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The Once and Future Forest: Consequences of Mountain Pine Beetle Treatment Decisions

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Entomologists and silviculturists have long recommended management of stand basal area and/or mean tree diameter to mitigate the risk of mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins) outbreaks while simultaneously reducing wildfire risk. In recent decades, however, wildfire suppression and reduced harvests in western North America have created a forest landscape that is densely stocked and increasingly susceptible to bark beetle infestations, especially as the climate becomes warmer and drier. We examine the various MPB treatment options available to land managers, including insecticides, semiochemicals, sanitation, and silvicultural treatments, and describe their long-term consequences in terms of risk of future bark beetle outbreaks, wildfire, invasion by exotic weeds, loss of hydrologic values, and carbon sequestration. Paradoxically, the treatments that are most enduring and best preserve the ecosystem services of North American forests are ones that result in some thinning of these stands. We, therefore, propose a renewed focus on silvicultural treatments over large spatial scales, particularly in lodgepole pine (*Pinus contorta* Douglas ex Loudon), and recommend semiochemical treatments, which may not protect all trees, for the protection of high-value trees, especially for high-elevation pines that grow in smaller stands. Prophylactic insecticide applications should be reserved for situations where any tree mortality at all is unacceptable.

Keywords: adaptive management, *Dendroctonus*, insecticides, semiochemicals, thinning

> *Where certain insects play a dominant role in…silvics, the answer to silvicultural problems can be found by studying the natural systems which the insects apply. To paraphrase Solomon's advice, "Go to the ant, thou sluggard; consider her ways, and be wise." My advice to the silviculturist is to study the insects and learn of their ways.*
>
> F.P. Keen (1950)

Forestland managers have at their disposal an abundance of treatment tactics for mitigating tree mortality caused by MPB as well as other bark beetle species. These tactics include direct control treatments to reduce beetle populations and indirect control treatments intended to reduce tree or stand susceptibility to beetle infestation (*sensu* Wood et al. 1985), but all treatments present significant costs. The efficacy of these treatment options varies widely, with some offering nearly complete tree protection, for example, insecticide applications to the bole, and others, such as silvicultural thinnings, mitigating but not eliminating tree mortality. Resource managers are, therefore, faced with difficult choices. Depending on the extent of tree or stand protection, a potentially unintended consequence of any treatment choice is the species composition and structure of the postoutbreak residual stand, which will in turn follow different trajectories depending on the pattern and extent of tree mortality. For example, treatments that expose large surface areas of disturbed soil may promote the establishment and/or expansion of invasive weeds (McEvoy et al. 1993, D'Antonio and Meyerson 2002, Sutherland and Nelson 2010, Birdsall et al. 2012). Additionally, the failure to harvest-beetle-killed trees after severe outbreaks may compromise the hydrologic value of the residual stand as regeneration progresses by shifting stand species composition from primarily lodgepole pine (*Pinus contorta* Douglas ex Loudon) and aspen (*Populus tremuloides* Michx.), which have relatively low rates of canopy evapotranspiration, to subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), which has much higher rates of evapotranspiration (Alexander et al. 1990, Collins et al. 2011). Collins et al. (2011) concluded that, although mature subalpine fir-dominated stands are currently not common, untreated beetle-killed lodgepole stands will likely have, in the absence of wildfire, far more subalpine fir and other shade-tolerant species over a wide geographical area in Colorado, Wyoming, and British Columbia.

MPB treatment decisions can also affect the trajectory of hydrologic impacts of MPB outbreaks. The loss of forest canopy associated with MPB-induced tree mortality, especially in widespread lodgepole pine stands, can affect both water quantity (Potts 1984,

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Mikkelson et al. 2011) and water quality (Mikkelson et al. 2013). Effects on water quantity include canopy interception of precipitation and solar radiation, accumulation of snow, timing and rate of snowmelt and sublimation, soil infiltration, and evapotranspiration (Mikkelson et al. 2011). Modeling of the effects of MPB infestation indicated a decrease in evapotranspiration, increase in snowpack, and earlier and faster snowmelt and greater runoff volume, leading to higher risk of spring flooding and drought stress (Mikkelson et al. 2011). Likewise, large-scale tree mortality associated with MPB infestation resulted in adverse impacts on water quality, with higher total organic carbon concentrations and significantly more water disinfection by-products in MPB-infested source waters (Mikkelson et al. 2013). To the degree that MPB treatments mitigate these effects on water quantity and quality, they can help protect valuable water resources.

Kashian et al. (2011) found that the spatial patterns of MPB infestations in lodgepole pine are consistent across outbreak severities, with large-diameter trees (20–35 cm) and adjacent smaller trees most likely to be attacked and killed, altering stand structure and reducing susceptibility to future outbreaks. Klutsch et al. (2009) reported vast differences in the stand structure of beetle-infested versus uninfested lodgepole pine stands because of selective attack by MPB of larger-diameter trees. Similarly, Progar (2005) found that two consecutive years of antiaggregation pheromone (verbenone) treatments resulted in significantly different stand conditions in the treated lodgepole pine plots versus the untreated control plots because MPB had killed most of the susceptible large-diameter trees in the untreated stands. The choice of treatments, or even the choice not to treat, therefore, has consequences for many forest attributes that should be considered during the decisionmaking process.

Previous reviews (Wood et al. 1985, Whitehead et al. 2006, Fettig et al. 2007, 2014) provide excellent coverage of treatment options in various forest types, with an emphasis on indirect (or preventive) MPB treatment measures directed toward improving overall forest health. There is also a large body of knowledge regarding direct control treatment options (summarized in Wood et al. 1985 and Carroll et al. 2006), including cultural and mechanical techniques (killing beetles before they emerge by brood tree removal, debarking, or other methods), insecticides, and semiochemicals (both aggregation and antiaggregation semiochemicals, including pheromones, host volatiles, and nonhost volatiles). Newer and more effective semiochemical treatments for mitigation of MPB-caused damage (which includes both sublethal effects and MPB-caused tree mortality) are described elsewhere (Gillette and Munson 2009, Progar et al. 2014) and these reviews provide managers with additional options.

Managers make treatment decisions cognizant of the longer-term sustainability of the residual stand in terms of resilience to wildfire, future bark beetle infestations, forest hydrology (erosion, water quality, and water quantity), stand susceptibility to pathogens and invasive weeds, and carbon sequestration (Cheng 2010, Collins et al. 2011, Kashian et al. 2011). In addition, it must be recognized that there is a need for forest restoration treatments in recreation areas such as campgrounds, ski areas, and administrative sites so that these areas will meet long-term vegetation sustainability objectives. There are, of course, effects of treatments on other resource attributes, such as fisheries and terrestrial wildlife habitat, but those effects are beyond the scope of this review. However, decisions are often driven primarily by costs or regulatory concerns. Furthermore, public opinion can be a tacit but important factor influencing treatment decisions (Wellstead et al. 2006). In the recent past, public opposition to the extraction of wood products from publicly owned forests has limited the degree of harvesting conducted in much of the western United States (Jones and Taylor 2005). In the absence of wildfire or prescribed fire, the consequence is a vast region of densely stocked forests that are increasingly susceptible to both wildfire and bark beetle outbreaks because of resulting changes in stand structure. Our focus in this review is primarily on lodgepole pine, the most widespread host of MPB, but we reference MPB in other hosts where relevant.

Research has indicated that the public is much more supportive of direct control measures than they are of proactive, indirect control tactics that may have more enduring positive outcomes for stand health (McFarlane et al. 2006). Here, we describe the range of potential outcomes that may be expected from various treatment tactics, with the intent of encouraging a decision process that focuses on long-term consequences and multiple outcomes. It is axiomatic that past fire suppression efforts in some forests have exacerbated the severity of bark beetle outbreaks by creating dense and even-aged stand conditions that increase tree susceptibility to bark beetle infestation (Weaver 1943, Wood et al. 1985, Hessburg et al. 1994, McCullough et al. 1998, Keane et al. 2002, Simard et al. 2011). Climate change is expected to exacerbate these conditions (Kurz et al. 2008, Bentz et al. 2010, Preisler et al. 2012, Fettig et al. 2013c), suggesting that thinning of stands by prescribed fire, beetles, or both, may benefit our forests if it reduces the susceptibility of residual stands to future bark beetle outbreaks and catastrophic wildfire. Certainly increasing stand structural and species diversity may help mitigate the more catastrophic effects of climate change on western North American forests, in particular the effects on insect populations (Fettig et al. 2013c). Indeed, Kashian et al. (2011) provided evidence that moderate- to high-level MPB outbreaks (32–44% tree mortality per year over a 3-year period) increase the resilience of lodgepole pine stands to beetle infestation by reducing the susceptibility of forests to future MPB-caused mortality. Collectively, this evidence suggests that some beetle-caused tree mortality may be a positive outcome because it can lower the risk of future outbreaks. While thinning can reduce susceptibility of stands to future MPB outbreaks, down woody fuel loads resulting from beetle kill should be treated to avoid wildfire risk, and thinning of stands by humans followed by appropriate slash reduction treatments may improve forest health and reduce wildfire risk (Jenkins et al. 2008, 2014, Stark et al. 2013).

Management Options and Residual Stand Structures

Mitigation of MPB-caused tree mortality can be accomplished either by reducing beetle populations or by increasing tree or stand resistance to beetle infestation (Whitehead et al. 2006). Accomplishment of the former has been attempted using various techniques such as brood tree removal and debarking, insecticide treatments, and semiochemical manipulations, whereas the latter is accomplished using a range of silvicultural manipulations of stand structure. Wood et al. (1985) distinguished these two approaches as direct (targeting beetle populations) versus indirect (targeting stand conditions) control (Figure 1; Table 1), and we maintain this distinction throughout the following discussion. The following is a brief summary of the approaches and the pattern and degree of protection they provide, as well as the implications for the residual

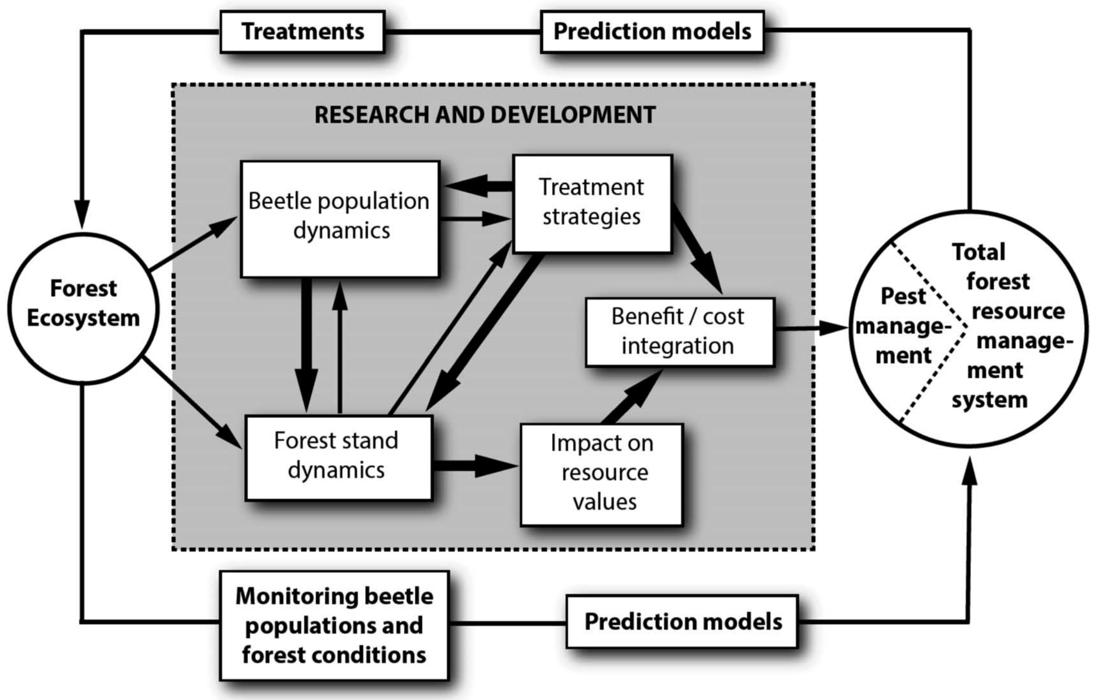

Figure 1. Generalized model of bark beetle management showing relationships (indicated by arrows) between components. Heavier arrows indicate direction of information flow for planning and decisions. Lighter arrows indicate feedback information flow to improve the efficacy and lower the cost of the treatment. Predictive models enable forest resource managers to forecast conditions. Monitoring provides the database for successive phases of pest management and input to the predictive models. Figure modified and redrawn from Stark and Waters (1985).

Table 1. Summary of direct and indirect treatment options for managing mountain pine beetles.

Management option	Area treated	Expected effectiveness	Length of effectiveness	Relative cost of treatments ($)	Future susceptibility of treated area to MPB*	References
Direct						
Insecticides	Single tree to small groups of trees	Very high	1–2 yrs	High	Increased, without repeated use of insecticides	Hastings et al. (2001), Fettig et al. (2006a, 2006b, 2013a, 2013b, 2013c)
Sanitation[a]	Usually < 100 ha	Can be high if implemented properly	1–2 yrs	Very high but some costs recouped	Increased, but variable depending on extent of MPB-caused mortality	Klein (1978), Negrón et al. (2001), Carroll et al. (2006), Wulder (2009)
Semiochemicals	Single tree to entire stands	Medium	1–2 yrs	Medium to high	Increased, but variable depending on extent of MPB-caused mortality	Bordon et al. (2006, 2007), Gillette et al. (2006, 2009, 2012a, 2012b), Progar et al. (2014)
Indirect						
Thinning from below	Small groups of trees to entire stands	High if residual stand is not too densely stocked	20 yrs	High, but some costs recouped	Decreased	Sartwell and Stevens (1975), Lang et al. (1978), Dahlsten and Rowney (1983), Mitchell et al. (1983), Fettig et al. (2007)
Crown thinning	Small groups of trees to entire stands	High if residual stand is not too densely stocked	30 yrs	High, but some costs recouped	Decreased	Ibid.
Selection thinning	Small groups of trees to entire stands	High if residual stand is not too densely stocked	20–30 yrs, but highly variable		Decreased	Ibid.
No action	NA	–	–	Very low	Variable and dependent on MPB populations, weather, and initial stand structure	Ibid.

[a]Treatments that kill the beetles after they have attacked the trees. These treatments include insolation, debarking, brood tree removal, etc.

stands. Factors beyond the treatments applied, such as the beetle population phase (endemic or epidemic) (Bentz et al. 1993), weather patterns, and the spatial character of beetle populations and stand conditions (Bentz et al. 1993, Negrón et al. 2001a, Withrow et al. 2013), will naturally affect the residual structure and composition of postoutbreak stands. These factors notwithstanding, different treatments will create different residual stands. Some treatments may result in more or less evenly spaced thinning of stands, whereas others may be more likely to yield a patchwork mosaic of openings and stands of varying ages or species depending on implementation (summarized in Table 1).

Direct Control

Several types of direct control have been tested for MPB mitigation, including insecticides, cultural methods, semiochemicals, and combinations thereof.

Insecticides

Insecticides may be a desirable option for preserving select, high-value trees for aesthetic or other purposes, especially those located in residential or administrative sites. While insecticides usually provide the most immediate and complete control of all pest management options, they have some clear drawbacks for use on public lands because of potential human and other nontarget toxicity. Application of insecticides, furthermore, requires good access for vehicles because of the equipment required for bole applications. In the past, chlorinated hydrocarbon and organophosphate formulations (Smith 1970, McCambridge 1982) were used both as bark surface treatments and as systemic insecticides that would penetrate the bark, killing the insects inside felled or standing trees. These have given way to newer, more environmentally acceptable pyrethroid and carbamate insecticides that are registered only as prophylactic treatments to prevent bark beetles from killing the trees (Gibson and Bennett 1985, Haverty et al. 1998, Fettig et al. 2006a, 2006b, 2008, 2013a, 2013b). Recently, a reduced risk pesticide, cyantraniliprole, has also shown promise in laboratory testing (Fettig et al. 2011). In addition, fall injections of emamectin benzoate have shown promise for protecting lodgepole pine from MPB (Fettig et al. 2013a). Until recently only carbaryl has provided protection in field tests for more than a single year, but its continued registration label for tree protection is in question (Hastings et al. 2001, Nancy Gillette, USDA Forest Service, Pacific Southwest Research Station, pers. comm., June 19, 2013). However, Fettig et al. (2013b) have recently demonstrated that a combination of emamectin benzoate and propiconazole may provide 2 years of protection. Frequent applications are, therefore, required to maintain the level of tree protection desired for high-value trees. However, land managers and home owners should be aware that the same trees will be at risk again in future bark beetle outbreaks, and the risk will increase as the trees age. Because of the high cost, the need for recurring treatments, and the lack of sustained risk reduction, treatment over large areas may be considered undesirable or impractical.

Sanitation

In this discussion, we use the term “sanitation” in the pest management sense rather than in the forestry sense, i.e., reduction of risk by removing insects from the infested area, in this case the forest stand. The forestry term “sanitation salvage” is frequently misunderstood because it is presumed to result in removal of beetles from the infested stands, but in fact by the time these treatments are conducted the beetle populations have usually already left the infested trees. While sanitation salvage does result in capture of economic benefits because merchantable timber is harvested, it does not necessarily reduce beetle populations. Salvage of beetle-killed trees should, therefore, not be confused with true sanitation methods that remove beetles from the stand. A number of such sanitation approaches are currently used to kill MPBs in place or remove them from the affected areas. Properly implemented, sanitation methods can reduce levels of infestation in residual trees (Coggins et al. 2011, N.E.G. et al. unpubl. data), but the efficacy of some methods in reducing tree mortality remains to be tested. In addition, implementing these tactics comes at a very high cost because they are very laborious, require repeated entries, and often require special equipment and vehicle access. Moreover, sanitation is often challenging to implement because it may be almost impossible, even for trained personnel, to identify all the infested trees before brood beetles emerge and attack other trees (Wulder et al. 2006, 2009, Coggins et al. 2011). Even a few missed trees will provide a source of beetles to infest new trees, seriously compromising the control efforts (Coggins et al. 2011). Furthermore, it can be logistically impossible to remove all infested trees before beetle emergence because the process is very time consuming and the seasonal window for this operation is limited to a few weeks in the fall of the year of beetle infestation and early spring of the following year.

The most promising approach to sanitation, brood tree removal, requires identifying infested trees, then felling them and removing them from the site or incinerating them prior to beetle emergence. This method has been experimentally demonstrated to reduce MPB infestations in the residual stands (Coggins et al. 2011, N.E.G. et al. unpubl. data) but must be conducted annually over multiple years when MPB populations are increasing. Adequate road access to the site is needed for this method to be effective, and the treated area should be spatially isolated from other sources of MPB infestation. The removed trees can be used commercially if there is sufficient local infrastructure to process the timber, but there remains the problem of removing or killing beetles before they emerge from the infested timber. Another approach, which can be effective in killing beetles but has not been experimentally shown to reduce subsequent MPB infestations in residual stands, is mechanically debarking felled or standing trees (Klein 1978, Whitney et al. 1978). This approach exposes the beetles to lethal desiccation and predation, but it has, in practice, encountered methodological obstacles (Carroll et al. 2006). The use of solar radiation has also been shown to effectively kill beetles in felled trees (Colorado State Forest Service 2009, Negrón et al. 2001b), but as with debarking infested trees, it is extremely labor intensive and has yet to be tested for reducing subsequent levels of tree mortality. It can be of use when road access is lacking, harvesting the trees for utilization is costly, or both. With this technique it is essential to maintain sufficient heat, which can be accomplished using various techniques (Negrón et al. 2001b). All of these sanitation methods are expensive and logistically difficult, which limits their application to small areas. Sanitation approaches are most effective in slowing the course of an MPB outbreak when at least half the infested trees in the stand are treated (Wulder et al. 2009, Coggins et al. 2011). Depending on the intensity of the outbreak, then, beetle-caused mortality may have reduced the proportion of susceptible host trees in the stand, making the residual stand less susceptible to subsequent outbreaks.

Semiochemical Methods

A wide range of semiochemical tactics has been developed, including single-tree protection using high release formulations; small plot treatments using similar formulations; and large-area treatments using lower-rate, dispersible formulations (summarized in Progar et al. 2014). Most of the research was conducted on lodgepole pines, but recent results from other MPB host species has shown that the lodgepole pine results are generally relevant for other MPB host species such as whitebark (*Pinus albicaulis* Engelm.) and limber (*Pinus flexilis* James) pines (Gillette et al. 2012a, 2012b, 2014). Trap tree, concentration and containment, and push-pull (peripheral antiattractant releasers combined with attractant-baited traps or trees) tactics using semiochemicals have also been used, with varying degrees of success (Borden et al. 1983a, 1983b, 2006, 2007, Vandygriff et al. 2000, Gillette et al. 2012b). In general, the efficacy of these methods is intermediate between insecticides and sanitation since in many cases the treatments do not provide complete protection and the residual stands are, therefore, modified by beetle-caused mortality, primarily through the mortality of larger-diameter trees and the creation of small openings resulting from group kills (Borden et al. 2006).

Indirect or Silvicultural Control

There is a long history of research into "beetle-proofing" stands by manipulating stand density, diameter distribution, basal area, species composition, and age structure (Keen 1950, Amman and Baker 1972, Daniel et al. 1979, Mitchell et al. 1983, Wood et al. 1985, Preisler and Mitchell 1993, Negrón and Popp 2004, Whitehead and Russo 2005, Whitehead et al. 2006, Fettig et al. 2007). These tactics include thinning from below ("low thin"), thinning from above ("crown thinning") to remove inferior dominant/codominant trees, and "selection thins" that remove the largest trees irrespective of status to favor smaller trees (Society of American Foresters 2008). In current practice, thinning from below is generally the least controversial choice on public lands because of the desire to preserve large and/or old trees for forest restoration, wildlife habitat, and aesthetic purposes (Andrews et al. 2005), although crown thins and selection thins are still commonly used on private lands. In addition, especially in ponderosa pine (*Pinus ponderosa* Dougl. *ex* Laws.) stands, thinning is frequently based on spacing intervals to meet basal area objectives without respect to the diameter of trees removed.

With thinning from below, stand basal area and densities are reduced by removing smaller trees, but mean tree diameter for the residual stand is increased. The most susceptible trees, presumably those with the largest diameters, are retained, but the removal of small trees reduces competition among the larger residual trees in the stand. This change can make the remaining trees more resilient to a variety of stressors, including MPB (Amman 1972, Waring and Pitman 1985). This approach requires multiple entries as the stand ages, however, and ultimately reduces stand structural diversity over time.

With crown thins, stand basal areas and densities are reduced, and mean diameter is also reduced, presumably leaving the stand less susceptible to MPB infestation. Reduction of basal area in lodgepole pine stands through "diameter-limiting" harvests that focused on removal of the largest trees were generally successful in reducing MPB-caused tree mortality compared to untreated stands (reviewed by Wood et al. 1985, Fettig et al. 2007). The evidence is less clear for crown thins in ponderosa pine stands, but the preponderance of studies suggests that removing larger-diameter trees also reduces ponderosa pine susceptibility to MPB (Wood et al. 1985, Fettig et al. 2007). To our knowledge, this approach has not been tested with high-elevation white pines. As with any harvesting operation, improper timing of harvests (i.e., near the time of beetle flight), failure to treat or remove slash, and incidental mechanical injury to trees could increase susceptibility to bark beetle attack (Hindmarch and Reid 2001), therefore best management practices (BMP) should be consistently followed.

Selection thins can consist of individual tree removal, group selection, removal of less vigorous overstory trees, or some combination thereof. Individual tree removal is generally conducted to improve intertree spacing and a reduction in basal area, while group selection is designed to create greater age class diversity and enhance spatial heterogeneity. Both types of selection harvest can minimize bark beetle susceptibility, but removal of only the less vigorous trees in the overstory may not reduce susceptibility. Selection thins have essentially the same effect as crown thins but usually with potentially even greater reductions in basal area and mean diameter of residual trees. Similarly, proper timing, slash treatment, and removal of harvested trees can reduce the likelihood of beetle infestation caused by release of attractive host volatiles.

No Action Taken

Left untreated, MPB outbreaks will create, in the short term, stands with lower mean diameters and densities, usually greater tree species diversity, and—unless entire stands are killed within a short time frame—a greater mosaic of pine age classes (Whitehead et al. 2006, Kashian et al. 2011). These attributes are all desirable in terms of stand resilience to future attacks but can only be attained at endemic to moderate outbreak levels. In severe outbreaks in monotypic lodgepole pine stands, nearly the entire stand can be lost with correspondingly severe implications for wildfire, forest hydrology, susceptibility to invasive weeds, and other attributes. The loss of extensive forest canopy that results from a decision not to take action can have severe impacts on ecosystem goods and services, and those impacts will be analyzed more thoroughly in the following section in which consequences are discussed.

Consequences of Treatments for the Future Forest

The treatment tactics described above can, based on past experience and research, be expected to result in stand conditions that range from virtually unchanged in the short term (as in the case of insecticide treatments, where all trees are completely protected) to almost complete stand removal (as in the case of no action taken in severe outbreaks, where entire stands are lost to bark beetle infestation). Here, we consider the effects of treatments on risk of future bark beetle attack, invasion by weeds, carbon sequestration, and forest hydrology.

Direct Control

Insecticides

The repeated use of insecticides, which is often deemed necessary in resort developments, campgrounds, administrative sites, and the wildland-urban interface where aesthetic values are high, may provide a temporary reprieve but it can have adverse nontarget effects (van den Bosch 1978). Such nontarget effects may include toxicity to fish, birds, or aquatic organisms (Devine and Furlong 2007), and risk to these organisms is problematic especially on publically managed lands. On the other hand, insecticide applications entail little risk of mechanical injury to trees that might serve as infection courts for pathogens and, aside from the risk of contamination, pose little threat to forest hydrologic values because they entail little soil disturbance. Likewise, since they do not create openings in the stand or result in windthrow, they do not increase the threat of invasive weeds. While the carbon sequestration value of the stand is preserved, its susceptibility to future bark beetle infestation increases steadily over time, making it less carbon-stable. Insecticide use, coupled with thinning, could create a more resilient and carbon-stable stand for high-value recreation and administrative areas but may prove cost prohibitive in other circumstances.

Sanitation

As usually applied, sanitation involves the mechanical treatment of individual or groups of infested trees, so mechanical damage to the residual stand is reduced compared to some silvicultural operations that require more fine-grained stand treatments. MPB-killed trees, which are often among the larger of trees in the stand, are normally removed or felled and treated along with any adjacent smaller beetle-killed trees. Thus, the impact is essentially to mimic the thinning action of the beetles but to somewhat slow the rate of infestation by removing sources of infesting beetles (Coggins et al. 2011). Invasive weed growth is unlikely to be exacerbated by sanitation methods, and forest hydrology and carbon sequestration are likely to be only minimally impacted unless large numbers of trees are involved. The residual stand is likely to be somewhat more resilient to future bark beetle infestation because the most susceptible trees have been killed by MPBs.

Semiochemicals and Combined (e.g., Trap Trees or Attract-and-Kill) Methods

Because semiochemical treatments do not usually provide complete protection from bark beetle infestation (Progar et al. 2014), they frequently result in stands in which the most susceptible trees have been killed by bark beetles. There is a considerable body of research conducted to develop more effective methods of deploying semiochemicals, such as baited trap trees, attract-and-kill, and push-pull methods (Progar et al. 2014). Semiochemical treatments are used in several host types because they have no nontarget affects, are safe, and can be very effective at low to moderate beetle population densities. MPBs preferentially attack larger trees with thicker phloem (Amman 1972), thus, to the extent that the treatment is ineffective, the residual stand has a lower mean diameter and is theoretically more resilient to future attack. Furthermore, since beetle-caused tree mortality generally occurs in a patchwork of small group kills at low to moderate population levels (Kashian et al. 2011), this type of treatment is not likely to create an environment favorable to invasive weeds. The risk from the standpoint of forest pathogens is unchanged from the pretreatment state, while some loss of carbon sequestration is likely. Forest hydrology is unlikely to be severely affected because, with the exception of trap tree removal (Borden et al. 2006), there is no heavy equipment or soil disturbance involved.

Indirect or Silvicultural Control

Careful and timely harvesting (e.g., using predetermined skid trails, directional felling, etc.) by thinning from below can produce stands that experience less competition and are, therefore, more resistant to future beetle infestation (Ager et al. 2007, Jenkins et al. 2008) and wildfire (Ager et al. 2007) and should minimize the potential for future weed invasions because large openings are not created. With any mechanical harvesting, heavy equipment can compromise water quality, cause soil compaction, and mechanically damage the leave trees thereby creating infection courts for forest pathogens. However, careful harvest practices can significantly limit this type of damage to soils and the residual stand, and we advocate strict adherence to BMP and contract specifications to minimize the risk of this type of damage. Thinning from below can improve future carbon sequestration by releasing the growth of the residual stand and increasing its resilience to renewed bark beetle attack.

No Action Taken

The range of effects that might result depends on beetle populations, weather patterns, and initial stand structure. Under severe MPB outbreak conditions in a monotypic lodgepole stand, the entire overstory may be killed but once it regenerates, especially following fire, the result is a densely stocked stand of pines. If the extent and severity of the outbreak are great, visual impacts can be considerable (Sheppard and Picard 2006). In mixed-species stands, larger overstory pines are killed leaving shade-tolerant conifers, and those stands can be converted to a mix of suppressed lodgepole pines and nonhost species. Historically, however, endemic levels of beetle-induced tree mortality, unlike current epidemic levels, have resulted in stands with a mosaic of age classes and species, with overall lower stand density and susceptibility to future bark beetle attack (Kashian et al. 2011).

Boreal forest fires are predicted to increase in area by as much as 50% with climate warming, and wildfire is also a strong driver of carbon cycling in forest ecosystems (Kasischke et al. 1995). The influence of MPB-caused tree mortality on wildfire behavior, however, depends primarily on the time elapsed since the outbreak, with wildfire risk initially heightened but diminishing over time (Jenkins 2011, Jenkins et al. 2012). Generally, extreme fire potential exists in stands that have suffered high levels of MPB-caused tree mortality until the likelihood of torching (the transition of fire from the surface to the canopy) and crowning (spread from crown to crown) are minimized, and this process can take a decade (Jenkins et al. 2012). From the standpoint of carbon stores, Hurteau and Brooks (2011) recommend managing such forests based on the inherent ecologies of those forest types rather than strictly for maximizing carbon stores because carbon sequestration and carbon stability require short-term tradeoffs. Maximizing carbon stores may, therefore, ultimately severely compromise the carbon stability of the stand by creating overly dense stands, which is the case when no action is taken to mitigate MPB risk.

In the absence of mitigating treatments, endemic-level MPB-induced tree mortality would have little effect on water processes because the extent of damaging effects have been shown to be related to degree of infestation (Mikkelson et al. 2013). However, at severe outbreak levels, where extensive areas of canopy are lost to MPB-induced mortality, snowpack, snowmelt, water quality and water quantity are all predicted to be significantly affected by the changes in forest canopy structure (Potts 1984, Mikkelson et al. 2011, 2013, Pugh and Small 2012), with corresponding negative implications for water supplies, forest recreation, and other ecosystem goods and services.

In addition to potential impacts on carbon storage, water processes, and risk of future MPB infestation and wildfire, there are other disadvantages that may accrue from the decision not to treat. Because of changing land-use patterns, the MPB outbreak area in the inland West is increasingly within the wildland-urban interface, where the impact of MPB on aesthetic and recreational values is dramatic. Hazard tree removal and restoration costs can be considerable if the level of MPB-caused tree mortality is high. The loss of overstory trees on ski resorts can shorten the ski season and impact water cycling, since the snowpack melts more rapidly without the shading provided by the overstory trees (Mikkelson et al. 2011). Tree mortality along road corridors or developed trails results in significant costs to remove the standing dead and down trees. Finally, high-elevation host species such as whitebark and limber pines are especially at risk because of both MPB and an introduced invasive disease, white pine blister rust (*Cronartium ribicola* J.C. Fisch.) (Schoettle 2004), and failure to control MPB outbreaks in the high-elevation islands where these trees grow may eliminate crucial "plus" trees that have been identified as seed sources for blister-rust-resistant regeneration (Schoettle and Sniezko 2007).

Treatment and Policy Decisions

At the outset, it is important to acknowledge that many tree-killing bark beetle species, including MPB, are native to North and Central America and play important roles as natural disturbance agents in forests, promoting plant and animal diversity and nutrient cycling (Waters 1985). Endemic beetle populations and relatively small-scale outbreaks facilitate species and stand-structure diversity over the landscape (Lundquist and Negrón 2000). However, decades of fire suppression and reduced levels of harvesting have resulted in overly dense and homogeneous forests, creating the conditions for the current MPB outbreak—affecting as much as 8.9 million ha across the US Interior West from 2000–2012—which is unprecedented in scale (USDA Forest Service 2012).

Policies regarding the management of MPB outbreaks are typically made within the context of ecological, economic, and social frameworks (Wellstead et al. 2006). More than two-thirds of forested land in the western United States is publically owned (USDA Forest Service 2001); resource managers of these lands are entrusted with a public asset which, in the case of the National Forest System lands (USDA Forest Service), is required to be managed using both best available science and public input according to the National Forest Management Act of 1976 (NFMA) (Daniel et al. 1979).

In this paper, we have reviewed some of the basic MPB management options at a land manager's disposal and defined some of their consequences, but overall MPB management responses will be governed by social and economic considerations as well agency staffing levels, which have remained at historically low levels for the last several decades. As McFarlane et al. (2006) demonstrated in the analysis of public surveys, the Canadian public prefers measures directed toward killing beetles rather than proactive measures that would increase forests' resilience to future beetle infestation. Similar surveys have not, to our knowledge, been conducted in the United States, but the American public has demonstrated a similar active interest in how public lands are managed (Jones and Taylor 2005). Further, within the past 2 decades, policy decisions and litigation outcomes regarding silvicultural treatments have in some cases trumped research findings and prevented treatment implementation (Jones and Taylor 2005, Stokstad 2005, Thomas et al. 2006). Fire suppression, combined with a lack of other management treatments in the Interior West, has contributed to the MPB epidemic. Whereas public sentiment often favors direct control of MPB outbreaks, decades of research—past and ongoing—demonstrate that many direct control methods are ineffective at large temporal and spatial scales because they fail to lower the risk of future infestations or subsequent tree mortality (Coulson and Stark 1982, Wood et al. 1985, Wulder et al. 2009, Fettig et al. 2014). Furthermore, such methods do little to reduce fuel loads and the risk of increased wildfire severity. On the other hand, indirect control—primarily through proactive silvicultural treatments—has the capacity to create forests that are more resilient in the face of multiple threats, including those that are exacerbated by climate change.

Some salvage harvesting of the MPB-affected landscape has been conducted to recover the commercial value of standing MPB-killed trees. However, in most areas within the interior western United States on severely MPB-impacted sites, the response of land managers has been somewhat limited to reactive safety-related concerns such as removal of hazard trees killed by MPB and mitigation of wildfire risk from beetle-killed trees. However, the timing and scale of the most recent outbreaks left little time for proactive response, especially with reduced agency staffing levels. Hazard tree removal near and around roads, campgrounds, and trails has been a management priority (USDA Forest Service 2011). Beyond these areas, however, millions of acres have been impacted by substantial bark beetle-caused tree mortality (USDA Forest Service 2012). While there is concern about the impacts of potential wildfire on communities and watersheds, studies have resulted in a range of sometimes contradictory conclusions regarding the risk of wildfire in postoutbreak stands (Bentz et al. 2009, Simard et al. 2011, Hicke et al. 2012, Page et al. 2012, Jenkins et al. 2014). Despite some uncertainties surrounding postoutbreak fire risk and behavior, the scientific evidence suggests a clear benefit to proactive silvicultural management: Thinning stands can increase resilience to future bark beetle attacks (Amman and Baker 1972, Wood et al. 1985, Schmid and Mata 1992, Negrón and Popp 2004, Fettig et al. 2007).

While much of the currently affected terrain is inaccessible for silvicultural treatments because it is too steep, remote, lacking in roads, and/or formally designated as wilderness/roadless, stands that are accessible provide an opportunity for proactive silvicultural treatments that may reduce the risk of excessive tree mortality from future beetle attacks while simultaneously reducing fuel loads that exacerbate wildfires (Jenkins et al. 2008, 2012). Indirect control using silvicultural methods should be considered well before outbreaks begin to build, ideally at least a decade, and should be a continuous process in the management of forested public lands. Thinning treatments are a way to reduce competition and increase resilience so that when stressors such as drought, increased temperatures, or air pollution occur, individual trees are less vulnerable, and the beetle populations remain at endemic levels. Such proactive silvicultural treatments are usually more enduring in effect than reactive treatments but can be expensive, time consuming, and difficult to implement because of the time required for planning, marketplace fluctuations, and unfavorable public perceptions regarding logging on public lands. Once an outbreak occurs, however, the risks and costs associated with silvicultural treatments increase. Hazard trees threaten human safety and lumber prices, used to offset treatment costs, may decline depending on the quality of the timber. In addition, the largest benefits that may result from silvicultural treatments will occur if treatments are done in advance of another outbreak. Specifically, the risk of bark beetle outbreaks may also be reduced as a result of fuels reduction treatments conducted to mitigate wildfire risk (Jenkins et al. 2008).

A number of factors may enable a more supportive sociopolitical environment and more robust proactive management to restore and maintain the sustainability of western forests (Nelson 2007). The scientific and forest management communities both have key roles to play if we are to make progress toward the goal of creating more resilient and carbon-stable forests. Transparency and two-way learning between forestry professionals and the public will be critical. For example, the public is generally opposed to logging in wildland forests, yet forest entomologists, ecologists, and biologists propose increased logging activity through thinning prescriptions that are expected to reduce the risk of future fires and bark beetle infestations. Increasing public awareness of the benefits of thinning remains a critical challenge for forestry professionals, especially forest managers. On the other hand, results from a survey of households (738 respondents) in northern Colorado and southern Wyoming suggest that public perceptions may be evolving (Czaja et al. 2012). In that survey, the vast majority of respondents (92%) agreed that managers should use beetle-killed trees for wood products and biomass and disagreed that beetle-killed trees should be left in the forest (75%). Slightly more than a majority of respondents (59%) agreed that managers are doing everything possible to effectively respond to the beetle outbreak. A better understanding of public perceptions and reactions may help managers to better inform the public about management options such as using proactive silvicultural treatments to decrease future vulnerabilities to both bark beetle outbreaks and wildfire (Czaja et al. 2012). In addition, changing perceptions related to wildfire risk may increase the public's willingness to accept silvicultural treatments intended to decrease vulnerabilities related to both bark beetles and wildfire.

Economic considerations are another hurdle to be addressed. While there are crucial ecosystem goods and services that are of primary concern in forest management, there is also a financial cost for silvicultural treatments that cannot be offset by those values. To be sustainable, costs for silvicultural treatments should be offset by timber revenues, and this in turn is dependent on existent timber-processing infrastructure. A reliable change in policy to enable more silvicultural treatments could create a long-term economic stimulus that might trigger reestablishment of timber-processing infrastructure, especially in areas such as Colorado, Idaho, Montana, Utah, and New Mexico where the timber industry has all but vanished. Without these policy changes, however, the management community will be left with few economically viable alternatives for applying silvicultural treatments, and the now-familiar risks of future bark beetle outbreaks and extreme wildfires will persist. Furthermore, MPB has already expanded its range into a new host and region, infesting jack pines (*Pinus banksiana* Lambert) in the Canadian province of Alberta (Cullingham et al. 2011), indicating that there may be no natural barrier to the eastward spread of the MPB through the boreal forests. The problem may, therefore, expand into new geographical regions of North America.

A final consideration that forms the backdrop to present-day forest management policy and management discussions is climate change. Elevated concentrations of atmospheric carbon dioxide, warmer temperatures, and changed precipitation patterns are altering the structure and function of forested ecosystems (Dale et al. 2001, Perkins and Roberts 2003, Easterling and Apps 2005, Boisvenue and Running 2006, Bytnerowicz et al. 2007, Chmura et al. 2011, Silva and Anand 2013) with important consequences for management (Chmura et al. 2011). For example, as temperatures increase, MPB outbreaks are moving to higher elevations (Aukema et al. 2008, Robertson et al. 2009, Cudmore et al. 2010) and threatening whitebark pine (Logan et al. 2010, Raffa et al. 2013), an already at-risk keystone species that provides a crucial food resource for endangered grizzly bears. Furthermore, recent studies have shown that a warming environment has resulted in higher larval survival in winter (Bentz et al. 2010) and a decrease in developmental time resulting in summer emergence of adults that could possibly produce a second annual generation (Mitton and Ferrenberg 2012, but see Bentz et al. 2014).

A key challenge for forest science is to predict and understand climate-induced changes and adapt our management to safeguard forest health (Raffa et al. 2009, Ryan et al. 2010, Runyon et al. 2012). Healthy forests can play an important role in mitigating climate change by serving as carbon sinks (Pan et al. 2011). At the landscape scale, a combination of disturbed, regenerating, and mature stands create a carbon bank that is relatively stable (McKinley et al. 2011). However, landscape-scale disturbances such as the current MPB epidemic can alter the carbon balance of entire regions, converting them from carbon sinks to carbon sources (Kurz et al. 2008). Managing forests to reduce fuels and the risk of crown fire will not only decrease susceptibility to beetles and fire, but may contribute to the stability of the carbon bank (Ryan et al. 2010). Furthermore, recent findings from fire/fire surrogate research indicate that mechanical thinning can effectively mitigate fire risk without the risk of damage to the residual stand that might exacerbate future bark beetle damage (Stark et al. 2013), so this approach should be seriously considered for the multiple advantages it offers.

Managing for biologically diverse and resilient forests is our best and only available long-term, sustainable response to the multitude of stressors—insects and disease outbreaks, fires that are unprecedented in severity, and drought—that are likely to increase in frequency as the climate changes. It is only by managing for diversity and resilience on a landscape-scale that we can meet the challenge of our charge to the public to "sustain the health, diversity, and productivity of the Nation's forests and grasslands to meet the needs of present and future generations." In the case of bark beetles and many other stressors, this calls for greater, science-based use of silvicultural treatments that, paradoxically, require some tree mortality for the greater resilience of the entire forest.

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