Bark beetles as agents of change in social–ecological systems

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Due to recent outbreaks of native bark beetles, forest ecosystems have experienced substantial changes in landscape structure and function, which also affect nearby human populations. As a result, land managers have been tasked with sustaining ecosystem services in impacted areas by considering the best available science, public perceptions, and monitoring data to develop strategies to suppress bark beetle epidemics, and in some cases to restore affected lands and ecosystem services. The effects of bark beetle outbreaks are often detrimental to the provision of ecosystem services, including degraded landscape aesthetics and diminished air and water quality. However, there have been instances where bark beetle outbreaks have benefited communities by, for example, improving habitat for grazing animals and enhancing real-estate values. As a consequence of the interaction of a warming climate and susceptible forest stand conditions, the frequency, severity, and extent of bark beetle outbreaks are expected to increase and therefore will continue to challenge many social–ecological systems. We synthesize experiences from recent outbreaks to encourage knowledge transfer from previously impacted communities to potentially vulnerable locations that may be at risk from future bark beetle epidemics.

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Native bark beetles are major disturbance agents that promote forest succession and help to maintain forest health in many ecosystems around the world. The recent upsurge of bark beetle populations in many locations is mainly attributable to climate change – specifically increasing temperatures – which affects thresholds and rates of beetle development while at the same time enhancing beetle winter survival rates (Bentz *et al.* 2010). In addition to climate warming, tree density and landscape history are also important contributors to outbreaks (Fettig *et al.* 2007; O'Connor *et al.* 2014). Together, these factors have resulted in millions of hectares of tree mortality in conifer forests worldwide; for instance, the ongoing native bark beetle outbreak in western North America has affected over 47 million ha of forest since the 1990s (Raffa *et al.* 2008), with the associated social, aesthetic, and economic losses exceeding those caused by wildfire and other forest disturbances (Dale *et al.* 2001). The scale, severity, and economic impacts of many recent bark beetle outbreaks, including those in western North America, are widely believed to be unprecedented (Bentz *et al.* 2009).

In a nutshell:

- Expected future changes in the climate system are likely to lead to more frequent, severe, and/or extensive bark beetle outbreaks
- Bark beetle outbreaks have profound effects on forested landscapes, affecting society through alterations in the provision of ecosystem services
- It is essential to transfer knowledge from communities recently affected by bark beetles to areas that are likely to experience outbreaks in the future

Model forecasts indicate that protracted warming over the course of the 21st century will facilitate the expansion of beetle populations into ecosystems where they were previously restricted by prevailing climate conditions (Seidl *et al.* 2008; Buotte *et al.* 2016). This climate-mediated range expansion may lead to non-linear shifts in disturbance regimes in many ecosystems, particularly those in high-latitude and high-elevation regions (Cudmore *et al.* 2010). In addition to climate warming, host tree density and vigor, which may be influenced by human activities, are also important factors in promoting severe outbreaks (Fettig and Hilszczański 2015; Kulakowski *et al.* 2016). The cumulative pressures on forests from climate warming, associated drought, land-use change, and shifts in the frequency and intensity of

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bark beetle outbreaks, as well as other disturbances, have the potential to degrade forested landscapes, potentially leading to negative economic and ecological outcomes (Carpenter *et al.* 2009; Seidl *et al.* 2011).

Forests provide many societal goods and functions of considerable ecological, monetary, and cultural value, often collectively referred to as ecosystem services (MA 2005). Ecosystem services from forests include public assets such as air purification, control of water runoff and soil erosion, wood and other forest products, and regulation of climate through carbon storage, biogenic aerosol production, and biophysical processes that affect the planetary energy balance. The effects of recent bark beetle disturbances have had measurable impacts on communities, especially in areas that have experienced disruptions to ecosystem services as a result of outbreaks (Seidl *et al.* 2016). Beetle-caused tree mortality affects a variety of ecosystem services, mostly at local to regional scales, including property values, quantity and quality of marketable timber products, landscape aesthetics, recreational experiences, and tourism appeal (Flint *et al.* 2009), among others. The monetary value of most ecosystem services impacted by bark beetles remains unquantified, although several recent efforts help to address this knowledge gap (Maguire *et al.* 2015).

Here, we synthesize the current body of literature to provide insights on the feedbacks and dynamics within social–ecological systems (SES) affected by bark beetle outbreaks. Our synthesis is timely given that the impacts of recent outbreaks in western North America have been severe, long-lasting, and generally well-documented (Kurz *et al.* 2008). We view the social and ecological dimensions of beetle disturbances as inherently one entity, and not simply as the interaction of two independent systems. An SES approach is a powerful model for managing landscapes because the state of a system at any given time is a function of how past events shape potential future conditions (Liu *et al.* 2007). With bioclimatic models forecasting range expansions for several bark beetle species during this century (Bentz *et al.* 2010), our goal here is to encourage the transfer of knowledge from recently impacted SES to those located in potentially vulnerable regions. Our collective expertise centers on North America and Europe, but this work is also relevant to other regions susceptible to bark beetle outbreaks, such as Southeast Asia and Central America (Kirkendall *et al.* 2008; Rojas *et al.* 2010).

Outbreak drivers

Climate

The addition of anthropogenic greenhouse gases to the atmosphere indirectly promotes bark beetle outbreaks (Bentz *et al.* 2010). Bark beetles are poikilotherms, so the duration and timing of their life cycles are affected by temperature changes. For example, the North American spruce beetle (*Dendroctonus rufipennis*), which primarily colonizes Engelmann spruce (*Picea engelmannii*) and white spruce (*Picea glauca*) trees, typically has a 2-year reproductive cycle under normal climate conditions (Schmid and Frye 1977); however, in the future, some proportion of the population may produce one generation per year in response to sustained temperature increases (Hansen *et al.* 2001). In the Rocky Mountains of western North America, mature spruce beetles emerge to seek out host trees when the daily maximum temperature reaches 16°C (Dyer 1969). Once the temperature threshold for emergence occurs, spruce beetles select host trees based on chemical cues emitted by the host and by other colonizing beetles. In dense forests, the close proximity of suitable host trees facilitates successful pheromone communication among colonizing beetles, which is critical to the success of their mass attack strategy. Upon selection of a host tree, beetles bore through the outer bark to access phloem tissue, where the females create egg galleries and inoculate the tree with perhaps several of many potential fungal obligates (Six and Bentz 2003; James *et al.* 2011). Host trees defend against invading beetles by flushing bore cavities with volatile-rich resin, resulting in the formation of pitch tubes; however, if a host tree is moisture stressed, it may produce less resin to repel invading beetles (Kolb *et al.* 2016). Climate change (specifically warmer temperatures and enhanced moisture deficits) elevates tree stress, which can be exacerbated in sites where competition for available water and nutrients is high, such as in dense forests. For a handful of aggressive bark beetle species, the pheromone-mediated mass attacks that occur during outbreaks are generally sufficient to overwhelm the defensive strategies of otherwise healthy, vigorous trees (Schmid and Frye 1977).

Stand conditions

Tree and stand conditions also facilitate beetle outbreaks. Older, larger, and stressed trees are less able to mount defenses against beetle attack, and denser stands increase competition among trees for resources, leading to greater stress and higher susceptibility to infestation. Contiguous stands of susceptible trees across a landscape allow beetle populations to enlarge to epidemic levels over substantial areas. Land-use practices that either directly or indirectly modify the density and continuity of suitable host trees are important factors in the susceptibility of a forest to bark beetle epidemics. Many forested landscapes have complex land-use histories, resulting from the impacts and interactions of livestock grazing, logging, and fire suppression, among other factors (Kulakowski *et al.* 2016); the cumulative effects of these activities have influenced spruce beetle outbreaks in subalpine forest ecosystems throughout the southwestern US, for instance (O'Connor *et al.* 2014). Management agencies describe densities of suitably sized host trees by using hazard rating systems that are instructive for preventative silvicultural treatments, including thinning of overstocked stands (Netherer and Nopp-Mayr 2005).

Managing stand conditions

When adequate supporting data, political will, legal authority, and financial resources are available, proactive management strategies tend to favor silvicultural treatments that focus on reducing the susceptibility of forests to bark beetle infestations (DeRose and Long 2014; Nowak *et al.* 2015). Many studies have demonstrated the importance of relative stand density to characterize host competition that ultimately stresses trees and increases host suitability to bark beetle reproduction and population growth (Fettig *et al.* 2007). For example, thinning has been shown to reduce tree mortality caused by the mountain pine beetle (MPB; *Dendroctonus ponderosae*) (Egan *et al.* 2010). For many pines, including economically important species such as lodgepole (*Pinus contorta*) and ponderosa (*Pinus ponderosa*), reducing the density of forests via mechanical thinning may improve their drought tolerance and resistance to beetle attack. Although only a small number of studies have evaluated this important issue (Sartwell and Stevens 1975; Amman *et al.* 1988; Bottero *et al.* 2017) it is important for policy makers and forest user groups to consider the effectiveness and limitations of proactive thinning programs in reducing levels of beetle-induced tree mortality. Modifying forest density may be a practical means of mitigating bark beetle outbreaks because natural resource agencies often possess the tools, information, and policies to modify stand conditions.

In the US, several statutes have been introduced at the federal level to address remediation of beetle-impacted lands in order to reduce fuel loads. In 2003, the Healthy Forests Restoration Act called for thinning of overstocked stands, among other provisions, to reduce hazardous fuels (USA PL 108–148). More recently, the Agricultural Act of 2014 allocated $200 million to mitigate fire hazards created by bark beetle outbreaks throughout US national forest lands (USA PL 113–791). Accordingly, many post-outbreak management strategies involve the removal of dead trees to lower wildfire risk, extent, and intensity (Hicke *et al.* 2012; Hansen *et al.* 2016), which may also lead to modification of wildfire management strategies (Jenkins *et al.* 2014). Research suggests that post-outbreak forests may be more (Lynch *et al.* 2006) or less (Hart *et al.* 2015) fire-prone as compared with unaffected forests. The susceptibility of a forest to wildfire depends, at least to some degree, on how recently the beetle outbreak occurred (Harvey *et al.* 2014), as well as the structure and composition of the associated forested landscape (Hansen *et al.* 2016). In some instances, outbreaks may have reduced the severity of wildfires, as recently observed in the US Pacific Northwest (Meigs *et al.* 2016), but the relationship is complex and depends on many factors, including forest type, and disturbance severity and timing.

Ecosystem services

Natural resources

Bark beetle outbreaks can enhance or diminish ecosystem services. For instance, outbreaks may increase water yield, which is generally perceived as beneficial for society, especially in mountain communities that rely on recharge from seasonal snowpack (Bearup *et al.* 2014); on the other hand, bark beetle outbreaks can also harm human health (Embrey *et al.* 2012) by impairing water quality as a result of higher concentrations of nutrients and heavy metals (Mikkelson *et al.* 2013), as well as by reducing air quality due to the release of volatile organic compounds and biogenic aerosols (Berg *et al.* 2013).

Tourism

Landscape aesthetics tend to be adversely affected by bark beetle outbreaks, and are of particular concern among forest user groups and the outdoor recreation industry (Czaja *et al.* 2012; McGrady *et al.* 2016). Some research indicates that outbreaks influence the quality of visitor experiences and the frequency of subsequent visitation (Hollenhorst *et al.* 1993; Sheppard and Picard 2006). Landscape aesthetics and the perception of a "natural" environment are important attractors for outdoor visitors; the appearance of surrounding landscapes is therefore valuable to communities that rely on revenues generated by nature-based tourism. Yet, little research has been conducted to assess forest user experiences following bark beetle outbreaks. In one such study, Brown and Reed (2000) surveyed visitors to three national forests in Colorado and Wyoming that had been impacted by MPB outbreaks to examine how tourists valued these forests; perhaps unsurprisingly, the researchers found that landscape aesthetics and recreational opportunities were the most important considerations among survey respondents.

Property values

Forest disturbances, including bark beetle outbreaks and wildfires, are generally thought to lower property values due to a perceived reduction in the attractiveness of the affected landscapes (Flint *et al.* 2009); outbreaks also increase the potential for damage from falling trees, with negative consequences for homeowners and municipalities. In southern California, bark beetle outbreaks affected how home sales were advertised, and alternative prices were listed with (and without) dead tree removal (Fettig unpublished data). In densely populated communities located along wildland–urban interfaces, such as those along the Colorado Front Range, real-estate values often decrease following bark beetle outbreaks because homes that were once secluded by dense forest are now visible due to high levels of tree mortality (>75%; Witcosky 2007). In Colorado, home values depreciated by up to $70,000 following outbreaks, due to the combined effects of loss of privacy, perceived higher risk of wildfires, and potentially hazardous conditions from falling trees (Price *et al.* 2010; Cohen *et al.* 2015).

In contrast, the values of homes located in dispersed rural communities may increase following bark beetle outbreaks due to enhancement of aesthetic factors, such as improved views. Homeowners on Alaska's Kenai Peninsula, for example, realized net increases in real-estate value (up to $6200) from better views, as well as from the successional transitions to tree species that were perceived by potential home buyers to be more aesthetically appealing (Table 1; Hansen and Naughton 2013). In some areas, increases in the availability of sunlight, water, and nutrients after beetle outbreaks promoted the growth of understory grasses, thereby improving forage for animals and enhancing wildlife viewing and hunting opportunities, which may also be beneficial for property values, especially among properties located at the wildland–urban interface (Saab *et al.* 2014).

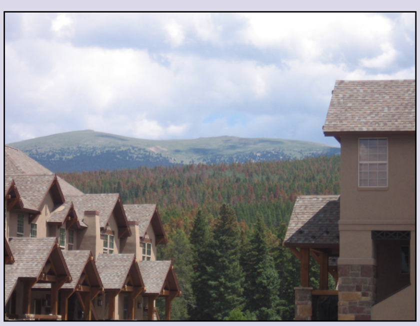
Societal responses

Public perception

In scientific and popular publications, the spatial scale and intensity of recent outbreaks are typically portrayed as unprecedented (Raffa *et al.* 2008; Bentz *et al.* 2009), a perception that is due in part to the limited availability of longer-term ecological records to contextualize recent outbreaks (Waller 2013). Improving our understanding of past bark beetle dynamics would be useful for discussing recent outbreaks in terms of commonly used management metrics, such as disturbance return interval (Fettig *et al.* 2007). Ultimately, establishing a knowledge base that incorporates longer-term ecological records from archives, such as tree rings and lake sediments, is necessary to assess the "precedence" for a disruption to ecosystem services resulting from bark beetle outbreaks and other forest disturbances (Dearing *et al.* 2015; Jeffers *et al.* 2015).

Education level shapes expectations of forest recovery, as well as the role of land managers and policy makers. For example, a survey of landowners in Virginia indicated that college-educated residents were more willing to participate in the state's Southern Pine Beetle Prevention Program (Watson *et al.* 2013), which promotes thinning of forests to reduce their susceptibility to the southern pine beetle (SPB; *Dendroctonus frontalis*). Conifer forests affected by bark beetles are often viewed as degraded, but in many locations bark beetles are native agents that promote forest renewal (Zeppenfeld *et al.* 2015). Having sustained an outbreak, observational evidence suggests that most forests can be expected to recover in the absence of human intervention (Figure 1). As many communities will presumably experience bark beetle outbreaks during the coming century, evidence of forest recovery from past beetle disturbance, which may be necessary to allay public concerns, are likely to be unavailable in these regions.

Table 1. Bark beetle outbreaks affect home values differently depending on the environmental context



	Colorado	*Alaska*
Impact	Home values decreased by up to $70,000	Home values increased by up to $6200
Hypothesized reason	Forest health and hazard	Emerging mountain and ocean views
Locations	Grand, Larimer, and Boulder counties	Kenai Peninsula
Beetle species	*Dendroctonus ponderosae*	*Dendroctonus rufipennis*
Study periods	1995–2011	2001–2010
Sources	Price *et al.* (2010); Cohen *et al.* (2015)	Hansen and Naughton (2013); Hansen (2014)
Take away	Impacts of bark beetles on property values are likely contextually dependent and result from trade-offs between environmental amenities that are degraded versus those that are enhanced by outbreaks.	

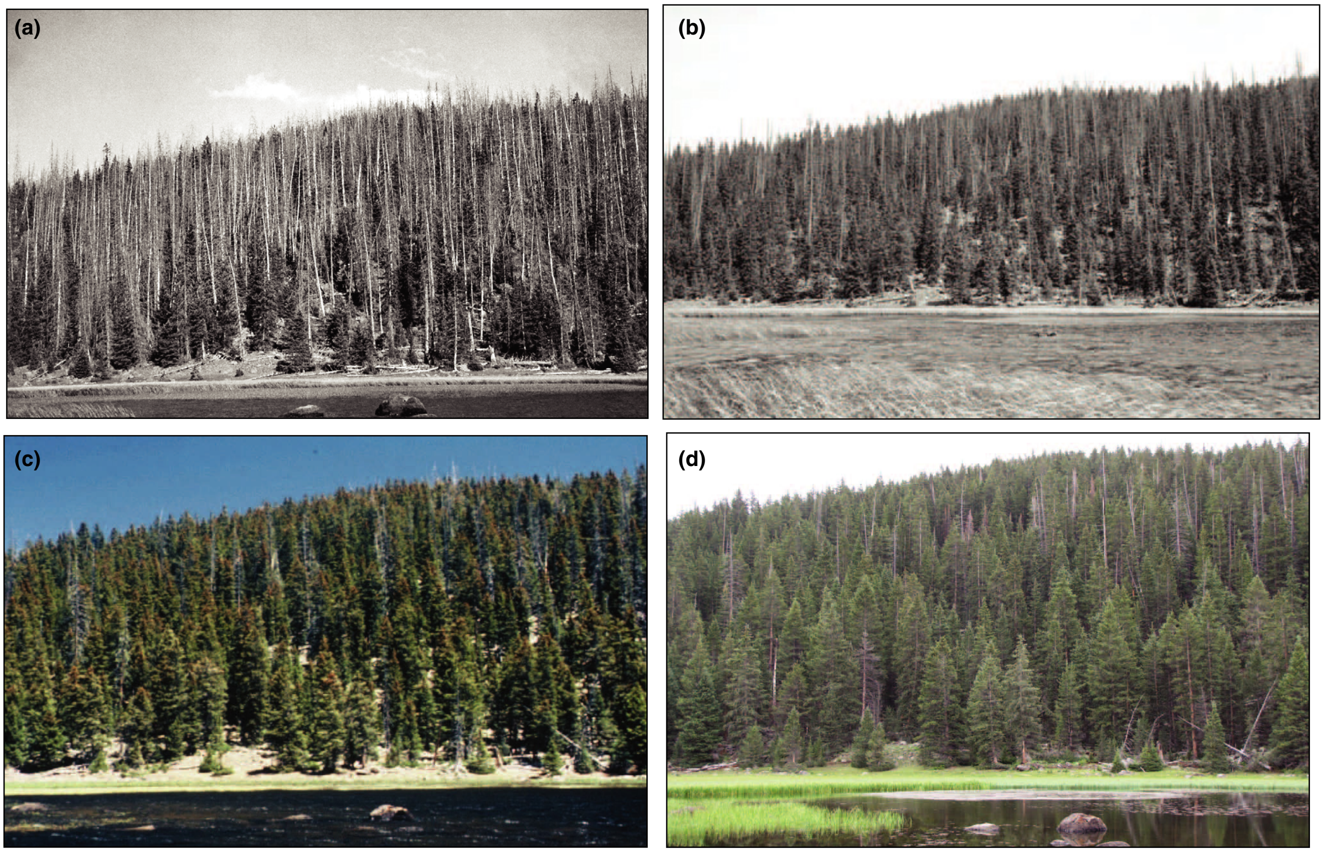


Figure 1. *Rephotographic series showing forest recovery following a high-severity spruce beetle (*Dendroctonus rufipennis*) outbreak around Purple Lake, Utah, in the 1940s (Morris and Brunelle 2012). These images were taken in (a) 1948, (b) 1968, (c) 1992, and (d) 2010.*

Flint *et al.* (2009) emphasized the importance of understanding how communication of scientific information and management strategies related to bark beetles will influence public perceptions of outbreaks, as well as associated efforts to control for undesirable social and environmental outcomes. One potential path forward is to develop "practical adaptation initiatives", which assess appropriate mechanisms for addressing ecological disturbances. Often, adaptation initiatives are region-specific and seek to inform societal responses to environmental change that are specific to the affected landscapes and communities (Smit and Wandel 2006). Identification of effective social and ecological adaptive responses requires a critical understanding of current and region-specific management strategies, the efficacy of those strategies, the capacity of a management agency to promote and adopt new strategies, and the real and perceived barriers that constrain implementation of these adaptive strategies (Engle 2011).

Public perceptions of and policies related to silvicultural treatments are important factors that can further motivate (or diminish) enthusiasm for forest thinning or salvage programs in response to outbreaks (Figure 2). In some regions, public views on fuel reduction programs are mostly favorable; for instance, in a survey concerning three national forests in Colorado and Wyoming that were heavily impacted by MPB during the 1990s, Clement and Cheng (2011) found that, following the outbreak, the majority of respondents favored logging to reduce forest fuels and to benefit wildlife habitat. However, survey participants were less supportive of salvage logging conducted purely for economic reasons.

Governance

Knowledge transfer and feedback among bark beetle ecologists, associated municipalities, and governance institutions are complex. It can be challenging to identify where critical linkages exist in the exchange of information within a SES. This difficulty often results from mismatches in the scaling of available spatial and temporal data. If relevant ecological data are available and disseminated effectively, governance institutions have the capacity to lead suppression strategies and shape the trajectory of ecological change related to bark beetles to bolster forest and community resilience (Folke *et al.* 2009). Prior to, during, and after bark beetle outbreaks, societal expectations may dictate a variety of management and policy responses that may (or may not) be effective in attaining the intended goals set forth by local, regional, and national mandates. In some cases, public attitudes and values influence management-led actions and policies aimed at addressing bark beetle disturbances (McGrady *et al.* 2016). For instance, during an outbreak of MPB, a majority of surveyed recreational users of public lands in western Colorado and Wyoming generally supported management practices, and agreed with the position of "do what you need to save the forest" (Czaja *et al.* 2012).

Governance policies to address bark beetles vary across regional jurisdictions and are based on many factors, including economic interests, and human perceptions and behavior. However, regional distinctions also exist in terms of how bark beetles are managed on public versus private lands (Scarlett and Boyd 2015). In the US, most federally managed forests are administered as national forest lands that occur mainly in the western, Great Lakes, and Appalachian regions. Broadly, these forests are separated from major population centers (southern California is an exception) and are composed of coniferous tree genera (eg *Picea*, *Pinus*, *Pseudotsuga*) susceptible to bark beetle infestation. Federal land-management goals in these regions often focus on achieving multiple, sometimes competing objectives, including recreation and timber production, among others (Littell *et al.* 2012). In contrast, the pine-dominated forests of the northeastern and southeastern regions of the US are generally managed by private landowners and are relatively close to major population centers. There are important differences in management strategies between public and private land agencies, including how policies and strategies are implemented, the procedural challenges to augmenting strategies, and the timelines of implementation (Scarlett and Boyd 2015).

Although public opinion is an important factor in shaping governance policies and associated actions (Wellstead *et al.* 2006), only a handful of studies have assessed the social acceptance of various suppression strategies to deal with bark beetle outbreaks. Several case studies note that user attitudes toward management actions vary considerably when compared at the regional scale. For example, McFarlane *et al.* (2006) examined public attitudes toward MPB outbreaks in western Canada's Banff National Park and Kootenay National Park, and found that most visitors agreed with the view that "allowing the outbreak to follow its course without intervention" was unacceptable. However, this perspective differed from that of survey respondents in Germany, who generally expressed a neutral attitude toward intervention during an outbreak of the European spruce bark beetle (*Ips typographus*) in Bavarian Forest National Park. The respondents were disinclined to support management control measures within the park (Müller and Job 2009). In both studies, education level was an important factor in shaping perceptions about management interventions. In general, visitors to Bavarian Forest National Park possessed greater scientific understanding of the associated land-management implications than did visitors to the Canadian parks, or those to North American destinations in general. Assessing how education level influences public perception of land-management strategies is an important, albeit understudied, research topic that has the potential to facilitate knowledge transfer among regional governance agencies.

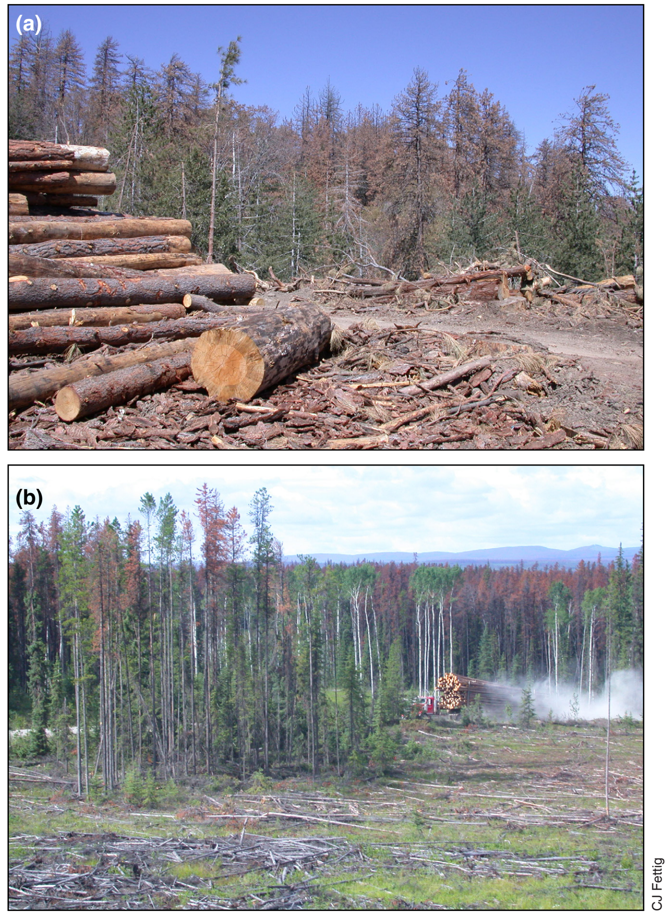


Figure 2. *Salvage logging following bark beetle outbreaks in (a) southern California and (b) British Columbia, Canada.*

The importance of region-specific policies will increase as bark beetles expand their ranges, and as new groups of public and private managers respond to these disturbances. For instance, outbreaks of SPB in New York, New Jersey, and Connecticut are novel events in the 20th-century context, and have occurred on both private and federally managed forests (Clarke *et al.* 2016). Although SPB management guidelines are well established in the southern US, historically there has been little need to adopt such strategies in northern forests, where SPB exhibits different host colonization behaviors (Fettig *et al.* 2007). In some instances, information about effective treatment methods and other usable data that may be instructive for preventative treatments (eg cut-and-leave or cut-and-remove) is unavailable or difficult to access. Moreover, the presence (or absence) of local timber harvesting and processing infrastructure in a region may create additional challenges to those attempting to carry out timely and effective suppression measures (Clarke *et al.* 2016).

Synthesis

Given the above description of social–ecological dynamics associated with bark beetle outbreaks, we propose

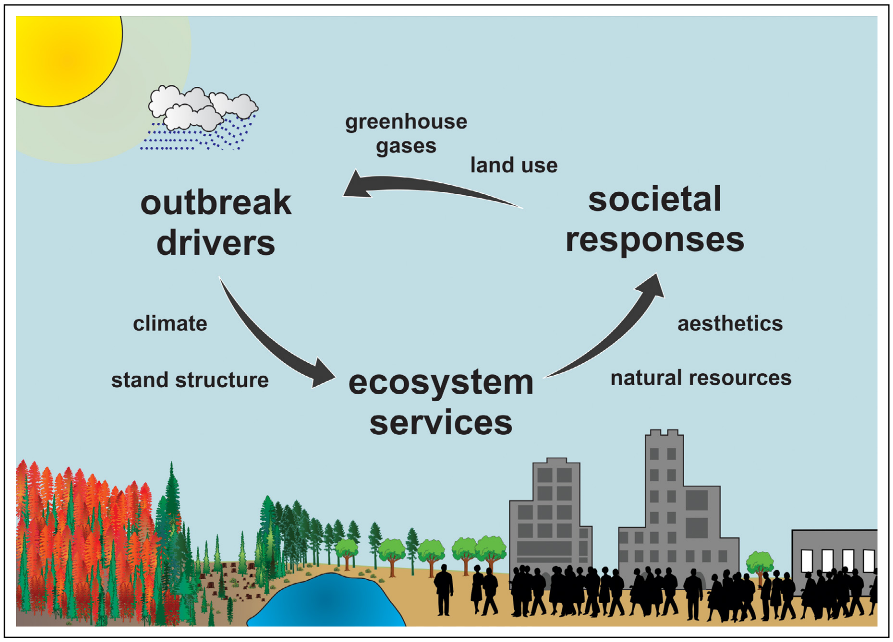


Figure 3. *Framework for understanding the interaction of bark beetle disturbances within a social–ecological system.*

a conceptual model depicting the prominent interactions and feedbacks within a regional SES that has experienced (or has the potential to experience) a severe outbreak (Figure 3). In our assessment, the regional governance agencies are emphasized because numerous studies have demonstrated their efficacy, and because jurisdictional reach tends to overlap at this spatial scale (eg Simmie and Martin 2010). As noted above, the primary drivers of bark beetle outbreaks are the interacting factors of a warming climate and susceptible stand conditions. Severe outbreaks modify the provision of ecosystem services relative to undisturbed forests, including landscape aesthetics, and the quality and quantity of timber and water resources. How humans perceive and respond to these phenomena depends on the cognitive traits of individuals, which are shaped by level of education, values, attitudes, norms, beliefs, intentions, and ultimately behaviors. Human behavior – including social norms, lifestyle choices, beliefs, and attitudes – are often expressed in both scientific and mainstream media. In turn, patterns of human behavior both directly and indirectly shape public policy and economic programs (Rokeach 1973; Clement and Cheng 2011). Feedback loops exist within these cognitive traits; for example, information provided by scientific and popular media help to shape human beliefs, attitudes, and behaviors, which may in turn enhance (or diminish) the impacts of forest disturbances and/or land-use practices on SES (Flint *et al.* 2009; McGrady *et al.* 2016).

The potential for bark beetle outbreaks to affect communities and management paradigms in regions that historically have not experienced severe beetle outbreaks is perhaps an eventual outcome of climate warming during the 21st century. Rising temperatures have already expanded the spatial range of suitable thermal habitat, and, at least in some cases, have also enhanced the reproductive capacity of bark beetles. Changes in bark beetle populations have enabled historically novel host interactions, such as the infestation of jack pine (*Pinus banksiana*) by MPB in Canada's boreal forest (Cullingham *et al.* 2011; Sambaraju *et al.* 2012). However, although a beetle species is capable of moving into new landscapes, this does not mean that the new tree species it encounters will be a susceptible host (Bentz *et al.* 2017). Similarly, regionally synchronous outbreaks are not necessarily a given, and only a few studies have explored how past climate dynamics influenced outbreak synchrony and intensity at any spatial scale (Jarvis and Kulakowski 2015).

Contrasting shifts in property values suggest that quantifying the relative changes resulting from the impacts of bark beetle outbreaks on economies are shaped by regionally and culturally specific perspectives; this complexity will necessitate evaluating the ecosystem services affected by outbreaks and their dynamics over time. For instance, the appreciation of property values following an outbreak in Alaska, described above, suggests an emerging paradigm for assessing disturbance-mediated impacts; to accurately account for adjustments in market prices after outbreaks, both benefits and disruptions to aesthetics and ecological services must be measured.

Conclusions and future research

Recent bark beetle outbreaks in North America and Europe have had considerable impacts on forests and the provision of ecosystem services that challenge SES resilience and adaptive capacity. Novel approaches to address these issues are likely to attract interest from governance agencies, the public, and private managers as outbreaks spread into previously unaffected regions. Potential innovations that could aid in monitoring and suppressing outbreaks include the development of (1) low cost, technologically advanced equipment to assess the intensity, and spatial and temporal synchrony of outbreaks; (2) methods to better and more fully evaluate the net impact of outbreaks on SES beyond the current, frequently used metrics (eg area affected, host tree mortality rates, and changes in forest structure and composition); (3) models that forecast future bark beetle (and host) range shifts due to changes in suitable thermal habitat that are integrated with risk and hazard rating systems; (4) a better understanding of how public attitudes and values toward bark beetle outbreaks interface with associated management actions and policies; (5) adaptation strategies that emphasize the regional spatial scale; and (6) improved methods for transferring, maintaining, and applying knowledge learned during recent outbreaks to future outbreaks (Morris *et al.* 2016). Specifically, it is imperative that the information gained from SES research be transferred to land managers, governance agencies, and grassroots leaders in a practical and useful framework that sustains ecosystem resilience, the services it provides to dependent communities, and the knowledge base of the people living in affected regions.

The seemingly unprecedented occurrence of outbreaks in novel regions should motivate research programs to produce high-resolution retrospective studies, specifically those that help to constrain the climate and land-use drivers that promote high-severity infestations. To achieve advances in these areas, new research agendas may benefit from exploring metrics commonly used in SES that facilitate comparison across regions and among forest types. Comparing disparate regions and dissimilar forest types could potentially be addressed by explicitly linking ecosystem services to monetary values or other emerging marketplace standards, such as carbon.

There is a clear need to improve assessments of how human perspectives respond to outbreaks and evaluations of how stakeholders respond to changing landscape aesthetics, which may foster deeper understanding as to why specific user groups prefer some landscape qualities over others. Management agencies must weigh trade-offs between shaping landscapes to be reflective of past environmental conditions and the aesthetic expectations of forest user groups, the outdoor recreation industry, and adjacent communities. However, landscape treatments designed to meet multiple-use objectives will undergo scrutiny from the public based on the type of silvicultural methods applied and the proximity of the landscape to residential areas. To address divergent public opinion, researchers must facilitate timely dissemination of scientific results through various specialized and popular media outlets, as well as provide a platform to engage the concerns of a diversity of user groups. The sensitivity and resilience of ecosystem services to disturbance is likely regionally specific, and dependent on the ability of various public and private agencies to adapt to and manage beetle-impacted landscapes. Communicating the role of disturbances in forest ecology is an important aspect of educating governance agencies, forest user groups, and the general public.

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