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REVIEW ARTICLE

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Managing bark beetle outbreaks (*Ips typographus*, *Dendroctonus spp.*) in conservation areas in the 21st century

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Abstract. Forests in Europe and North America are being affected by large and severe outbreaks of bark beetles, which have caused widespread concern about forest health and have led to proposals for tree removal in affected or susceptible forests. Any such intervention, as well as broader decisions of whether any active interventions are appropriate, should be based on the best scientific data. This is true for all forests, including those whose purposes include timber production, watershed protection, biogeochemical function and recreation, and especially protected and conservation areas as the latter often provide particularly unique and important cultural, social, scientific and other ecosystem services. Here, I summarize peer-reviewed literature on the effects of bark beetle outbreaks and on silvicultural treatments aimed at mitigating beetle-induced tree mortality. From an objective scientific perspective, beetle outbreaks do not destroy forests. Instead, in many cases they play an important role in promoting wildlife, biodiversity and other ecological services. The best available data indicate that logging in conservation areas is unlikely to stop ongoing bark beetle outbreaks and instead may be more ecologically detrimental to the forests than the outbreaks themselves. If the purpose of a forest is timber production, then logging is desirable and can be planned based on appropriate analyses of timber yield and economic profit. However, in areas in which conservation is the determined goal, it is recommended that cutting trees be limited to removing hazards, such as trees that might fall in areas of high human activity in order to limit property damage and personal injury. Based on extensive research in Europe and North America, logging beetle-affected forests is inconsistent with most conservation goals.

Key words: *Dendroctonus*, disturbances, ecosystem based management, *Ips typographus*, Picea, Pinus

1. Introduction

Forests in Europe (Seidl et al. 2011) and North America (Raffa et al. 2008) are being affected by large and severe outbreaks of bark beetles (*Ips typographus* and *Dendroctonus* species, respectively). These dramatic outbreaks have caused widespread concern about forest health and have led to proposals for tree removal in forests that have been affected by outbreaks or that are thought to be susceptible to outbreaks (e.g., United States Senate 2010; United States House of Representatives 2013; Polskje Ministerstwo Srodowiska 2016). Such proposals stem in part from perceptions that bark beetle outbreaks harm forests and that active intervention is therefore necessary to stop or prevent outbreaks, or to restore beetle-affected forests (Rocca and Romme 2009; Black et al. 2013). Management strategies have been applied prior to, during, or after outbreaks to attempt to prevent or stop outbreaks or to modify their effects. Any such intervention, as well as the broader decision of whether any active interventions are appropriate, should be based on the best available science. This is true for all forests including those whose purposes include timber production, watershed protection, biogeochemical function, and recreation, but it may be especially important in wilderness, protected, and other conservation areas as these areas often provide particularly unique and important cultural, social, scientific, and other ecosystem services. Furthermore,

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conservation areas often differ from other forests in having been shaped by natural rather than anthropogenic forces for relatively long periods of time.

Here, I review peer-reviewed literature published in ISI (International Scientific Indexing) journals on the ecological effects of bark beetle outbreaks and on silvicultural treatments aimed at reducing beetle-caused tree mortality. Although articles published in ISI journals are certainly not the only sources of valuable information, they are internationally recognized as being at a high level and often are readily available to international audiences. The current overview is brief and a much longer article could be devoted to exploring and elucidating each topic considered here. However, the goal of this article is not to exhaustively examine all aspects of the topics considered here, but rather to provide a concise overview, which may be useful to managers and policy makers in its brevity. As outbreaks and questions of their management are important in Europe and North America, I draw on literature from both continents to optimize insight and understanding. The main aim of this manuscript it to review relevant literature in order to inform ongoing debates about managing bark beetle outbreaks in conservation areas.

The recognition that ecosystems are dynamic and that change and instability are inherent to ecosystem function has been a major shift in perception over the past century among scientists and resource managers (Pickett and White 1985, Botkin 1990). Formerly, there was a widespread expectation of a "balance of nature" that was reflected in concepts that stressed stability, such as the climax concept or homeostatic self-regulation of ecosystem properties. Today, ecosystem change is regarded as the norm, and periods of slow as well as relatively rapid change (including natural disturbances) are widely expected, including in Europe (Kulakowski et al. 2016). Consequently, modern ecosystem management is based on the recognition that ecosystems are not static and that change occurs due to both human and natural influences (Swanson et al. 1993, Morgan et al. 1994).

Nevertheless, in the popular press and elsewhere, forest affected by outbreaks continue to sometimes be described as having been destroyed, leaving readers with the impression that beetles kill every tree in their path and that beetle-affected forests are lost, perhaps forever (Rocca and Romme 2009). A closer look, however, reveals that the beetle-caused mortality and consequent changes in stand structure are extremely heterogeneous (Rocca and Romme 2009). Surviving trees are present even in stands that have been severely affected by outbreaks, which is important because these survivors are integral to forest development following the outbreak. Beetles selectively kill larger trees of target species, whereas most other species as well as smaller trees and saplings of the target species survive. From an objective scientific perspective, beetle outbreaks do not destroy forests and in many cases they play valuable ecological roles.

2. Ecological effects of bark beetle outbreaks

Endemic and epidemic bark beetle outbreaks are important sources of structural heterogeneity and biodiversity in the forests of Europe and North America. Bark beetles are parts of many forest food webs and can be associated with a large number of organisms (Dahlsten 1982). They can be hosts for parasites and food for a variety of animals, including spiders, birds and other beetles (Koplin and Baldwin 1970). The actual effect of any particular bark beetle outbreak on subsequent biodiversity depends on the initial forest conditions, the intensity of the outbreak and the types of organisms considered.

Bark beetles have far reaching impacts on ecological structures and biodiversity which, when considered across scales from individual trees to entire landscapes, reveal their important roles as ecosystem engineers. At the scale of individual beetle galleries they establish and maintain a microflora of fungi and bacteria that create a complex web of biosynthetic interactions affecting tree resistance and success of beetle attack. By reducing tree resistance, beetle attack creates opportunities for a wide diversity of saprogenic competitors (Raffa et al. 2008). Bark beetles themselves are an important food source for a diverse group of arthropods and vertebrates, including birds such as woodpeckers that are highly adapted to digging out larvae of wood boring insects. In general, a bark beetle outbreak initializes a release of resources that, in the short term, promotes the growth of populations of insectivorous birds (Saab et al. 2014). Overall, approximately twice as many bird species have been found to increase, as opposed to decrease, in forests with bark beetle outbreaks (Saab et al. 2014). The longer- term impact on avian diversity of large outbreaks has not been widely studied but is likely to depend on the amount of tree mortality and the rate of recovery of un-attacked host conifers as well as non-host trees.

At the scale of forest stands, bark beetle-caused tree mortality increases structural heterogeneity through the creation of canopy gaps and enhanced growth of understory plants, which is likely to create favorable habitat for many invertebrates and vertebrates. Outbreaks create snags that may be used by various birds and mammals (Saab et al. 2014). At a landscape scale, beetle outbreaks are likely to alter biodiversity through the creation of more diverse patch configurations and edge effects favoring some wildlife species. Wildlife associated with early seral habitats, such as deer and elk, are expected to be favorably influenced by an outbreak once there has been enough time for understory resources to respond to the creation of canopy openings (Saab et al. 2014). The consequences of a beetle outbreak for biodiversity at the scale of large stands and landscapes will depend both on the intensity of the outbreak and on the pre-outbreak forest landscape structure.

Another particularly important effect of beetle outbreaks on ecosystem structure and biodiversity is evident in riparian habitats of mountain streams (Jackson and Wohl 2015). Beetle-killed trees contribute to recruitment of large coarse woody debris into riparian areas and stream systems, which exerts important beneficial influences on storage of sediment and organic matter and on river and floodplain habitat for numerous animal species, including trout. In comparison to timber harvesting that can remove all riparian wood and severely deplete subsequent instream wood recruitment, beetle outbreaks provide a source of instream wood loads for decades following a beetle outbreak.

After large outbreaks of *Ips* in *Picea abies* forests in south-eastern Germany, maximum nitrate concentrations in run-off used for drinking water increased significantly but only temporarily at the headwater scale (Beudert et al. 2015). Moreover, this major criterion of water quality remained consistently far below the limit recommended by the World Health Organization. At the same time, biodiversity, including numbers of Red-listed species, increased for most taxa across a broad range of lineages. Therefore, Beudert et al. (2015) recommended allowing natural disturbance-recovery processes to operate unimpeded in conifer-dominated mountain forests, especially within protected areas.

3. Strategies for controling bark beetle outbreaks

Despite the important roles that bark beetle outbreaks play in creating wildlife habitat, promoting biodiversity and providing other ecological services, active management treatments are sometimes applied before, during or after outbreaks in order to attempt to prevent or stop outbreaks or to change their effects. The simultaneous goals of control of insect pests and compliance of conservation targets has intensified public debate about post-disturbance management, particularly in protected areas.

3.1. Prior to Outbreaks

The effectiveness of thinning to reduce forest susceptibility to bark beetles is believed to be related to tree vigor (Fettig et al. 2007); which may increase as moisture stress is decreased, and which in turn may make trees less susceptible to insect infestation. The premise is that if trees are healthy and vigorous, they may be able to defend themselves against attacking beetles by essentially flooding the entrance site with resin that can push out or drown the beetle.

Some studies have suggested that competition for light and water may reduce the vigor of surviving trees and increase susceptibility to bark beetle attacks (Fettig et al. 2007) and that thinning may, therefore, improve outbreak resistance. However, studies that have looked directly at the effects of thinning on tree vigor have shown mixed results. While some studies have found that thinning reduces stand susceptibility in some circumstances (Fettig et al. 2007), other research has found bark beetles do not preferentially infest trees with declining growth. Under some circumstances, thinning may alleviate tree stress at the stand level but importantly, it is unlikely to be effective at mitigating susceptibility against extensive or severe outbreaks (Safranyik and Carroll 2006). For example, thinned stands of lodgepole pine in Oregon were initially unattractive to mountain pine beetles (*Dendroctonus*); but when the number of attacking beetles became large, colonization rates were similar in thinned and un-thinned stands (Preisler and Mitchell 1993). Similarly, beetle-caused tree mortality with lower basal area under endemic conditions, but if the stand was in the path of an ongoing beetle outbreak, spacing and density of trees had little effect (Amman et al. 1988).

While thinning has the potential to reduce tree stress, which can reduce susceptibility to insect attack during endemic phases, it also has the potential to bring about other conditions that can increase susceptibility. For example, thinning may injure surviving trees and their roots, which can provide entry points for pathogens and ultimately reduce tree resistance to other organisms (Hagle and Schmitz 1993; Paine and Baker 1993; Goyer et al. 1998). Although thinning can be effective in maintaining adequate growing space and resources, tree injury, soil compaction, and temporary stress due to changed environmental conditions caused by thinning may increase susceptibility of trees to bark beetles and pathogens (Hagle and Schmitz 1993).

Given the potential risks of logging, especially in conservation areas, mechanical bark treatments, such as debarking, have been promoted as an on-site method of pest control that accounts for conservation targets because woody biomass is retained and some unintended consequences of logging are minimized. Mechanical bark treatments have been used prior to outbreaks (when beetle populations are still small) as well as after populations have erupted to epidemic levels. For example, both debarking and bark-scratching significantly decrease numbers of emerging *Ips typographus* (Thorn et al. 2016). Debarking also significantly reduces the species density of wood-inhabiting fungi, saproxylic beetles, and parasitoid wasps. By contrast, bark-scratching does not reduce the overall density of these other species. Using techniques such as bark scratching, particularly in protected areas, will foster ecosystem integrity at lower economic cost compared to debarking. However, bark-scratching does have some negative effects in common with debarking, such as the significant reduction of wood wasps emergence holes and the reduction of holes made by foraging woodpeckers. Therefore, while bark-scratching and debarking may be a preferred alternative to logging conservation areas, Thorn et al. (2016) concluded that even these relatively low-intensity techniques might affect higher trophic levels of biodiversity and should be applied only if pest management is urgently needed.

From an adaptive management standpoint, it is most prudent to implement thinning or other mechanical treatments in appropriate settings (e.g., already degraded areas in need of restoration) with sufficient controls that would lead to an improved understanding of the efficacy of these approaches, particularly under a range of climatic conditions. It is also important to consider how such strategies may alter normal stand structure. For example, thinning can create novel conditions that can be atypical for some ecosystems in which tree density is naturally high. More importantly, thinning forest stands before epidemics is not likely to prevent major outbreaks (Preisler and Mitchell 1993; Amman et al. 1988), likely due to the overriding influence of climatic stress in driving outbreaks.

3.2. During Outbreaks

There is general agreement that silvicultural treatments cannot effectively stop outbreaks once a large-scale insect infestation has started. Citing multiple sources, Hughes and Drever (2001) found that most control efforts have had little effect on the final size of outbreaks. In another review, Romme et al. (2006) point out that once an extensive outbreak has started, timber management is unlikely to stop it. Control of such outbreaks is theoretically possible, but it would require treatment of almost all of the infected trees (Hughes and Drever 2001) and in practice, is likely to result in killing more trees than would have been killed by the outbreak itself (Tempereli et al. 2014).

Silvicultural efforts to stop developed outbreaks of *Ips* in Europe have not been successful due to similar dynamics as those that characterize bark beetle outbreaks on other continents. For example, Stadelmann et al. (2013) examined the efficacy of logging to prevent *Ips* outbreaks following wind disturbance. Although their analysis focuses on storm damage as initiating an outbreak, their results apply to outbreak dynamics regardless of the initial trigger. Stadelmann et al. (2013) found that higher intensity of sanitation felling decreases the number of infestation spots of *Ips* that are expected following wind disturbances, but this decrease is small. Furthermore, sanitation felling is only effective when carried out before *Ips* have emerged (Wermelinger et al. 2012), which may be difficult to achieve, because there is often a lag between infestation and its visual manifestation. Consequently, Stadelmann et al. (2013) concluded that mass infestations by *Ips* cannot be prevented even with thorough salvage logging. Indeed, the general consensus is that after *Ips* reach an outbreak phase, the biological and ecological dynamics change substantially (e.g., Økland et al. 2016) and outbreaks become impossible or difficult to control.

If a bark beetle infestation is relatively restricted and concentrated in a limited area, it may be feasible to reduce the impact of that outbreak by removing infested trees from a forest stand, or by thinning a stand to reduce stress of trees competing for limited nutrients, sunlight, and moisture. However, specific climatic conditions are believed to be required for beetle populations to reach epidemic levels. As such, a small population of beetles is not sufficient for an outbreak to occur and would not necessarily lead to an outbreak. Conversely, under climatic conditions favorable for an outbreak, bark beetle outbreaks can erupt simultaneously in numerous, dispersed stands across the landscape. Thus, even if a growing population of beetles is successfully removed from one stand or the stand is thinned to increase vigor, under climatic conditions suitable for outbreaks, beetles from other stands are likely to spread over a landscape. Given that climate typically favors beetle populations and stresses trees over very large areas, successfully identifying and treating stands over a large enough region to have a significant impact on the overall infestation is impractical and costly.

3.3 Following Outbreaks

Post-disturbance logging is common practice on forest lands and is designed to remove trees or other biomass in order to produce timber or other resources. This type of resource extraction has the potential to inadvertently lead to heightened insect activity (Nebeker 1989; Hughes and Drever 2001; Romme et al. 2006). In particular, snags and fallen logs contribute to the protection of soils and water quality and provide habitat for numerous cavity and snag-dependent species (Romme et al. 2006), many of which prey on bark beetles and other economically destructive insects. Therefore, outbreaks could be prolonged because of a reduction in the beetle's natural enemies (Nebeker 1989), including both insects and bird species that feed on mountain pine beetles (Koplin and Baldwin 1970; Shook and Baldwin 1970; Otvos 1979). Furthermore, post-disturbance harvest can damage soil and roots by compacting them (Lindenmayer et al. 2008) leading to greater water stress in trees, which may reduce conifer regeneration by increasing sapling mortality (Donato et al. 2006) and, in general, may cause more damage to forests than that caused by natural disturbance events (DellaSala et al. 2006).

4. Conclusions

Climate change and other factors are leading to dramatic changes in forest ecosystems. One consequence of recent and predicted climate change is increased bark beetle activity leading to tree mortality over large areas in Europe, North America and elsewhere. While such outbreaks have led to widespread concern, beetles do not destroy forests, but instead create habitat, promote biodiversity, and preserve other important ecosystem services, especially in conservation areas. In contrast, logging following outbreaks often does not promote these attributes but instead often damages ecosystems more than the initial disturbance. Insect containment measures have yielded mixed results and may pose significant risks to forested ecosystems. The best available science indicates that logging in conservation areas is unlikely to stop ongoing bark beetle outbreaks and instead may be more ecologically detrimental to forests than the outbreaks themselves. If the desired purpose of a forest is timber production, then logging is desirable and can be planned based on appropriate analyses of timber yield and economic profit. But in areas in which conservation is that determined goal, it is recommended that cutting trees be limited to removing hazardous trees that might fall in areas of high human use in order to limit property damages and potential loss of life. Based on extensive research in Europe and North America, logging beetle-affected forests is ineffective at stopping ongoing outbreaks and is inconsistent with most conservation goals.

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