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Effects of Bark Beetle-Caused Tree Mortality on Wildfire

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Abstract

Millions of trees killed by bark beetles in western North America have raised concerns about subsequent wildfire, but studies have reported a range of conclusions, often seemingly contradictory, about effects on fuels and wildfire. In this study, we reviewed and synthesized the published literature on modifications to fuels and fire characteristics following beetle-caused tree mortality. We found 39 studies addressing this topic with a variety of methods including fuels measurements, fire behavior simulations, an experiment, and observations of fire occurrence, severity, or frequency. From these publications, we developed a conceptual framework describing expected changes of fuels and fire behavior. Some characteristics of fuels and fire are enhanced following outbreaks and others are unchanged or diminished, with time since outbreak a key factor influencing changes. We also quantified areas of higher and lower confidence in our framework based on the number of studies addressing a particular area as well as agreement among studies. The published literature agrees about responses in many conditions, including fuels measurements and changes in stands with longer times since outbreak, and so we assigned higher confidence to our conceptual framework for these conditions. Disagreement or gaps in knowledge exist in several conditions, particularly in early postoutbreak phases and crown fire behavior responses, leading to low confidence in our framework in these areas and highlighting the need for future research. Our findings resolved some of the controversy about effects of bark beetles on fire through more specificity about time since outbreak and fuels or fire characteristic. Recognition of the type of study question was also important in resolving controversy: some publications assessed whether beetle-caused tree mortality caused differences relative to unattacked locations, whereas other publications assessed differences relative to other drivers of wildfire such as climate. However, some disagreement among studies remained. Given the large areas of recent bark beetle and wildfire disturbances and expected effects of climate change, land and fire managers need more confidence in key areas when making decisions about treatments to reduce future fire hazard and when fighting fires.

keywords: wildfire; bark beetles; fire behavior; fuels; forest disturbances

1. Introduction

Wildfire and bark beetle outbreaks are major disturbances in the conifer forests of North America. Wildfires have burned millions of hectares in recent decades (Littell et al., 2009), and bark beetle outbreaks have affected tens of millions of hectares in western North America since 1990 (Raffa et al., 2008). Both disturbances are influenced by climate (e.g., Westerling et al., 2006; Bentz et al., 2010) as well as stand conditions (Fettig et al., 2007), and projected future changes in climate are expected to increase wildfire and beetle outbreaks (Bentz et al., 2010; Pechony and Shindell, 2010).

In addition to effects on many resources such as timber production, water quantity, recreation, and wildlife habitat, bark beetle-caused tree mortality may alter fuels and therefore wildfire characteristics (Table 1). Potential modifications to forest fire behavior following beetle outbreaks could have multiple critical effects. The possibility of more extreme crown fire behavior in beetle-killed stands has led to concern about public safety and structure loss. Firefighting operations may be affected in areas with beetle-killed trees, with the increase in downed woody debris posing challenges for suppression and control, and more extreme fire behavior affecting firefighter safety (Cahill, 1977; Alexander and Stam, 2003). Altered fuels and fire characteristics following beetle outbreaks are of interest to water and wildlife managers because of possible changes in water quality and habitat that may occur following wildfire.

Despite these potential influences, there is a lack of consensus in the published literature about responses, with some publications reporting large effects of beetle-killed trees on fuels and fire (e.g., Jenkins et al., 2008) and other studies reporting no effect or a reduced impact (e.g., Berg and Anderson, 2006; Bond et al., 2009). This range of responses leads to confusion among scientists, resource managers, and the public, increasing uncertainty about decisions during firefighting operations and treatments to reduce wildfire impacts.

Here we report on a synthesis of the effects of bark beetle outbreaks on different fuels and fire characteristics. Past publications have reviewed the literature on this topic (Parker et al., 2006; Romme et al., 2006; Jenkins et al., 2008; Kaufmann et al., 2008; Simard et al., 2008; Gibson and Negron, 2009; Black et al., 2010); we provide an updated and more detailed review, critically evaluating each publication and identifying key characteristics for synthesis. We developed a conceptual framework from the published literature describing expected changes to characteristics following outbreaks, quantified agreement and disagreement among published studies, and assessed confidence in the developed framework. Our synthesis describes issues and challenges for studies of this topic and identifies gaps in knowledge.

2. Methods

We first identified aspects of studies that permitted valid comparisons. Key among these were a) forest type and insect species; b) fuels or wildfire characteristic studied (Table 1); c) types of study (observational, experimental, simulation modeling); d) consideration and type of study control that allowed comparisons with uninfested locations; e) sources of infestation and fire data; f) mortality rate following bark beetle outbreak (number of attacked trees); g) time since outbreak; and h) question addressed by study (does beetle-caused tree mortality alter fuels or fire characteristics relative to unattacked locations versus relative to influences of other drivers such as climate?).

Using standard search methods that included reference databases, the Internet, and personal inquiry, we identified all publications that reported new results on the effects of bark beetle outbreaks on fuels or wildfire characteristics. For each study, we identified the reported response of one or more combinations of fuels or fire characteristic in one or more postoutbreak phases for subsequent grouping and analysis. We also rated fuels or fire behavior characteristic/phase/study combinations for use in our conceptual framework; using such combinations allowed us to separate findings within one study that may have been obtained with different methods (e.g., findings from observations versus modeling results that were reported in one publication). Combinations were rated from low (1) to high (3) according to an established set of criteria that considered several factors (Table 2). The type of publication influenced the ratings: briefing papers or reports that did not undergo peer review received lower ratings, whereas articles in peer-reviewed refereed journals received higher ratings, and government publications received intermediate ratings. Publications describing qualitative observations were rated lower, and scientific studies with hypotheses or objectives and quantitative measurements or modeling were rated higher. We gave studies that relied on simulation modeling lower ratings than studies based on ground-based observations. Studies that included appropriate control sites or preoutbreak times for comparison with infested sites and times were rated higher than those without controls. Because multiple factors influence wildfire behavior (weather, fuels, topography), higher ratings were assigned to studies that included consideration of important explanatory variables representing these factors, and lower ratings were assigned to studies that considered only one or a few explanatory variables and did not include some major factors. Finally, we rated studies that lacked sufficient details on key aspects (as discussed above) lower.

Guided by the scientific literature, we developed a conceptual framework that describes expected patterns of fuels and fire characteristics as a function of time since outbreak. In conditions where knowledge gaps or disagreement occurred, we used scientific understanding about bark beetle outbreaks and fuels and fire behavior to suggest responses. Following bark beetle attack, stands move through several phases as time progresses (Hopkins, 1909; Amman et al., 1990; Wulder et al., 2006; Simard et al., 2011). After trees are killed, foliar moisture content decreases (Gibson and Negron, 2009; Jolly et al., in press) and in many bark beetle-attacked conifer species such as pines, needles fade to red within a year ("red phase"). Other conifers such as some spruce may fade to yellowish or remain green instead of turning red (Holsten et al., 1999). Following needledrop in 3-5 years (typical for lodgepole pine, *Pinus contorta*; other forest types have different timing (Clifford et al., 2008)), killed trees turn gray ("gray phase"). Within one to several decades, snags fall (Keen, 1955; Schmid et al., 1985; Mitchell and Preisler, 1998), understory vegetation increases (McCambridge et al., 1982; McMillin et al., 2003), and new tree seedlings establish (Astrup et al., 2008) ("old phase"). We assumed that stands at each phase are composed of relatively pure conditions (e.g., mostly red trees within the red phase). This simplifying assumption allowed us to focus on changes on fuels and fire following beetle attack without the confounding factor of variability within a stand; implications of this assumption will be discussed later in Section 3.3.

We also gauged the level of controversy among studies as well as identified gaps in knowledge by determining the level of agreement or disagreement among published studies. We used a specific fuels or fire characteristic reported for a particular postoutbreak phase by a study ("combination") and our rating for that combination as we describe above. We identified each characteristic/phase/study combination as either agreeing or disagreeing with our conceptual framework. We then summed ratings for each of the agreeing and disagreeing sets of combinations. Higher summed values resulted from more studies that addressed a given fuels or fire characteristic as well as the rating of each study. As a hypothetical example, suppose our conceptual framework listed a decrease in foliar moisture in the red phase, and five studies reported results about this characteristic in this phase. Four of the studies agreed (they reported that foliar moisture decreased), and one disagreed (the authors found that foliar moisture increased). All characteristic/phase/study combinations were rated medium (2). The summed value for agreement would be 4 x 2 = 8, and the summed value for disagreement would be 2. We assigned higher confidence in our conceptual framework to combinations with several studies and substantial agreement among studies. Lower confidence was assigned to combinations with either fewer published studies or for which disagreement occurred. Gaps in knowledge were identified in conditions where there were few or no studies that addressed a particular fuels or fire characteristics/phase combination.

Several studies defined an "epidemic" phase that did not separate red phase stands from gray phase stands (Page and Jenkins, 2007a; Page and Jenkins, 2007b; Jenkins et al., 2008); we placed associated characteristics into our gray phase. Combinations from the following three studies were not rated because postoutbreak phase was not reported. Pollet and Omi (2002) reported reduced fire severity in beetle-killed stands, Lundquist (2007) reported no effect of bark beetles on fuels, and Kulakowski and Jarvis (2011) used dendroecological methods to identify bark beetle-caused tree mortality but did not report time since outbreak relative to fires.

We assessed variability in fuels among undisturbed stands for comparison with fuels differences in attacked versus unattacked stands. To accomplish this, we compared measurements in lodgepole pine stands from the USDA Forest Service Natural Fuels Photo Series (Ottmar et al., 2000) with those from studies included in our review. The Natural Fuels Photo Series describes the average fuels characteristics for selected sites. At each photo series site, measurements of fuel loading and vegetation characteristics such as canopy cover, stand structure, understory vegetation, and surface fuels were recorded. The Volume III, Rocky Mountain version of the photo series includes lodgepole pine stands. We identified five lodgepole pine sites in late seral stages (LP7, LP10-13). We then compared measurements from these sites with reported measurements of fuels in beetle outbreak locations in lodgepole pine (Page and Jenkins, 2007b; Klutsch et al., 2009; Simard et al., 2011). There is some uncertainty associated with how representative the photo series stands are compared with average lodgepole pine stands across its range. However, our purpose was to illustrate variability in fuels, and some uncertainty was therefore acceptable.

3. Results

3.1 Characteristics of studies

We found a total of 56 published studies that discussed the potential effect of bark beetle outbreaks on subsequent wildfire. Of these, 17 studies addressed the subject but did not provide evidence, and were not considered further (see Supplementary Information). Of the remaining

39 studies, 22 were published in peer-reviewed scientific journals, nine were government publications such as USFS General Technical Reports or Technical Notes, three were briefing or informal reports that were limited in detail and/or were not products of scientific studies, four were graduate student theses/dissertation, and one was a book chapter (Table S1 in Supplementary Information). Broadly, these studies addressed one of several categories: 1) fuels measurements; 2) fuels measurements and fire behavior modeling; 3) landscape modeling of fuels and fire behavior; 4) wildfire observations, including statistical analyses; and 5) experiments (Table S1). Publications discussing changes in fuels following bark beetle outbreaks typically used field observations, whereas studies of fire behavior typically relied on simulation modeling. Only two publications reported experimental results (from the same project). Publications discussing fire occurrence, frequency, severity, and size generally utilized retrospective (historical) databases and statistical analyses.

The selected studies addressing fuels or fire behavior produced 119 characteristic/phase/study combinations (Table S2 in Supplementary Information). Combinations rated 2 were most common, and relatively few combinations were rated either 1 or 3 (Figure 1).

3.2 Conceptual framework of fuels and fire behavior

Our conceptual framework of fuels and fire behavior characteristics illustrates substantial variability in responses following a bark beetle outbreak (Figure 2). Canopy bulk density (see Table 1 for definitions) remains unchanged initially following bark beetle outbreak, but declines during the gray phase, and recovers as the forest regrows during the old phase. In response, fine surface fuels increase during gray phase, then decrease as these fuels decompose. Coarse fuels increase significantly only during the old phase as branches and snags fall. Ladder fuels increase as shrubs and seedlings establish and surviving subdominant trees grow during the gray and old phases.

Fire behavior is modified as a result of these changes in fuels characteristics (Figure 2). Surface fire behavior properties (rate of spread, reaction intensity, flame length) increase in response to increased surface fuel loads. Torching potential increases in the red phase as a result of reduced foliar moisture in killed trees. In the gray phase, torching potential remains elevated as a result of increased surface fuel loads and no change in canopy base height. In the old phase, torching potential increases as ladder fuels increase. The potential for active crown fire increases in the red phase as a result of reduced foliar moisture. However, active crown fire potential declines through the gray phase following reductions in canopy bulk density and increases slowly in the old phase as the forest regrows.

Substantial agreement exists in the published literature for most characteristic/phase/study combinations (Figure 3). More studies reported results in gray and old phases; fewer studies addressed the red phase. More agreement occurred in the old phase than in the red and gray phases, with substantial agreement also occurring in some fuels or fire characteristics in the gray phase. This agreement led to higher confidence in the conceptual framework in these phases (Figure 2). We put lower confidence in our conceptual framework for characteristics in the red phase and in some characteristics in the gray phase because of disagreement among studies and, for the red phase, few studies. Some disagreement occurred within each phase and for most fuels and fire characteristics. Disagreement will be discussed in more detail below in Section 3.3.

We analyzed subsets of characteristic/phase/study combinations to explore patterns. The summed combinations from only publications in peer-reviewed journals illustrated similar patterns for all combinations (which are shown in Figure 3). The majority of disagreement in the combinations displayed in Figure 3 (i.e., considering all types of publications) came from these peer-reviewed journal publications. Government publications contributed both agreement and disagreement to combinations, and mostly addressed surface fuels characteristics. Combinations that were rated highly (≥2.5) generally addressed fuels in gray and old phases, in part because of the use of ground-based observations. Combinations rated 2 also were in gray and old phases typically, and included fire behavior characteristics as well as fuels. Lower-rated combinations (<2) were typically associated with fire behavior characteristics, in part because of the reliance on modeling. Lower-rated combinations also occurred across many characteristics in the red phase. Disagreement occurred in combinations with all ratings. More combinations were associated with lodgepole pine forest types, with some combinations addressing spruce or other/mixed/unknown forest types. Disagreement occurred in each type. Observational studies typically addressed fuels, whereas modeling studies typically addressed fire behavior. Both study types had some disagreement with our conceptual framework.

The choice of assigning rating values 1-3 may have minimized the effect of these ratings on the summed values (bar heights in Figure 3 representing level of agreement or disagreement) relative to the number of studies associated with a given combination. To test the sensitivity of our results shown in Figure 3 to the values used, we expanded the range of ratings from 1-3 to 1-9. This expansion increased the weight of combinations rated higher compared with combinations rated lower, and provided the possibility of increasing the importance of a single, highly rated study relative to multiple, lower rated studies, for example. Summed patterns did not change much from Figure 3. Most combinations were rated “M” (2 in the original numeric rating), and fewer were rated “L” or “H” (Figure 1). The major effect on summed ratings was therefore the number of studies, with the rating of each combination having only a minor effect.

3.3 Disagreement among studies

Published studies reported disagreement both with commonly held views or expectations and with other publications about whether bark beetle outbreaks affect fuels and wildfire. We found that aspects of this disagreement were reduced when studies and conditions were characterized with more specificity. Description of three areas in particular reduced disagreement and led to a more consistent framework with higher confidence. Time since disturbance and fuels or fire characteristic clearly cause variability in responses, and so discussions of effects should specify these conditions. In addition, perceived controversy in the literature exists because studies addressed different research questions. Studies that asked “What was the importance of beetle outbreaks compared with other potential modifiers or causes of fuels and wildfire?” reported different effects than studies that asked “What was the effect of beetle outbreaks compared with an identical stand without beetle infestation?” (as in our conceptual framework). Both are useful questions, but answers to each have different implications about beetle impacts. Clearer identification of the study question when evaluating results is needed.

Disagreement among studies with similar study questions, time since outbreak, and characteristic also occurred, causing some studies to disagree with our conceptual framework. Several reasons for this disagreement exist. Although using discrete postoutbreak phases as in this review is useful for understanding processes and responses, such a classification also hides complexity, and phases are actually part of a continuum of responses. For example, finer fuels such as twigs remain in the canopy in the gray phase (defined as after needledrop), gradually falling off trees in later years, implying the possibility of differences in crown fire behavior within the gray phase. Because bark beetles can attack trees for many years within one stand, some studies had mixtures of green, red, and gray trees within red or gray phases, which muted impacts to fuels and/or fire behavior (e.g., Simard et al., 2011). Similarly, the number of killed trees within an attacked location varied substantially within and among publications, and often was unspecified (Armour, 1982; Schulz, 1995, 2003; Taylor et al., 2005; Jenkins et al., 2008; Gibson and Negron, 2009). Mortality within attacked stands was as low as 6%, with 30-60% common. A wide range of mortality rates may lead to differences in fuels and fire behavior within locations identified as infested (Turner et al., 1999). Some studies lacked sufficient details about fuels characteristics and therefore postoutbreak phase, requiring us to use time since outbreak to identify postoutbreak phase and potentially leading to incorrect placement within our conceptual framework.

Variability in fuels contributed to disagreement. Such variability occurred among stands within the same postoutbreak phase (e.g., coefficients of variation of 50-100%, Page and Jenkins, 2007b; Klutsch et al., 2009). In addition, our analysis of fuels in undisturbed stands relative to attacked stands illustrates the large variability in fuels (Figure 4). Many of the fuels observations from the three bark beetle/fire studies analyzed were within the variability of unattacked, later seral stands represented by these studies and the Natural Fuels Photo Series data. High variability within a postoutbreak phase requires more sampling to identify statistically significant differences among phases, and therefore ascertaining any effect of beetles on fuels. Thus, disagreement among studies may have occurred because of limited sampling of this variability and/or the difficulty of identifying study controls in unattacked locations that were similar to attacked locations.

3.4 Disagreement of the conceptual framework with the published literature

As discussed above, studies disagree with our conceptual framework in the common situation in which there was a lack of consensus in the literature about the response of a particular characteristic/phase/study combination (Figure 3), and consequently, we used our scientific understanding to suggest responses. In addition, for three combinations, we chose a response that was not suggested by the majority of studies. The greatest disagreement was associated with our expected no change in canopy base height in gray phase stands with which four out of six studies disagreed with this response (Clifford et al., 2008; DeRose and Long, 2009; Jorgensen and Jenkins, 2011; Klutsch et al., 2011). Possible explanations include earlier development of the understory in these studies than we assumed in our conceptual framework. In addition, methods of calculating canopy base height suggested some uncertainty in comparing results among studies. Some studies calculated canopy base height using a representative live tree as a stand average (Page and Jenkins, 2007b; Jorgensen and Jenkins, 2011). Clifford et al. (2008) reported a decreased canopy base height using live trees only. Other studies (DeRose and Long, 2009; Klutsch et al., 2011) relied on methods of calculating stand-average canopy base height that do not include dead trees within a stand (Reinhardt and Crookston, 2003), It is unclear how beetle-caused tree mortality would cause a decrease in canopy base height in the absence of understory development (Clifford et al., 2008). Understanding the response of this variable is critical because of its use as an input to calculate fire behavior in fire simulation models.

For two other combinations, our chosen response disagreed with the single relevant publication. First, we expected no change in canopy bulk density in the red phase based on our assumption that trees still retained their foliage. Simard et al. (2011), however, reported reduced values, likely as a result of the mixing of gray and red trees within their red phase stands, as discussed above. Second, our conceptual framework suggests a lack of change in surface fire behavior in the red phase because of the expected lack of change in surface fuels. However, Simard et al. (2011) reported reduced surface fire intensity and spread rate in these stands, possibly related to variability in fuels and difficulties in sampling as discussed above.

3.5 Probability of fire occurrence and burn severity

Based on our conceptual framework of the response of fuels and fire behavior, we developed expected responses of two additional fire characteristics, probability of fire occurrence and burn severity of attacked stands compared with unattacked stands. We considered different probabilities of occurrence and burn severity for surface fire versus crown fire because of different response of surface and crown fires in our conceptual framework. Given conditions sufficient for the occurrence of a fire (ignition, amount and moisture content of fuels), we expect that in the red phase, probability of occurrence increases for crown fires because of increases in the potential for torching and active crown fire, but does not change for surface fires because of the lack of modification of surface fuels. In the gray and old phases, surface fire probability increases following increased surface fuel loads. Crown fire probability in these phases may decrease because of reduced canopy bulk density but may increase as a result of increased torching potential; we hypothesize that the reduced canopy bulk density is the stronger effect.

Burn severity of the forest floor (consumption of surface fuels and modified soil characteristics, Keeley, 2009) is unchanged in the red phase as a result of no change in fuels and increases in the gray and old phases because of higher surface fuel loads and greater reaction intensity. We considered separately burn severity of the canopy (tree mortality, Keeley, 2009), which we expect will increase in the red phase following higher torching and active crown fire potential as a result of reduced foliar moisture. As with probability of occurrence, we expect lower canopy burn severity in the gray and old phases because we expect that the effects of reduced canopy bulk density outweigh increased torching potential associated with higher surface fuel loads.

The different responses of surface versus crown fires for probability of occurrence and burn severity prevented us from developing a conceptual framework of these two fire characteristics, and it is unclear what the combined surface and crown fire responses are. Studies of probability of occurrence (Bebi et al., 2003; Kulakowski et al., 2003; Taylor et al., 2005; Berg and Anderson, 2006; Berg et al., 2006; Lynch et al., 2006; Kulakowski and Veblen, 2007; Bisrat, 2010; West, 2010; Kulakowski and Jarvis, 2011) or burn severity (Turner et al., 1999; Pollet and Omi, 2002; Bigler et al., 2005; Kulakowski and Veblen, 2007; Bond et al., 2009) following bark beetle-caused tree mortality did not separate responses into surface versus canopy. However, we note some observations about these studies. The effect of beetle outbreaks on probability of occurrence or burn severity were smaller than other drivers such as climate, topography, blowdown, and cover type (Bigler et al., 2005; Kulakowski and Veblen, 2007; Bisrat, 2010). Three studies found that within studied outbreak areas, fires did not occur for decades to centuries following beetle attack (Bebi et al., 2003; Berg et al., 2006; West, 2010), indicating that fires do not necessarily occur following beetle outbreaks and highlighting the importance of ignition and weather in addition to fuels in driving wildfires (Agee, 1993).

Bond et al. (2009) reported that drought- and beetle-caused tree mortality in the red phase did not affect burn severity associated with a fire in southern California. Studies of gray phase stands reported no change in probability of occurrence of wildfire (Lynch et al., 2006; West, 2010). West (2010) also estimated no change in occurrence in old phase stands, whereas Lynch et al. (2006) found an increase in occurrence. Kulakowski et al. (2003) reported that beetle-attacked stands with more mortality were less affected by a low-severity fire 1-4 years following outbreak than stands with lower mortality. Old phase stands have a higher probability of burning at high severity (Bigler et al., 2005). Burn severity depends on the extent of beetle damage, however. Turner et al. (1999) reported that intermediate damage decreased the likelihood of crown fire relative to other burn severity classes, and severe beetle damage increased the likelihood of crown fire.

Studies that addressed probability of fire and burn severity were typically observational studies of historical conditions. A difficulty for these studies is to assess responses relative to unattacked stands (i.e., with all other variables the same) because many types of useful information, such as weather, are unavailable.. A few studies used USDA Forest Service Aerial Detection Survey (ADS) data sets to map beetle-killed trees. Polygons identifying bark beetle attack in these data sets also include live trees, and so there may be uncertainty in the location of killed trees within these polygons in these data sets (West, 2010). However, precise overlap of killed trees and burned area is critical for understanding impacts.

3.6 Other findings

Several studies reported that factors such as past disturbances, stand structure, topography, and vegetation type were more important than beetle outbreaks for influencing fuels characteristics (Ager et al., 2007; Lundquist, 2007), crown fire behavior (Ager et al., 2007), severity (Bigler et al., 2007; Kulakowski and Veblen, 2007; Bond et al., 2009), frequency (Kulakowski and Jarvis, 2011), and extent (Kulakowski and Veblen, 2007). Microclimate changes following beetle attack such as increased wind speed resulting from a more open canopy affected simulated fire behavior substantially, often more than changes in fuel loadings (Page and Jenkins, 2007a). Surface fuels are expected to dry as a result of a more open canopy following outbreak, yet observations of changes in surface temperature were variable and inconclusive (Simard et al., 2011). The odds of a fire becoming larger were higher in locations in the red phase but not in locations in the gray phase (Preisler et al., 2010), consistent with our conceptual framework for enhanced torching and active crown fire potential in the red phase and reduced active crown fire potential in the gray phase. Taylor et al. (2005) found large burned areas in red phases relative to other phases in British Columbia for several bark beetle species, with some species also exhibiting larger burned area in subsequent phases. In a low productivity lodgepole pine forest with little surface fuels, logs from past beetle outbreaks provided the means of allowing fire to spread across the surface (Gara et al., 1985). Such surface fire spread via smoldering logs is not included in commonly used fire behavior models. Results from observational studies suggest that fires do not necessarily occur following attack (Bebi et al., 2003; Berg et al., 2006; West, 2010).

Multiple factors influence fuels or fire behavior, including the distribution and amount of fuels that may be modified by insect outbreaks, but also including climate, weather, topography, and forest type. These multiple influences suggest that studies analyzing one or a few drivers at a time may miss important interactions in which the effect of one variable (beetle-attack) may be confounded by variability in other factors. For example, some studies discussed the probable influence of weather on fire behavior but did not include this factor (Kulakowski and Veblen, 2007; Bond et al., 2009).

4. Key knowledge gaps

Several fuels and fire characteristics have either no or few studies associated with them or a significant amount of disagreement (Figure 3), suggesting gaps in understanding. Changes in fuels and fire behavior in the red phase are not well understood. Additional studies are needed on the effects of altered foliar moisture and volatile organic compounds on fire behavior in forest types other than lodgepole pine. In addition, more information is required on the influence of red phase stands on fire characteristics in less extreme weather conditions (e.g., early season, lower wind speeds). The influence of a range of mortality rates and times since initial attack within a stand on fire behavior has not been documented, yet most studies reported a mixture of green, red, and/or gray trees within an attacked stand. Documenting responses of fuels and fire characteristics across a gradient of mortality is critical for understanding if thresholds representing major shifts exist. Studies of ember and firebrand production and spotting in beetle-attacked locations are needed to improve understanding of fire behavior or large fire events.

Wildfire experiments could provide much-needed observations, yet are difficult to set up and risky because of potential impacts to assets and public safety. Thus, simulation modeling will continue to be an important decision-support tool for advancing our understanding of the responses of fuels and fire behavior. Commonly used fire behavior models (e.g., BehavePlus (Andrews et al., 2005)) are only sensitive to variables included within the model, yet do not simulate key processes associated with beetle outbreaks and thus have limitations that constrain their usefulness for some conditions, such as the red phase. A major assumption in most models is that canopy fuels are alive, and so parameterizations were developed for foliar moisture in live, not killed, trees, and some variables such as canopy base height do not consider dead trees. Spatial variability in fuels is not considered, yet is significant in beetle-attacked stands. Limitations of these models to simulate realistic fire behavior have been documented recently (Cruz and Alexander, 2010). Newer models that incorporate physics-based methods in a three-dimensional spatial framework are able to test the importance of these effects, though are computationally expensive and difficult to run (Linn et al., 2002; Mell et al., 2009).

Most of the studies to date have addressed cooler, moister forest types (lodgepole pine and spruce). There was both agreement and disagreement among studies of each forest type, suggesting no definitive conclusions could be made about forest type. Little information is available on differences in effects among these forest types (Jenkins et al., 2008). Furthermore, few studies have addressed drier forest types such as ponderosa pine (*Pinus ponderosa*) or piñon pine (*P. edulis* and *P. monophylla*). However, these forest types have different tree and stand structure characteristics compared with lodgepole pine and spruce forests that likely lead to differences in responses (Clifford et al., 2008). For example, forest structure is different, with high canopy bulk density, lower canopy base height, and multiple ages in ponderosa pine stands compared with closed canopy, even-aged stands of lodgepole pine (Steele and Copple, 2009; Stiger, 2009). Longer ponderosa pine needles lead to needledrape of fallen needles on understory plants, perhaps facilitating torching (Steele and Copple, 2009; Stiger, 2009).

Multiple key processes in beetle-attacked stands need study. Wide ranges of snagfall rates have been published (e.g., Mielke, 1950; Keen, 1955; Schmid et al., 1985; Mitchell and Preisler, 1998); additional research is needed to understand this range and develop models. Studies have documented increases in herbaceous and/or shrubby vegetation following beetle outbreaks (e.g., McCambridge et al., 1982; Reid, 1989; Schulz, 1995; Stone and Wolfe, 1996; McMillin et al., 2003; Page and Jenkins, 2007b; Klutsch et al., 2009), yet the net impacts on increased fuel loads, ladder fuels, and fuel moisture have yet to be determined (Kaufmann et al., 2008). No study has addressed firefighting safety and operations in bark beetle outbreak locations (although some work has documented effects in broadleaf stands attacked by sudden oak death (Lee et al., 2010)). Few studies have addressed microclimate changes (Simard et al., 2011), yet simulations have highlighted the importance of altered wind speeds (Page and Jenkins, 2007a). Other microclimate effects, such as on snowpack accumulation and duration and subsequent influences on fuel moisture during spring and summer, have yet to be quantified.

Significant challenges exist for future studies that seek to address the above knowledge gaps. Inclusion of all drivers of fire occurrence or severity is critical, yet studies are usually hampered by the lack of some information, often weather. Identification of similarity in study locations, whether among beetle-attacked areas or between beetle-attacked and control areas, is challenging but important. Limitations of current data sets (such as aerial survey databases) and commonly used fire behavior models need consideration.

Given the above difficulties, assessments of personal observations or anecdotes of field personnel may yield substantial insight into fire behavior in locations with widespread outbreaks, as has been reported for fires in other forest types (Lee et al., 2010). Challenges exist as to the means of including these observations in a scientifically sound study, but such analyses would draw on substantial number of observations and provide a unique perspective.

5. Conclusions

Published studies suggest that bark beetle outbreaks can indeed affect fuels and fire behavior. The types of change, however, depend on the research question addressed, time since outbreak, and fuels or fire characteristic of interest, suggesting that generalizations about the effects of bark beetle-caused tree mortality on fire characteristics are unwarranted. Although many studies reported that beetle outbreaks were not as important as other factors in driving fire behavior, extent, or severity, the impact of beetle-killed trees can become significant when compared with unattacked stands. Furthermore, differences may only occur under some environmental conditions. For example, effects may be manifested during intermediate wind speeds (Simard et al., 2011) or in moister conditions, such as earlier in the fire season (Steele and Copple, 2009). Past controversy on this topic can be partly reconciled by this consideration of more specificity about study question, time since outbreak, and fuels or fire characteristic when describing results.

Our conceptual framework developed from the literature describes responses of different fuels and fire behavior characteristics as a function of time since outbreak. Substantial agreement among the literature and with our conceptual framework existed, yet disagreement occurred for some characteristics as well (beyond more specification described in the previous paragraph).

Lower confidence in areas of our conceptual framework that resulted from gaps in knowledge or disagreement among studies limits certainty about impacts of beetle-caused tree mortality on fuels and fire, particularly in key areas such as the red phase and fire behavior. Yet resource managers urgently need information about this interaction. Beetle outbreaks and wildfire are both influenced by climate, and warming projections imply increasing forest disturbances in the coming decades (Westerling et al., 2006; Bentz et al., 2010). Greater understanding of the effect of beetle-killed trees will provide better information to resource managers who need to consider how such trees affect future wildfire characteristics. Payoffs of investments of time, money, and effort to treat stands to reduce fire hazard will be maximized with such knowledge. Fire managers will also benefit from greater certainty about possible changes in fire behavior and effects on suppression and control in locations with beetle-caused tree mortality when developing firefighting plans that include considerations of safety and property loss.

Although our detailed review provides a conceptual framework based on published studies and identifies that significant agreement exists in some situations, we reiterate that substantial gaps in knowledge exist. Large variability in forest structure, mortality rate, and environmental conditions within areas attacked by bark beetles suggests challenges in characterizing general responses of fuels and fire characteristics applicable across affected forests. Additional research across this variability will increase confidence in our understanding of this key topic in western North America.

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Figure Captions

Figure 1. Distribution of fuels or fire characteristic/phase/study combination by study rating.

Figure 2. Conceptual framework of (a) fuels characteristics and (b) fire behavior relative to preoutbreak conditions for red, gray, and old (snagfall and regrowth) phases. Surface fire properties include reaction intensity, rate of spread, and flame length. For postoutbreak phases, solid lines indicate higher confidence in responses based on Figure 3, and dashed lines indicate lower confidence (more disagreement, fewer studies, or knowledge gaps).

Figure 3. Level of agreement (green bars) or disagreement (red bars) with conceptual framework (Figure 2) by fuel/fire characteristic and postoutbreak phase. Bar heights illustrate strength of agreement or disagreement and result from the number of individual studies (boxes) and each study/characteristic/phase combination rating (height of each box). "O" indicates result based on observations, "M" indicates process model result. Expected response of each fuels or fire characteristic ("-", decrease; "+", increase; "0", no change) at each postoutbreak phase (taken from Figure 2) is shown across the top of each panel. Surface fire properties include reaction intensity, rate of spread, and flame length; canopy base height is the reported ladder fuel variable.

Figure 4. Relative fuel values in each fuel category in lodgepole pine stands from USDA Forest Service Natural Fuels Photo Series (Ottmar et al., 2000) (plusses, leftmost within each category) as well as mean values reported in publications included in this review that addressed bark beetle

impacts (Page and Jenkins (2007b), asterisks; Simard et al. (2011), diamonds; Klutsch et al. (2009), triangles and rightmost within each category). Green symbols are for observations from undisturbed stands (from the Photo Series as well as reviewed studies), red symbols from red phase stands, gray symbols from gray phase stands, purple symbols from old phase stands. Values have been scaled so all categories fit on same y-axis; pairs of numbers below each category label on the x-axis indicate the minimum and maximum values used for scaling. In many cases, the range of undisturbed values (green symbols) is similar to or exceeds the range of beetle-attacked stands (red, gray, purple symbols).

Table 1. Fuels or fire characteristic potentially affected by bark beetle-caused tree mortality and their definitions.

Category	Characteristic	Definition
canopy fuels	canopy base height	lowest height for which there is sufficient canopy biomass to initiate crown fire or torching
	canopy bulk density	mass of fuel in canopy
	foliar moisture content	moisture content in foliage
surface fuels	fine fuel load	litter; dead surface fuels <1” in diameter
	coarse fuel load	dead surface fuels >1” in diameter
	total surface fuel load	fine plus coarse fuel load
	understory vegetation	herbaceous vegetation, shrubs, seedlings, saplings, smaller trees
fire	probability of occurrence	probability that a fire occurs
	surface fire properties • reaction intensity • rate of spread • flame length	 • energy release by fire • rate of advance of fire front • distance from ground to tip of flame
	torching potential	potential for a surface fire igniting a tree or group of trees
	potential for active crown fire	potential for wildfire burning the crowns of trees, with spread associated with both crown and surface fire
	burn severity	effects of fire on ecosystem properties (soil and vegetation)

Table 2. Criteria used to determine study ratings.

Criterion	Lower ratings	Higher ratings
type of study	• briefing papers or reports	• scientific study with objectives/hypothesis and measurements/modeling • refereed journal
methodology	• simulation modeling • use of aerial detection surveys	• inclusion of control in space or time • consideration of all explanatory variables • ground-based observations
reported details of study	• little or no details provided	• detailed description, especially of • tree mortality rate/amount • time since outbreak and fuel condition • study control

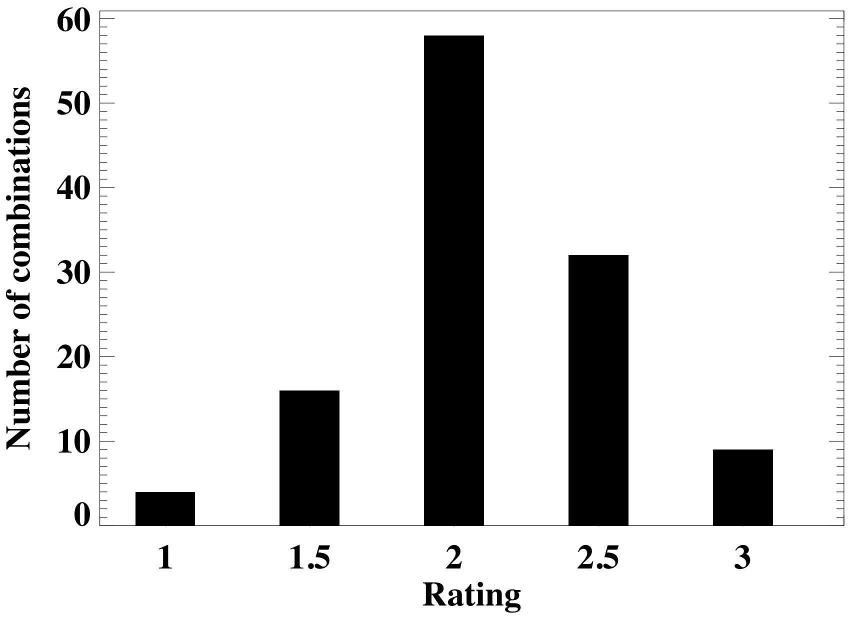
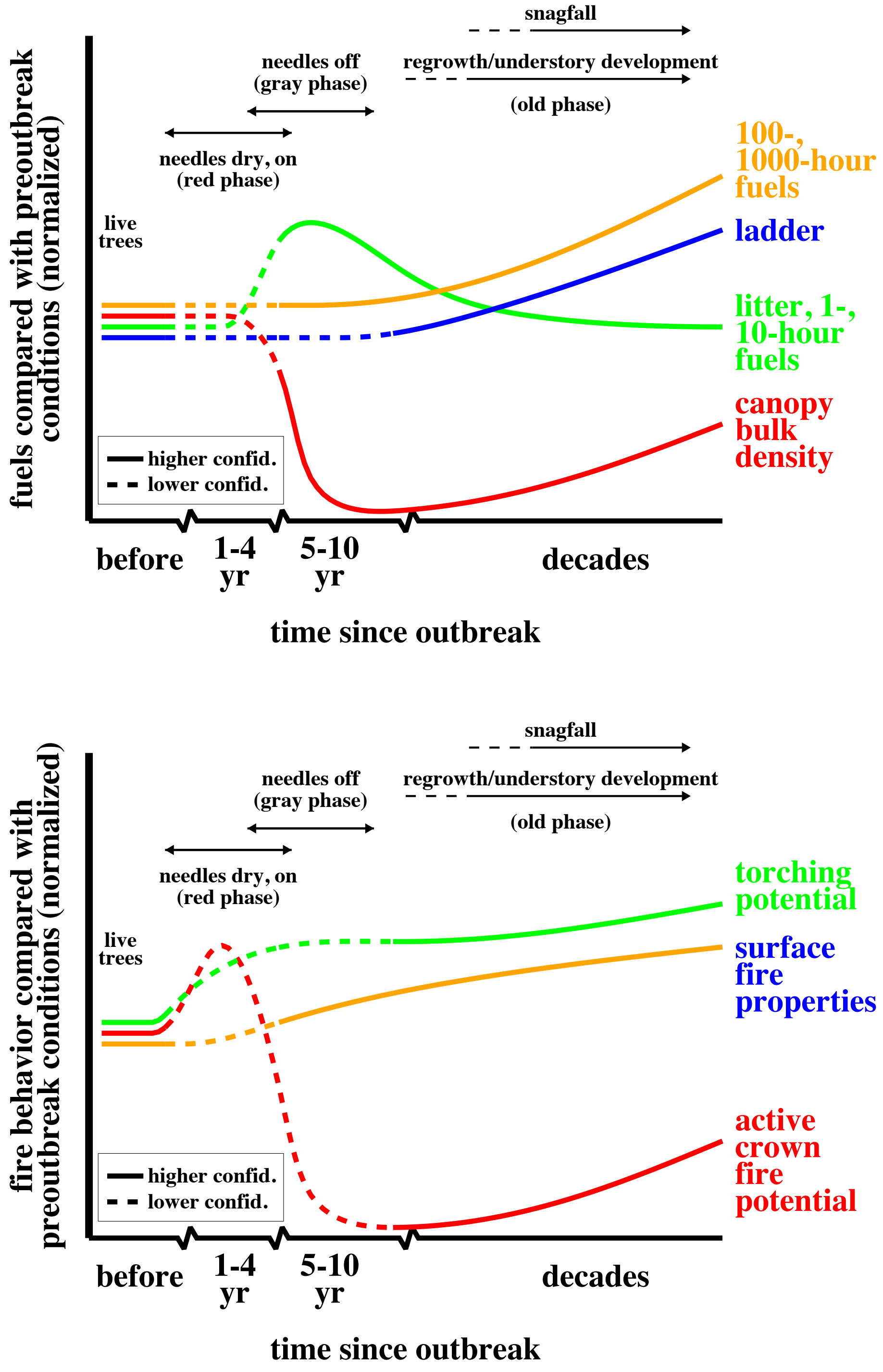


Figure 1. Distribution of fuels or fire characteristic/phase/study combination by study rating.



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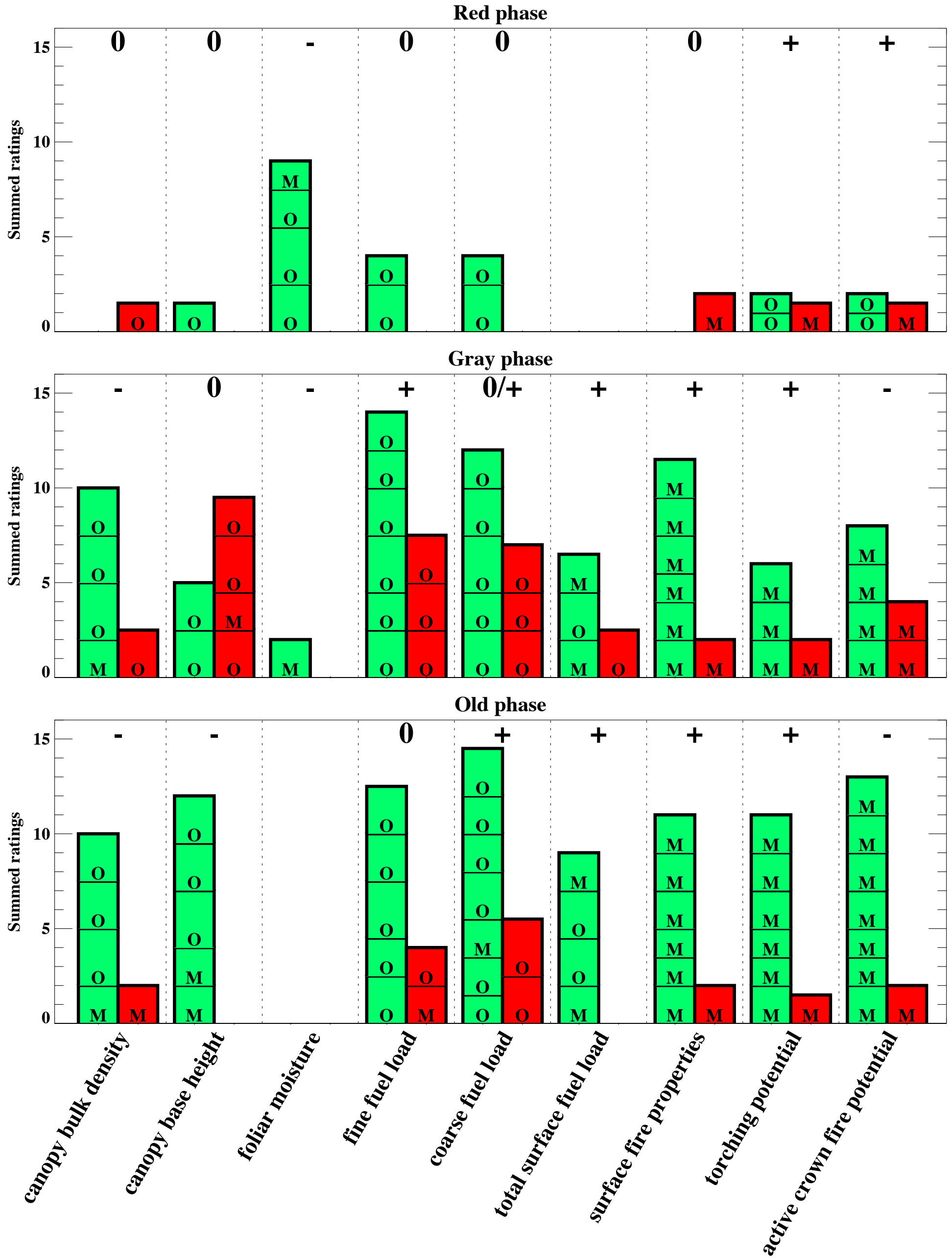

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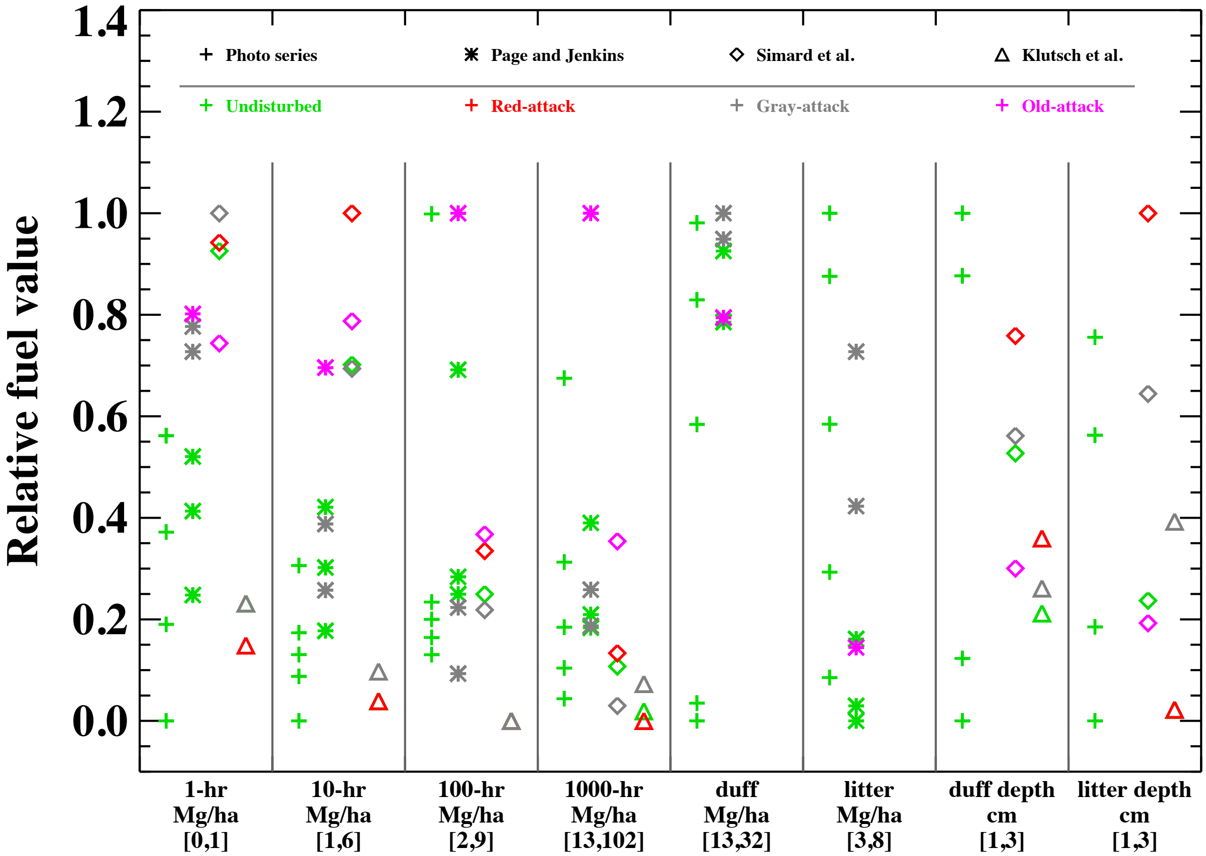

Figure 4. Relative fuel values in each fuel category in lodgepole pine stands from USDA Forest Service Natural Fuels Photo Series (Ottmar et al., 2000) (plusses, leftmost within each category) as well as mean values reported in publications included in this review that addressed bark beetle impacts (Page and Jenkins (2007b), asterisks; Simard et al. (2011), diamonds; Klutsch et al. (2009), triangles and rightmost within each category). Green symbols are for observations from undisturbed stands (from the Photo Series as well as reviewed studies), red symbols from red phase stands, gray symbols from gray phase stands, purple symbols from old phase stands. Values have been scaled so all categories fit on same y-axis; pairs of numbers below each category label on the x-axis indicate the minimum and maximum values used for scaling. In many cases, the range of undisturbed values (green symbols) is similar to or exceeds the range of beetle-attacked stands (red, gray, purple symbols).

Supplementary Information

S1. Cited publications that do not provide new evidence

The following studies discussed the potential effect of bark beetle-caused tree mortality on subsequent wildfire, but did not provide new observations, experiments, or model results to support any statements. Often these publications referenced other studies, described viewpoints, or discussed effects in the context of other conclusions of their studies.

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Table S1a. Summary of studies reviewed: Fuels measurements.

Study	**Fire characteristic**	**Location/forest type/insect**	**Mortality rate**	**Time since outbreak**	**Methods**	**Type of control**	**Conclusions**
Armour (1982)	surface fuels	Glacier National Park, MT/lodgepole pine/mountain pine beetle	61-96% for early postoutbreak stages; undetermined for 30, 80 years since outbreak classes	seven time period classes: control, 2-80 years since outbreak, climax	three plots per class of time since outbreak in each of two habitat types fuels measured along transects	paired plots	fuel dynamics following beetle outbreaks were functions of time since outbreak and habitat type
Cahill (1977)	fuels	Colorado/spruce/spruce beetle	unspecified	outbreak in 1939-1951; study carried out in 1972, 21-22 years postoutbreak (old phase)	standard stand inventory at 189 locations, including amount of dead material and snag characteristics	no control for relevant variables	beetle outbreak generated a large amount of dead wood and snags
Jolly et al. (in press)	foliage moisture and chemistry	Colorado and Montana/ lodgepole pine/mountain pine beetle	N/A (tree-level study)	within one year (includes red phase)	at several sites within study locations, measured foliar moisture and chemical content of needles from unattacked trees, recently attacked trees (but not yet red), and dead, red trees; time to ignition also measured	unattacked trees	reduced foliar moisture and altered chemical content of red needles decreased time to ignition
Lundquist (2007)	fuels of various sizes	Black Hills, SD/ponderosa pine and other species/bark beetles	unspecified, but focus of paper is on small-scale disturbances	unspecified	156 30 m x 30 m plots established (31 had bark beetles); fuels measured, disturbances noted path model identified relative importance of disturbances and strength of interactions	plots without beetles	beetles were only a minor disturbance compared with other disturbances
Schulz (1995)	fuel loading	Kenai Peninsula, AK/spruce/ spruce beetle	unspecified	uninfested, gray phase, old phase	identified 129 plots in the following stages of outbreak: uninfested, potential, ongoing, past, and 20 years postoutbreak fuels measured using Brown's transects	uninfested plots	fuel loads increased as time since outbreak progressed
Schulz (2003)	fuel loading	Kenai Peninsula, AK/spruce/ spruce beetle	author noted variability among sites but did not quantify	remeasurements occurred in 1999/2000, >10 years postoutbreak (gray phase, some snagfall)	remeasurement of 127 plots that were originally measured in 1987 prior to beetle outbreak	measurements before outbreak	fuel loads increased 10 years following outbreak

Table S1b. Summary of studies reviewed: Fuels measurements and fire behavior modeling.

Study	Fire characteristic	Location/forest type/insect	Mortality rate	Time since outbreak	Methods	Type of control	Conclusions
Clifford et al. (2008)	surface and ground fuels; fire behavior	New Mexico/pinyon pine/pinyon ips	relatively low (6%) and relatively high (25%) mortality sites	mortality in 2002; measurements in 2005; in gray phase when measured (needle retention was 0-9 months postattack)	Brown's transects measured in 105 field plots custom fuel models developed from average fuel loads in low and high mortality sites fire behavior modeled with NEXUS under range of weather scenarios	low mortality sites	in gray phase, greater potential for torching and reduced potential for active crown fire in high mortality sites
DeRose and Long (2009)	modeled fuels and fire behavior	Utah/Engelmann spruce/spruce beetle	simulated 0%, 50%, and 81-96% spruce mortality; spruce was 48-89% of stand basal area	0-100 years postoutbreak in 10-year time steps; first time step is gray phase second time step is old phase (based on increase in canopy bulk density)	measured stand and fuel characteristics at five study sites with some spruce beetle outbreak, identified fuel model(s) for each site that were then used in fire behavior modeling developed three beetle outbreak severity scenarios: a) low severity/preoutbreak, reconstructed from field measurements; b) mid-severity, reconstructed assuming 50% spruce mortality; c) high severity, specified with field measurements (81-96% spruce mortality by basal area, 39-86% stand mortality by basal area) used FVS-FFE to model future projections of fuel characteristics and fire behavior; considered 97th percentile fire weather case	"low-severity" (preoutbreak) scenario reconstructed from field data within outbreak sites	high amounts of tree mortality within a stand caused reduced potential for active crown fire potential for several decades
Gibson and Negron (2009)	fuels, modeled fire behavior	Colorado/lodgepole, ponderosa pine/mountain pine beetle, roundheaded beetle	unspecified	unspecified	for own/new results, reported field measurements within plots of fuel loadings, foliar moisture and modeled fire behavior with FVS-FFE and Behave	varied, from unspecified to comparisons with preoutbreak conditions to comparisons with live trees	beetle outbreaks modify fuel and fire behavior; changes are a function of time since outbreak
Jenkins et al. (2008)	fuels and fire behavior	Intermountain West/lodgepole pine, Douglas-fir, Engelmann spruce/Douglas-fir beetle, mountain pine beetle, spruce beetle	unspecified	epidemic (mixture of red and gray phase) and 20 years post-epidemic (old phase)	field measurements of fuels within endemic (little beetle activity), epidemic, and post-epidemic stands custom fuel models developed based on field observations for use in fire behavior modeling	endemic stands with minimal mortality	change in fuels and fire behavior results from beetle outbreaks, with effects different depending on time since outbreak

Study	Fire characteristic	Location/forest type/insect	Mortality rate	Time since outbreak	Methods	Type of control	Conclusions
Jorgensen (2010), Jorgensen and Jenkins (2011)	fuels, simulated fire behavior	Utah/spruce-fir/spruce beetle	61% (of all trees in stand)	various beetle condition classes: endemic, epidemic (<5 years), post-epidemic stages (>5 years)	measured fuels in two stands within each of beetle condition class used BehavePlus, FOFEM with custom fuel models to estimate fire behavior	preoutbreak stands with similar structural characteristics	fuels and fire behavior are modified by beetle outbreaks, and effects varied with time since outbreak
Klutsch et al. (2009; 2011)	surface and ground fuels; modeled fire behavior	Colorado/lodgepole pine/mountain pine beetle	6-100% of lodgepole pine	measurements 0-3 years (red phase) and 4-7 years postattack (gray phase); modeled fuels following 10% and 80% snagfall (here 80% is used as old phase); fire behavior modeling for gray, old phases	randomly selected 221 plot locations within lodgepole pine forest type; classified plots as uninfested, infested 0-3 years prior, or infested 4-7 years prior; measured stand and fuels characteristics; modeled snagfall, assessed impacts on fuels simulated fire behavior by creating custom fuel models based on measurements; used FFE-FVS to calculate canopy bulk density; ran FFE-FVS	uninfested plots	some fuels were modified following outbreak; torching potential was not different in infested plots; surface fire properties and active crown fire potential were greater
Page and Jenkins (2007a; 2007b)	fuels, modeled fire behavior	Utah, Idaho/lodgepole pine/mountain pine beetle	52-80% of lodgepole pine by number	epidemic (mixture of red and gray phases) and 20 years post-epidemic (old phase)	two study sites with current epidemics, one site with epidemic 20 years prior (post-epidemic) fuels measured in plots within two stands per site plus two control stands per site; custom fuel models developed for each sites BehavePlus used to model surface fire; used BehavePlus and FOFEM for simulating crown fire potential	endemic stands with minimal mortality	substantial change in fuels and fire behavior following beetle outbreaks, with effects dependent on time since outbreak
Simard et al. (2011)	fuels and modeled fire behavior	Greater Yellowstone Ecosystem/lodgepole pine/mountain pine beetle	38-82% by basal area	defined time-since-disturbance classes: undisturbed, 1-2 years (red phase), 3-5 years (gray phase), 8-18, 25, 35 years (old phase)	field measurements: two chronosequences, first measured in 2007, 25 sites, undisturbed to 36 years postdisturbance, all fuel components measured; second measured in 1981, 10 sites, undisturbed to 18 years postdisturbance air and ground temperature and relative humidity measured at three sites of each time-since-disturbance class stand-level fire behavior modeling performed with NEXUS	undisturbed stands	bark beetle outbreaks modify some fuels but not others; some aspects of fire behavior were altered and others were not

Table S1c. Summary of studies reviewed: Landscape modeling of fuels and fire behavior.

Study	**Fire characteristic**	**Location/forest type/insect**	**Mortality rate**	**Time since outbreak**	**Methods**	**Type of control**	**Conclusions**
Ager et al. (2007)	area with potential active crown fire behavior	Blue Mountains, OR/mix of species; host species (ponderosa and lodgepole pine) were 20-35% of study site by basal area	modeled 10% (in no-thin simulation) and 22% (in thin simulation) loss of stand volume	outbreak in 2030-2038 (peaking in 2038); output at 2040 = gray phase; at 2050 = old phase	simulated management scenarios within a 16,000-ha study area with and without thinning over 60 years, coupled with a mountain pine beetle outbreak (at 30 years) simulations performed with Forest Vegetation Simulator, Fire and Fuels Extension, and Westwide Pine Beetle Model	model simulations without beetle-caused tree mortality	beetle-caused tree mortality caused increased active crown fire potential; beetle effects on fire behavior were smaller than thinning effects
McMahan et al. (2008)	area with potential active crown fire behavior	Deschutes National Forest, OR/mixed conifer/mountain pine beetle	4-8% by basal area	six years postoutbreak, suggesting gray phase	simulated scenarios within a 70,000-ha study area with and without thinning and with and without 7-year mountain pine beetle outbreak simulations performed with Forest Vegetation Simulator, Fire and Fuels Extension, and Westwide Pine Beetle Model within ArcFuels	model simulations without beetle-caused tree mortality	beetle-caused tree mortality resulted in increased surface fuels and active crown fire potential

Table S1d. Summary of studies reviewed: Wildfire observations, including statistical analyses.

Study	Fire characteristic	Location/forest type/insect	Mortality rate	Time since outbreak	Methods	Type of control	Conclusions
Bebi et al. (2003)	fire occurrence	Colorado/spruce/spruce beetle	varied across study site; use presence or absence (>30% dead/down as threshold)	outbreak in 1940s, fires from 1948-1990 (3-50 years postoutbreak); mostly gray, old phases	visually classified aerial imagery from 1970s, 1980s within 2800 km^2 study area 303 fires from USFS fire atlas digitized, >95% <2.1 ha; fire density = #fires/(total area of a specific habitat type); spatial overlay analysis: compared observed fire density in attacked and unattacked areas (#/area with beetle-kill or without beetle-kill) with expected (#/(sum of attacked and unattacked areas)	unattacked areas	fire occurrence not more frequent in beetle-affected areas
Berg and Anderson (2006), Berg et al. (2006)	fire frequency	Kenai Peninsula, AK/white and Lutz spruce/spruce beetle	unspecified, but for one spruce beetle outbreak in 1870-1880s, 60% of surviving trees released with 17 or 23 sites showing evidence of major thinning	various/continuous (study period is several hundred years), thus includes all postoutbreak phases	Berg et al. estimated spruce beetle outbreak activity using dendrochronology at sites in 23 spruce forests Berg and Anderson used 121 radiocarbon-dated soil charcoal samples at 22 sites to estimate the regional fire history for the last 2500 years, compared this fire regime to spruce beetle regime of Berg et al.	very long temporal extent suggests control in time	multiple beetle outbreaks for each fire cycle; fire is not inevitable following bark beetle outbreaks
Bigler et al. (2005)	probability of burning at various fire severity levels within one fire	Colorado/spruce/spruce beetle	used presence/absence, defined as >30% dead/downed	outbreak in 1940s, fire in 2002; the 50-60 years postoutbreak suggests old phase	beetle outbreak locations identified with presence/absence from classification of aerial imagery within 26,000-ha study area forest type and structure/size from USFS RIS database. fire severity from dNBR, Landsat TM, divided into four severity classes. used overlay analysis, where observed area of one fire severity class compared with expected area used ordinal logistic regression model to relative important of explanatory variables (1800s fires, beetle outbreak, forest cover type, stand structure, topography)	unattacked locations	although less important than other variables, beetle-killed stands had a higher probability of burning than uninfested stands

Study	Fire characteristic	Location/forest type/insect	Mortality rate	Time since outbreak	Methods	Type of control	Conclusions
Bisrat (2010)	probability of fire occurrence	western conterminous US/four forest types (spruce/fir, lodgepole, ponderosa, Douglas-fir)/bark beetles	not included; presence or absence only at 100 m spatial resolution; 1000 m grid cells formed as % 100-m grid cells with presence	0-5 years, evaluated separately (red phase)	statistical analysis of fire activity in western US; response variable: 2000-2005 MODIS burned area; explanatory variables: 2000-2004 ADS bark beetle locations: used 1-km grid cell resolution also included climate, vegetation (forest type, NPP), and topography as potential explanatory variables analysis done first for all areas that experienced fire (and pseudoabsences) within each forest type, then done using only BB-affected areas within each forest type	areas without fire	bark beetle-caused tree mortality does not increase probability of fire occurrence compared with other drivers
Bond et al. (2009)	fire severity	Southern California/mixed conifer/western and mountain pine beetle	varied; used #dead trees/acres in 2003 from Aerial Detection Surveys (beetles or drought not differentiated, usually >1 tree killed per acre)	significant tree mortality in 2002-2003; fire in 2003 (1 year postoutbreak) (red phase)	studied 5860-ha wildfire; used 469 randomly sampled points from spatially explicit vegetation structural characteristics, topography, and prefire mortality (from Aerial Detection Surveys) as potential explanatory variables, and fire severity classes from Landsat RdNBR as response variable; assessed two statistical modeling methods, binomial and ranked-order logistic	locations with no prefire mortality	prefire mortality from beetles and drought does not affect fire severity
Gara et al. (1985)	fire spread	southcentral OR/lodgepole pine/mountain pine beetle	unspecified	decades (down logs) (old phase)	observations/field notes of several burned sites	none	in regions of low forest productivity, fires use beetle-killed logs for spread
Kulakowski and Veblen (2007)	severity and extent of 2002 fire	Colorado/spruce, lodgepole pine/spruce beetle and mountain pine beetle	varied across study area; used presence/absence of ADS polygons	beetle outbreaks in 1997-2002, although Figure 1 suggest most of the outbreak occurred in 2002; fire in 2002; thus stands in red phase	within 84,000-ha study area, used FS aerial and field surveys for salvage logging and ADS for insect outbreak locations used Landsat dNBR to map four burn severity classes used two classification trees to identify important explanatory variables (one for extent, one for severity); potential explanatory variables included previous disturbances (incl. beetles), forest type and cover, topography	none specifically to test the influence of beetles compared with undisturbed locations	beetle-caused mortality was not as important as other variables for explaining fire extent and severity

Study	Fire characteristic	Location/forest type/insect	Mortality rate	Time since outbreak	Methods	Type of control	Conclusions
Kulakowski et al. (2003)	presence/absence of fire	Colorado/spruce/spruce beetle	varied across study area	spruce beetle outbreak occurred in 1946-1949 (mode 1947), fire in 1950; stands were 1-4 years postattack (thus red or gray phases)	stand disturbance history reconstructed at 54 points within 4600-ha study area into 54 homogeneous patches with aerial photos; assessed severity of beetle outbreak by recording DBH, species, live/dead for all canopy trees within five 10m x 10m plots at 30-m intervals within each patch (500 m2 within each patch, or 0.18% of average patch). low-severity fire of 450 ha identified from tree cores used overlay analysis to assess whether fire more or less often than expected in beetle-affected patches. Because fire occurred at elevations <2985 m, overlay analysis conducted only at those elevations.	considered low, medium, high beetle-caused mortality classes	stands with high beetle-caused tree mortality less affected by low-severity fire than stands with low beetle-caused mortality
Kulakowski and Jarvis (2011)	occurrence of fires	Colorado, Wyoming/lodgepole pine/mountain pine beetle	not reported	various but unspecified	in 20 burned and 20 unburned stands, used dendroecological methods to determine previous MPB outbreaks; compared drought in fire versus prefire years as well	unburned stands and, for drought, prefire years	climate more important than beetles for fire frequency; no detectable increase of high-severity fire frequency following MPB outbreaks
Lynch et al. (2006)	presence/absence of burned area in 1988	Yellowstone National Park/lodgepole pine/mountain pine beetle	unspecified; used presence/absence from ADS	fire in 1988; two outbreaks, first in 1980-83 (fire was 5-8 years postoutbreak, likely gray phase); second in 1972-1975 (13-16 years postoutbreak, likely old phase)	studied outbreaks in Yellowstone National Park; beetle locations from digitized Aerial Detection Survey polygons climate interpolated from three met stations also considered topographic variables, vegetation type, previous fire history as potential explanatory variables fire from National Park Service multiple statistical analyses based on logistic regression	unattacked areas	slight increase in burn probability for areas of earlier outbreak (likely old phase); no significant increase in probability of burning for areas of later outbreak (likely gray phase)

Study	Fire characteristic	Location/forest type/insect	Mortality rate	Time since outbreak	Methods	Type of control	Conclusions
Pollet and Omi (2002)	severity	Yellowstone National Park/lodgepole pine/presumably mountain pine beetle	unspecified	unspecified	not given; anecdotal evidence	adjacent unburned area	beetle-killed trees lowered fire severity
Preisler et al. (2010)	fire size	Oregon, Washington/multiple forest types/multiple beetle species	various; used number of trees killed	various	beetle outbreaks in Washington and Oregon identified using 1 km x 1 km grid that summed number of trees killed within grid cells from Aerial Detection Surveys climate data (temperature, Palmer Drought Severity Index) from climate divisions fire location, date, and size from database produced by Desert Research Institute multinomial logistic regression analysis	unattacked locations as one of level of treatment	red phase areas had larger fires, and gray phase had no effect on fire size
Steele and Copple (2009)	surface fuel and fire behavior	N. US Rocky Mountains/ponderosa and lodgepole pine/mountain pine beetle	unspecified	red phase	personal observations of several fires in 2009	none	red phase increased likelihood of crown fire behavior
Stiger (2009)	fuels and fire behavior	N. US Rocky Mountains/ponderosa and lodgepole pine/unspecified bark beetle	unspecified	red phase	personal observations of several fires in 2009	none	fire behavior differences exist in between red phase lodgepole and ponderosa pine stands
Taylor et al. (2005)	burned area within outbreak areas	British Columbia/multiple forest types/multiple species	unspecified	various/continuous over 40-year study period, thus includes all postoutbreak phases	digital mapping of insect (4 beetles and 7 defoliators) and fire (>20ha) outbreaks in BC in 1960-2000 used presence/absence (not mortality rate) for insect outbreak information computed percent area burned of total area available for various times since outbreak	unattacked times/areas	time since disturbance influences burned area

Study	**Fire characteristic**	**Location/forest type/insect**	**Mortality rate**	**Time since outbreak**	**Methods**	**Type of control**	**Conclusions**
Turner et al. (1999)	burn severity	Yellowstone National Park/lodgepole pine/mountain pine beetle	varied: four classes from none (0%) to severe (>50%)	outbreak in 1969-mid 1980s, fire in 1988, thus 5-17 years since outbreak, suggesting gray to old phases	field plots established at 100 sampling points over 1 km x 1 km grid at three locations observations recorded annually 1-4 years post fire statistical relationships assessed using chi square analysis	uninfested plots	severe beetle damage increased likelihood of crown fire relative to other burn severity classes, but intermediate damage decreased likelihood of crown fire
West (2010)	fire occurrence	Colorado/lodgepole pine/mountain pine beetle	unspecified; used presence/absence from Aerial Detection Surveys	studied fires up to 25 years postoutbreak, thus includes all postoutbreak phases	beetle locations within two National Forests in 1980/1981-1987 from digitized Aerial Detection Survey polygons; buffered by 50 m fire locations (occurrence of ignition) 1935-2005 from USFS statistical analysis of fire frequency and ignitions within beetle-affected areas; also considered human influences, topography, drought	areas without beetles	mountain pine beetle outbreaks did not lead to increased fire frequency in the subsequent 25 years

Table S1e. Summary of studies reviewed: Experiments.

Study	**Fire characteristic**	**Location/forest type/insect**	**Mortality rate**	**Time since outbreak**	**Methods**	**Type of control**	**Conclusions**
Schroeder and Mooney (2009) and Government of Alberta (2009)	crown fire ignition, intensity, and rate of spread	Alberta/jack pine/simulated mountain pine beetle	>90%	trees girdled in 2007 Schroeder and Mooney: burns occurred in 2008 (trees still green) Government of Alberta: burns in 2009 (red phase)	six plots delineated (0.12-4.0 ha each) to simulate beetle attack, trees were girdled in the eastern half of each stand field measurements of fuels, fire behavior	one-half of each plot left untreated	foliar moisture was reduced following girdling, but the rapid crown fire development in both treated and control stands precluded conclusions about differences in crown fire behavior; more extreme crown fire behavior in red phase stands

Table S2. Summary of fuel or fire characteristic/stage/study combinations. An electronic version of this table is available upon request from the authors.

Fuel/fire characteristic	**Time since disturbance category**	**Expected change from undisturbed conditions based on conceptual framework**	**Study**	**Agree (A) or disagree (D) with conceptual framework**	**Study type (modeling or observations)**	**Publication type**	**Forest type**	**Fuel/ fire category**	**Rating**
canopy base height	gray phase	none	Clifford et al. 2008	D	observations	government publication	pinyon pine	canopy fuels	2.5
canopy base height	gray phase	none	DeRose and Long 2009	D	modeling	peer-reviewed journal article	spruce	canopy fuels	2
canopy base height	gray phase	none	Jorgensen 2010, Jorgensen and Jenkins 2011	D	observations	thesis	spruce	canopy fuels	3
canopy base height	gray phase	none	Klutsch et al. 2011	D	observations	peer-reviewed journal article	lodgepole pine	canopy fuels	2
canopy base height	gray phase	none	Page and Jenkins 2007b	A	observations	peer-reviewed journal article	lodgepole pine	canopy fuels	2.5
canopy base height	gray phase	none	Simard et al. 2011	A	observations	peer-reviewed journal article	lodgepole pine	canopy fuels	2.5
canopy base height	old phase	decrease	Ager et al. 2007	A	modeling	peer-reviewed journal article	mixed conifer	canopy fuels	2
canopy base height	old phase	decrease	DeRose and Long 2009	A	modeling	peer-reviewed journal article	spruce	canopy fuels	2
canopy base height	old phase	decrease	Jorgensen 2010, Jorgensen and Jenkins 2011	A	observations	thesis	spruce	canopy fuels	3
canopy base height	old phase	decrease	Page and Jenkins 2007b	A	observations	peer-reviewed journal article	lodgepole pine	canopy fuels	2.5
canopy base height	old phase	decrease	Simard et al. 2011	A	observations	peer-reviewed journal article	lodgepole pine	canopy fuels	2.5
canopy base height	red phase	none	Simard et al. 2011	A	observations	peer-reviewed journal article	lodgepole pine	canopy fuels	1.5
canopy bulk density	gray phase	decrease	DeRose and Long 2009	A	modeling	peer-reviewed journal article	spruce	canopy fuels	2

canopy bulk density	gray phase	decrease	Jorgensen 2010, Jorgensen and Jenkins 2011	A	observations	thesis	spruce	canopy fuels	3
canopy bulk density	gray phase	decrease	Klutsch et al. 2011	A	observations	peer-reviewed journal article	lodgepole pine	canopy fuels	2.5
canopy bulk density	gray phase	decrease	Page and Jenkins 2007b	D	observations	peer-reviewed journal article	lodgepole pine	canopy fuels	2.5
canopy bulk density	gray phase	decrease	Simard et al. 2011	A	observations	peer-reviewed journal article	lodgepole pine	canopy fuels	2.5
canopy bulk density	old phase	decrease	Ager et al. 2007	D	modeling	peer-reviewed journal article	mixed conifer	canopy fuels	2
canopy bulk density	old phase	decrease	DeRose and Long 2009	A	modeling	peer-reviewed journal article	spruce	canopy fuels	2
canopy bulk density	old phase	decrease	Jorgensen 2010, Jorgensen and Jenkins 2011	A	observations	thesis	spruce	canopy fuels	3
canopy bulk density	old phase	decrease	Page and Jenkins 2007b	A	observations	peer-reviewed journal article	lodgepole pine	canopy fuels	2.5
canopy bulk density	old phase	decrease	Simard et al. 2011	A	observations	peer-reviewed journal article	lodgepole pine	canopy fuels	2.5
canopy bulk density	red phase	none	Simard et al. 2011	D	observations	peer-reviewed journal article	lodgepole pine	canopy fuels	1.5
coarse fuel load	gray phase	none or increase	Armour 1982	A	observations	thesis	lodgepole pine	surface fuels	2.5
coarse fuel load	gray phase	none or increase	Jenkins et al. 2008	A	observations	peer-reviewed journal article	multiple	surface fuels	2
coarse fuel load	gray phase	none or increase	Jorgensen 2010, Jorgensen and Jenkins 2011	A	observations	thesis	spruce	surface fuels	3
coarse fuel load	gray phase	none or increase	Klutsch et al. 2009	D	observations	peer-reviewed journal article	lodgepole pine	surface fuels	2.5
coarse fuel load	gray phase	none or increase	Page and Jenkins 2007b	A	observations	peer-reviewed journal article	lodgepole pine	surface fuels	2.5
coarse fuel load	gray phase	none or increase	Schulz 1995	A	observations	government publication	spruce	surface fuels	2
coarse fuel load	gray phase	none or increase	Schulz 2003	D	observations	government publication	spruce	surface fuels	2
coarse fuel load	gray phase	none or increase	Simard et al. 2011	D	observations	peer-reviewed journal article	lodgepole pine	surface fuels	2.5
coarse fuel load	old phase	increase	Armour 1982	D	observations	thesis	lodgepole pine	surface fuels	2.5

coarse fuel load	old phase	increase	Cahill 1977	A	observations	government publication	spruce	surface fuels	1.5
coarse fuel load	old phase	increase	Jenkins et al. 2008	A	observations	peer-reviewed journal article	multiple	surface fuels	2
coarse fuel load	old phase	increase	Jorgensen 2010, Jorgensen and Jenkins 2011	D	observations	thesis	spruce	surface fuels	3
coarse fuel load	old phase	increase	Klutsch et al. 2009	A	modeling	peer-reviewed journal article	lodgepole pine	surface fuels	2
coarse fuel load	old phase	increase	Page and Jenkins 2007b	A	observations	peer-reviewed journal article	lodgepole pine	surface fuels	2.5
coarse fuel load	old phase	increase	Schulz 1995	A	observations	government publication	spruce	surface fuels	2
coarse fuel load	old phase	increase	Schulz 2003	A	observations	government publication	spruce	surface fuels	2
coarse fuel load	old phase	increase	Simard et al. 2011	A	observations	peer-reviewed journal article	lodgepole pine	surface fuels	2.5
coarse fuel load	red phase	none	Klutsch et al. 2009	A	observations	peer-reviewed journal article	lodgepole pine	surface fuels	2.5
coarse fuel load	red phase	none	Simard et al. 2011	A	observations	peer-reviewed journal article	lodgepole pine	surface fuels	1.5
fine fuel load	gray phase	increase	Armour 1982	D	observations	thesis	lodgepole pine	surface fuels	2.5
fine fuel load	gray phase	increase	Gibson and Negron 2009	A	observations	conference proceedings	unspecified	surface fuels	2.5
fine fuel load	gray phase	increase	Jenkins et al. 2008	A	observations	peer-reviewed journal article	multiple	surface fuels	2
fine fuel load	gray phase	increase	Jorgensen 2010, Jorgensen and Jenkins 2011	A	observations	thesis	spruce	surface fuels	3
fine fuel load	gray phase	increase	Klutsch et al. 2009	D	observations	peer-reviewed journal article	lodgepole pine	surface fuels	2.5
fine fuel load	gray phase	increase	Page and Jenkins 2007b	A	observations	peer-reviewed journal article	lodgepole pine	surface fuels	2.5
fine fuel load	gray phase	increase	Schulz 1995	A	observations	government publication	spruce	surface fuels	2
fine fuel load	gray phase	increase	Schulz 2003	A	observations	government publication	spruce	surface fuels	2
fine fuel load	gray phase	increase	Simard et al. 2011	D	observations	peer-reviewed journal article	lodgepole pine	surface fuels	2.5
fine fuel load	old phase	none	Armour 1982	A	observations	thesis	lodgepole pine	surface fuels	2.5

fine fuel load	old phase	none	Jenkins et al. 2008	A	observations	peer-reviewed journal article	multiple	surface fuels	2
fine fuel load	old phase	none	Jorgensen 2010, Jorgensen and Jenkins 2011	A	observations	thesis	spruce	surface fuels	3
fine fuel load	old phase	none	Klutsch et al. 2009	D	modeling	peer-reviewed journal article	lodgepole pine	surface fuels	2
fine fuel load	old phase	none	Page and Jenkins 2007b	A	observations	peer-reviewed journal article	lodgepole pine	surface fuels	2.5
fine fuel load	old phase	none	Schulz 2003	D	observations	government publication	spruce	surface fuels	2
fine fuel load	old phase	none	Simard et al. 2011	A	observations	peer-reviewed journal article	lodgepole pine	surface fuels	2.5
fine fuel load	red phase	none	Klutsch et al. 2009	A	observations	peer-reviewed journal article	lodgepole pine	surface fuels	2.5
fine fuel load	red phase	none	Simard et al. 2011	A	observations	peer-reviewed journal article	lodgepole pine	surface fuels	1.5
foliar moisture	gray phase	decrease	Simard et al. 2011	A	modeling	peer-reviewed journal article	lodgepole pine	canopy fuels	2
foliar moisture	red phase	decrease	Gibson and Negron 2009	A	observations	conference proceedings	lodgepole pine	canopy fuels	2.5
foliar moisture	red phase	decrease	Schroeder and Mooney 2009	A	observations	government publication	lodgepole pine	canopy fuels	2
foliar moisture	red phase	decrease	Jolly et al. in press	A	observations	peer-reviewed journal article	lodgepole pine	canopy fuels	3
foliar moisture	red phase	decrease	Simard et al. 2011	A	modeling	peer-reviewed journal article	lodgepole pine	canopy fuels	1.5
potential for active crown fire	gray phase	decrease	Ager et al. 2007	D	modeling	peer-reviewed journal article	mixed conifer	fire	2
potential for active crown fire	gray phase	decrease	Clifford et al. 2008	A	modeling	government publication	pinyon pine	fire	2
potential for active crown fire	gray phase	decrease	DeRose and Long 2009	A	modeling	peer-reviewed journal article	spruce	fire	2
potential for active crown fire	gray phase	decrease	Klutsch et al. 2011	A	modeling	peer-reviewed journal article	lodgepole pine	fire	2
potential for active crown fire	gray phase	decrease	McMahan et al. 2008	D	modeling	government publication	mixed conifer	fire	2

potential for active crown fire	gray phase	decrease	Simard et al. 2011	A	modeling	peer-reviewed journal article	lodgepole pine	fire	2
potential for active crown fire	old phase	decrease	Ager et al. 2007	D	modeling	peer-reviewed journal article	mixed conifer	fire	2
potential for active crown fire	old phase	decrease	DeRose and Long 2009	A	modeling	peer-reviewed journal article	spruce	fire	2
potential for active crown fire	old phase	decrease	Gibson and Negron 2009	A	modeling	conference proceedings	unspecified	fire	1.5
potential for active crown fire	old phase	decrease	Jenkins et al. 2008	A	modeling	peer-reviewed journal article	multiple	fire	1.5
potential for active crown fire	old phase	decrease	Jorgensen 2010	A	modeling	thesis	spruce	fire	2
potential for active crown fire	old phase	decrease	Klutsch et al. 2011	A	modeling	peer-reviewed journal article	lodgepole pine	fire	2
potential for active crown fire	old phase	decrease	Page and Jenkins 2007a	A	modeling	peer-reviewed journal article	lodgepole pine	fire	2
potential for active crown fire	old phase	decrease	Simard et al. 2011	A	modeling	peer-reviewed journal article	lodgepole pine	fire	2
potential for active crown fire	red phase	increase	Government of Alberta 2009	A	observations	informal report	lodgepole pine	fire	1
potential for active crown fire	red phase	increase	Simard et al. 2011	D	modeling	peer-reviewed journal article	lodgepole pine	fire	1.5
potential for active crown fire	red phase	increase	Steele and Copple 2009	A	observations	informal report	ponderosa and lodgepone pine	fire	1
surface fire intensity/ROS/flame length	gray phase	increase	Clifford et al. 2008	A	modeling	government report	pinyon pine	fire	2
surface fire intensity/ROS/flame length	gray phase	increase	DeRose and Long 2009	A	modeling	peer-reviewed journal article	spruce	fire	2

surface fire intensity/ROS/flame length	gray phase	increase	Jenkins et al. 2008	A	modeling	peer-reviewed journal article	multiple	fire	1.5
surface fire intensity/ROS/flame length	gray phase	increase	Jorgensen 2010	A	modeling	thesis	spruce	fire	2
surface fire intensity/ROS/flame length	gray phase	increase	Klutsch et al. 2011	A	modeling	peer-reviewed journal article	lodgepole pine	fire	2
surface fire intensity/ROS/flame length	gray phase	increase	Page and Jenkins 2007a	A	modeling	peer-reviewed journal article	lodgepole pine	fire	2
surface fire intensity/ROS/flame length	gray phase	increase	Simard et al. 2011	D	modeling	peer-reviewed journal article	lodgepole pine	fire	2
surface fire intensity/ROS/flame length	old phase	increase	DeRose and Long 2009	A	modeling	peer-reviewed journal article	spruce	fire	2
surface fire intensity/ROS/flame length	old phase	increase	Gibson and Negron 2009	A	modeling	conference proceedings	unspecified	fire	1.5
surface fire intensity/ROS/flame length	old phase	increase	Jenkins et al. 2008	A	modeling	peer-reviewed journal article	multiple	fire	1.5
surface fire intensity/ROS/flame length	old phase	increase	Jorgensen 2010	A	modeling	thesis	spruce	fire	2
surface fire intensity/ROS/flame length	old phase	increase	Klutsch et al. 2011	A	modeling	peer-reviewed journal article	lodgepole pine	fire	2
surface fire intensity/ROS/flame length	old phase	increase	Page and Jenkins 2007a	A	modeling	peer-reviewed journal article	lodgepole pine	fire	2

surface fire intensity/ROS/flame length	old phase	increase	Simard et al. 2011	D	modeling	peer-reviewed journal article	lodgepole pine	fire	2
surface fire intensity/ROS/flame length	red phase	none	Simard et al. 2011	D	modeling	peer-reviewed journal article	lodgepole pine	fire	2
torching potential	gray phase	increase	Clifford et al. 2008	A	modeling	government report	pinyon pine	fire	2
torching potential	gray phase	increase	DeRose and Long 2009	A	modeling	peer-reviewed journal article	spruce	fire	2
torching potential	gray phase	increase	Klutsch et al. 2011	D	modeling	peer-reviewed journal article	lodgepole pine	fire	2
torching potential	gray phase	increase	Simard et al. 2011	A	modeling	peer-reviewed journal article	lodgepole pine	fire	2
torching potential	old phase	increase	DeRose and Long 2009	A	modeling	peer-reviewed journal article	spruce	fire	2
torching potential	old phase	increase	Gibson and Negron 2009	A	modeling	conference proceedings	unspecified	fire	1.5
torching potential	old phase	increase	Jenkins et al. 2008	A	modeling	peer-reviewed journal article	multiple	fire	1.5
torching potential	old phase	increase	Jorgensen 2010	A	modeling	thesis	spruce	fire	2
torching potential	old phase	increase	Klutsch et al. 2011	D	modeling	peer-reviewed journal article	lodgepole pine	fire	1.5
torching potential	old phase	increase	Page and Jenkins 2007a	A	modeling	peer-reviewed journal article	lodgepole pine	fire	2
torching potential	old phase	increase	Simard et al. 2011	A	modeling	peer-reviewed journal article	lodgepole pine	fire	2
torching potential	red phase	increase	Government of Alberta 2009	A	observations	informal report	lodgepole pine	fire	1
torching potential	red phase	increase	Simard et al. 2011	D	modeling	peer-reviewed journal article	lodgepole pine	fire	1.5
torching potential	red phase	increase	Steele and Copple 2009	A	observations	informal report	ponderosa and lodgepone pine	fire	1
total surface fuel load	gray phase	increase	Ager et al. 2007	A	modeling	peer-reviewed journal article	mixed conifer	surface fuels	2
total surface fuel load	gray phase	increase	Armour 1982	D	observations	thesis	lodgepole pine	surface fuels	2.5
total surface fuel load	gray phase	increase	Clifford et al. 2008	A	observations	government report	pinyon pine	surface fuels	2.5
total surface fuel load	gray phase	increase	McMahan et al. 2008	A	modeling	government report	mixed conifer	surface fuels	2

total surface fuel load	old phase	increase	Ager et al. 2007	A	modeling	peer-reviewed journal article	mixed conifer	surface fuels	2
total surface fuel load	old phase	increase	Armour 1982	A	observations	thesis	lodgepole pine	surface fuels	2.5
total surface fuel load	old phase	increase	Gibson and Negron 2009	A	observations	conference proceedings	ponderosa pine	surface fuels	2.5
total surface fuel load	old phase	increase	Gibson and Negron 2009	A	modeling	conference proceedings	lodgepole pine	surface fuels	2

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