig. 3).

Plots with ponderosa pine that became infested with both bark beetles and dwarf mistletoe had different basal areas and densities pre-infestation than plots not infested with either disturbance agent (Tables 1 & 2). The basal area and density of trees in plots with ponderosa pine infested individually by either bark beetles or dwarf mistletoe were not different when compared to plots with both bark beetle- and dwarf mistletoe-infested trees, as well as plots without infested trees (Tables 1 & 2).

Density of all species of live trees in plots with infestations of bark beetles and dwarf mistletoe were no different than plots with trees not infested (Tables 1 & 2). However, the basal area of ponderosa pine was greater in plots with trees infested with dwarf mistletoe compared to plots with a component of bark beetle-induced mortality; while the density of ponderosa pine was greater in plots with both bark beetles and dwarf mistletoe, when compared only to plots without trees infested by either disturbance (Tables 1 & 2).

To determine if live tree SDI was different between plot infestation types, the SDI was calculated for each plot infestation type. There were no differences in SDI of all tree species between plots without infested trees ($391 \text{ SDI} \pm 26.4$), plots with bark beetle-induced mortality ($356 \text{ SDI} \pm 26.5$), plots with dwarf mistletoe infestation ($471 \text{ SDI} \pm 39.5$), and plots with both bark beetle-induced mortality and dwarf mistletoe infestation ($383 \text{ SDI} \pm 22.4$). Plots with trees infested with dwarf mistletoe had greater ($p=0.039$) live ponderosa pine SDI (418

SDI $\pm$ 48.4) as compared to plots with bark beetle-induced mortality (239 SDI $\pm$ 30.5), bark beetle-induced mortality and dwarf mistletoe-infested trees (286 SDI $\pm$ 29.7) and baseline plots (301 SDI $\pm$ 34.7).

Bark beetles selectively infested larger diameter ponderosa pine in plots that had trees with only bark beetle infestation, when comparing the diameter distribution of reconstructed to live ponderosa pine (Fig. 2D). However, in plots with both dwarf mistletoe and bark beetle infestations, the comparison of the diameter distributions of reconstructed to live ponderosa pine was not significantly different (Fig. 2H). When bark beetles were also in plots with trees infested with dwarf mistletoe, the bark beetle communities were different, as compared to plots without dwarf mistletoe infestations in trees. The adjusted mean density of *Ips* spp.-induced mortality was greater in plots with trees infested with dwarf mistletoe and bark beetle-induced mortality, as compared to plots with only bark beetle-induced mortality (104.9 stems/ha (S.E.=22.19) and 25.4 stems/ha (S.E.=24.76) respectively; $p=0.0074$). By comparison, the density of mountain pine beetle-induced mortality was not different in plots with trees infested with dwarf mistletoe and with bark beetle-induced mortality compared to plots with only bark beetle-induced mortality. The basal area of mountain pine beetle- and *Ips* spp.-induced mortality was not different in plots with trees infested with dwarf mistletoe and with bark beetle-induced mortality, as compared to plots with only bark beetle-induced mortality. The mortality in non-host species found in plots with dwarf mistletoe is in the smaller diameter classes (Fig 2E).

The height of live ponderosa pines was not different between plots with trees infested with dwarf mistletoe, bark beetle, dwarf mistletoe and bark beetle, and plots trees that are not infested. Mean height of live ponderosa pine ranged from $7.9 \text{ m} \pm 0.77$ to $9.6 \text{ m} \pm 0.51$.

Site and stand characteristics

In the CLRD study area, the elevation of the fuel plots ranged from 2063 to 2746 m and annual precipitation averaged 46.2 cm (The PRISM Group at Oregon State University 2006). The most common site and stand characteristics that were significant covariates in explaining fuel parameters were: aspect, slope position, average annual yearly temperatures and precipitation, habitat type from Peet (1981), stand basal area and density of all live and dead tree species, ratio of density of ponderosa pine to Douglas-fir, and dbh and height of all dead and alive tree species (Appendix I Table I-1). Elevation and percent slope were not significant covariates.

Mountain pine beetle

Fuel loads. The amount of downed wood was different in plots with mountain pine beetle-induced mortality, depending on the time since infestation. When compared to plots without mountain pine beetle-induced mortality, adjusted means of 10, 100, and 1000 hour fuel loads were greater in plots with the highest density or basal area of mountain pine beetle-induced mortality that was categorized as greater than or equal to 4 years since infestation (old mortality); and correspondingly, the same fuel class loads were greater in plots

with the highest level of total density of mountain pine beetle-induced mortality (Fig. 4C-D, Fig. 5A-B). One hour fuel loads were not different in plots with the highest basal area or density of old or total mountain pine beetle-induced mortality, compared to plots without mountain pine beetle-induced mortality (Fig. 4C-D). The adjusted means of 1, 10, 100, and 1000 hour fuel loads were not significantly different between plots with a density or a basal area of mountain pine beetle-induced mortality that was categorized as less than 4 years after beetle infestation (recent mortality) within fuel type (Fig. 4A-B, 5A-B).

Combined fine fuels were greater in plots with a high basal area of recent, old, and total mountain pine beetle-induced mortality, as compared to plots without bark beetle-induced mortality (Fig. 6). The same pattern existed for the old and total stems/ha of mountain pine beetle-induced mortality (Fig. 6). The plots with the highest category of density and basal area of old and total mountain pine beetle-induced mortality also were associated with greater total fuel loading, as compared to plots without mountain pine beetle-induced mortality (Fig. 7).

The models for the fuel loads controlled for a number of stand and site characteristics, though covariates were different for each fuel class model (Fig. 4A-F, 5A-F, Appendix I Table I-1). The mean density of *P. flexilis* was a significant covariate in the models describing 1 hour fuel (Fig. 4A-F). One hour fuel load was significantly higher ($p < 0.01$) in plots with greater than 75 stems/ha of live and dead *P. flexilis* (0.86 Mg/ha, S.E.=0.094) when compared to plots

without *P. flexilis* (0.36 Mg/ha, S.E.=0.029) or plots with less than 75 stems/ha of *P. flexilis* (0.40 Mg/ha, S.E.=0.084), regardless of disturbance agents.

Vegetation related fuel parameters. The areas with a high density of recent mountain pine beetle-induced mortality did not have different downed wood fuel loads, but instead were associated with areas with different fuel arrangements. Compared to plots without mountain pine beetle infestations, greater duff depth and percent vegetation cover were found in plots with the highest stems/ha and basal area of recent mountain pine beetle-induced mortality (Fig. 8A-B, 9A-B). Plots with the highest density of old and total mountain pine beetle-induced mortality and plots with the highest basal area of old mountain pine beetle-induced mortality did not have greater percent vegetation cover compared to plots without mountain pine beetle-induced mortality (Fig. 9A-B). Fuel bed height was not different in plots with the highest density and basal area of recent, old, or total mountain pine beetle-induced mortality compared to plots without mountain pine beetle-induced mortality (N=149 plots) (Table 3)

Stand characteristics. Mountain pine beetle infestation of stands was associated with differences in ponderosa pine percent live crown, but not a change in total stand characteristics. Percent live crown for all species was not different in plots with mountain pine beetle-induced mortality compared to plots without mountain pine beetle-induced mortality (Table 4). Percent live crown for ponderosa pine was lesser in plots with the highest density or basal area of recent, old, and total mountain pine beetle-induced mortality when compared to

plots without mountain pine beetle-induced mortality (Table 4). Mean and minimum height to bottom of live crown of all species and only ponderosa pine were not different in plots with mountain pine beetle-induced mortality compared to plots without mountain pine beetle-induced mortality. Ranges of mean height to bottom of live crown for ponderosa pine were $2.1\text{m} \pm 0.19$ to $2.4\text{m} \pm 0.19$. Height to bottom of live crown of all tree species ranged from $1.3\text{m} \pm 0.10$ to $1.7\text{m} \pm 0.12$. See appendix I for full tables (Appendix I Tables I-2 & I-3).

***Ips* spp.**

Fuel loads. Coarse and total fuel amounts, but not fine fuels, were greater in stands with trees infested with *Ips* spp., compared to stands without *Ips* spp. infestation. Fine fuel loads, total and broken into fuel classes were not different in plots with *Ips* spp.-induced mortality, compared to plots without *Ips* spp.-induced mortality. However, in the plots with < 62 stems/ha of old *Ips* spp.-induced mortality the 10 hour fuel loads were greater, when compared to the plots > 62 stems/ha of *Ips* spp.-induced mortality (Table 5). Total fine fuel loads ranged from $3.4 \text{ Mg/ha} \pm 1.40$ to $6.7 \text{ Mg/ha} \pm 1.00$ (Appendix I Table I-4). One thousand hour fuels were greater in plots with the total basal area of *Ips* spp.-induced mortality, compared to plots without *Ips* spp.-induced mortality (Fig. 10A). One thousand hour fuels were not different in plots with recent *Ips* spp.-induced mortality, compared to plots without *Ips* spp.-induced mortality (Fig 10A-B). Total fuel loads were greater in plots with the highest basal area of old and total *Ips* spp.-induced mortality, as compared to plots without *Ips* spp.-induced

mortality (Fig. 11A). The total fuel load was not different in plots with greater stems/ha of *lps* spp.-induced mortality (Fig. 11B).

Vegetation related fuel parameters. Duff depth, percent vegetation cover, and fuel bed height were not different in plots with *lps* spp.-induced mortality when compared to plots without *lps* spp.-induced mortality. The mean duff depth ranged from 1.7 cm $\pm$ 0.3 to 2.5 cm $\pm$ 0.2. Percent vegetation cover ranged from 26.7% $\pm$ 3.3 to 34.8% $\pm$ 4.4. Finally, the range for fuel bed height was 6.3 cm $\pm$ 1.5 to 10.2 cm $\pm$ 1.0 (See appendix I for complete tables [Appendix I Tables I-5, I-6, I-7]).

Stand characteristics. Percent live crown of all species was less in plots with > 50 stems/ha of old *lps* spp.-induced mortality, as compared to plots without *lps* spp.-induced mortality (Table 6). In plots with recent, total, or the highest level of old basal area of *lps* spp.-induced mortality, the percent live crown of all species was not different than plots without *lps* spp.-induced mortality (Table 6). Percent live crown of ponderosa pine was less in plots with the highest density of old and total *lps* spp.-induced mortality, compared to plots without *lps* spp.-induced mortality (Table 6).

Mean and minimum height to bottom of live crown of all species and ponderosa pine were not different in plots with *lps* spp.-induced mortality, compared to plots without *lps* spp.-induced mortality. The range of height to bottom of live crown of ponderosa pine was 2.2 m $\pm$ 0.19 to 2.4 m $\pm$ 0.19. Minimum height to bottom of crown for ponderosa pine ranged from 0.4 m $\pm$ 0.15 to 0.8 m $\pm$ 0.19 (See appendix I for complete tables [Appendix I Table I-8 & I-9]).

Southwestern dwarf mistletoe

Fuel loads. Fine fuel load, including classes 1 and 100 hour, were greater in plots with a mean ponderosa pine dmr > 4 compared to plots with dmr < 4, while coarse and total fuel loads were not different between plots in these dwarf mistletoe classes. Adjusting for density of old, and basal area of recent and old bark beetle-induced mortality, total fine fuel load was greater in plots with a dmr > 4 (Fig. 12). Also, adjusting for density of recent bark beetle-induced mortality, 1 and 100 hour fuel loads were greater in plots with a dmr > 4, when compared to plots with a dmr < 4 (Table 7). One hundred hour fuel loads were greater in plots with a dmr > 4, when compared to plots with a dmr < 4, adjusting for basal area of old bark beetle-induced-mortality or density of total bark beetle-induced mortality (Table 7). The range of 1000 hour fuel was 16.4 Mg/ha $\pm$ 4.45 to 26.1 Mg/ha $\pm$ 4.10 and the range of the total fuel load was from 23.2 Mg/ha $\pm$ 5.22 to 35.6 Mg/ha $\pm$ 5.53 (Appendix I Table I-10, I-11).

Vegetation related fuel parameters. Duff depth, percent vegetation cover, and fuel bed height were not different in plots with a mean ponderosa pine dmr > 4, when compared to plots with a dmr < 4, adjusting for recent, old, or total bark beetle-induced-mortality. The range for duff depth was 2.0 cm $\pm$ 0.2 to 2.4 cm $\pm$ 0.1. Percent vegetation cover ranged from 27.9% $\pm$ 2.5 to 32.8% $\pm$ 2.9. The range of fuel bed height was 7.1 cm $\pm$ 1.0 to 9.9 cm $\pm$ 1.1. See appendix I for complete tables (Appendix I Tables I-12, I-13, I-14).

Stand characteristics. Plots with trees infested with a high amount of dwarf mistletoe ($\text{dmr} > 4$) had differences in both ponderosa pine tree characteristics and the total stand characteristics, compared to plots with a low dwarf mistletoe infestation or no infestation. Mean percent live crown for all tree species was greater in plots with a mean ponderosa pine $\text{dmr} > 4$, when compared to plots with a $\text{dmr} < 4$, adjusting for density and basal area of recent and old bark beetle-induced mortality (Table 8). Likewise, adjusting for recent bark beetle-induced mortality and density of old and total bark beetle-induced mortality, percent live crown for ponderosa pine was greater in plots with a $\text{dmr} > 4$, when compared to plots with a $\text{dmr} < 4$ (Table 8). Height to bottom of live crown (both mean and minimum) for all tree species was not different in plots with a $\text{dmr} > 4$, when compared to plots with a $\text{dmr} < 4$, adjusting for stems/ha or basal area of recent, old, or total bark beetle-induced mortality (Fig. 13A-F). However, the mean height to bottom of live crown for ponderosa pine was lower in plots with a $\text{dmr} > 4$ when compared to plots with a $\text{dmr} < 4$, adjusting for density and basal area of recent and total bark beetle-induced mortality and density of old bark beetle-induced mortality (Fig. 13A-F).

Mountain pine beetle and southwestern dwarf mistletoe interactions

Fuel loads. The 100 hour fuel load was the only fuel class with a significant interaction between mountain pine beetle and dwarf mistletoe infestations that yielded significant differences in fuel loads. One hundred hour fuel load was greater in plots with a mean ponderosa pine $\text{dmr} > 4$ and > 5.3

m²/ha basal area of old mountain pine beetle-induced mortality, as compared to plots with a lower basal area of old mountain pine beetle-induced mortality and mean ponderosa pine dmr < 4 (Fig. 14).

Vegetation related fuel parameters. Plots with dmr > 4 and a density of recent mountain pine beetle greater than 4.9 m²/ha had a greater mean fuel bed height than plots with no mountain pine beetle and less dwarf mistletoe infestation (Fig. 15). There were no other interactions between dwarf mistletoe intensities and densities of recent, old, or total bark beetle-induced mortality that yielded significant differences of duff depth, percent vegetation cover, and fuel bed height.

Stand characteristics. Mean height to bottom of live crown of ponderosa pine was less in plots with a mean ponderosa pine dmr > 4 and without old mountain pine beetle-induced mortality, when compared to plots with a mean ponderosa pine dmr < 4 and < 5.0 m²/ha basal area of old mountain pine beetle-induced mortality (Fig. 16). There were no other interactions between dwarf mistletoe intensities and densities of recent, old, or total bark beetle-induced mortality that yielded significant differences of percent live crown and height to bottom of live crown of all species and ponderosa pine.

Discussion

Stand structure and regeneration

Within ponderosa pine, bark beetles and dwarf mistletoe are contributing to changes in stand structure. In terms of density, bark beetle and dwarf

mistletoe infestations bring stands that were significantly different pre-infestation to a post-infestation density that is not different from stands not infested. However, the difference in density for ponderosa pine is still maintained post-infestation. Mountain pine beetle infestations reduce stand basal area by selectively infesting the larger diameter classes. The presence of dwarf mistletoe-infested ponderosa pine changes the bark beetle population structure and is associated with greater densities of *Ips* spp.-infested ponderosa pine. The ponderosa pine in the northern Front Range with dwarf mistletoe may be more susceptible to *Ips* spp. infestation than trees not infested with dwarf mistletoe, especially in the smaller diameter classes. Researchers have shown relationships between *Ips* spp. infestations and dwarf mistletoe presence in ponderosa pine (Negrón & Wilson 2003, Kenaley et al. 2006, Russell Beam unpublished data, CSU BSPM, Ft. Collins, CO 80523-1177). Infestation of stands by bark beetles and dwarf mistletoe thin out ponderosa pine in already dense stands. Also, when both disturbances are in combination, small diameter ponderosa pine are killed along with larger diameter trees. These thinner stands potentially have higher surface wind speed and lower relative humidity as compared to more dense stands, which could increase fire hazard by increasing the fire rate of spread (Agee et al. 2000, Pollet & Omi 2002).

The presence of dwarf mistletoe infestations in ponderosa pine was equally distributed on all tree sizes in plots without bark beetle-induced mortality (Fig. 3). In the ponderosa pine of the northern Front Range of Colorado, McCambridge and others (1982b) found that dwarf mistletoe infection was

uniform across diameter classes. Conversely, Hawksworth (1961) states that the larger size classes of trees have a higher frequency of dwarf mistletoe infestation - smaller trees are small targets for the projectile seeds, though they are equally susceptible to infestation (Hawksworth 1961).

In this study, there was a large component of dead non-host in plots with ponderosa pine infested with dwarf mistletoe (Fig. 2E). Both the occurrence of dwarf mistletoe and the non-host species could be related to fire history (Hawksworth 1961). If the modern fire return interval was longer than the historic fire return interval, densities of both dwarf mistletoe and less fire resistant non-host species could be promoted. A large component of the non-host species was Douglas-fir, which has had periods of spruce budworm (*Choristoneura occidentalis* Freeman) defoliation, most notably in the period between 1974-1985 (Lessard & Schmid 1990, Hadley & Veblen 1993). Previous spruce budworm defoliation events, or other sources of mortality, could have killed non-southwestern dwarf mistletoe host species; and without fire, the snags or logs of dead trees were left to decay.

Dwarf mistletoe and bark beetle infestations were not related to differences in regeneration densities. Laven and others (1980) also determined that there was no correlation between regeneration and fire episodes in a study site north of Rustic, CO. Climate and stand structure are related to regeneration of ponderosa pine in the Colorado Front Range (Kaufmann et al. 2000, Shepperd et al. 2006). The lack of tree regeneration in areas with tree mortality due to dwarf mistletoe or bark beetles leads to a maintenance of lower live tree

densities created after disturbance events in the northern Front Range of Colorado. The species composition of the regeneration was composed mainly of species that are not host to mountain pine beetle and southwestern dwarf mistletoe. This regeneration contributes to the number of non-host species making up a large portion of the small diameter trees with the potential of replacement of ponderosa pine as a dominant species (Keane et al. 1990). However, the presence of a large proportion of non-host species in host stands does not change the susceptibility of the host species to bark beetle infestation in ponderosa pine (Amman & Baker 1972, McGregor 1978, McCambridge et al. 1982b).

Bark beetles

Old mortality contributed more to the fuel loads found in infested plots than does more recent tree mortality. The addition of these 10, 100, and 1000 hour fuels to the overall downed wood fuel load is dependent on the rate at which the bark beetle killed trees fall to the ground. Studies on the natural falling rate of mountain pine beetle killed trees show that time since infestation, tree size, soil conditions, and high wind events influence the rate of fall of dead ponderosa pine (Keen 1955, Schmid et al. 1985). In a study of ponderosa pine killed by mountain pine beetle in the northern Front Range of Colorado, trees fell at a rate of 3 to 5% per year after the initial first 2 years, in which no trees fell (Schmid et al. 1985).

Lynch and others (2006) found the odds of the 1988 Yellowstone fire burning an area increased 11% where an old, 13 to 16 years previous, mountain pine beetle infestation of lodgepole pine occurred as compared to areas unaffected. A newer mountain pine beetle outbreak – 5 to 8 years before the fire – did not correlate with fire occurrence. The correlation between areas with old mountain pine beetle-induced mortality and the 1988 Yellowstone fire was attributed to the delay of vegetation response and release after mountain pine beetle infestation of the overstory and stand structure, as opposed to fuel amounts increasing after mountain pine beetle mortality (Lynch et al. 2006). In the Colorado Front Range, the population of mountain pine beetle in ponderosa pine is endemic, as compared to the repeated and extensive mountain pine beetle outbreak in Yellowstone (Harris 2006, Lynch et al. 2006). The response of vegetation and understory trees from smaller and more sporadic populations of mountain pine beetle, such as those found in the northern Front Range of Colorado, may be more spatially fragmented and not as great of a response than from repeated large mountain pine beetle infestations. In our study area, there was a mountain pine beetle outbreak in the early 1980s; the trees killed from this outbreak were most likely too deteriorated to be attributed to mortality from mountain pine beetle in our study. Also, the greater fuel load found in areas with a high density of mountain pine beetle-induced mortality ≥ 4 years previous may not necessarily lead to an increase in fire hazard, as compared to areas with more recent mountain pine beetle-induced mortality or areas without infestation.

Lundquist (2007) examined interactions of different disturbances and showed the complex effects of multiple disturbances on fuel complexes in the Black Hills, SD. Mountain pine beetle-induced mortality had a null effect on the amount of fuels loads present, while other disturbances, most significantly root rot, were correlated with fuel amounts (Lundquist 2007). Like the northern Front Range of Colorado, the mountain pine beetle population in the Black Hills were not epidemic. The investigation of time since mortality by bark beetles may have brought out a better correlation with fuel loads in the Black Hills study (Lundquist 2007). The previous fire history, timber harvest activity, and stand characteristics of the areas with trees infested with mountain pine beetle in the northern Front Range of Colorado may have contributed to the increased fuel levels found in plots with high densities of old mountain pine beetle-induced mortality.

The needles that are cast when trees die from any cause, but more specifically in this example because of bark beetles, are deposited on the forest floor and are slowly incorporated into the duff layer – which is the decaying organic matter above the mineral soil. A tree killed by mountain pine beetle starts casting needles the year after initial infestation, and will be without needles 1 to 2 years later. With time, needles and other fine material may be moved off site from wind and water; and after being incorporated into duff, the organic layers start compacting due to snow and decay. In areas with recent mountain pine beetle-induced mortality, the needles are introduced into the duff layer and not compacted as much as in areas with old mountain pine beetle-induced mortality. Also, the vegetation cover fuel arrangement in areas with a high

density of recent mountain pine beetle-induced mortality is different, as compared to areas not infested with mountain pine beetle. When bark beetles open up a stand by causing trees to die, more light penetrates the canopy, allowing the vegetation to respond by increasing the amount of area in which grasses, forbs and shrubs grow (McCambridge et al. 1982a, Stone & Wolfe 1996, McMillin & Allen 2000, McMillin et al. 2003). The arrangement of these vegetation fuels in plots with recent mountain pine beetle-induced mortality makes them more accessible to surface fires.

The live tree fuel arrangement was also different in areas with lower percent live ponderosa pine crowns in areas with mountain pine beetle-induced mortality, when compared to areas without mountain pine beetle. Trees that developed in dense stands have less percent live crowns as a result of competition and light availability. There was a reduction of live tree density in areas with mountain pine beetle-induced mortality, and the live trees left had less percent live crown than if they had grown under their post-infestation density. The crowns with less percent live foliage in areas with mountain pine beetle-induced mortality may provide less available crown fuels for crown fire initiation and spread.

Dwarf mistletoe

A greater amount of fine downed woody fuel in areas with $dmr > 4$ compared to areas with $dmr < 4$ may not make an important difference in potential fuel behavior as the high fuel loads associated with areas with high

mountain pine beetle-induced mortality. In a pre-commercial ponderosa pine forest in Oregon, Koonce & Roth (1985) found significantly greater fine fuel loads in plots with high dwarf mistletoe infestations in trees, when compared to plots with healthy trees (3.0 Mg/ha and 1.1 Mg/ha respectively). However, 1000 hour fuel loads made up a significantly lower percentage of total fuel loading in plots with high dwarf mistletoe intensities than in plots with healthy trees (Koonce & Roth 1985). Similarly, in the current study, the total fine fuel load was greater in plots with $dmr > 4$, as compared to plots without dwarf mistletoe or with $dmr < 4$, with the 100 hour fuel class making up the majority of the total fine fuel amount. Stands in such different conditions - precommercial ponderosa pine forest in Oregon and un-even aged mixed species ponderosa pine forest in Colorado's northern Front Range - both have greater fine fuel amounts in areas with high dwarf mistletoe severity. The abnormal shoot growth of witches' brooms in infected ponderosa pine may contribute fine fuels to the forest floor by dropping excess branches or entire witches' brooms before the tree is killed.

In ponderosa pine in northern Arizona, Hoffman and others (2007) found there were four times greater total fuel loads in plots with high dwarf mistletoe intensities than in plots without dwarf mistletoe-infested trees. In comparison, in the northern Front Range of Colorado, the total average fuel load was not different between plots with $dmr > 4$ (25.8 Mg/ha) and plots with $dmr < 4$ or those not infested with dwarf mistletoe (27.2 Mg/ha), adjusting for density of bark beetle-induced mortality, canopy cover, and proportion of stand that was ponderosa pine. There were differences in fuel loads when broken into fuel

classes: the 100 hour fuel loads were significantly greater in areas with average ponderosa pine dmr > 4 in both the Hoffman and others (2007) study area and in the current study. Similarly, the other fine fuels, duff depth, and fuel bed height were not different between infestation classes for dwarf mistletoe infestation in both the Hoffman and others (2007) study and this study, with the exception of 1 hour fuel. The height to bottom of live crown was not different between dwarf mistletoe infestation classes for the ponderosa pine in the Hoffman and others (2007) study area, but was lower in the areas sampled in the northern Front Range of Colorado (Fig. 13).

The ponderosa pine in the northern Front Range of Colorado grow in poorer site conditions and are more heterogeneous, with un-even stands and a large component of other species as compared to the more even-aged stands of ponderosa pine in Arizona (Morgen 1956, Peet 1981, Kaufmann et al. 2000, Hoffman et al. 2007). The fire regimes are also more variable in the northern Front Range of Colorado, as compared to northern Arizona (Laven et al. 1980, Brown et al. 1999, Ehle & Baker 2003). Weaver (1951) reported the average interval between fires ranged from 4.8 to 11.9 years in 5 study areas in Arizona from fire scarred stump sections of ponderosa pine, whereas other researchers have recorded longer periods between fires in Colorado's northern Front Range (Laven et al 1980, Brown et al. 1999, Veblen et al. 2000). One study by Veblen and others (2000) found a conservative estimate of mean fire return interval in the lowest elevational range of 1884-2015 m was 14.4 years (S.D. = 11.7) and in the highest elevational range of 2630-2670 m the mean fire return interval was

34.3 years (S.D. = 32.0), for ponderosa pine forests in the northern Front Range of Colorado. In a study area in Colorado where elevation ranged from 2500-2800 m and was located north of the Veblen and others (2000) sites, the mean fire interval (time between two fire scars) was 45.8 years (Laven et al. 1980).

The lower elevations of the northern Front Range of Colorado more resemble the Arizona ponderosa pine fire regime, whereas the elevations above 2500 m have more variable and longer periods between fire episodes. The differences in structure, fire regimes, and possible dead woody material degradation rate in ponderosa pine forests in Arizona and northern Front Range of Colorado confound some comparisons of fuel loads.

The within tree fuel arrangements in plots with dwarf mistletoe-infested trees were different compared to plots with a dmr < 4. Dwarf mistletoe-infested branches are induced to form abnormal shoot growth and witches' brooms, with an increase in radial growth of infected branches and the retention of infected branches (Hawksworth 1961, Tinnin et al. 1982, Geils et al. 2002). This abnormal growth leads to greater percent live ponderosa pine crown compared to trees not infested with dwarf mistletoe. The prevention of self pruning of dwarf mistletoe-infested trees also leads to lower height to bottom of live ponderosa pine crown compared to trees not infested with dwarf mistletoe (Fig. 13). In a limited study, Harrington & Hawksworth (1990) found that trees infested with dwarf mistletoe had lower average crown heights than trees not infested, therefore leading to greater bole scorch. However, in the mixed species stands that comprise the northern Front Range of Colorado, the half meter difference

between height to bottom of live ponderosa pine in areas with a dmr > 4 compared to areas with ponderosa pine with a dmr < 4, may not influence potential fire behavior because the height to bottom of live crown for all species was not significantly different in areas with a dmr > 4 compared to areas with a dmr < 4. Also, the minimum height to bottom of live crown was not different for ponderosa pine or all species in plots with a dmr > 4 as compared to plots with dmr < 4.

Bark beetle and dwarf mistletoe interaction

There were few significant bark beetle and dwarf mistletoe interactions that resulted in differences in fuel amounts or fuel arrangements. In this study, 100 hour fuel load, fuel bed height, and height to bottom of live ponderosa pine crown were variables that had a significant interaction between dwarf mistletoe intensity and the density of mountain pine beetle-induced mortality.

The greater 100 hour fuel load associated with areas with dmr > 4 and > 5.3 m²/ha basal area of mountain pine beetle-induced mortality show that dwarf mistletoe and mountain pine beetle may together influence fuel loads and arrangements in areas infested with both disturbances. The fuel bed height was greater in plots with > 4.9 m²/ha of recent mountain pine beetle-induced mortality and dmr > 4, when compared to plots in other infestation classes. The lowering of ponderosa pine crowns and an association with greater 100 hour fuel classes of infestations of dwarf mistletoe, along with the needle and small twig deposition to the fuel bed from recently killed trees from mountain pine beetle, creates a

situation of greater fuel bed depth, as compared to plots in other infestation classes. Also, the compaction of the fuel bed may occur 4 years after mountain pine beetle infestation, therefore reducing available vertical fuels.

Canopy fuels were not assessed in this study. Typically, a significant amount of snags, which are a result of bark beetle and dwarf mistletoe infestation, would contribute to the available canopy fuels and affect torching and crowning potentials. The time and money required to dissect trees and witches' brooms – to precisely measure canopy bulk density and other canopy fuel parameters – are extensive. Equations that predict canopy fuels are not designed for trees with abnormal crowns, such as the crowns affected by dwarf mistletoe infestations. Further research into the composition, amount and arrangement of canopy fuels in trees infested with dwarf mistletoe would be very useful, so as to identify more precisely the crowning and torching potential of infested trees and stands.

Conclusions

Within the Canyon Lakes Ranger District in the northern Colorado Front Range ponderosa pine, total fuel loads (13.3 to 43.0 Mg/ha) were within the range found by Battaglia and others (2005) in the southern Front Range of Colorado (0.0 to 47.3 Mg/ha). The total fuel loads in areas with mountain pine beetle- or *Ips* spp.-induced mortality are greater than in areas without bark beetle-induced mortality in the northern Front Range of Colorado. Tree mortality from mountain pine beetle and *Ips* spp. that has occurred greater than 4 years

previous is contributing to the fuel loading in these areas, and is related to the natural falling rates of dead ponderosa pine. Consequently, there is a potential for the surface fire hazard to increase 4 years after infestation by bark beetles.

The fuel arrangement in ponderosa pine is different in plots with high dwarf mistletoe severity, when compared to areas with less dwarf mistletoe, creating the possibility that the torching potential of individual ponderosa pine trees will be altered. While high intensities of dwarf mistletoe infestation slowly alter within tree fuel arrangements, such as height to bottom of live ponderosa pine crown, it may have a negligible impact in changing the potential fire behavior of the entire stand. This is because the height to bottom of live crown of all tree species was not significantly different, when compared to stands with less or no dwarf mistletoe infestation.

Bark beetles and dwarf mistletoe, by selectively infesting more dense stands, may make forest density more uniform across the landscape without the input of fire. However, these disturbances act as agents that create more flammable patches within the forest, which may increase fire hazard by contributing to the build-up of downed woody fuel, altering fuel arrangements and opening up stands, lowering relative humidity and increasing potential surface wind speeds (Pollet & Omi 2002). Together these disturbances create heterogeneity in fuel amounts, fuel arrangements and stand microclimates, which can be translated into spatially dependent patterns of fire behavior related to the distribution of mountain pine beetle, *Ips* spp., and dwarf mistletoe infestations.

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Table 1. Adjusted means and standard errors of basal area (m²/ha) of reconstructed trees and live trees in areas with bark beetle-induced mortality and dwarf mistletoe infestation in the northern Front Range of Colorado, 2005-2006.

plot infestation type	reconstructed trees		difference between reconstructed tree means (p<0.05)	live trees		difference between live tree means (p<0.05)	p-value for reconstructed and live tree means
	mean	SE		mean	SE		
all tree species							
not infested	23.1	1.61	a	20.9	1.61	a	0.96
bark beetle	28.9	1.55	ab	17.6	1.55	a	<0.0001
dwarf mistletoe	30.5	2.30	ab	23.2	2.30	a	0.23
bark beetle and dwarf mistletoe	29.4	1.39	b	19.5	1.39	a	<0.0001
ponderosa pine							
not infested	16.8	1.65	a	16.3	1.65	ab	1.0
bark beetle	20.9	1.53	ab	11.9	1.53	a	0.0003
dwarf mistletoe	22.9	2.36	ab	22.1	2.36	b	1.0
bark beetle and dwarf mistletoe	23.0	1.39	b	14.3	1.39	a	<0.0001

Note: Reconstructed trees include trees that were alive about 20 years previous to sampling and represent a pre-infestation stand. N=150 plots.

Table 2. Adjusted means and standard errors of density (stems/ha) of reconstructed trees and live trees in areas with bark beetle induced-mortality and dwarf mistletoe infestation in the northern Front Range of Colorado, 2005-2006.

plot infestation type	reconstructed trees		difference between reconstructed tree means (p<0.05)	live trees		difference between live tree means (p<0.05)	p-value for reconstructed and live tree means
	mean	SE		mean	SE		
all tree species							
not infested	941.4	89.01	a	796.4	89.01	a	0.9171
bark beetle	1211.7	89.61	ab	847.7	89.61	a	0.046
dwarf mistletoe	1429.4	126.94	ab	1000.6	126.94	a	0.2164
bark beetle and dwarf mistletoe	1319.9	75.38	b	945.8	75.38	a	0.0023
ponderosa pine							
not infested	416.5	66.84	a	405.5	66.84	a	1.0
bark beetle	637.5	66.46	ab	535.3	66.46	ab	0.9525
dwarf mistletoe	675.2	99.31	ab	653.4	99.31	ab	1.0
bark beetle and dwarf mistletoe	873.3	55.57	b	609.6	55.57	b	0.0085

Note: Reconstructed trees include trees that were alive about 20 years previous to sampling and represent a pre-infestation stand. N=150 plots.

Table 3. Adjusted means (standard errors) of fuel bed height (cm) in areas with different densities of mountain pine beetle (MPB)-induced mortality in ponderosa pine, categorized by the amount of time since mortality in the northern Front Range of Colorado, 2005-2006.

	basal area of recent MPB- induced mortality	density of recent MPB- induced mortality	basal area of old MPB- induced mortality	density of old MPB- induced mortality	basal area of total MPB- induced mortality	density of total MPB- induced mortality
absence of MPB	7.0 (1.5)	7.4 (1.2)	8.5 (1.1)	9.0 (1.0)	8.1 (1.1)	7.7 (1.2)
low	8.7 (1.3)	9.9 (1.3)	7.4 (1.4)	8.3 (1.2)	8.2 (1.0)	8.3 (1.0)
high	10.8 (1.8)	10.7 (1.7)	9.0 (1.2)	9.7 (1.3)	10.6 (1.2)	10.8 (1.6)

Note: The cutoff for high and low of MPB-induced mortality was: recent basal area of 4.9 m²/ha, recent density of 92 stems/ha, old basal area 3.7 m²/ha, old density of 105 stems/ha, total basal area 7.0 m²/ha, and total density of 187 stems/ha. N=149 plots.

Table 4. Adjusted means (standard errors) of percent live crown in areas with different densities of mountain pine beetle (MPB)-induced mortality in ponderosa pine, categorized by the amount of time since mortality in the northern Front Range of Colorado, 2005-2006.

		basal area of recent MPB-induced mortality		density of recent MPB-induced mortality		basal area of old MPB-induced mortality		density of old MPB-induced mortality		basal area of total MPB-induced mortality		density of total MPB-induced mortality	
		all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine
absence	adjusted mean	73.5	72.1 a	74.9	71.8 a	72.8	68.2 a	72.7	66.5 a	72.7	66.4 a	72.8	69.1 a
	SE	1.66	2.32	1.79	2.19	1.49	2.01	1.55	1.72	1.55	2.46	1.56	2.02
low	adjusted mean	71.8	66.6 ab	71.8	65.9 ab	70.2	63.5 ab	72.4	62.0 ab	72.4	64.6 a	72.4	65.5 ab
	SE	1.78	2.46	2.51	3.20	1.93	2.67	1.43	2.32	1.43	2.26	1.85	2.45
high	adjusted mean	71.0	62.4 b	71.6	62.4 b	70.8	61.4 b	72.2	57.4 b	72.2	58.6 b	71.8	61.7 b
	SE	1.91	2.54	1.92	2.40	1.62	2.33	1.60	2.12	1.60	2.38	1.35	1.69

Note: The cutoff for high and low of MPB-induced mortality was: recent basal area of 3.1 m²/ha, recent density of 49 stems/ha, old basal area 3.5 m²/ha, old density of 81 stems/ha, total basal area 6.4 m²/ha, and total density of 70 stems/ha. N=150 plots. Different letters denote significance at p<0.05 of comparisons between levels of MPB-induced mortality.

Table 5. Adjusted means (standard errors) of fine fuels (Mg/ha) in areas with different densities of *lps* spp.-induced mortality in ponderosa pine, categorized by the amount of time since mortality in the northern Front Range of Colorado, 2005-2006.

	basal area of recent <i>lps</i> spp.- induced mortality	density of recent <i>lps</i> spp.- induced mortality	basal area of old <i>lps</i> spp.- induced mortality	density of old <i>lps</i> spp.- induced mortality	basal area of total <i>lps</i> spp.- induced mortality	density of total <i>lps</i> spp.- induced mortality
1 hour fuel						
absence of <i>lps</i> spp.	0.5 (0.03)	0.4 (0.04)	0.5 (0.04)	0.4 (0.04)	0.4 (0.04)	0.4 (0.05)
low	0.5 (0.09)	0.4 (0.08)	0.4 (0.07)	0.5 (0.06)	0.5 (0.06)	0.5 (0.06)
high	0.3 (0.07)	0.3 (0.09)	0.4 (0.07)	0.3 (0.08)	0.3 (0.06)	0.3 (0.07)
10 hour fuel						
absence of <i>lps</i> spp.	1.8 (0.27)	1.9 (0.29)	1.9 (0.27)	1.4 (0.29) ab	1.5 (0.27)	1.9 (0.31)
low	1.1 (0.57)	1.4 (0.55)	2.0 (0.48)	2.4 (0.41) a	1.7 (0.38)	2.2 (0.39)
high	2.3 (0.51)	2.1 (0.63)	2.1 (0.47)	1.1 (0.53) b	2.0 (0.40)	1.8 (0.45)
100 hour fuel						
absence of <i>lps</i> spp.	3.3 (0.50)	3.3 (0.53)	3.0 (0.38)	2.6 (0.41)	2.7 (0.41)	3.3 (0.46)
low	2.7 (0.96)	1.9 (0.92)	2.6 (0.72)	2.5 (0.64)	3.1 (0.57)	3.3 (0.60)
high	3.0 (0.84)	3.3 (0.97)	2.1 (0.71)	1.5 (0.72)	1.9 (0.59)	1.7 (0.62)

Note: The cutoff for high and low of *lps* spp.-induced mortality was: recent basal area of 0.56 m²/ha, recent density of 50 stems/ha, old basal area 0.34 m²/ha, old density of 62 stems/ha, total basal area 0.9 m²/ha, and total density of 73 stems/ha. N=150 plots. Different letters denote significance at p<0.05 of comparisons between levels of *lps* spp.-induced mortality.

Table 6. Adjusted means and standard errors of percent live crown of all species and ponderosa in areas with different densities of *lps* spp.-induced mortality in ponderosa pine, categorized by the amount of time since mortality in the northern Front Range of Colorado, 2005-2006.

		basal area of recent <i>lps</i> spp.-induced mortality		density of recent <i>lps</i> spp.-induced mortality		basal area of old <i>lps</i> spp.-induced mortality		density of old <i>lps</i> spp.-induced mortality		basal area of total <i>lps</i> spp.-induced mortality		density of total <i>lps</i> spp.-induced mortality	
		all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine
<i>lps</i> spp.- induced mortality													
absence	adjusted mean	72.6	66.6	72.8	66.0 ab	72.9	66.9	73.0 a	65.8 a	73.3	64.7	73.4	69.1 a
	SE	1.16	1.62	1.33	1.66	1.10	1.62	1.15	1.51	1.27	2.05	1.26	1.61
low	adjusted mean	71.7	70.8	73.5	74.0 a	70.2	65.5	75.1 a	66.3 a	72.3	64.7	73.3	69.8 a
	SE	2.67	3.56	2.72	3.46	2.19	3.08	1.84	2.39	1.76	2.57	1.76	2.24
high	adjusted mean	72.0	63.7	72.0	60.0 b	70.5	60.7	65.8 b	53.8 b	71.7	60.1	70.4	57.4 b
	SE	2.12	2.87	2.81	3.50	2.25	2.95	2.34	2.77	1.82	2.70	2.08	2.52

Note: The cutoff for high and low of *lps* spp.-induced mortality was: recent basal area of 0.54 m²/ha, recent density of 45 stems/ha, old basal area 0.35 m²/ha, old density of 50 stems/ha, total basal area 0.7 m²/ha, and total density of 65 stems/ha. N=150 plots. Different letters denote significance at p<0.05 of comparisons between levels of *lps* spp.-induced mortality.

Table 7. Adjusted means (standard errors) of fine fuels (Mg/ha) in areas with trees infested with dwarf mistletoe (DM) compared to areas with less or no tree infestation of dwarf mistletoe, adjusting time since mountain pine beetle (MPB)- and *Ips* spp.-induced mortality in the northern Front Range of Colorado, 2005-2006.

	basal area of recent MPB- and <i>Ips</i> spp.- induced mortality	density of recent MPB- and <i>Ips</i> spp.- induced mortality	basal area of old MPB- and <i>Ips</i> spp.- induced mortality	density of old MPB- and <i>Ips</i> spp.- induced mortality	basal area of total MPB- and <i>Ips</i> spp.- induced mortality	density of total MPB- and <i>Ips</i> spp.- induced mortality
1 hour fuel						
absence of DM or dmr < 4	0.4 (0.05)	0.3 (0.06) a	0.4 (0.04)	0.4 (0.04)	0.4 (0.04)	0.4 (0.04)
dmr > 4	0.5 (0.05)	0.5 (0.05) b	0.5 (0.05)	0.4 (0.06)	0.5 (0.05)	0.5 (0.05)
10 hour fuel						
absence of DM or dmr < 4	1.6 (0.34)	1.6 (0.37)	1.8 (0.30)	1.6 (0.31)	1.7 (0.26)	1.8 (0.28)
dmr > 4	1.9 (0.39)	2.1 (0.38)	2.3 (0.35)	1.7 (0.38)	1.8 (0.35)	2.07 (0.35)
100 hour fuel						
absence of DM or dmr < 4	2.4 (0.58)	1.9 (0.61) a	1.9 (0.44) a	1.7 (0.43)	2.0 (0.37)	2.1 (0.39) a
dmr > 4	3.6 (0.67)	3.7 (0.65) b	3.2 (0.49) b	2.7 (0.53)	3.1 (0.50)	3.4 (0.49) b

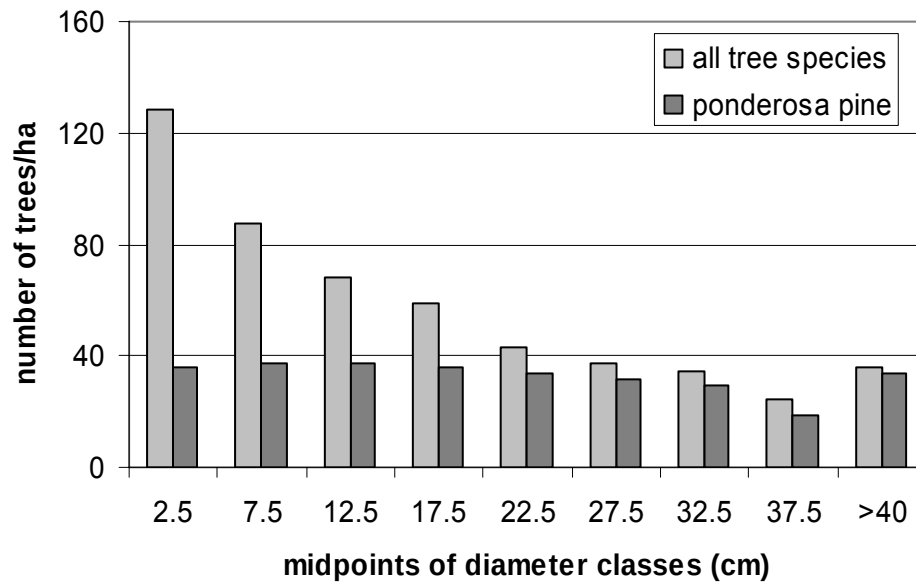
Note: Dwarf mistletoe rating is abbreviated as dmr and N=150 plots. Different letters denote significance at $p < 0.05$ of comparisons between levels of DM infestation.

Table 8. Adjusted means and standard errors of percent live crown of all species and ponderosa pine in areas with trees infested with dwarf mistletoe (DM) compared to areas with less or no tree infestation of dwarf mistletoe, adjusting for the time since mountain pine beetle (MPB)- and *Ips* spp.-induced mortality in the northern Front Range of Colorado, 2005-2006.

		adjusting for basal area of recent MPB- and <i>Ips</i> spp.-induced mortality		adjusting for density of recent MPB- and <i>Ips</i> spp.-induced mortality		adjusting for basal area of old MPB- and <i>Ips</i> spp.-induced mortality		adjusting for density of old MPB- and <i>Ips</i> spp.-induced mortality		adjusting for basal area of total MPB- and <i>Ips</i> spp.-induced mortality		adjusting for density of total MPB- and <i>Ips</i> spp.-induced mortality	
		all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine
absence of DM or dmr < 4	adjusted mean	66.3 a	63.9 a	66.8 a	63.6 a	65.4 a	62.3	65.4 a	59.6 a	66.8	61.3	66.6	62.1 a
	SE	1.52	2.05	1.75	2.15	1.38	1.97	1.34	1.64	1.19	1.88	1.23	1.54
dmr > 4	adjusted mean	78.0 b	70.1 b	78.7 b	69.7 b	77.1 b	66.4	77.2 b	64.3 b	78.0	65.0	78.1	68.8 b
	SE	1.63	2.26	1.81	2.24	1.60	2.22	1.50	1.98	1.52	2.47	1.58	2.13

Note: Dwarf mistletoe rating is abbreviated as dmr and N=150 plots. Different letters denote significance at $p < 0.05$ of comparisons between levels of DM infestation.

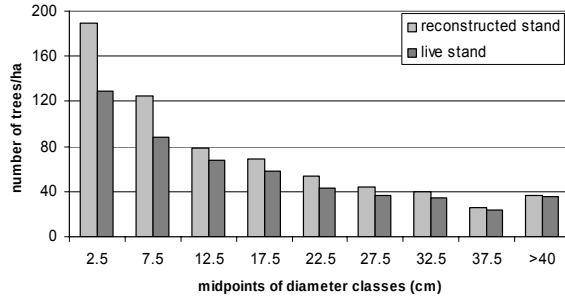
Figure 1. Diameter distribution of trees in areas without bark beetle-induced mortality and (or) dwarf mistletoe infestation in the northern Front Range of Colorado, 2005-2006.



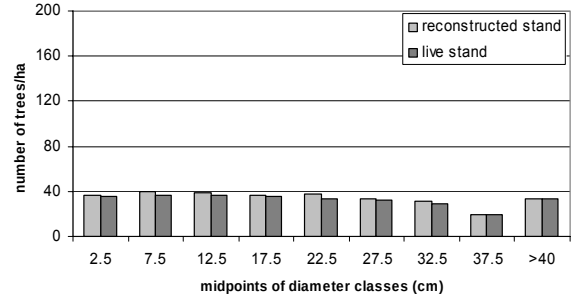
Note: Chi-squared analysis significant at $p < 0.0001$ and $N = 38$ plots.

Figure 2. Diameter distributions of reconstructed and live trees in areas with and without southwestern dwarf mistletoe and bark beetle infestation in the northern Front Range of Colorado, 2005-2006.

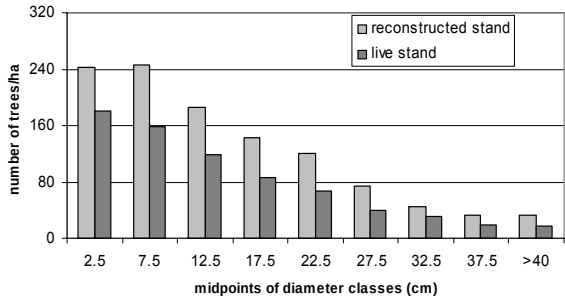
(A) Not infested – all tree



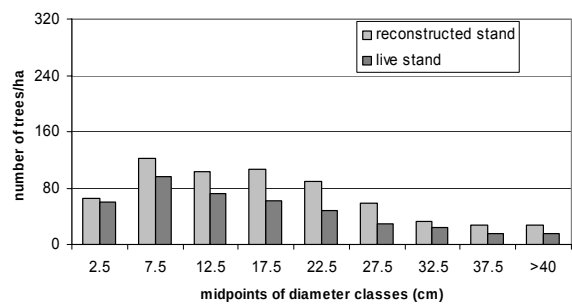
(B) Not infested – ponderosa pine



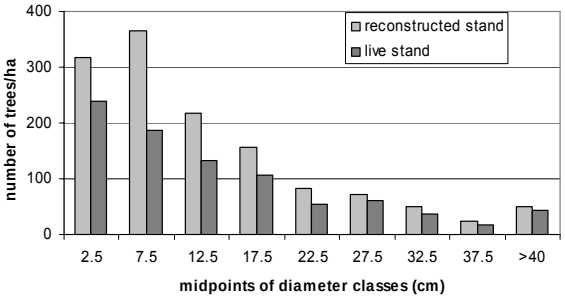
(C) Bark beetles only – all tree species



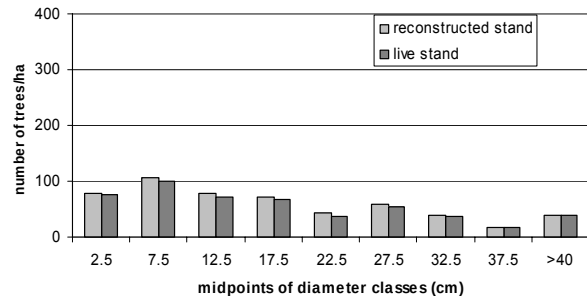
(D) Bark beetles only – ponderosa pine



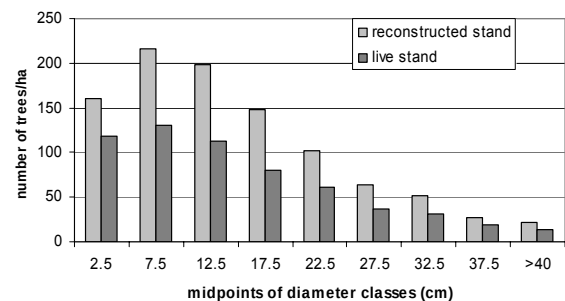
(E) Dwarf mistletoe only – all tree species



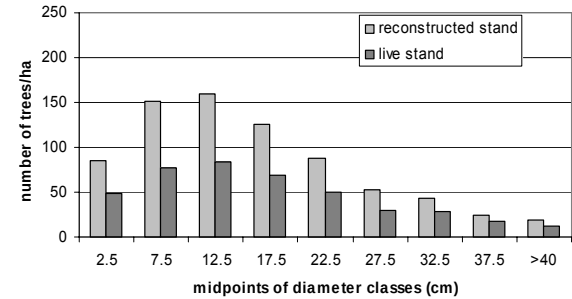
(F) Dwarf mistletoe only – ponderosa pine



(G) Bark beetles and dwarf mistletoe – all tree species

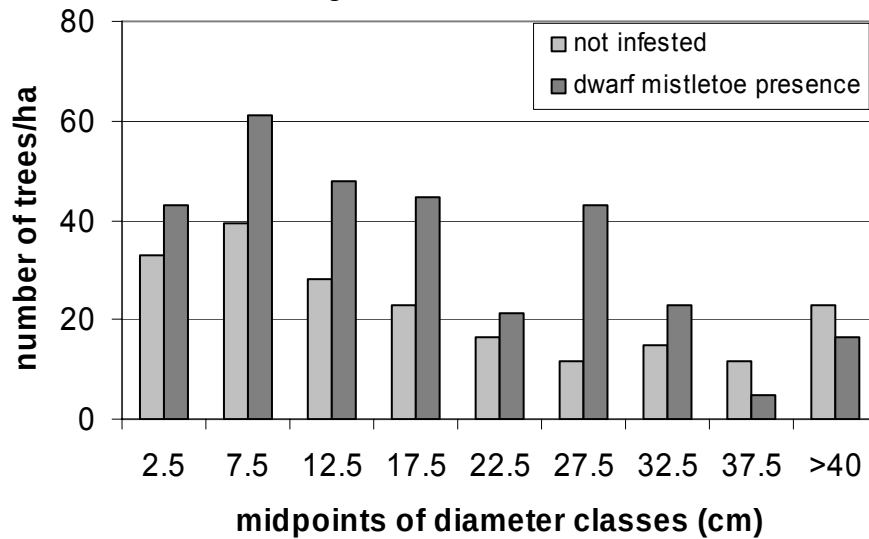


(H) Bark beetles and dwarf mistletoe – ponderosa pine



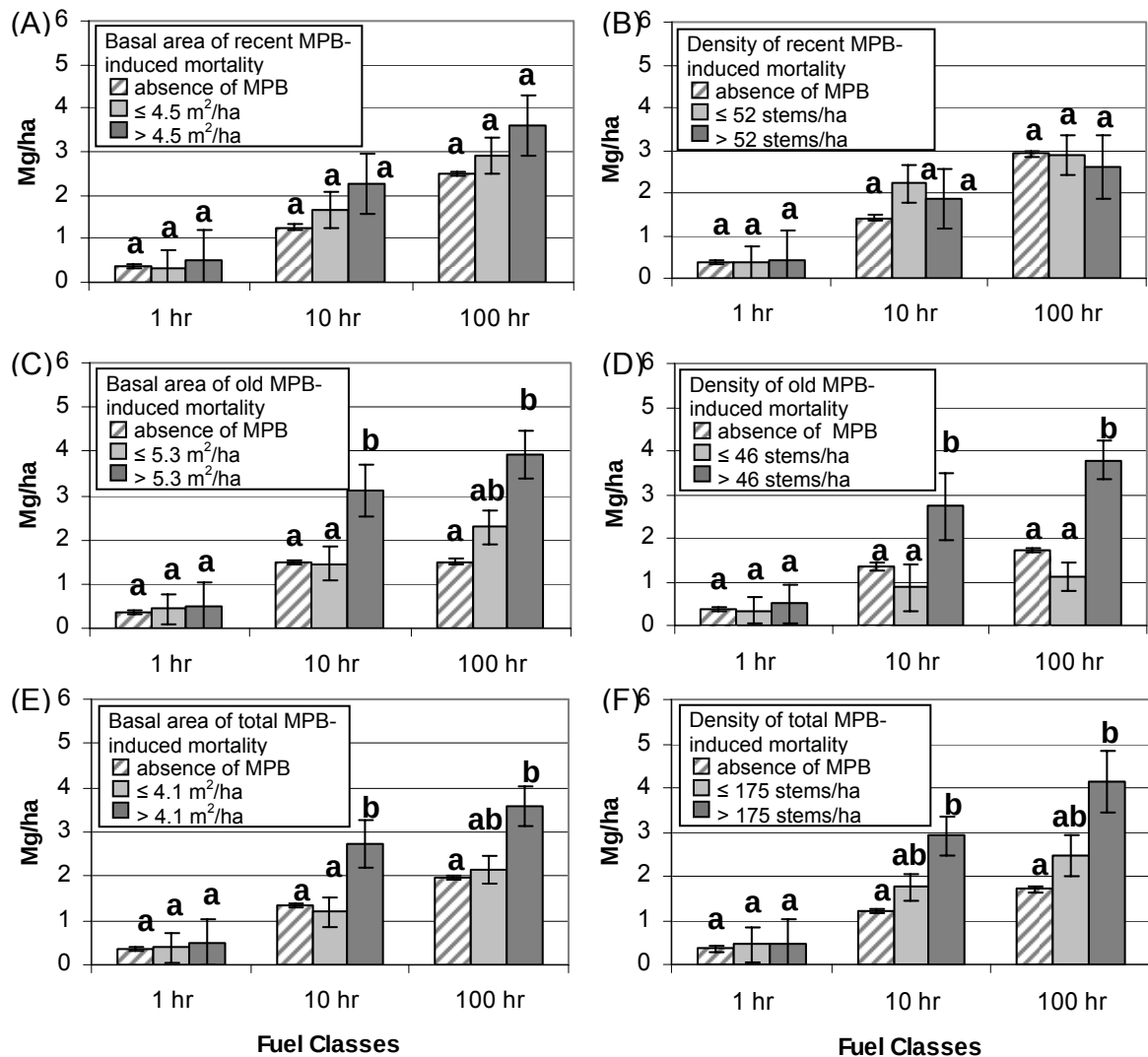
Note: Chi-squared tests: (A) $p=0.60$, $N=38$ plots; (B) $p=1.0$, $N=38$ plots; (C) $p=0.52$, $N=37$ plots; (D) $p=0.09$, $N=37$ plots; (E) $p=0.30$, $N=17$ plots; (F) $p=0.10$, $N=17$ plots; (G) $p=0.34$, $N=58$ plots; and (H) $p=0.84$, $N=58$ plots.

Figure 3. Diameter distribution of ponderosa pine in areas with trees infested with southwestern dwarf mistletoe and without bark beetle-induced mortality in the northern Front Range of Colorado, 2005-2006.



Note: Chi-squared analysis not significant at $p=0.25$ and $N=17$ plots.

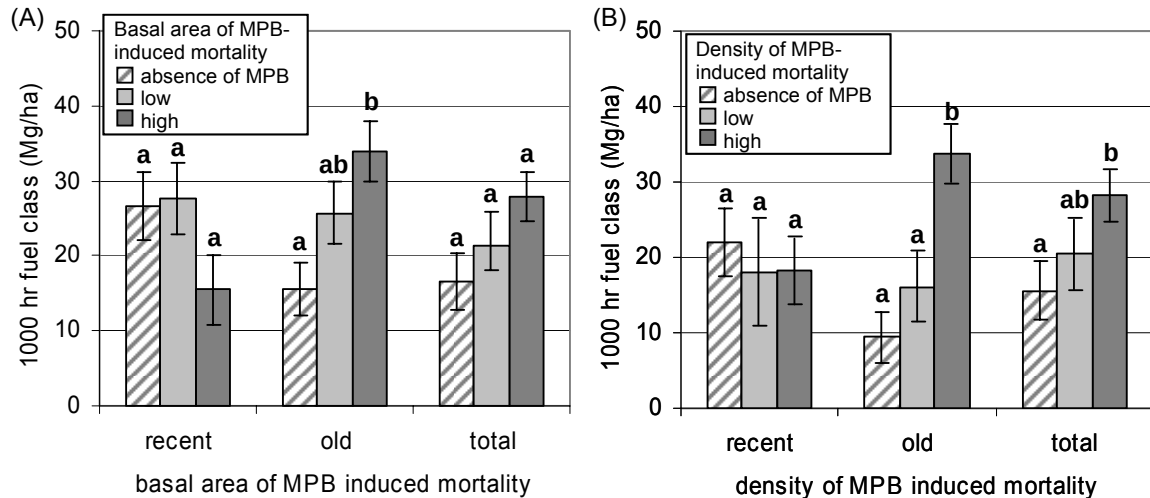
Figure 4. Adjusted means of fine fuels in areas with different densities of mountain pine beetle (MPB) induced-mortality in ponderosa pine, categorized by the amount of time since mortality in the northern Front Range of Colorado, 2005-2006.



Note: (A) basal area recent of MPB-induced mortality; (B) stems/ha of recent MPB-induced mortality; (C) basal area old of MPB-induced mortality; (D) stems/ha of old MPB-induced mortality; (E) basal area of total MPB-induced mortality; and (F) stems/ha of total MPB-induced mortality.

Different letters denote significance at $p < 0.05$ within fuel class. Error bars are standard errors. N=150 plots.

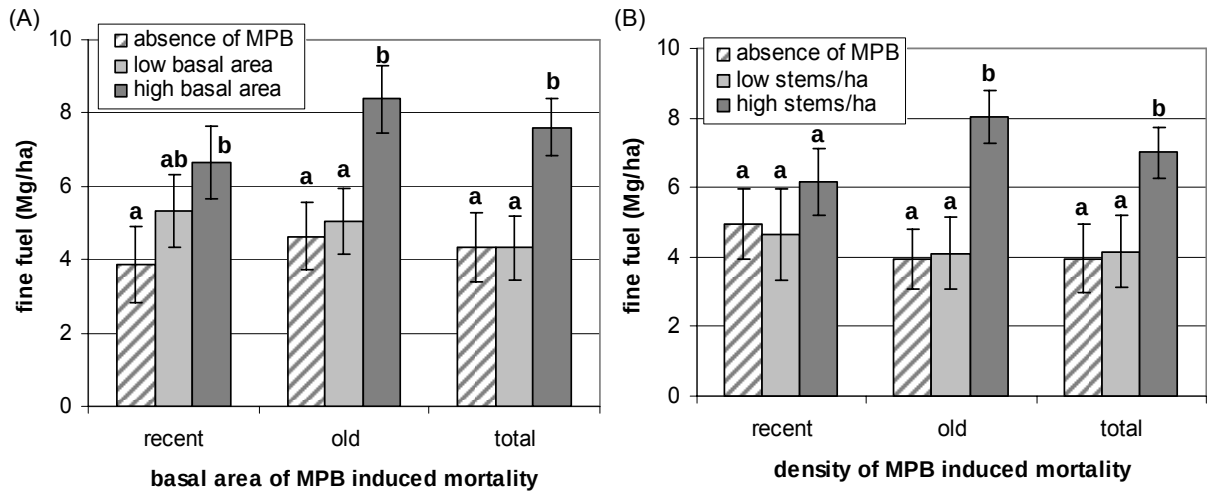
Figure 5. Adjusted means of 1000 hour fuel class in areas with different densities of mountain pine beetle (MPB)-induced mortality in ponderosa pine, categorized by the amount of time since mortality in the northern Front Range of Colorado, 2005-2006.



Note: (A) The cutoff for high and low basal area of recent, old, and total MPB-induced mortality was: 3.1 m²/ha, 4.5 m²/ha, and 4.6 m²/ha, respectively; (B) The cutoff for high and low density of recent, old, and total MPB-induced mortality was: 49 stems/ha, 70 stems/ha, and 70 stems/ha, respectively.

Different letters denote significance at $p < 0.05$ within category of time since infestation by MPB. Error bars are standard errors. N=150 plots.

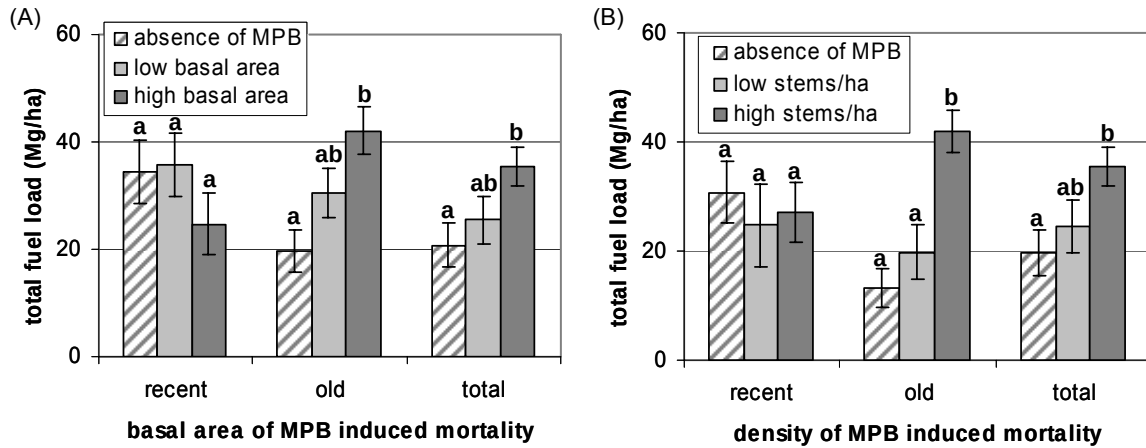
Figure 6. Adjusted means of total fine fuels in areas with different densities of mountain pine beetle (MPB)-induced mortality in ponderosa pine, categorized by the amount of time since mortality in the northern Front Range of Colorado, 2005-2006.



Note: (A) The cutoff for high and low basal area of recent, old, and total MPB-induced mortality was: 3.1 m²/ha, 4.5 m²/ha, and 4.6 m²/ha, respectively; (B) The cutoff for high and low density of recent, old, and total MPB-induced mortality was: 49 stems/ha, 70 stems/ha, and 70 stems/ha, respectively.

Different letters denote significance at $p < 0.05$ within category of time since infestation by MPB. Error bars are standard errors. N=150 plots.

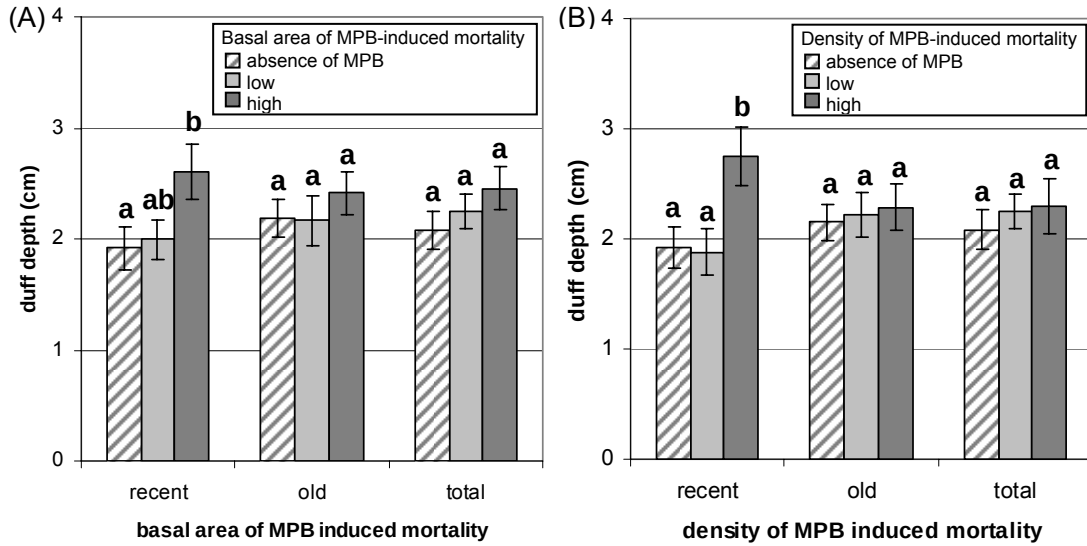
Figure 7. Adjusted means of total fuels in areas with different densities of mountain pine beetle (MPB)-induced mortality in ponderosa pine, categorized by the amount of time since mortality in the northern Front Range of Colorado, 2005-2006.



Note: (A) The cutoff for high and low basal area of recent, old, and total MPB-induced mortality was: 3.1 m²/ha, 4.5 m²/ha, and 4.6 m²/ha, respectively; (B) The cutoff for high and low density of recent, old, and total MPB-induced mortality was: 49 stems/ha, 70 stems/ha, and 70 stems/ha, respectively.

Different letters denote significance at $p < 0.05$ within category of time since infestation by MPB. Error bars are standard errors. N=150 plots.

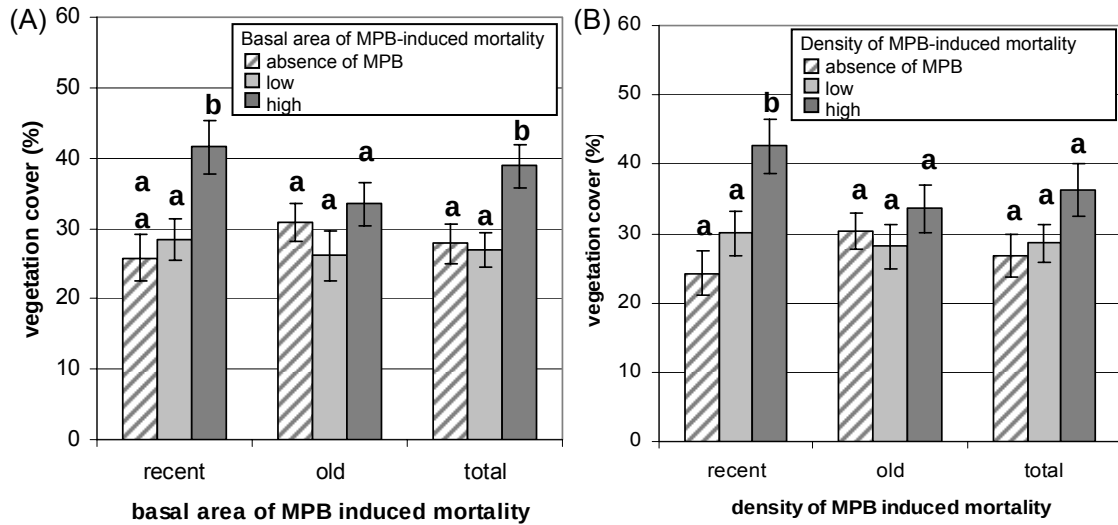
Figure 8. Adjusted means of duff depth in areas with different densities of mountain pine beetle (MPB)-induced mortality in ponderosa pine, categorized by the amount of time since mortality in the northern Front Range of Colorado, 2005-2006.



Note: (A) The cutoff for high and low basal area of recent, old, and total MPB-induced mortality was: 4.9 m²/ha, 3.7 m²/ha, and 7.0 m²/ha, respectively; (B) The cutoff for high and low density of recent, old, and total MPB-induced mortality was: 92 stems/ha, 105 stems/ha, and 187 stems/ha, respectively.

Different letters denote significance at $p < 0.05$ within category of time since infestation by MPB. Error bars are standard errors. N=150 plots.

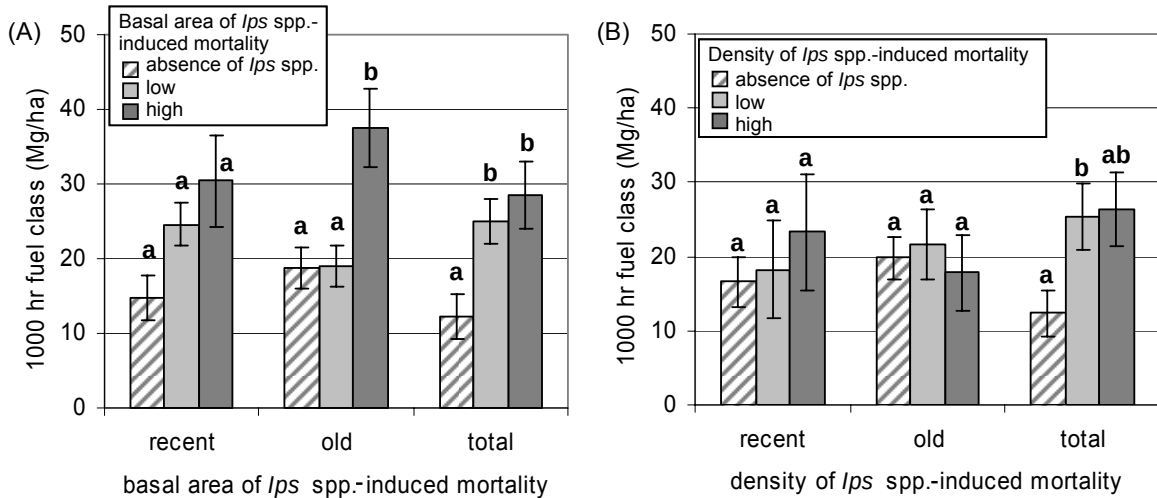
Figure 9. Adjusted means of percent vegetation cover in areas with different densities of mountain pine beetle (MPB)-induced mortality in ponderosa pine, categorized by the amount of time since mortality in the northern Front Range of Colorado, 2005-2006.



Note: (A) The cutoff for high and low basal area of recent, old, and total MPB-induced mortality was: 4.9 m²/ha, 3.7 m²/ha, and 7.0 m²/ha, respectively; (B) The cutoff for high and low density of recent, old, and total MPB-induced mortality was: 92 stems/ha, 105 stems/ha, and 187 stems/ha, respectively.

Different letters denote significance at $p < 0.05$ within category of time since infestation by MPB. Error bars are standard errors. N=150 plots.

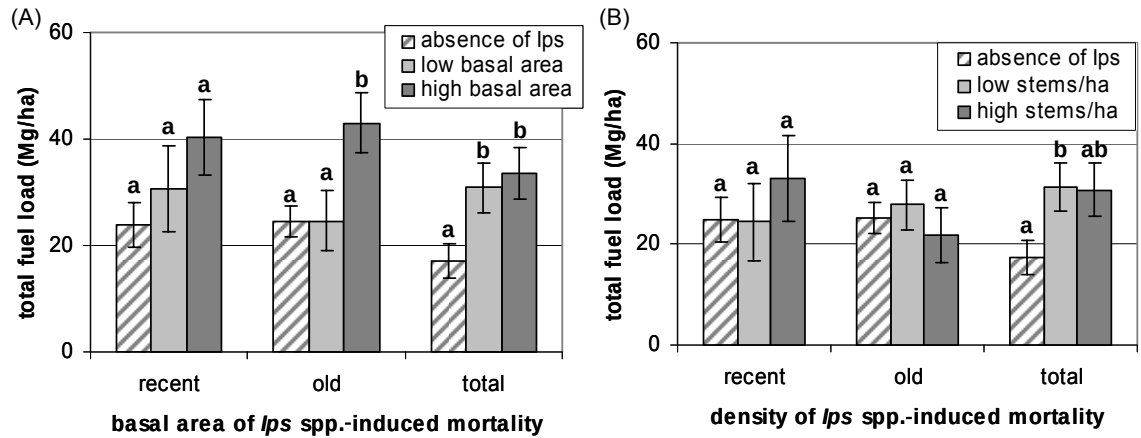
Figure 10. Adjusted means (standard errors) of 1000 hour fuel class in areas with different densities of *Ips* spp.-induced mortality in ponderosa pine, categorized by the amount of time since mortality in the northern Front Range of Colorado, 2005-2006.



Note: (A) The cutoff for high and low basal area of recent, old, and total *Ips* spp.-induced mortality was: 0.57 m²/ha, 0.34 m²/ha, and 0.70 m²/ha, respectively; (B) The cutoff for high and low density of recent, old, and total *Ips* spp.-induced mortality was: 50 stems/ha, 50 stems/ha, and 50 stems/ha, respectively.

Different letters denote significance at $p < 0.05$ within category of time since infestation by *Ips* spp. Error bars are standard errors. N=150 plots.

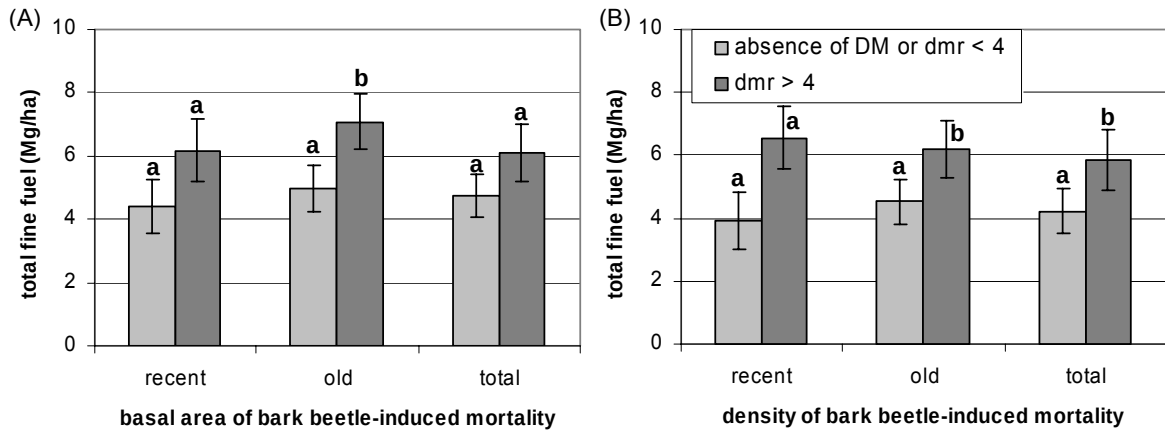
Figure 11. Adjusted means (standard errors bars) of total fuels (Mg/ha) in areas with different densities of *Ips* spp.-induced mortality in ponderosa pine, categorized by the amount of time since mortality in the northern Front Range of Colorado.



Note: (A) The cutoff for high and low basal area of recent, old, and total *Ips* spp.-induced mortality was: 0.57 m²/ha, 0.34 m²/ha, and 0.70 m²/ha, respectively; (B) The cutoff for high and low density of recent, old, and total *Ips* spp.-induced mortality was: 50 stems/ha, 50 stems/ha, and 50 stems/ha, respectively.

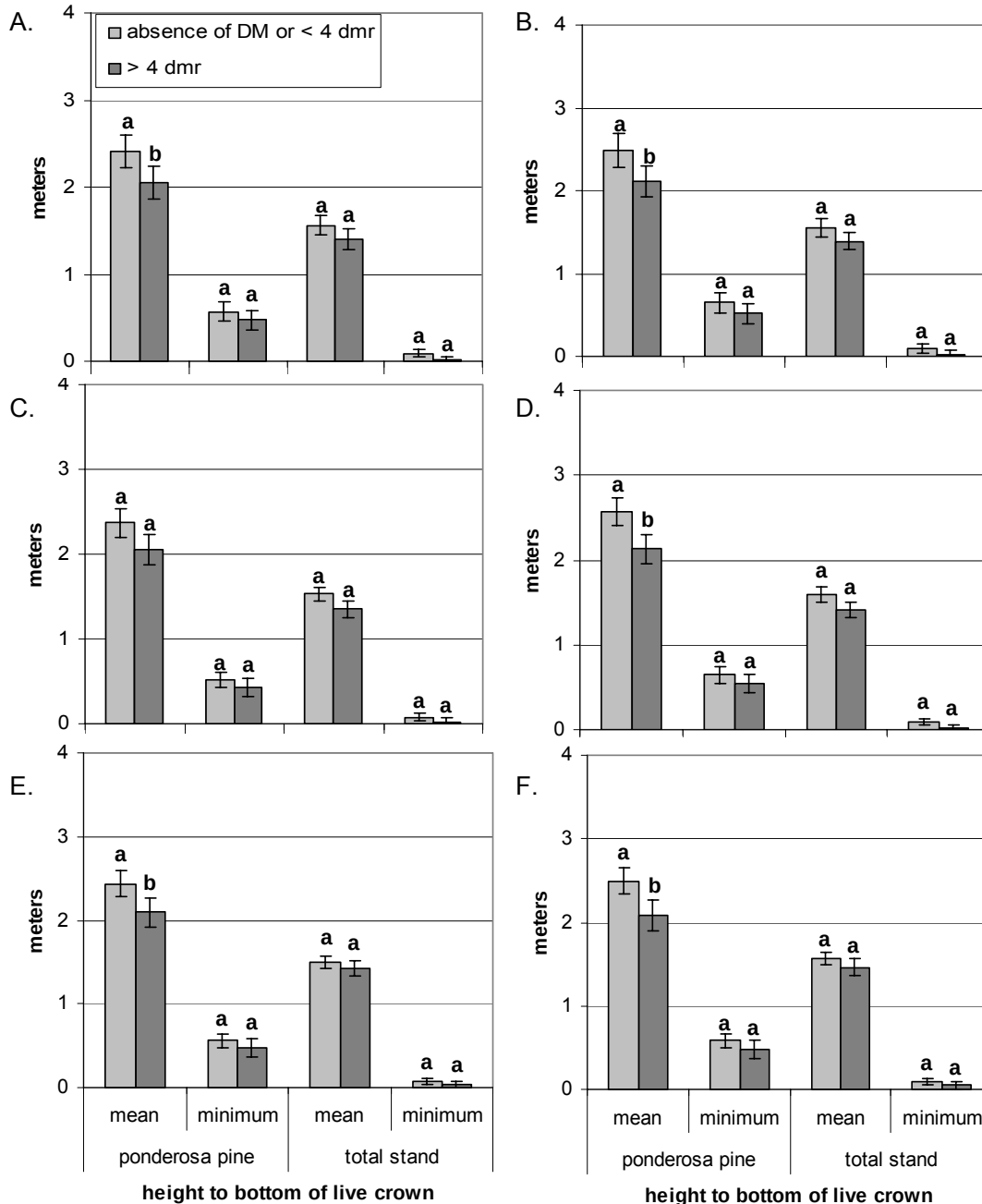
Different letters denote significance at $p < 0.05$ within category of time since infestation by *Ips* spp. Error bars are standard errors. N=150 plots.

Figure 12. Adjusted means (standard error bars) of total fine fuels (Mg/ha) in areas with trees infested with dwarf mistletoe (DM) compared to areas with less or no tree infestation of dwarf mistletoe, adjusting time since bark beetle-induced mortality in the northern Front Range of Colorado, 2005-2006.



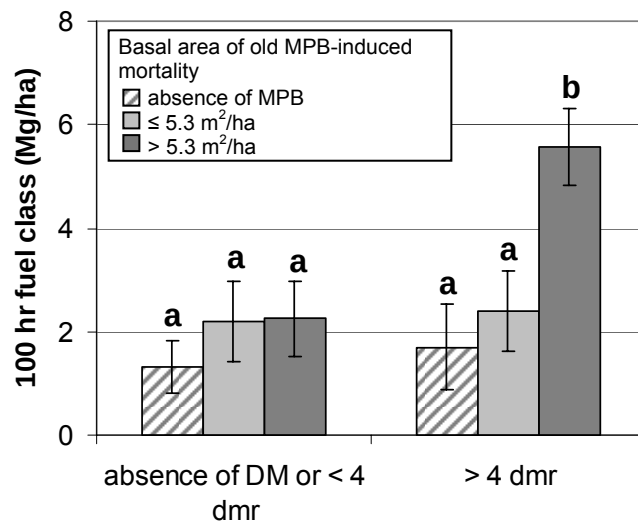
Note: (A) means adjusting for recent, old, and total basal area (m^2/ha) of bark beetle-induced mortality; (B) adjusting for recent, old, and total density (stem/ha) of bark beetle-induced mortality. Different letters denote significance at $p < 0.05$ within category of time since infestation by *Ips* spp. Error bars are standard errors. N=150 plots.

Figure 13. Adjusted means and minimums for height to bottom of live crown of all species and ponderosa pine in areas with trees infested with dwarf mistletoe (DM) compared to areas with less or no tree infestation of dwarf mistletoe, adjusting for the time since bark beetle-induced mortality in the northern Front Range of Colorado, 2005-2006.



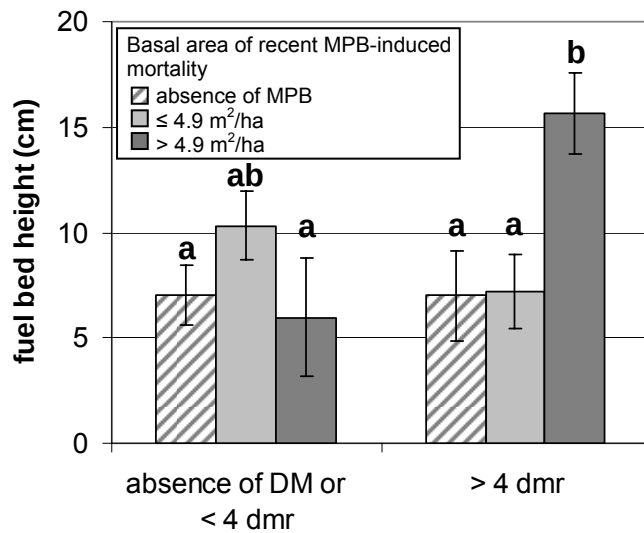
Note: (A) adjusting for recent basal area of bark beetle-induced mortality; (B) adjusting for recent density of bark beetle-induced mortality; (C) adjusting for old basal area of bark beetle-induced mortality; (D) adjusting for old density of bark beetle-induced mortality; (E) adjusting for total basal area of bark beetle-induced mortality; (F) adjusting for total density of bark beetle-induced mortality. Different letters denote significance at $p < 0.05$. Error bars are standard errors. Dwarf mistletoe rating is abbreviated as dmr and $N=150$ plots.

Figure 14. Adjusted means of 100 hour fuel class in areas with trees infested with dwarf mistletoe (DM) and old mountain pine beetle (MPB)-induced mortality in the northern Front Range of Colorado, 2005-2006.



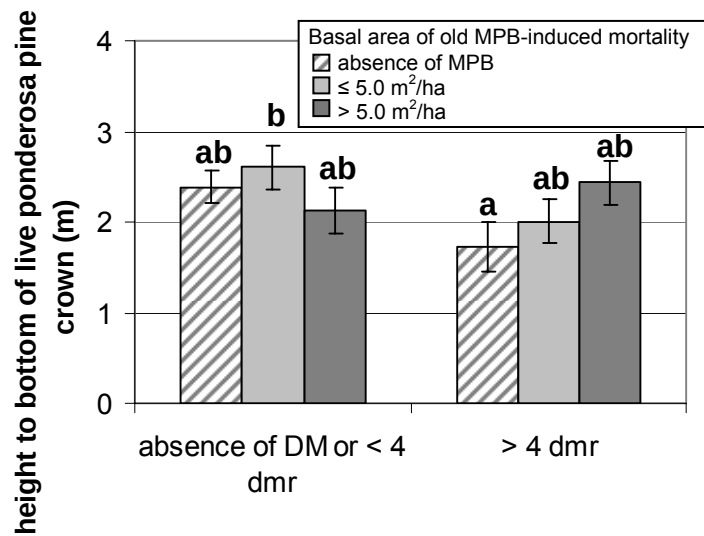
Note: Different letters denote significance at $p < 0.05$. Error bars are standard errors. Dwarf mistletoe rating is abbreviated as dmr and $N=150$ plots.

Figure 15. Adjusted means of fuel bed height in areas with trees infested with dwarf mistletoe (DM) and recent mountain pine beetle (MPB)-induced mortality in the northern Front Range of Colorado, 2005-2006.



Note: Different letters denote significance at $p < 0.05$. Error bars are standard errors. Dwarf mistletoe rating is abbreviated as dmr and $N=149$ plots.

Figure 16. Adjusted means of height to bottom of live ponderosa pine crown in areas with trees infested with dwarf mistletoe (DM) and old mountain pine beetle (MPB)-induced mortality in the northern Front Range of Colorado, 2005-2006.



Note: Different letters denote significance at $p < 0.05$. Error bars are standard errors. N=150 plots.

APPENDICES

APPENDIX I.

Additional tables and figures

Table I-1. Main effects and covariates used in models for fuel loads, duff depth, fuel bed height, percent vegetation cover, height to bottom of live crown, percent live crown, and density of regeneration in northern Front Range of Colorado, 2005-2006.

	Main effects - Dwarf mistletoe rating class and:	covariates	R ²
1 hour	Recent, old, and total stems/ha and basal area of BB-induced mortality	canopy cover, density of live and dead limber pine, stand density of live and dead trees, and average annual minimum temperature	0.30-0.34
10 hour	Recent, old and total stems/ha and old basal area of BB-induced mortality	canopy cover, stand density of live and dead trees, Peet (1981) habitat types, average annual precipitation, dwarf mistletoe rating classes, and MPB induced mortality	0.13-0.24
	Recent and total basal area of BB-induced mortality	canopy cover, stand density of live and dead trees, Peet (1981) habitat types	0.14-0.21
100 hour	Recent stems/ha and basal area of BB-induced mortality	canopy cover, slope position	0.12
	Old basal area, and old and total stems/ha of BB-induced mortality	canopy cover	0.11-0.15
	Total basal area of BB-induced mortality	canopy cover, basal area of live and dead trees,	0.10
1000 hour	Recent stems/ha and basal area, old stems/ha of BB-induced mortality	canopy cover	0.02-0.18
	Old and total basal area and total stems/ha of BB-induced mortality	canopy cover, ratio of ponderosa pine to Douglas-fir	0.17-0.25
Total fine fuels	Recent, old and total basal area and old and total stems/ha of BB-induced mortality	canopy cover, slope position, Peet (1981) habitat types, ratio of ponderosa pine to Douglas-fir	0.26-0.33
	Recent stems/ha of BB-induced mortality	canopy cover, slope position, Peet (1981) habitat types,	0.19

Table I-1 continued.

Main effects - Dwarf mistletoe rating class and:	covariates	R ²
Total fuel		
Recent basal area and stems/ha of BB-induced mortality	canopy cover, slope position	0.10-0.13
Old and total basal area and total stems/ha of BB-induced mortality	canopy cover, ratio of ponderosa pine to Douglas-fir	0.19-0.27
Old stems/ha of BB-induced mortality	canopy cover	0.22
Duff depth		
Recent stems/ha and basal area, and old and total stems/ha of BB-induced mortality	canopy cover, Peet (1981) habitat type, stand basal area of live and dead trees, and average annual temperature	0.29-0.34
Old and total basal area of BB-induced mortality	canopy cover, stand basal area of live and dead trees, and average annual minimum temperature	0.29-0.30
Vegetation cover		
Recent, old, and total stems/ha and basal area of BB-induced mortality	canopy cover, Peet (1981) habitat type, stand basal area of live and dead trees, and average annual temperature	0.29-0.35
Fuel bed height		
Recent, old, and total stems/ha and basal area of BB-induced mortality	canopy cover, ratio of density of ponderosa pine to Douglas-fir, slope position, and yearly average maximum temperature	0.24-0.35
Percent live crown of all species		
Recent stems/ha of BB-induced mortality	canopy cover, Peet (1981) habitat type, ratio of density of ponderosa pine to Douglas-fir, aspect, mean stand health/decay status, stand density of live and dead trees, and mean stand height	0.81
Recent, old and total basal area, and total stems/ha of BB-induced mortality	canopy cover, ratio of density of ponderosa pine to Douglas-fir, aspect, mean stand health/decay status, stand density of live and dead trees, and mean stand height	0.80-0.81
Old stems/ha of BB-induced mortality	canopy cover, slope connectivity, ratio of density of ponderosa pine to Douglas-fir, aspect, mean stand health/decay status, stand density of live and dead trees, and mean stand height	0.83
Percent live crown of ponderosa pine		
Recent and old basal area, and recent stems/ha of BB-induced mortality	canopy cover, Peet (1981) habitat type, aspect, mean stand health/decay status, and stand basal area of live and dead trees	0.62-0.64
Old stems/ha of BB-induced mortality	canopy cover, aspect, mean stand health/decay status, stand basal area of live and dead trees, and mean height of standing ponderosa pine trees	0.65

Table I-1 continued.

Main effects - Dwarf mistletoe rating class and:	covariates	R ²
Percent live crown of ponderosa pine (cont.)		
Total stems/ha of BB-induced mortality	canopy cover, Peet (1981) habitat type, aspect, mean stand health/decay status, and stand basal area of live and dead trees	0.62
Total basal area of BB-induced mortality	canopy cover, slope position, Peet (1981) habitat type, aspect, mean stand health/decay status, and stand basal area of live and dead trees	0.65
Mean height to bottom of live crown of all species		
Recent, old, and total stems/ha of BB-induced mortality	canopy cover, average height of all trees, stand density of live and dead trees, slope connectivity, ratio of density of ponderosa pine to Douglas-fir, average annual precipitation	0.64-0.65
Recent basal area of BB-induced mortality	canopy cover, average height of all trees, stand basal area of live and dead trees, ratio of density of ponderosa pine to Douglas-fir, average annual precipitation	0.57
Old and total basal area of BB-induced mortality	canopy cover, average height of all trees, stand density of live and dead trees, ratio of density of ponderosa pine to Douglas-fir, average annual precipitation	0.64-0.65
Mean height to bottom of live crown of ponderosa pine		
Recent, old, and total stems/ha and basal area of BB-induced mortality	canopy cover, stand structure, stand basal area of live and dead trees	0.39-0.41
Minimum height to bottom of live crown of all species		
Recent, old, and total stems/ha and basal area of BB-induced mortality	canopy cover, mean height of all trees, stand density of live and dead trees, ratio of density of ponderosa pine to Douglas-fir, average annual precipitation	0.30-0.33
Minimum height to bottom of live crown of ponderosa pine		
Recent, old, and total stems/ha and basal area of BB-induced mortality	canopy cover, slope connectivity, density of live and dead ponderosa pine, density of live and dead limber pine	0.10-0.19
Density of regeneration - all tree species		
Density of BB-induced mortality	canopy cover, aspect, density of live and dead trees	0.27-0.34
Density of regeneration - ponderosa pine		
Density of BB-induced mortality	canopy cover, slope position, Peet (1981) habitat type, dbh of all live and dead tree species	0.18-0.23

Table I-2. Adjusted means and standard errors of height to bottom of live crown of all species and ponderosa pine in areas with different densities of mountain pine beetle (MPB)-induced mortality in ponderosa pine, categorized by the amount of time since infestation in the northern Front Range of Colorado, 2005-2006.

MPB-induced mortality		basal area of recent MPB-induced mortality		density of recent MPB-induced mortality		basal area of old MPB-induced mortality		density of old MPB-induced mortality		basal area of total MPB-induced mortality		density of total MPB-induced mortality	
		all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine
absence	adjusted mean SE	1.5 0.12	2.2 0.20	1.5 0.11	2.2 0.20	1.4 0.09	2.1 0.19	1.6 0.09	2.3 0.17	1.5 0.10	2.2 0.18	1.5 0.10	2.2 0.18
low	adjusted mean SE	1.6 0.11	2.2 0.20	1.5 0.11	2.4 0.19	1.4 0.11	2.3 0.20	1.6 0.10	2.4 0.19	1.6 0.09	2.3 0.18	1.7 0.12	2.3 0.21
high	adjusted mean SE	1.4 0.15	2.3 0.23	1.4 0.19	2.3 0.31	1.4 0.11	2.3 0.19	1.4 0.14	2.3 0.22	1.3 0.10	2.3 0.18	1.4 0.08	2.3 0.16

Note: The cutoff for high and low of MPB-induced mortality was: recent basal area of 4.2 m²/ha, recent density of 140 stems/ha, old basal area 5.0 m²/ha, old density of 150 stems/ha, total basal area 5.9 m²/ha, and total density of 73 stems/ha. N=150 plots

Table I-3. Adjusted means and standard errors of minimum height to bottom of live crown of all species and ponderosa pine in areas with different densities of mountain pine beetle (MPB)-induced mortality in ponderosa pine, categorized by the amount of time since infestation in the northern Front Range of Colorado, 2005-2006.

MPB-induced mortality		basal area of recent MPB-induced mortality		density of recent MPB-induced mortality		basal area of old MPB-induced mortality		density of old MPB-induced mortality		basal area of total MPB-induced mortality		density of total MPB-induced mortality	
		all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine
absence	adjusted mean	0.0	0.5	0.0	0.5	0.1	0.4	0.1	0.5	0.1	0.5	0.1	0.5
	SE	0.05	0.12	0.05	0.11	0.05	0.10	0.05	0.10	0.05	0.11	0.05	0.11
low	adjusted mean	0.1	0.6	0.1	0.6	0.1	0.5	0.1	0.6	0.1	0.5	0.1	0.5
	SE	0.05	0.11	0.05	0.11	0.05	0.11	0.05	0.11	0.05	0.10	0.06	0.13
high	adjusted mean	0.1	0.5	0.1	0.6	0.0	0.6	0.0	0.8	0.0	0.6	0.0	0.6
	SE	0.06	0.14	0.09	0.21	0.05	0.13	0.07	0.16	0.05	0.11	0.04	0.09

Note: The cutoff for high and low of MPB-induced mortality was: recent basal area of 3.1 m²/ha, recent density of 49 stems/ha, old basal area 3.5 m²/ha, old density of 81 stems/ha, total basal area 6.4 m²/ha, and total density of 70 stems/ha. N=150 plots

Table I-4. Adjusted means (standard errors) of total fine fuels (Mg/ha) in areas with different densities of *lps* spp.-induced mortality in ponderosa pine, categorized by the amount of time since mortality in the northern Front Range of Colorado, 2005-2006.

	basal area of recent <i>lps</i> spp.- induced mortality	density of recent <i>lps</i> spp.- induced mortality	basal area of old <i>lps</i> spp.- induced mortality	density of old <i>lps</i> spp.- induced mortality	basal area of total <i>lps</i> spp.- induced mortality	density of total <i>lps</i> spp.- induced mortality
absence of <i>lps</i> spp.	6.0 (0.71)	6.0 (0.77)	5.9 (0.69)	5.0 (0.73)	5.1 (0.76)	4.9 (0.79)
low	3.4 (1.40)	3.9 (1.32)	6.1 (1.15)	6.7 (1.00)	5.7 (0.96)	5.7 (0.99)
high	6.4 (1.22)	5.8 (1.48)	6.1 (1.11)	4.4 (1.12)	5.5 (0.97)	4.4 (1.09)

Note: The cutoff for high and low of *lps* spp.-induced mortality was: recent basal area of 0.57 m²/ha, recent density of 50 stems/ha, old basal area 0.34 m²/ha, old density of 50 stems/ha, total basal area 0.7 m²/ha, and total density of 50 stems/ha. N=150 plots.

Table I-5. Adjusted means (standard errors) of duff depth (cm) in areas with different densities of *lps* spp.-induced mortality in ponderosa pine, categorized by the amount of time since mortality in the northern Front Range of Colorado, 2005-2006.

	basal area of recent <i>lps</i> spp.- induced mortality	density of recent <i>lps</i> spp.- induced mortality	basal area of old <i>lps</i> spp.- induced mortality	density of old <i>lps</i> spp.- induced mortality	basal area of total <i>lps</i> spp.- induced mortality	density of total <i>lps</i> spp.- induced mortality
absence of <i>lps</i> spp.	2.2 (0.1)	2.3 (0.1)	2.1 (0.1)	2.1 (0.1)	2.1 (0.1)	2.0 (0.2)
low	1.7 (0.3)	2.1 (0.3)	2.5 (0.2)	2.3 (0.2)	2.5 (0.2)	2.3 (0.2)
high	2.5 (0.2)	2.2 (0.3)	2.1 (0.3)	2.3 (0.3)	2.3 (0.2)	2.3 (0.2)

Note: The cutoff for high and low of *lps* spp.-induced mortality was: recent basal area of 0.55 m²/ha, recent density of 57 stems/ha, old basal area 0.42 m²/ha, old density of 71 stems/ha, total basal area 0.66 m²/ha, and total density of 57 stems/ha. N=150 plots.

Table I-6. Adjusted means (standard errors) of percent of vegetation cover in areas with different densities of *lps* spp.-induced mortality in ponderosa pine, categorized by the amount of time since mortality in the northern Front Range of Colorado, 2005-2006.

	basal area of recent <i>lps</i> spp. induced mortality	density of recent <i>lps</i> spp. induced mortality	basal area of old <i>lps</i> spp. induced mortality	density of old <i>lps</i> spp. induced mortality	basal area of total <i>lps</i> spp. induced mortality	density of total <i>lps</i> spp. induced mortality
absence of <i>lps</i> spp.	32.3 (2.1)	33.6 (2.3)	30.5 (2.2)	30.6 (2.5)	32.3 (2.3)	32.1 (2.5)
low	29.4 (4.8)	32.2 (4.5)	25.1 (3.7)	26.9 (3.5)	27.2 (3.1)	26.7 (3.3)
high	34.1 (3.8)	31.1 (4.7)	34.8 (4.4)	34.6 (4.0)	34.0 (3.2)	32.9 (3.5)

Note: The cutoff for high and low of *lps* spp.-induced mortality was: recent basal area of 0.55 m²/ha, recent density of 57 stems/ha, old basal area 0.42 m²/ha, old density of 71 stems/ha, total basal area 0.66 m²/ha, and total density of 57 stems/ha. N=150 plots.

Table I-7. Adjusted means (standard errors) of fuel bed height (cm) in areas with different densities of *lps* spp.-induced mortality in ponderosa pine, categorized by the amount of time since mortality in the northern Front Range of Colorado, 2005 2006.

	basal area of recent <i>lps</i> spp.- induced mortality	density of recent <i>lps</i> spp.- induced mortality	basal area of old <i>lps</i> spp.- induced mortality	density of old <i>lps</i> spp.- induced mortality	basal area of total <i>lps</i> spp.- induced mortality	density of total <i>lps</i> spp.- induced mortality
absence of <i>lps</i> spp.	10.1 (1.1)	10.0 (.9)	9.6 (0.8)	9.2 (0.9)	9.8 (0.9)	10.2 (1.0)
low	7.8 (2.1)	9.6 (1.9)	6.3 (1.5)	9.7 (1.4)	8.6 (1.3)	9.4 (1.3)
high	8.7 (1.7)	8.4 (2.0)	8.8 (1.8)	8.1 (1.6)	8.5 (1.3)	7.3 (1.4)

Note: The cutoff for high and low of *lps* spp.-induced mortality was: recent basal area of 0.55 m²/ha, recent density of 57 stems/ha, old basal area 0.42 m²/ha, old density of 71 stems/ha, total basal area 0.66 m²/ha, and total density of 57 stems/ha. N=149 plots.

Table I-8. Adjusted means and standard errors of height to bottom of live crown of all species and ponderosa pine in areas with different densities of *lps* spp. induced mortality in ponderosa pine, categorized by the amount of time since mortality in the northern Front Range of Colorado, 2005-2006.

<i>lps</i> spp. induced mortality		basal area of recent <i>lps</i> spp. induced mortality		density of recent <i>lps</i> spp. induced mortality		basal area of old <i>lps</i> spp. induced mortality		density of old <i>lps</i> spp. induced mortality		basal area of total <i>lps</i> spp. induced mortality		density of total <i>lps</i> spp. induced mortality	
		all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine
absence	adjusted mean	1.5	2.2	1.5	2.2	1.5	2.1	1.4	2.3	1.5	2.2	1.5	2.2
	SE	0.08	0.20	0.09	0.20	0.07	0.19	0.08	0.17	0.07	0.18	0.08	0.18
low	adjusted mean	1.5	2.2	1.5	2.4	1.6	2.3	1.4	2.4	1.5	2.3	1.4	2.3
	SE	0.20	0.19	0.16	0.19	0.14	0.20	0.11	0.19	0.11	0.18	0.11	0.21
high	adjusted mean	1.5	2.3	1.4	2.3	1.2	2.3	1.7	2.3	1.4	2.3	1.6	2.3
	SE	0.14	0.23	0.18	0.31	0.14	0.19	0.17	0.22	0.12	0.18	0.13	0.16

Note: The cutoff for high and low of *lps* spp.-induced mortality was: recent basal area of 0.53 m²/ha, recent density of 50 stems/ha, old basal area 0.36 m²/ha, old density of 76 stems/ha, total basal area 0.7 m²/ha, and total density of 62 stems/ha. N=150 plots.

Table I-9. Adjusted means and standard errors of minimum height to bottom of live crown of all species and ponderosa pine in areas with different densities of *lps* spp.-induced mortality in ponderosa pine, categorized by the amount of time since mortality in the northern Front Range of Colorado, 2005-2006.

		basal area of recent <i>lps</i> spp.-induced mortality		density of recent <i>lps</i> spp.-induced mortality		basal area of old <i>lps</i> spp.-induced mortality		density of old <i>lps</i> spp.-induced mortality		basal area of total <i>lps</i> spp.-induced mortality		density of total <i>lps</i> spp.-induced mortality	
		all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine	all tree species	ponderosa pine
<i>lps</i> spp.- induced mortality													
absence	adjusted mean	0.1	0.5	0.1	0.5	0.0	0.6	0.0	0.5	0.1	0.5	0.1	0.5
	SE	0.03	0.07	0.04	0.09	0.03	0.07	0.04	0.09	0.04	0.08	0.04	0.08
low	adjusted mean	0.0	0.04	0.0	0.7	0.0	0.4	0.0	0.4	0.0	0.5	0.0	0.4
	SE	0.09	0.19	0.08	0.17	0.07	0.15	0.06	0.12	0.05	0.12	0.05	0.12
high	adjusted mean	0.1	0.7	0.1	0.5	0.1	0.4	0.1	0.8	0.1	0.6	0.1	0.7
	SE	0.07	0.14	0.09	0.20	0.07	0.15	0.07	0.19	0.05	0.13	0.06	0.15

Note: The cutoff for high and low of *lps* spp.-induced mortality was: recent basal area of 0.53 m²/ha, recent density of 50 stems/ha, old basal area 0.36 m²/ha, old density of 76 stems/ha, total basal area 0.7 m²/ha, and total density of 62 stems/ha. N=150 plots.

Table I-10. Adjusted means (standard error) of 1000 hour fuel class (Mg/ha) in areas with trees infested with dwarf mistletoe compared to areas with less or no tree infestation of dwarf mistletoe, adjusting for the time since mountain pine beetle (MPB)- and *Ips* spp.-induced mortality in the northern Front Range of Colorado, 2005-2006.

	adjusting for basal area of recent MPB- and <i>Ips</i> spp.- induced mortality	adjusting for density of recent MPB- and <i>Ips</i> spp.- induced mortality	adjusting for basal area of old MPB- and <i>Ips</i> spp.- induced mortality	adjusting for density of old MPB- and <i>Ips</i> spp.- induced mortality	adjusting for basal area of total MPB- and <i>Ips</i> spp.- induced mortality	adjusting for density of total MPB- and <i>Ips</i> spp.- induced mortality
absence of dm or dmr < 4	20.4 (4.02)	16.4 (4.45)	24.4 (3.25)	20.0 (3.13)	23.3 (2.99)	22.8 (3.03)
dmr > 4	26.1 (4.10)	22.3 (4.38)	25.7 (3.61)	19.5 (3.63)	20.5 (3.77)	20.0 (3.86)

Note: Dwarf mistletoe rating is abbreviated as dmr and N=150 plots.

Table I-11. Adjusted means (standard error) of total fuel load (Mg/ha) in plots with trees with dwarf mistletoe, adjusting for the amount and time since infestation of mountain pine beetle (MPB)- and *Ips* spp.-induced mortality in the northern Front Range of Colorado, 2005-2006.

	adjusting for basal area of recent MPB- and <i>Ips</i> spp.- induced mortality	adjusting for density of recent MPB- and <i>Ips</i> spp.- induced mortality	adjusting for basal area of old MPB- and <i>Ips</i> spp.- induced mortality	adjusting for density of old MPB- and <i>Ips</i> spp.- induced mortality	adjusting for basal area of total MPB- and <i>Ips</i> spp.- induced mortality	adjusting for density of total MPB- and <i>Ips</i> spp.- induced mortality
absence of dm or dmr < 4	27.6 (4.90)	23.2 (5.22)	29.1 (3.45)	24.4 (3.29)	28.0 (3.18)	27.2 (3.23)
dmr > 4	35.6 (5.53)	31.8 (5.63)	32.4 (3.83)	25.5 (3.81)	26.4 (4.01)	25.8 (4.11)

Note: Dwarf mistletoe rating is abbreviated as dmr and N=150 plots.

Table I-12. Adjusted means (standard error) of duff depth (cm) in areas with trees infested with dwarf mistletoe compared to areas with less or no tree infestation of dwarf mistletoe, adjusting for the time since infestation of mountain pine beetle (MPB)- and *Ips* spp.-induced mortality in the northern Front Range of Colorado, 2005-2006.

	adjusting for basal area of recent MPB- and <i>Ips</i> spp.- induced mortality	adjusting for density of recent MPB- and <i>Ips</i> spp.- induced mortality	adjusting for basal area of old MPB- and <i>Ips</i> spp.- induced mortality	adjusting for density of old MPB- and <i>Ips</i> spp.- induced mortality	adjusting for basal area of total MPB- and <i>Ips</i> spp.- induced mortality	adjusting for density of total MPB- and <i>Ips</i> spp.- induced mortality
absence of dm or dmr < 4	2.3 (0.2)	2.3 (0.2)	2.4 (0.2)	2.3 (0.2)	2.4 (0.1)	2.3 (0.1)
dmr > 4	2.0 (0.2)	2.1 (0.2)	2.2 (0.2)	2.1 (0.2)	2.1 (0.2)	2.1 (0.2)

Note: Dwarf mistletoe rating is abbreviated as dmr and N=150 plots.

Table I-13. Adjusted means (standard error) of percent of vegetation cover in areas with trees infested with dwarf mistletoe compared to areas with less or no tree infestation of dwarf mistletoe, adjusting for the time since infestation of mountain pine beetle (MPB)- and *lps* spp.-induced mortality in the northern Front Range of Colorado, 2005-2006.

	adjusting for basal area of recent MPB- and <i>lps</i> spp.- induced mortality	adjusting for density of recent MPB- and <i>lps</i> spp.- induced mortality	adjusting for basal area of old MPB- and <i>lps</i> spp.- induced mortality	adjusting for density of old MPB- and <i>lps</i> spp.- induced mortality	adjusting for basal area of total MPB- and <i>lps</i> spp.- induced mortality	adjusting for density of total MPB- and <i>lps</i> spp.- induced mortality
absence of dm or dmr < 4	32.5 (2.8)	32.8 (2.9)	27.9 (2.5)	29.5 (2.5)	30.4 (2.2)	30.2 (2.3)
dmr > 4	31.3 (3.0)	31.9 (2.9)	32.4 (3.0)	31.9 (2.8)	31.9 (2.7)	30.9 (2.8)

Note: Dwarf mistletoe rating is abbreviated as dmr and N=150 plots

Table I-14. Adjusted means (standard errors) of fuel bed height (cm) in areas with trees infested with dwarf mistletoe compared to areas with less or no tree infestation of dwarf mistletoe, adjusting for the time since infestation of mountain pine beetle (MPB)- and *Ips* spp.-induced mortality in the northern Front Range of Colorado, 2005-2006.

	adjusting for basal area of recent MPB- and <i>Ips</i> spp.- induced mortality	adjusting for density of recent MPB- and <i>Ips</i> spp.- induced mortality	adjusting for basal area of old MPB- and <i>Ips</i> spp.- induced mortality	adjusting for density of old MPB- and <i>Ips</i> spp.- induced mortality	adjusting for basal area of total MPB- and <i>Ips</i> spp.- induced mortality	adjusting for density of total MPB- and <i>Ips</i> spp.- induced mortality
absence of dm or dmr < 4	7.8 (1.4)	8.8 (1.2)	7.1 (1.0)	8.0 (1.0)	8.2 (0.9)	8.1 (0.9)
dmr > 4	9.9 (1.4)	9.8 (1.1)	9.5 (1.1)	10.0 (1.1)	9.7 (1.1)	9.8 (1.1)

Note: Dwarf mistletoe rating is abbreviated as dmr and N=149 plots.

APPENDIX II.

Plot Locations

Table II-1. Plot locations and percentage of trees affected by mountain pine beetle, *lps* spp. and dwarf mistletoe in the northern Front Range of Colorado, 2005-2006. GIS coordinates in UTM: Zone 13, WGS 1984.

plot number	date established	easting	northing	elevation (m)	percentage ponderosa pine affected		
					mountain pine beetle	<i>lps</i> spp.	dwarf mistletoe
2.02	5/19/2005	0458675	4503570	2241	11	11	89
2.03	5/19/2005	0458703	4503397	2241	0	0	0
3.01	5/24/2005	0451645	4520362	2388	58	0	0
3.02	5/24/2005	0451748	4520352	2377	0	0	0
4.01	5/24/2005	0450867	4520238	2422	27	9	0
4.02	5/25/2005	0451017	4520206	2430	0	0	0
5.01	5/25/2005	0449349	4520772	2411	43	0	0
5.02	5/25/2005	0449298	4520794	2425	0	0	0
5.03	5/26/2005	0449108	4520859	2450	20	0	0
6.01	6/1/2005	0453419	4527505	2408	33	17	0
6.02	6/1/2005	0453506	4527470	2418	0	0	0
7.01	6/1/2005	0456040	4521761	2439	56	67	0
7.02	6/2/2005	0456135	4521927	2444	0	0	0
8.01	6/2/2005	0455169	4522399	2433	47	6	0
8.02	6/3/2005	0455012	4522392	2414	0	0	0
101.01	6/22/2005	0451792	4522827	2485	0	0	0
101.11	6/22/2005	0451687	4523202	2557	6	3	0
102.01	7/28/2005	0455151	4510088	2377	0	3	0
102.11	7/28/2005	0455337	4510201	2379	46	8	0
121.01	8/3/2005	0449752	4521271	2468	13	5	0
121.02	8/3/2005	0449555	4521563	2590	17	0	0
121.03	8/3/2005	0449500	4521691	2566	0	0	0
123.01	6/20/2005	0448545	4514290	2640	3	0	0
123.11	6/20/2005	0448507	4514191	2630	38	2	0
124.01	6/21/2005	0449338	4513649	2604	0	0	0
124.11	6/21/2005	0449058	4513437	2634	11	0	0
124.12	6/23/2005	0449468	4513891	2595	17	11	0
124.13	6/23/2005	0449306	4513603	2604	4	0	0
126.01	6/17/2005	0449961	4508671	2617	0	0	0
134.01	6/16/2005	0455070	4494536	2582	0	0	0
148.01	6/28/2005	0465267	4465265	2673	10	0	0
148.02	6/28/2005	0465278	4465169	2610	0	0	0
148.03	6/28/2005	0465523	4465039	2596	35	0	100
151.01	8/2/2005	0451914	4530125	2592	0	0	0
155.01	8/1/2005	0450963	4522978	2584	0	0	0
158.01	8/4/2005	0446706	4515401	2670	0	0	0
158.02	8/4/2005	0446584	4515227	2696	6	6	0

Table A-1 continued.

plot number	date established	easting	northing	elevation (m)	percentage ponderosa pine affected		
					mountain pine beetle	<i>lps</i> spp.	dwarf mistletoe
160.01	7/26/2005	0454452	4515699	2474	0	0	0
167.01	8/11/2005	0474638	4505847	2092	33	0	0
167.02	8/11/2005	0474516	4505786	2066	0	0	0
167.03	8/11/2005	0474490	4506042	2131	33	6	0
167.04	8/11/2005	0474592	4505987	2093	19	5	81
169.01	6/30/2005	0466790	4498454	2409	18	0	0
169.02	7/11/2005	0466580	4498440	2426	17	14	92
169.03	7/14/2005	0466484	4498413	2440	0	0	61
169.04	7/14/2005	0466391	4498390	2440	0	9	0
169.11	6/30/2005	0466805	4498100	2364	19	5	0
185.01	8/9/2005	0464688	4467977	2746	100	0	0
185.02	8/9/2005	0464730	4468076	2739	0	0	0
185.03	8/9/2005	0464594	4468126	2715	0	8	8
188.01	7/19/2005	0471682	4484641	2300	0	0	0
188.11	7/19/2005	0471480	4484727	2237	20	0	0
188.12	7/19/2005	0471488	4484475	2314	4	0	0
200.01	6/29/2005	0470125	4491642	2088	0	0	0
200.11	6/29/2005	0470141	4491773	2139	11	0	0
200.12	6/29/2005	0470160	4491875	2147	0	29	57
200.13	6/29/2005	0469941	4491992	2185	50	0	0
204.01	8/15/2005	0453284	4501180	2482	0	0	0
204.02	8/16/2005	0453432	4500680	2488	4	14	22
204.11	8/15/2005	0453339	4501083	2450	36	0	0
204.12	8/16/2005	0453357	4500592	2495	41	14	0
204.13	8/16/2005	0453437	4501099	2444	33	0	0
206.01	8/3/2005	0448512	4522526	2585	0	0	0
207.01	7/5/2005	0465506	4464079	2599	38	40	83
207.02	7/6/2005	0465540	4463951	2602	0	39	94
207.03	7/6/2005	0465514	4463874	2585	0	0	0
207.04	7/6/2005	0465610	4463803	2596	17	0	33
207.11	7/7/2005	0465776	4463664	2553	58	17	83
208.01	7/8/2005	0464159	4465303	2568	0	0	15
208.02	7/12/2005	0464286	4465217	2623	0	0	38
208.03	7/12/2005	0464386	4465175	2656	39	0	75
208.04	7/13/2005	0464457	4465130	2669	0	0	0
208.05	7/13/2005	0464344	4465028	2627	0	0	89
213.01	7/27/2005	0454866	4511756	2445	9	0	0
213.02	7/27/2005	0454696	4511955	2517	0	0	100
213.03	7/27/2005	0455080	4511979	2503	0	0	0
218.01	7/20/2005	0470930	4485592	2285	53	7	0
218.02	7/20/2005	0471078	4485736	2278	17	0	83
218.03	7/20/2005	0471118	4485801	2268	13	0	33
218.04	7/21/2005	0471189	4485914	2285	5	5	90
218.05	7/21/2005	0470877	4485607	2303	0	0	0
227.01	8/17/2005	0466859	4498733	2433	13	9	24
227.02	8/17/2005	0467122	4498606	2428	22	48	74
244.01	7/18/2005	0470168	4484718	2354	0	0	0
252.01	8/2/2005	0456249	4535778	2495	0	0	0
255.01	7/25/2005	0455336	4510684	2296	0	0	0
255.02	7/26/2005	0455632	4510807	2414	0	0	17

Table A-1 continued.

plot number	date established	easting	northing	elevation (m)	percentage ponderosa pine affected		
					mountain pine beetle	<i>lps</i> spp.	dwarf mistletoe
255.03	7/28/2005	0455395	4510699	2397	0	2	7
256.01	8/8/2005	0462828	4478057	2267	0	0	0
256.02	8/8/2005	0462592	4477824	2342	40	0	70
256.11	8/8/2005	0462454	4477808	2337	33	22	64
301.01	9/10/2005	0482867	4490673	2063	0	0	53
301.02	9/10/2005	0482777	4490814	2083	7	2	76
301.03	9/10/2005	0482647	4490990	2080	0	0	0
401.01	5/31/2006	0466596	4464443	2476	20	18	93
401.02	5/31/2006	0466529	4464505	2479	54	4	46
401.03	5/31/2006	0466430	4464527	2493	39	0	79
401.04	5/31/2006	0466368	4464567	2501	0	0	22
402.01	6/1/2006	0466348	4464242	2532	11	16	86
402.02	6/1/2006	0466150	4464262	2540	0	0	0
402.03	6/2/2006	0466444	4464239	2511	20	7	57
403.01	6/1/2006	0465665	4462860	2272	13	0	31
404.01	6/6/2006	0453666	4500327	2511	6	0	75
404.02	6/6/2006	0453744	4500387	2519	38	6	31
404.03	6/6/2006	0453829	4500338	2497	7	7	27
404.04	6/6/2006	0453839	4500438	2493	0	0	41
405.01	6/7/2006	0457658	4501788	2391	0	11	0
405.02	6/7/2006	0457685	4501879	2410	0	0	100
405.03	6/7/2006	0457761	4501945	2423	14	0	71
405.04	6/7/2006	0457683	4501992	2400	41	0	47
405.05	6/7/2006	0457567	4502022	2363	36	7	100
405.06	6/15/2006	0457462	4501907	2335	0	0	20
406.01	6/12/2006	0457461	4492371	2360	33	11	89
407.01	6/13/2006	0455978	4498319	2496	79	5	100
407.02	6/13/2006	0456198	4498324	2539	30	0	70
407.03	6/13/2006	0456308	4498246	2526	8	0	33
407.04	6/13/2006	0456451	4498285	2530	22	0	94
407.05	6/13/2006	0456607	4498324	2583	14	0	93
407.06	6/14/2006	0456277	4498407	2579	0	0	50
407.07	6/14/2005	0456380	4498465	2583	7	14	100
407.08	6/14/2006	0456477	4498612	2602	40	0	27
407.09	6/14/2006	0456598	4498696	2622	14	0	90
407.10	6/14/2006	0456876	4498527	2613	13	13	100
408.01	6/15/2006	0454230	4496857	2538	0	0	0
408.02	6/15/2006	0453940	4496716	2551	0	5	0
409.01	6/15/2006	0455325	4496984	2480	0	0	0
410.01	6/20/2006	0454559	4498341	2571	0	2	86
410.02	6/20/2006	0454414	4498439	2591	46	23	100
410.03	6/20/2006	0454295	4498571	2605	21	43	89
410.04	6/20/2006	0454399	4498743	2570	18	0	100
410.05	6/27/2005	0454590	4498871	2527	0	0	100
411.01	6/21/2006	0457686	4500058	2449	24	10	99
411.02	6/21/2006	0457775	4499977	2433	0	0	93
411.03	6/21/2006	0457925	4500037	2425	0	0	77
411.04	6/21/2006	0458092	4500065	2430	0	0	57
411.05	6/21/2006	0458182	4500135	2422	0	0	0
411.06	6/21/2006	0458123	4499947	2389	33	17	92

Table A-1 continued.

plot number	date established	easting	northing	elevation (m)	percentage ponderosa pine affected		
					mountain pine beetle	<i>lps</i> spp.	dwarf mistletoe
411.07	7/10/2006	0457906	4499984	2418	18	14	90
411.08	7/11/2006	0458031	4499905	2371	9	12	91
412.01	6/22/2006	0456624	4500236	2455	47	33	67
412.02	6/22/2006	0456584	4500335	2452	60	13	73
412.03	6/26/2006	0456471	4500247	2460	12	0	88
412.04	6/26/2006	0456456	4500430	2453	57	0	100
412.05	7/11/2006	0456414	4500349	2443	0	3	69
413.01	6/27/2006	0457863	4500483	2531	0	5	95
413.02	6/27/2006	0458178	4500527	2531	0	0	0
414.01	6/27/2006	0454026	4498415	2590	0	0	0
415.01	6/28/2006	0454649	4512691	2546	4	11	50
415.02	6/28/2006	0454678	4512567	2539	9	17	100
416.01	7/12/2006	0466553	4498130	2389	13	9	91

APPENDIX III.

Expanded Methods, Codes and Data Sheets

Extent + Fuel Plot Procedure:

1. Sampling Area
 - Poudre River watershed
2. Population
 - Ponderosa pine type as top percentage of species cover in the CVU (Common Vegetation Unit)
 - Extent Transect: All stands with any component of ponderosa pine
 - Fuel Plot: Little evidence of disturbance by humans (firewood cutting or timber sales), less than 4 stumps accepted that are greater than 20 years old and no recent fires (< 5 years old)
3. Two Level Sampling – Fuel Plots and Extensive Survey Transects and Stops

Use Extent Stops to determine population frequency and distribution

- Within a ponderosa pine stand (identified by CVU data), establish an extent transect
 - o Locate the starting point at a random number of chains (1 digit) within a stand that has enough area with ponderosa pine to hold the three 500 meter transects
 - o At stopping points (every 50 meters), rate the average DMR and years since MPB or *Ips* infestations and number of trees affected
 - Record stop mortality and stand data on Extent Transect Plot sheet
 - Record the UTM at the 0, 10 and 20 stops or when the azimuth of the transect is changed
 - o The azimuth of the first leg is 30 degrees minus the azimuth that is perpendicular to the edge of the stand
 - o At the 10th and 20th stopping points, add 120 degrees to the azimuth and resume the 50 meter extent transect stops
 - o If transect heads out of ponderosa pine type, then redirect transect at a random azimuth so as to stay within stand and continue adjusting to stay within stand
 - Take UTMs at each turn

Fuel plots can either be within transect at stopping points or they can be located where MPB or DM trees are seen from the transect

- Ideally extent transects should have 3 infested fuel plots to 1 un-infested fuel plot but more infested plots can be established if there is enough disturbance and time.

- All infested trees that can be seen from the transect are all acceptable for fuel plot locations as long as other disturbances are not present (human, fire, logging). Fuel plots should be established at the first 3 infested areas that are encountered on the extent transect or can be seen from the extent transect. However, fuel plots have to be more than 100 meters from each other.
- If more than 5 infested plots are established along the extent transect then another un-infested plot should be established also.
- Un-infested fuel plots are chosen from selecting a random number between 1 and 20. Skip the that number of un-infested stops within the extent transect to establish un-infested fuels plot

Fuel Plot Establishment Procedure:

Infested Plot Center:

- On Transect: Document plot center with a wooden stake labeled with plot ID number, 'CSU', and date.
- Off Transect: Determine plot center by standing in the center of the disturbance area. Use the random number table to get an azimuth (3 digits). Then pick the distance by using the first 1 digit picked from the random number table. This number is the amount of meters to plot center at the required azimuth. If the plot center is not going to capture any part of the disturbance, then again start at the center of the disturbance and pick another 1 digit number. Document plot center with a wooden stake labeled with plot ID number, 'CSU', and date.

Tree Tags: Tag each standing and fallen tree starting from north and going clockwise. Nail tag facing plot center at DBH. Dead trees other than ponderosa pine do not need to be tagged though tree data still needs to be collected.

Sapwood Basal Area: At least 2 increment cores need to be taken at DBH for 2 trees in every plot. Identify the sample PIPO by starting north and picking the first co-dominant and first intermediate tree. Cores should be taken on the North and South side. Measure the length of sapwood for each core and record it on the tree plot sheet. If lengths are drastically different between both sides of the tree, then take another core perpendicular to the last two. Cores should be saved by inserting them into paper straws. Label each straw/core.

Time Since Death: Increment cores of all dead trees need to be taken and saved in straws. Only about 30 years needs to be sampled. Only one core per tree is required.

Plot and Transect Layout: The plot has an 11.35m fixed radius. Tree data will only be taken on trees within the plot. Three fuel transects will be in the plot radiating from the center at 120° from each other.

** All plot measurements are recorded in **centimeters** unless otherwise noted on data sheets (eg. heights of trees).*

Crown Class: Record the crown class for all live trees. Crown class is the description of the relative position of the tree crown with respect to competing vegetation surrounding the tree. Crown classes are a useful descriptor of competitive status of trees in all structural types of stands. The Crown Class for

each tree is determined in the context of its immediate environment, trees or shrubs that are competing for sunlight or moisture with the subject tree.

Percent Live Crown Ratio: Record % live crown ratio as the length of the live crown divided by tree height. Live crown length is assessed from the uppermost live leader or branch to the lowest live branch. Visually adjust large openings in the crown or lopsided crowns by transferring lower branches to fill in the holes. Compressing the live crown length because the crown appears "sparse" or contains "unhealthy" foliage is not appropriate.

Fuel Transects:

Establish the first transect going North from plot center to the edge of the plot and keep logger tape or string on ground. The transect represents a plane that vertically extends to 1.37 m. Maneuver the transect so that there are no obstructions such as large rocks, vegetation or trees preventing a straight transect line. Along transect count the fine and coarse woody debris at their respective transect measurement locations (1 and 10hr – 5.17 to 6.17m from plot center, 100hr – 4.17 to 7.17m from plot center, and 1000hr – 1.17 to 10.17m from plot center). Use the go/no-go gauge to determine diameter classes. Measure and record the diameter of CWD (1000hr or greater than 7.6cm in diameter). Continue with same procedures for the next 2 transect with each being 120 degrees from each other.

Duff: At 3 places along the transect sample for duff (2.84m, 5.67m, 8.51m). Use an edge tool to make a clean cut into the ground and pull away the dirt/duff. Measure and record the depth of duff.

Shrubs, Grasses, and Forbs: Along the transect, record the length of the transect that has shrubs/grasses/forbs under it. Record the average vegetation status and height.

Fuel Bed Depth: Measure vertical continuous fuel from duff up through shrubs/grasses/ regeneration. Record 3 times along the transect at the same places where duff/litter is being recorded (2.84m, 5.67m, 8.51m).

Regeneration Plots: Tree regeneration plots are centered on the transect (5.67m). Regeneration plots are 4 meters in diameter. Trees that are below 1.37m in height are considered regeneration. Document the species and percent cover of dead and live trees. Record the species, tree status, height, height to crown, DMR and damage type and severity for each regeneration tree.

Codes

Forest: 210 = Arapaho/Roosevelt, 212 = Pike/San Isabel

District: CL = Canyon Lakes, BL = Boulder, CC = Clear Creek

Date: mm/dd/yyyy

Crew: Initials of crew members

UTM zone and Datum: From GPS in meters

Plot Elevation: Elevation from plot center (m)

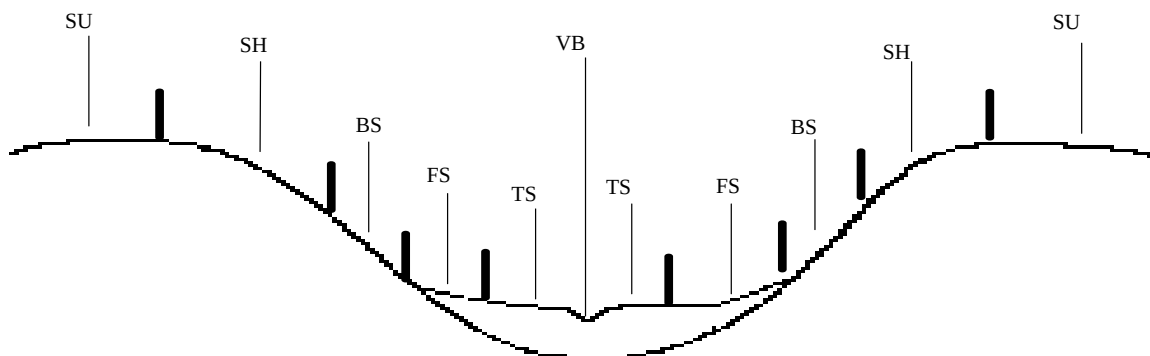
Plot Aspect: Direction, in degrees, which the plot faces (down slope)

Plot Slope: Average the down slope (%) and upslope measurements from plot center

Slope Position: Plot position on the landscape (National Soil Survey Handbook (Title 430-VI), USDA Soil Conservation Service 1993)

Code	Description
SU	Summit/Ridgetop/Plateau. The topographically highest hillslope position of a hillslope profile and exhibiting a nearly level surface.
SH	Shoulder. The hillslope position that forms the uppermost inclined surface near the top of a hillslope. It comprises the transition zone from backslope to summit.
BS	Backslope. The hillslope position that forms the steepest inclined surface and principal element of many hillslopes. In profile, backslopes are commonly steep, linear, and bounded by a convex shoulder above and descending to concave footslope. They may or may not include cliff segments. Backslopes are commonly erosional forms produced by mass movement and running water.
FS	Footslope. The hillslope position that forms the inner, gently inclined surface at the base of a hillslope. In profile, footslopes are commonly concave. It is a transition zone between upslope sites of erosion and transport.
TS	Toeslope. The hillslope position that forms the gently inclined surface at the base of a hillslope. Toeslopes in profile are commonly gentle and linear, and are constructional surfaces forming the lower part of a hillslope continuum that grades to valley bottom.
VB	Valley Bottom. Wide valley bottom beyond influence of toeslope.

Slope Position



Slope Configuration: Record the micro-site configuration of the plot.

Code	Description
BR	Broken. Cliffs, knobs and/or benches interspersed with steeper slopes generally characterized by sharp, irregular breaks. A marked variation of topography, or an irregular and rough piece of ground.
CC	Concave. The gradient decreases down the slope. Runoff tends to decelerate as it moves down the slope, and if it is loaded with sediment the water tends to deposit the sediment on the lower parts of the slope. The soil on the lower part of the slope also tends to dispose of water less rapidly than the soil above it.
CV	Convex. The gradient increases down the slope and runoff tends to accelerate as it flows down the slope. Soil on the lower part of the slope tends to dispose of water by runoff more rapidly than the soil above it. The soil on the lower part of a convex slope is subject to greater erosion than that on the higher parts.
LL	Linear or Planar. Substantially a straight line when seen in profile at right angles to the contours. The gradient does not increase or decrease significantly with distance (level or little relief).
PA	Patterned. A general term for any ground surface exhibiting a discernibly ordered, more-or-less symmetrical, morphological pattern of ground (i.e. micro relief of hummock and swales of several feet).
UN	Undulating. One or more low relief ridges or knolls and draws within the plot area.
UA	Unable to Assess.

Code	Description
CS	Closed Canopy Single story - A single even canopy characterizes the stand. The greatest number of trees are in a height class represented by the average height of the stand; there are substantially fewer trees in height classes above and below this mean.
CT	Closed Canopy Two story - Two height size classes are commonly represented in the stand. The various size classes tend to be uniformly distributed throughout the stand.
CM	Closed Canopy 3 or more stories – At least 3 height size classes are commonly represented in the stand. Generally, the canopy is broken and uneven although multiple canopy levels may be distinguishable. The various size classes tend to be uniformly distributed throughout the stand.
OS	Open Canopy Single story – Same as closed canopy single story though trees are spaced farther apart and sun reaches the forest floor.
OT	Open Canopy Two story – Same as closed canopy two story though trees are spaced farther apart and sun reaches the forest floor.
OM	Open Canopy 3 or more stories – Same as closed canopy 3 or more stories though trees are spaced farther apart and sun reaches the forest floor.
OI	Open Canopy Scattered Individuals - Woodland, open canopy, trees are dispersed throughout stand as individuals

Disturbance History: Record information about activities that occurred on, or affected the plot.

Description
Site Preparation
Artificial Regeneration
Natural Regeneration
Stand Improvement
Tree Cutting
Fire / Estimated Time Since
Other Silvicultural Treatments
Other Human Disturbance
Natural Disturbance
Land Clearing
Insect/Disease Outbreak
Animal Damage
Type Conversion
Mining

Status Classes: trees, CWD (logs), and stumps

Decay Class	Description
1	<u>Healthy</u> - < 5% visual damage to crown or stem
2	<u>Declining</u> – 6-50% crown showing symptoms or is damaged
3	<u>Dying</u> - > 50% crown showing symptoms or is damaged
4	<u>Greater than 10% of red needles still present.</u> All but the smallest twigs are present. All bark is intact. Sapwood is intact with minimal decay, heartwood is sound and hard. If standing, top of the crown is still present.
5	<u>Less than 10% of red or brown needles present.</u> Most of the small twigs and limbs are present. All bark is intact. Sapwood is mostly intact with minimal decay, heartwood is sound and hard. If standing, top of the crown is still present.
6	<u>All needles are gone.</u> Some small twigs and limbs are present. Bark is still intact. Sapwood is mostly intact with minimal decay, heartwood is sound and hard. If standing, top of crown still present but appears black.
7	<u>Most of the branches less than 2.5 cm in diameter are missing. 1 to 25% of bark is missing.</u> Sapwood is mostly intact with minimal to moderate decay, heartwood is sound. If standing, top of crown probably still present.
8	<u>Most of the branches less than 2.5cm in diameter are missing. 26 to 75% of the bark is missing.</u> Sapwood is mostly intact with minimal to moderate decay. If standing, top of crown probably still present.
9	<u>Only large branches still present. More than 75% of bark is missing.</u> Exposed wood is weathered. Sapwood is moderately decayed. If standing, the top of crown is probably not present.
10	<u>Most of log on ground. Very little bark remaining. Only large branches still present.</u> Sapwood decayed and sounds hollow when kicked. It sags if suspended for even moderate distances.
11	<u>Entire log is in contact with the ground.</u> Easy to kick apart but most of the piece is above the general level of the adjacent ground. If the central axis of the piece lies in or below the duff layer then it should not be included in the CWD sampling as the pieces act more like duff than wood when burned.

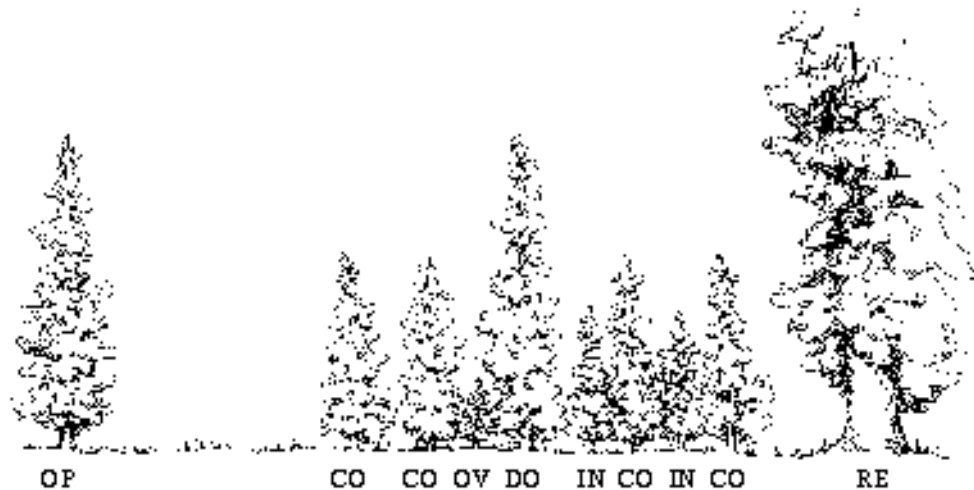
Tree Species:

Species Code	Scientific Name	Common Name
ABLA	<i>Abies lasiocarpa</i>	Subalpine Fir
PIEN	<i>Picea engelmannii</i>	Engelmann Spruce
PICO	<i>Pinus contorta</i>	Lodgepole Pine
PIFL	<i>Pinus flexilis</i>	Limber Pine
PIPO	<i>Pinus ponderosa</i>	Ponderosa Pine
POTR	<i>Populus tremuloides</i>	Quaking Aspen
PSME	<i>Pseudotsuga menziesii</i>	Douglas Fir
JUSC	<i>Juniperus scopulorum</i>	RM Juniper
PIPU	<i>Picea pungens</i>	Blue Spruce

Crown Class:

Tree Code	Description
OP	Open-grown, crown receives optimal sunlight above and sides
DO	Dominant, full sunlight from above and partly from sides
CO	Codominant, full sunlight from above, but little from sides
IN	Intermediate, sunlight only from holes in canopy
OV	Overtopped
PR	Predominant, an overstory tree remaining from an earlier stand that is at least 2 size classes (i.e. pole, sapling) larger than the newer stand
RE	Remnant
SU	Suppressed, no sunlight, below canopy in even-aged stands
UN	Understory

Crown Class Illustration

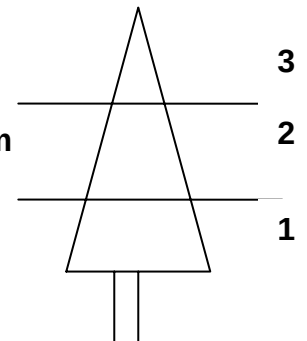


Dwarf Mistletoe Species: There are 3 species of DM that infect ponderosa pine. *Arceuthobium vaginatum* subsp. *cryptopodum* is Southwestern Dwarf Mistletoe on ponderosa pine. *A. americanum* is Lodgepole Pine Dwarf Mistletoe and only infects PIPO when growing with PICO and is found North of the Poudre Canyon. Also occurring, but rarely, is the infestation of PIPO with Limber Pine Dwarf Mistletoe (*Arceuthobium cyanocarpum*).

A. vaginatum subsp. *cryptopodum* = AV
A. americanum = AA
A. cyanocarpum = AC

DMR (Dwarf Mistletoe Rating): Hawksworth 0-6 class system

- Divide crown into thirds
- Rate and record each third
 - o 0= no mistletoe infections
 - o 1= <50% branches have infections
 - o 2= >50% branches have infections



Damage Types:

Code	Description	Code	Description
01	Mountain Pine Beetle	15	Foliage Diseases
02	Red Turpentine Beetle	16	Stem Rusts
03	<i>Ips</i> spp.	17	Broom Rusts
04	Other Bark Beetles	18	Fire
05	Twig Beetle	19	Animal Damage
06	Defoliators	20	Abiotic Damage
07	Boring Insects	21	Competition
08	Seed/Cone/Flower/Fruit Insects	22	Human Activities
09	Gallmaker Insects	23	Harvest
10	Insect Predators	24	Multiple Damages (insect/disease)
11	Parasitic/Epiphytic plants	25	Unknown
12	Root/Butt Diseases	26	Dead Top
13	Stem Decays/Cankers	27	Burl
14	Decline Complexes/Dieback/Wilts	28	Dwarf Mistletoe (unrateable dead trees)

Damage Severity:

If damage category not listed below then:

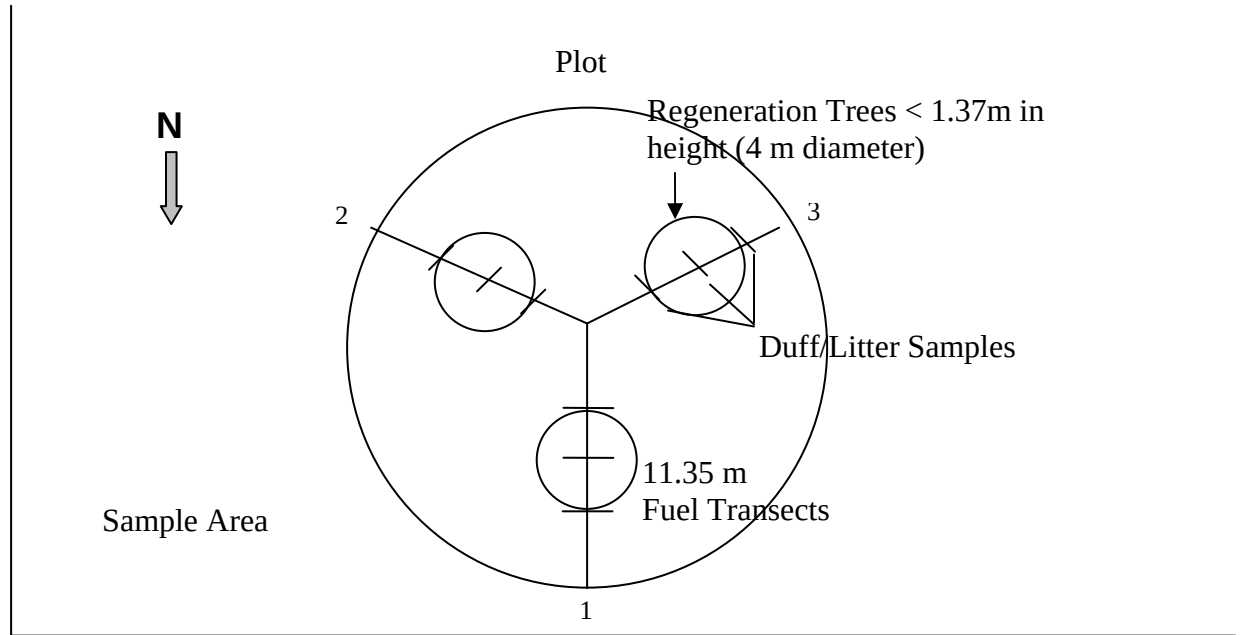
Severity code **1** = <20% of tree affected

Severity code **2** = >21% of tree affected

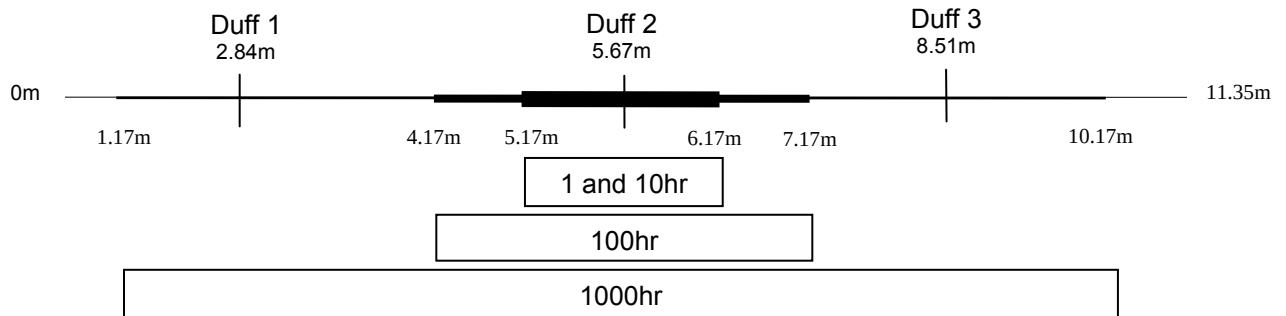
Severity code **3** = Topkill

Categories	Severity Code	Description
01, 02, 03, 04	1	Unsuccessful bole attack: pitchout and beetle brood absent
	2	Strip attacks: galleries and brood present
	3	Successful bole attack
	4	Topkill
05	1	Branch dieback in <50% of tree
	2	Branch dieback in >50% of tree
	3	Twig beetle infestation in dwarf mistletoe brooms
12	1	Tree within 9.14m (30ft) of tree with deteriorating crown, tree with symptoms or signs
	2	Pathogen or diagnostic symptoms detected - no crown deterioration
	3	Crown deterioration detected - no diagnostic symptoms or signs
	4	Both crown deterioration and diagnostic sign/symptoms detected

Plot and Transect Layout:



Dead Woody Class			Transect Location	Piece Diameter
DWD	FWD	1 hr	5.17 to 6.17m	0 to 0.6 cm
		10 hr	5.17 to 6.17m	0.6 to 2.5 cm
		100 hr	4.17 to 7.17m	2.5 to 7.6 cm
	CWD	1000 hr and greater	1.17 to 10.17m	greater than 7.6 cm



Shrubs, Grasses, and Forbs: Along the transect, record the length of the transect that has shrubs/grasses/forbs under it. Record the average vegetation status and height.

Tree and Vegetation Status Classes:

- 1 = Healthy – <5% visual damage to foliage or stem
- 2 = Declining – 6-50% foliage showing symptoms or is damage
- 3 = Dying – >50% foliage showing symptoms or is damaged
- 4 = Recent dead – no green but dead foliage still present
- 5 = Old dead – no fine twigs or foliage

Equipment List:

- 15m logger's tape
- 50 meter tape
- Diameter tape/Caliper
- Compass
- Clinometer
- Laser Range Finder
- Knife
- Tatum
- Data sheets (regular & rite in the rain)
- Data sheet file box
- File folders
- Pencil box
- Pencils/Sharpies
- Stapler
- GPS unit
- Binoculars
- Flagging
- Small wooden stakes
- Go/No-Go gauge
- Hatchet
- Edging tool
- Increment borer
- Straws
- Ruler
- Paper lunch bags
- Insect vials with 70% ethyl alcohol
- Duct tape
- Leather gloves
- Tree tags and nails

Data Sheets

Stand #: _____
Date: ____/____/____

Page _____ of _____

Extent Transect Plots (every 50m)

Skip #	Stand Structure	Avg. DBH	# Trees w/ DBH	Avg. MFB status	# Trees w/ MFB	Avg. Age status	# Trees w/ Age	Total Live PPO	UTM Northing	UTM Easting	Elevation	Comments
0												
1												
2												
3												
4												
5												
6												
7												
8												
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Notes:

Ist:

A:

B:

C:

D:

E:

Mountain Pine Beetle/Dwarf Mistletoe Fuel & Stand Structure Survey – Summer 2005

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Forest XXX	District XX	Stand Number	Fuel Plot Number

Date ____/____/____

Crew _____

Elevation _____m

Aspect _____° (declination = 12°)

Slope _____%

GPS Coordinates: N _____ E _____ Zone _____ Datum _____

Slope Position _____ (VB=valley/stream TS=bottom slope FS=lower slope, BS=mid slope, SH=upper slope, SU=ridge/summit)

Slope Configuration _____ (CC=concave, CV=convex, LL=even/linear, UN=undulating, BR=broken)

Stand Structure _____ (CS=closed, single story, CT=closed, two storied, CM=closed, multi-storied,

OS=open, single storied, OT=open, two storied, OM=open, multi-storied, OI=open, scattered individuals)

Dwarf Mistletoe Dist. _____ (1=none, 2=edge of disturbance center, 3=within disturbance center)

Mountain Pine Beetle Dist. _____ (1=none, 2=edge of disturbance center, 3=within disturbance center)

Disturbance History

Comments

Directions to stand and plot

Map to stand and plot

Page _____ of _____

[illegible][illegible][illegible]

Transect 1: % Cover and Species _____

Transect 2: % Cover and Species _____

Transect 3: % Cover and Species _____

[illegible]

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Transect 3: % Cover and Species _____

[illegible]

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APPENDIX IV.

Recommendations for Future Research and Research Hints

1. Fire behavior models could be used by inputting the fuel amounts and arrangements in areas with mountain pine beetle, *lps* spp. and dwarf mistletoe in Colorado's northern Front Range to determine potential fire behavior.
2. Determining the spatial distribution of mountain pine beetle, *lps* spp., and dwarf mistletoe across the landscape would allow for an analysis of how fire spreads across a landscape with trees infested with mountain pine beetle, *lps* spp., and dwarf mistletoe.
3. The canopy bulk density and other canopy fuel characteristics should be measured for trees with dwarf mistletoe to more precisely identify potential fire behavior.
4. By revisiting plots, the pattern of infestation of bark beetles on trees with dwarf mistletoe infections could be determined. Also, the forest development over time could be established by re-measuring plots.
5. Increment cores of live and dead trees were taken in this project. To more precisely calibrate tree degradation to time since death, the increment

cores should be analyzed. Also a master chronology could be established for the northern Front Range of Colorado.

6. If this research were done again with similar plot design, I would recommend assessing the amount of variability between the modified Brown's fuel transects within plots. Four fuel transects with longer sections to measure 1, 10, 100 hour fuel classes might have captured more fuel in areas where fuel placement was patchy and would have reduced the within plot variability. Also, the percent cover of bare ground and the depth of litter would be useful in further assessing the potential fuel hazard of areas in Colorado's northern Front Range.