

Bark Beetle-Induced Forest Mortality in the North American Rocky Mountains

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ABSTRACT

The epidemic of mortality by insects and disease throughout the Northern American Rocky Mountains exceeds previous records both in severity and spatial extent. Beetle attacks weaken trees and introduce blue-stain fungi that induce hydraulic failure leading to mortality. The magnitude of this outbreak spurs predictions of major changes to biogeochemical cycling and hydrologic response, changes in species assemblages, and increased wildfire risk. Review of emerging empirical studies reveals conflicting evidence of changes and limited environmental threats. However, widespread forest mortality generates net economic costs and losses by reducing or eliminating market and nonmarket value. Potential deadfall may threaten human life and infrastructure and add costs of programs for hazard-tree reduction. Although forest regeneration following insect epidemics indicates resilient ecological systems, synergistic interactions of beetle kill with other disturbance processes, exacerbated by warming temperatures and drought may stimulate longer-term environmental concerns.

6.1 INTRODUCTION

6.1.1 The Nature and Extent of Mortality by Insects and Disease

Commencing in the late twentieth century, epidemic infestations of bark-boring beetles escalated throughout the Rocky Mountains of North America. Estimates of forest mortality by insects and disease (commonly referred to as “beetle kill”) range from 6 to 11 million hectares (Meddens et al., 2012). The extent, duration, and severity of the outbreak are unprecedented in recent history (Raffa et al., 2008). Endemic beetle populations transitioned to epidemic levels as environmental conditions exceeded thresholds of natural

population controls (Raffa et al., 2008; Six et al., 2014). Population explosions are attributed to a synergistic combination of climate change (Bentz et al., 2010; Kurz et al., 2008; Logan and Powell, 2009), drought (Adams et al., 2012; Greenwood and Weisberg, 2008), dense forest structure resulting from fire suppression, and increased forest homogeneity from forest management practices (Raffa et al., 2008). The magnitude of the forest mortality and prediction of increased frequency and severity of future outbreaks (Hicke et al., 2006) raise concerns about multiple impacts addressed in this essay: altered biogeochemical cycling and hydrologic response, reductions in overall forest condition and economic value, future wildfire behavior, vegetation response and changes to forest composition, and interacting disturbance processes.

Nine species are identified as aggressive bark beetles, each associated with a host tree species (see Bentz et al., 2009 for an overview of beetle biology and infestation). Two beetle species are primarily responsible for forest mortality. The mountain pine beetle (*Dendroctonus ponderosae*) prefers lodgepole (*Pinus contorta*), ponderosa (*Pinus ponderosa*), limber (*Pinus flexilis*), and whitebark pine (*Pinus albicaulis*) as host tree species. At higher elevations, the spruce bark beetle (*Dendroctonus rufipennis*) utilizes Engelmann spruce (*Picea engelmannii*) to complete its life cycle. Although both species of beetles bore through the bark of their host, feed on phloem, and lay eggs, neither boring nor phloem feeding kills the trees. Both beetle species carry strains of the blue-stain fungi (*Grosmannia clavigera*) (Six and Bentz, 2003; Six and Wingfield, 2011), and through their action infect the host tree xylem with fungi, which spreads rapidly blocking the tree's water transport system, causing tree death due to hydraulic failure (Hubbard et al., 2013; Knight et al., 1991; Yamaoka et al., 1995).

Progression of beetle kill is described in five phases, green, red, gray, tree fall, and regeneration, and impacts vary by phase (Mikkelsen et al., 2013; Pugh and Gordon, 2013). In the green phase needles appear green, even after beetle attack has killed the tree (Wulder et al., 2006). During the red phase, needles change color to red and brown and fall to the ground (Pugh and Gordon, 2013). Only bare stems and branches of standing trees remain in the gray phase (Wulder et al., 2006) and dead trees fall from wind throw or simply gravity as roots decay. Regeneration of vegetation on the forest floor has been observed throughout the progression of beetle kill as the canopy opens and completion for water use by mature trees declines (Figure 6.1). Although several studies report on local regeneration patterns (Collins et al., 2011; Hadley and Veblen, 1993; Seidl et al., 2008), data on regeneration trends in the North American Rocky Mountains are limited. Forest mortality due to beetle infestations starts as scattered pockets and spread with nonlinear increase (Figure 6.2). Patterns of mortality vary within stands (Figure 6.3) due, in part, to mixed species composition and tree density. Mortality also varies between stands in close proximity to each other (Figure 6.4).



FIGURE 6.1 Regeneration following beetle kill of lodgepole pine (*Pinus contorta*) stand (Figure 6.1) with abundant seedlings and saplings. Photo: Hyde, K., August 25, 2014.

6.2 EFFECTS OF BARK BEETLE IMPACTS

6.2.1 Nitrogen

It has been hypothesized that the beetle epidemic would alter the forest nitrogen (N) cycle (Edburg et al., 2012). Although disturbances such as logging or severe storms can greatly increase stream N (Likens et al., 1970; Rhoades et al., 2013), and some model simulations showed a strong increase in available N locally due to beetle-caused mortality (Edburg et al., 2011), it was unclear how this excess N would move through the larger ecosystem. Although both litter N concentration and N-mineralization rates may increase in the early stages of beetle infestation (Griffin et al., 2011; Morehouse et al., 2008; Norton et al., 2015), stream N concentrations in a Colorado forest showed no change in a watershed heavily impacted by bark beetles (Rhoades et al., 2013) and stream-water nitrate was not significantly related to the percent of the basin impacted by beetles (Clow et al., 2011). The findings suggest that residual vegetation in the watershed was utilizing the excess N available from increased litter inputs and decreased uptake by the dominant forest canopy trees (Rhoades et al., 2013) rather than being transported out of the system in streamflow.

6.2.2 Carbon

Although beetle-caused forest mortality does not immediately change the total amount of ecosystem carbon like logging or wildfire, beetle impacts to carbon cycling in conifer systems have the potential to greatly alter the forest carbon balance (i.e., the rate of C exchange between ecosystem and atmosphere). Some modeling studies projected a large emission of carbon to the atmosphere in the years following beetle mortality (Edburg et al., 2011; Kurz et al., 2008).

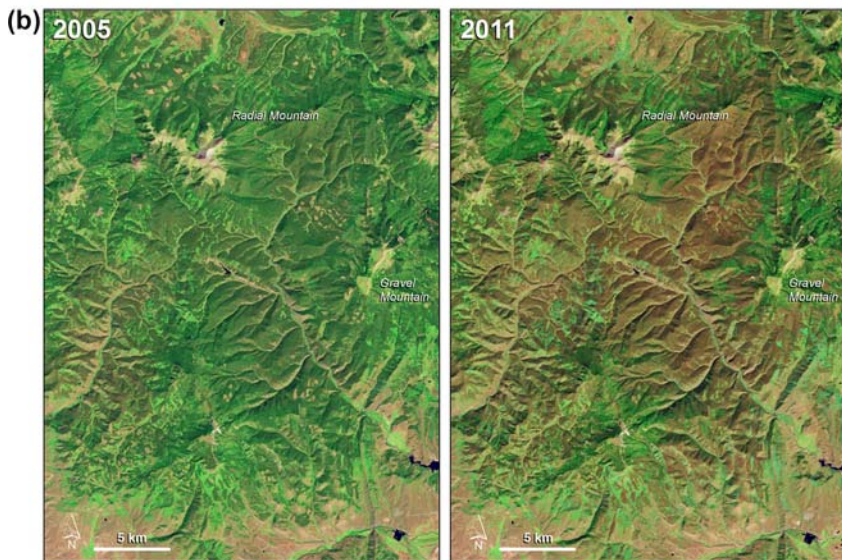
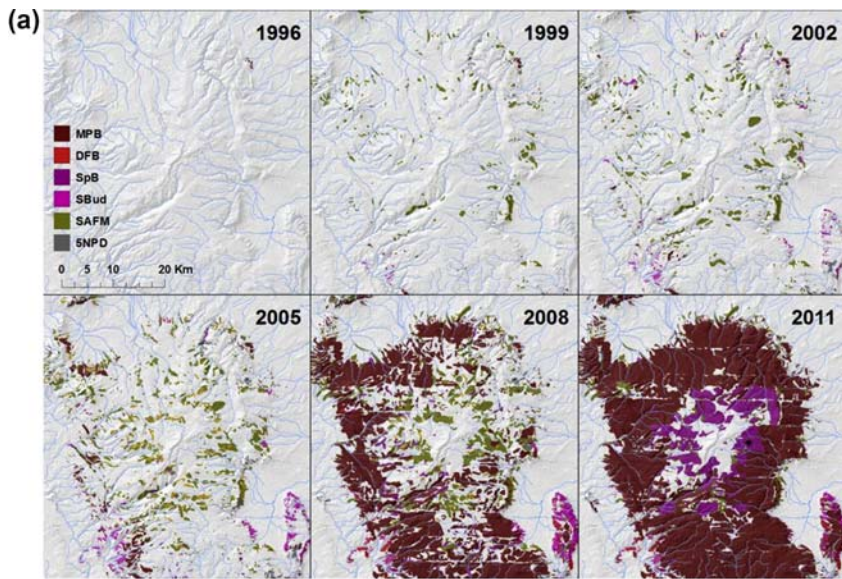


FIGURE 6.2 (a) Progression in 3 years increments of tree mortality due to insects and disease from 1996 to 2011, Snowy Range of the Medicine Bow Mountains, WY, USA. Six agents are mapped: MPB—mountain pine beetle (*Dendroctonus ponderosae*), DFB—Douglas fir beetle (*Dendroctonus pseudotsugae*), SPB—spruce beetle (*Dendroctonus rufipennis*), SBud—spruce budworm (*Choristoneura fumiferana*), SAFM—subalpine fir mortality complex, 5NPD—five needle pine decline. Mortality by SAFM and 5NPD involves multiple insect and disease pathogens (Maps: Hyde, K. Source data: Aerial detection survey, Region 2, USDA Forest Service. Available at: http://www.fs.usda.gov/detail/r2/forest-grasslandhealth/?cid=fsbdev3_041629. (accessed 27.11.14)), (b) Die-off in the lodgepole pine (*Pinus contorta*) forests near Grand Lake, Colorado, USA due to beetle infestation illustrated by Landsat-5 Thematic Mapper images acquired in Sept 2005 (left) and Sept 2011 (right). Forest die-off is most noticeable in the middle of this image pair. Brown areas in the 2011 image are mostly lodgepole pine stands, while the areas that remained green are either Engelmann spruce (*Picea engelmannii*) or aspen (*Populus tremuloides*) dominated forests that escaped infestation (Image-pair: Sivanpillai, R. Source data: Simmon, R., *Enhanced Landsat images*, NASA Earth Observatory. Available at: <http://earthobservatory.nasa.gov/IOTD/view.php?id=78677>).



FIGURE 6.3 Heterogeneous patterns of tree mortality reflecting, in part, mixed species composition—Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*), Snowy Range of the Medicine Bow Mountains, WY, USA. Photos: Hyde, K., August 12, 2014.

However, measurements at instrumented field sites suggest alternative trajectories. In Canada, researchers reported that stands with high levels of mortality were net carbon sinks within 5 years of infestation (Brown et al., 2012), whereas in the United States, Reed et al. (2014) reported no change in maximum carbon uptake as mortality in the stand increased from 30% to 78%. Despite canopy mortality levels exceeding 50%, drastic reduction in carbon uptake was not observed, and suggests that the remaining live trees and understory vegetation play a crucial role in the carbon cycle during the mortality event (Bowler et al., 2012; Brown et al., 2012; Collins et al., 2012b; Reed et al., 2014). However, in a high-elevation ecosystem of Engelmann spruce—subalpine fir, Frank et al. (2014) observed a 51% decrease in growing season C uptake where the majority of the canopy trees had died. These studies suggest that beetle-caused impacts to the carbon cycle may be dependent on the specific forest ecosystem affected.

6.2.3 Water

The primary impacts of beetle kill relative to water resources is loss of canopy leading to direct and indirect changes to hydrologic processes. A conceptual model based on a simple water balance approach follows that widespread forest mortality and canopy loss permit more rain and snow to reach the forest floor and significantly reduce transpiration. Therefore, more water moves into the soil and transfers to groundwater and streamflow; ideas confirmed by predictive modeling exercises (Mikkelsen et al., 2011). Several hypotheses extend from expected increases in streamflow. Water yields may increase, accompanied by higher peak flows, more frequent and extreme flooding, and elevated erosion of hillslope and stream channel (Adams et al., 2012; Redding et al., 2008). Sediments produced through erosion may impair water quality

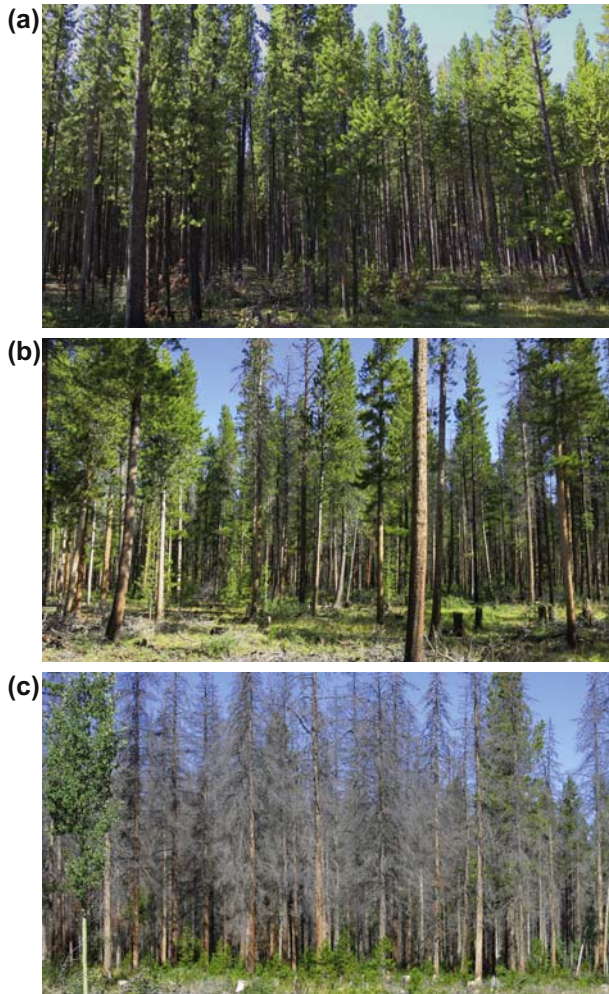


FIGURE 6.4 Progressive stages of beetle outbreak in stands of lodgepole pine (*Pinus contorta*): (a). no evidence of infestation, (b). 20–30% of trees killed, (c). mortality exceeded 80–90%. These stands are located within 100 m of each other illustrating the spatial variability of beetle-induced mortality even at fine scales. Note regeneration in stand (b) and (c) with more detail in [Figure 6.2](#). Photos: Hyde, K., August 25, 2014.

and threaten aquatic habitat and human uses. Baseflow during low-flow periods may also increase, with higher flows extending later into the warmer summer months. A contrary hypothesis suggests that water yields may decrease in drier forests under warming climate conditions ([Adams et al., 2012](#)).

The expectation of increased stream discharge following forest disturbance has been driven in part by observations of large increases in runoff following

wildfire (see [Moody et al., 2013](#)) and forest harvest (e.g., [Stednick, 1996](#); [Troendle and King, 1985](#)), however, the analogies are limited ([Adams et al., 2012](#); [Pugh and Gordon, 2013](#)). Harvest and wildfire cause rapid and commonly spatially continuous change to forest structure, where severe wildfire especially disrupts the entire biophysical system. Extreme fire events consume all biomass and destroy soil structure. By comparison, the gradual processes of mortality by insects and disease are generally not spatially continuous ([Figure 6.3](#)) and do not impair the potential of remaining vegetation to use water otherwise not consumed by impacted trees.

Results from empirical studies of observed hydrologic changes following forest mortality by insects and disease are mixed and contradictory ([Table 6.1](#)). Studies from 40 and 50 years ago reported stream discharge following beetle epidemics were observed to modestly increase within a few years immediately following an outbreak ([Potts, 1984](#)) or were most pronounced 15 years later ([Bethlahmy, 1974](#)). A more recent study found that groundwater contributions to streamflow increased due to reduced summer transpiration as trees succumbed to beetle attacks ([Bearup et al., 2014](#)). However, comparative analysis of discharge from multiple catchments found no detectable changes in streamflow ([Hyde et al., 2014](#); [Somor, 2010](#)) and in one catchment, streamflow significantly declined ([Somor, 2010](#)). No changes or declines in streamflow may be due to observed compensations where increases in evaporation due to open canopy outpaces decreased transpiration ([Biederman et al., 2014a](#)), or where increased transpiration from accelerated growth of recovering vegetation ([Ewers et al., 2013](#)) outpaces decreased transpiration from tree mortality ([Brown et al., 2014](#)). Response of surviving trees adjacent to gaps opened by dead trees may provide an additional compensatory mechanism. Living roots rapidly fill the root gaps ([Parsons et al., 1994b](#)) and may explain muted impacts both with nutrient cycling ([Parsons et al., 1994a](#)) and hydrologic response as living roots exploit freed resources.

Snowmelt infiltration drives the overall hydrology and therefore streamflow of many of the areas impacted by beetle infestations. Complex process interactions controlling snow accumulation and melt are therefore expected to strongly influence hydrologic response to widespread tree mortality ([Mikkelsen et al., 2011](#); [Pugh and Gordon, 2013](#); [Pugh and Small, 2012, 2013](#)). Impacted processes include evapotranspiration, soil infiltration, solar transmission and energy storage, needle fall, wind speed, canopy interception, sublimation, snowmelt timing, and water yield and the relative process role and interactions vary by the stages of infestation and mortality (see [Pugh and Gordon, 2013](#) for a thorough discussion of processes and interactions). Research into interactions between snow processes and beetle infestation are beginning to emerge ([Table 6.1](#)). Low ablation rates (loss of snow from evaporation, sublimation, and wind redistribution) and increased ground-snow accumulation were found to lengthen the snowmelt period

TABLE 6.1 Summary of empirical studies of streamflow change and snow hydrology related to impacts of beetle infestations itemizing study location and dominant conifer species

Location	Dominant Species	Summary	Sources
Streamflow Change Studies			
Colorado, USA	Lodgepole pine	30 ± 15% increase in late-season contribution of groundwater to streamflow, probably from transpiration losses—hydrograph separation and stable-isotope analysis	Bearup et al. (2014)
Colorado, USA	Engelmann spruce	Modest increases in streamflow, most pronounced 15 years following epidemic outbreak	Bethlahmy (1974)
British Columbia, Canada	Lodgepole pine	Increased transpiration from spurred growth of residual vegetation compensated for reduced water use	Brown et al. (2014)
Wyoming, USA	Mixed subalpine conifer	No detectable changes in discharge after accounting for variable snow inputs	Hyde et al. (2014)
Montana, USA	Lodgepole pine/mixed conifer	15% Increase in average annual water yield with earlier peak flow and 10% increase in low flows	Potts (1984)
Colorado and Montana, USA	Lodgepole pine/mixed subalpine conifer	No detectable changes in discharge observed in 7 catchments—significantly reduced streamflow in one catchment	Somor (2010)
Snow Hydrology Studies			
Colorado, USA	Lodgepole pine	Snowpack depth and density increased in dead stands	Pugh and Gordon (2013)
British Columbia, Canada	Lodgepole pine/mixed subalpine conifer	Litter from dead and dying trees accumulates on snowpack, decreases albedo and increase snowpack ablation	Winkler et al. (2010)
Colorado and Wyoming, USA	Lodgepole pine	No change in streamflow—vapor loss from evaporation and snowpack sublimation counteracts decreased transpiration and canopy interception losses	Biederman et al. (2014a)
Colorado and Wyoming, USA	Lodgepole pine	Increased sublimation losses from snow-surface compensates for decreased loss from canopy interception and sublimation	Biederman et al. (2014b)
British Columbia, Canada	Lodgepole pine	Snow accumulation while ablation rates remained similar leading to longer snowmelt period	Boon (2007)

(Boon, 2007). Needles dropped from dead and dying trees interact with other factors to alter snow-surface albedo and ablation rates (Winkler et al., 2010). Snow accumulated to greater depths in dead stands due to reduced interception and sublimation, compared to nearby live stands (Pugh and Small, 2012, 2013). Yet another study observed no difference in peak snow–water equivalent between infested and uninfested forest stands, concluding that increased snowpack sublimation compensated for reduced canopy sublimation (Biederman et al., 2014b).

6.2.4 Vegetation Response

Concerns about long-term vegetation response to beetle kill include possible changes to species assemblages, widespread die-off, and changes to wildfire risk. A combination of field and modeling studies in Colorado and Wyoming, USA, indicated that in lodgepole pine stands where subalpine fir seedlings established prior to an outbreak, fir will become the dominant species as vegetation recovers (Collins et al., 2011). Increases in fir density are expected to vary by lodgepole forest type and moisture conditions (Kayes and Tinker, 2012). Impacts of beetle infestations may be amplified by other forest disturbance processes, especially wildfire, and drought (Adams et al., 2012), contributing to current global trends in widespread forest die-off under warming climates (Allen et al., 2010).

Evidence is mixed on changes to wildfire risk due to insect-related mortality. The time since the onset of infestation strongly influences changes in fire behavior and confidence varies in the likelihood of the range of possible changes to fire behavior (see Hicke et al., 2012 and Jenkins et al., 2014 for thorough reviews). In the Intermountain West, USA, insect epidemics in any coniferous stands may result in increased fire spread rates, fire intensities, and potential for passive crown fires (Jenkins et al., 2008), and downed trees in impacted lodgepole pine stands are expected to increase coarse fuel loads (Collins et al., 2012a). Yet in contrast to these predictions of increased fire severity, field observations found fire severity to be unrelated to the severity of prefire beetle outbreaks throughout coniferous stands in the Northern Rocky Mountains, USA (Harvey et al., 2014).

6.2.5 Economic Costs and Losses

Concerns about the direct threat to life and property from falling trees killed by the bark beetle outbreaks have prompted a widespread campaign to identify and remove hazardous trees throughout public lands in the United States (see <http://www.fs.usda.gov/main/barkbeetle/safety>). The cost of hazardous tree removal is substantial. For example, on the Laramie Ranger District of the Medicine Bow–Routt National Forest hazardous trees are identified and removed adjacent to highways (Figure 6.5), power lines, and forest roads and



FIGURE 6.5 Hazardous trees marked for removal (blue blaze) along Hwy 130 through the Snowy Range of the Medicine Bow Mountains, WY, USA. *Photo: Hyde, K., December 12, 2014.*

within and adjacent to campgrounds.¹ Cost for physical removal of hazardous trees ranges from \$1.5K to \$2K per acre with costs along highways at the upper end of the range or higher. This estimate does not include personnel time to cruise and mark trees or time to manage contracting and sales administration. Since 2010 approximately 100 miles of highways and forest roads have been treated at an average of 15 acres per mile for an estimated cost of \$2.25M. To put this in perspective, six Ranger Districts occur in this National Forest and as many as 97 National Forests occur in the Western US where hazardous tree removal may be required.

In addition to the costs of removal of hazardous trees, bark beetle epidemics cause substantial economic losses to timber markets and nonmarket economic values. Where large volumes of timber are killed, salvage operations create a short-run pulse of timber and drive prices down. This results in a transfer of wealth from timber producers (growers) to timber consumers (mills); producers lose and consumers gain and the net effect is an unambiguous loss of economic value (Holmes, 1991). For example, analysis of the timber market, based on three decades of data concluded that southern pine beetle (SPB) (*Dendroctonus frontalis* Zimmermann) epidemics resulted in an average annual loss of \$13M in the U.S. South (Pye et al., 2011). Although timber mortality from bark beetle epidemics can increase timber prices over the long run, due to relative timber scarcity, the average annual long-run

1. This information provided via personal communication with S. Alberts on January 7, 2015.

market impacts of SPB have historically been small relative to the short-run market impacts (Pye et al., 2011).

The potential for economic benefit from salvage logging in areas impacted by bark beetles depends upon the scale of the outbreak relative to the processing capacity of local timber markets. The current scale of processing capacity in Idaho, Montana, Washington, Oregon, California, and South Dakota appears adequate to absorb the supply of timber salvaged from the current MPB epidemic while maintaining positive economic returns for producers and consumers (Prestemon et al., 2013). Although the relatively small scale of timber processing capacity in Colorado and Wyoming, where substantial volumes of salvageable timber occur, is too small to economically salvage all of the timber killed by MPB, the reopening of a sawmill in Wyoming to salvage timber from the Medicine Bow National Forest shows that new economic opportunities exist. In another example, timber salvage operations in British Columbia resulting from the recent MPB outbreak created a short-term boom for the regional timber economy as well as the service and retail sectors (Patriquin et al., 2007). However, in the longer run, the magnitude of the MPB epidemic suggested that the scarcity of future timber supplies will not allow the regional timber economies to return to preepidemic levels once all merchantable timber has been salvaged.

A second category of economic damage resulting from bark beetle outbreaks is the impact on nonmarket economic values such as recreation and landscape aesthetics. An early study of the recreational impacts of MPB, using the travel cost method, was conducted on the Targhee National Forest by comparing use of campgrounds with different levels of MPB infestations (Michalson, 1975). The authors found a substantial loss of economic value to campers, due to less frequent visits and shorter stays, in the areas with heavier MPB infestations, and the annual losses on this Forest were estimated to exceed \$500K. A similar study was conducted in East Texas reservoir campgrounds and found that economic losses from SPB outbreaks exceeded \$1M for some campgrounds (Leuschner and Young, 1978). However, the authors correctly recognized that although some campers may be discouraged from using specific campgrounds where bark beetle activity is severe, they may choose to utilize other, unattacked sites. Substitution of unattacked campgrounds, where available, was found to reduce economic impacts by 85–90%.

In contrast to the studies of bark beetle impacts on actual recreational use, as described above, another approach is to interview recreationists to determine how their recreational choices might change due to infestations by bark beetle, and how much they are willing to pay for specific levels of healthy tree cover (Walsh and Olienyk, 1981). Using this approach in the Colorado Rocky Mountains Front Range, the authors found that a 1% decrease in the number of live trees found on recreation sites results in a 0.28% decrease in recreation demand. Despite the magnitude of the recent MPB outbreak in the Western

US, we are unaware of recent studies documenting the impact of bark beetles on recreation demand.

However, economists have conducted studies of the impact of the recent MPB outbreak on the value of residential properties using the hedonic valuation method. A loss in the value of homes located in residential forests impacted by bark beetle outbreaks results from the loss of aesthetic quality of surrounding landscapes and the costs of removing hazardous trees. Econometric analysis was used to analyze transactions of properties sold in Grand County, Colorado, which had experienced heavy infestations of MPB (Price et al., 2010), and it was found that the loss to homeowners was approximately \$648/tree for trees located within 0.1 km of their home. A second hedonic valuation study of the impact of MPB on residential property values was conducted in Larimer and Boulder Counties, Colorado (Cohen et al., 2014). The authors estimated that, for homes with host trees within 0.1 km, the average loss per home was roughly \$66K. Losses to residents in these counties who sold their home during the study period were estimated to be about \$36M and, when these estimates were extrapolated to all homes in the study area, the total losses were about \$137M.

6.3 SUMMARY

The epidemic of mortality by insects and disease throughout the North American Rocky Mountains exceeds previous records both in severity and spatial extent. Despite the magnitude of this outbreak, predictions of major changes to biogeochemical cycling and hydrologic response, changes in species assemblages, and increased wildfire risk have not been observed. In fact, evidence supports the conclusion that ecosystems recover quickly from impacts from beetle outbreak and local effects are muted at broader scales (Ewers et al., 2013). Forest regeneration following insect epidemics indicates highly resilient ecological systems. On the other hand, direct threats to life and infrastructure from falling trees have prompted costly programs to remove hazardous trees. Further, direct economic losses accrue as forest mortality reduces or eliminates market and nonmarket value.

However, as suggested by Adams et al. (2012), long-term environmental threats to impacted forests may emerge as warming temperatures exacerbate widespread drought. Beetle kill in water-stressed forests may synergistically interact with other anthropogenic and natural disturbance processes (Bigler et al., 2005; Kaiser et al., 2013; Raffa et al., 2008; Temperli et al., 2013) resulting in transformative landscape change (Adams, 2013; Allen et al., 2010; Breshears et al., 2005; Wilcox et al., 2012). In spite of the resiliency so far observed in the impacted forests, the possibility of wide-scale vegetation die-off indicates need to diligently monitor for long-term effects of mortality by insects and disease.

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