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Review

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.

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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

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	• Energy release by fire
	• Rate of spread	• Rate of advance of fire front
	• Flame length	• 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	• Inclusion of control in space or time • Consideration of all explanatory variables
	• Use of aerial detection surveys	• 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

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 $4 \times 2 = 8$, 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,b; 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 (Fig. 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 (Fig. 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 (Fig. 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 (Fig. 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 (Fig. 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.

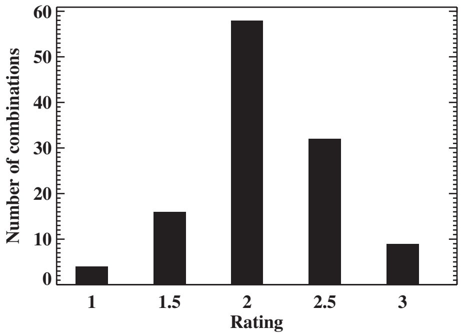

Fig. 1. Distribution of fuels or fire characteristic/phase/study combination by study rating.

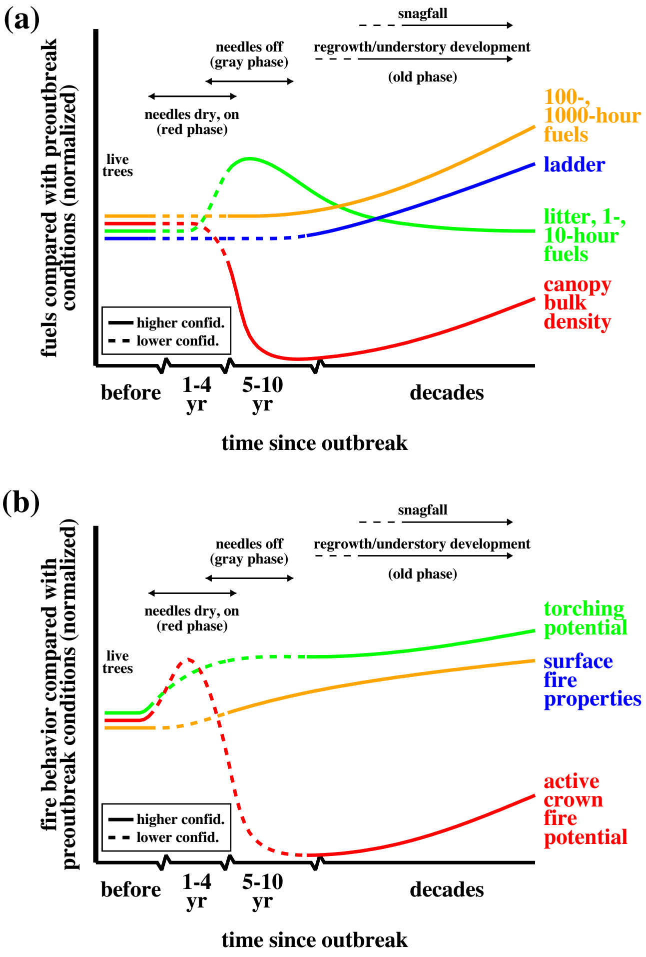

Fig. 2. Conceptual framework of (a) fuels characteristics and (b) fire behavior relative to preoutbreak conditions for red, gray, and old (snagfall and regrowth) phases. Surface fire properties include reaction intensity, rate of spread, and flame length. For postoutbreak phases, solid lines indicate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

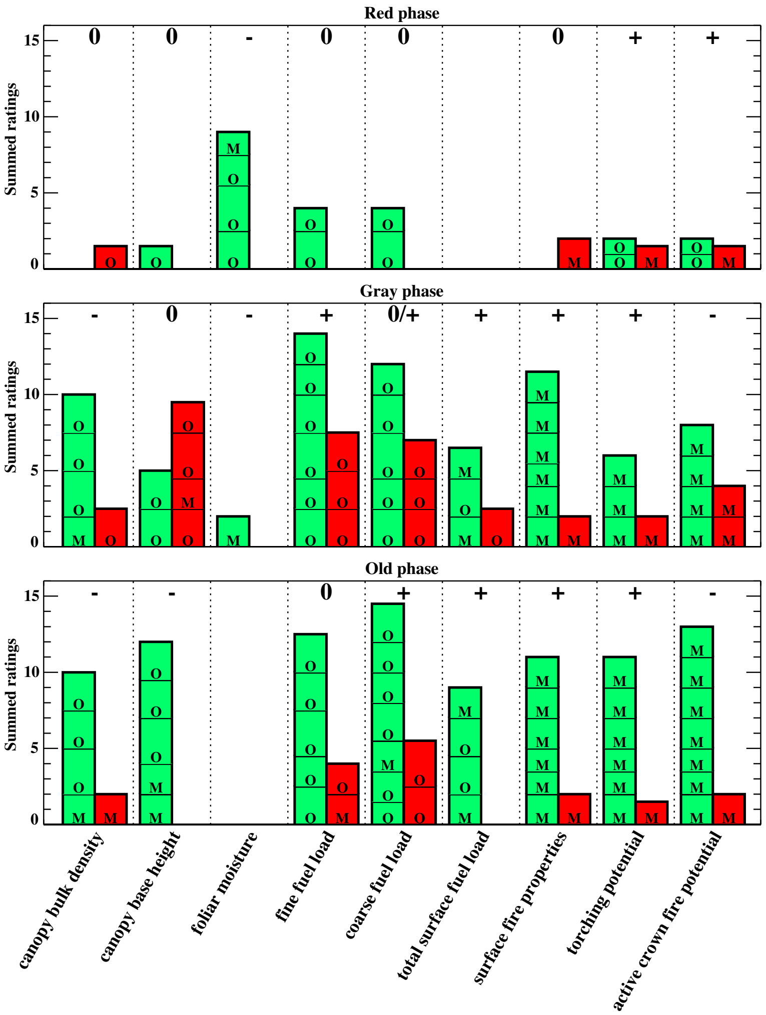

Fig. 3. Level of agreement (green bars) or disagreement (red bars) with conceptual framework (Fig. 2) by fuel/fire characteristic and postoutbreak phase. Bar heights illustrate strength of agreement or disagreement and result from the number of individual studies (boxes) and each study/characteristic/phase 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 Fig. 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.

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 Fig. 3). The majority of disagreement in the combinations displayed in Fig. 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 values1–3 may have minimized the effect of these ratings on the summed values (bar heights in Fig. 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 Fig. 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 Fig. 3. Most combinations were rated "M" (2 in the original numeric rating), and fewer were rated "L" or "H" (Fig. 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 (Fig. 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 (Fig. 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; 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). A 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

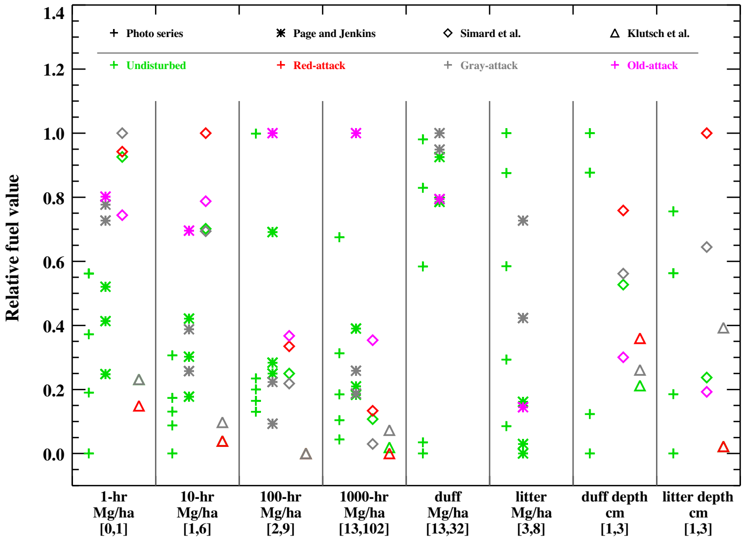

Fig. 4. Relative fuel values in each fuel category in lodgepole pine stands from USDA Forest Service Natural Fuels Photo Series (Ottmar et al., 2000) (plusses, leftmost within each category) as well as mean values reported in publications included in this review that addressed bark beetle impacts (Page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

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 (Fig. 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 (*Pinus edulis* and *Pinus 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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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.foreco.2012.02.005.

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