Climate Change and Ecosystem Disruption: The Health Impacts of the North American Rocky Mountain Pine Beetle Infestation

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In the United States and Canada, pine forest ecosystems are being dramatically affected by an unprecedented pine beetle infestation attributed to climate change. Both decreased frequency of extremely cold days and warmer winter temperature averages have led to an enphytotic devastating millions of acres of pine forest. The associated ecosystem disruption has the potential to cause significant health impacts from a range of exposures, including increased runoff and water turbidity, forest fires, and loss of ecosystem services. We review direct and indirect health impacts and possible prevention strategies. The pine beetle infestation highlights the need for public health to adopt an ecological, systems-oriented view to anticipate the full range of potential health impacts from climate change and facilitate effective planned adaptation. (*Am J Public Health.* 2012; 102:818–827. doi:10.2105/AJPH.2011.300520)

Globally, there is abundant evidence of accelerating ecosystem disruption associated with climate change.[1] Many of these disruptions are likely to have significant direct and indirect health effects through a variety of overlapping pathways.[2–4] Ecosystem changes can affect human health both directly and indirectly, from shifts in disease vector range and behavior to loss of ecosystem services. The current climate-driven pine beetle infestation of North America serves as a key example, although its health impacts have been little studied.

Predators of mountain pine beetles play a limited role in reducing pine beetle populations, and historically, temperatures have been the largest contributor to mortality.[5] In recent years, unusually high proportions of beetle larvae have survived over the winter, resulting in a devastating epiphytotic in North American pine forests[6] that is expected to continue and expand during the next century.[7] This is in sharp contrast to previous, smaller outbreaks, which were halted by temperature fluctuations and human interventions, such as stand thinning and insecticide application.[8–10]

As a result of these new dynamics, what were once sporadic epiphytotics are becoming a large enphytotic, with periodic epiphytotics expanding beyond the beetle's northern range. (For specialized terms used in this article, see box on the next page.) With its unprecedented scale, the current infestation is believed to have diminished a range of ecosystem services provided by pine forests and may increase the risk of several direct health effects resulting from increased runoff, surface water turbidity, and forest fires, along with their associated waterborne disease and respiratory disease impacts.

We explore the potential human health impacts of the current pine beetle infestation and apply a public health framework to identify interventions that may reduce future impacts.

MOUNTAIN PINE BEETLE AND BLUE STAIN FUNGUS ECOLOGY

Mountain pine beetles and related bark beetles are native, bark-burrowing insects found throughout the United States and parts of Mexico and Canada (Figure 1).[7] We focus on the *Dendroctonus* genus, the most destructive to the forests of the American West and western Canada. The beetles infest pine trees—particularly ponderosa, lodgepole, whitebark, Scots, and limber pines[7,12]—burrowing through bark and into tree phloem in the summer, where they feed and lay eggs. Pupae hatch and overwinter under the bark, maturing and migrating to a new tree by the following summer.[10]

Although the attack by beetles is harmful in itself, the dominant cause of tree mortality lies in the mutualistic relationship between the beetles and virulent blue stain fungi, including several from the genera *Grossmannia*, *Ophiostoma*, and *Leptographium*.[12] The beetles disperse the fungal spores with their mouthparts, inoculating host tree phloem while burrowing. The resulting fungal infection blocks the trees' vasculature, resulting in circulatory failure and death.[13] Both the fungi and beetles are well adapted to cold temperatures, enabling their mutual spread across the American West and western Canada.[14] The average beetle life span is approximately 1 year, and although they have natural predators, climate typically limits beetle populations.[15,16]

Climatological Drivers

The *Dendroctonus* life cycle is governed strongly by temperature.[17] Whereas adult and developing beetles are highly resistant to cold, larvae are unable to survive at temperatures below −40°C, which cause rapid mortality.[6,18] Shifts in seasonal temperature norms, particularly extreme cold, can thus interact to facilitate or limit beetle development, affecting abundance and population viability.[7,17]

Periodic, widespread pine beetle infestations, defined in terms of beetle population size relative to the abundance of available hosts,[19] are correlated with changing temperatures.[8] Hot and dry summers are often associated with outbreaks because the heat causes stress to the tree and root system and increases susceptibility to attack.[7] Warmer winters can promote increased survival of overwintering beetle larvae, resulting in greater initial spring beetle populations and larger infestations.[20,21] Cold spells have coincided with high rates of pine beetle mortality, ending or significantly diminishing the scope of infestations in British Columbia, for example, in 1949, 1972, 1979, 1984, and 1991.[8]

Glossary of Specialized Terms

Term	Definition
Enphytotic	A plant disease that persists in a plant population over a given period of time, similar to endemic disease in human populations.
Epiphytotic	Epidemic plant disease where the pathogen suddenly and rapidly affects many plants in a specific area, similar to epidemic disease in human populations.
Ecosystem services	The benefits to humankind from processes and natural resources that are supplied by natural ecosystems.
Annex I Country	An industrialized country and an economy in transition as classified by the United Nations Framework Convention on Climate Change.

Recent Changes in Pine Beetle Ecology

Since the mid-1970s, minimal winter temperatures have increased across North America, reducing the frequency of cold events below the −40°C survival threshold in areas traditionally inhabited by pine beetles.[8] Populations of both larval and adult stages have increased in size and become persistent in a larger geographic area, resulting in a widespread and rapidly expanding infestation of millions of acres of pine forest .[22–24]

The primary infestations responsible for current tree mortality began in 1996 in northern central Colorado and 1999 in central British Columbia.[25] As of 2008, the extent of the pine beetle infestation in the western United States and Canada had reached 35 million acres, 10 times larger than any previous recorded event.[24] This area of infestation is expected to increase with increased availability of climatically suitable habitat (Figure 2). In 2006, the US Forest Service estimated that 58 million acres of trees were at risk of dying by 2020 through insect-related disease in the United States, and bark beetles made up 7 of the top 11 etiological agents listed.[28]

The change in temperatures in the Rocky Mountains and Pacific Northwest has allowed the pine beetle to spread its range northward, and several projections estimate that continued temperature increases will allow for a large further increase in the area suitable for beetle habitation in northern latitudes.[23] Such a northward shift could potentially allow infestation of the susceptible species *Pinus banksiana*, which has been historically untouched by pine beetle because it is distributed exclusively in high northern latitudes.[23] Recent evidence suggests that the leading edge of the epiphytotic has begun to affect these trees, potentially threatening the vast North American boreal forest.[29] If the pine beetle spreads further north and becomes established in Canadian *P banksiana* stands, the infestation could then move eastward across Canada and reenter the United States in the Great Lakes region, opening up new areas for infestation (Figure 1).[23]

INFESTATION CONTAINMENT STRATEGIES AND THEIR EFFICACY

Containment strategies rely on early detection of infestations, initial aggressive direct control with selective logging or pesticides, and continued direct control actions.[30] Aggressive containment actions are warranted until the ratio of the pine beetle population and available hosts is maintained at an equilibrium endemic level where beetle populations persist at low numbers across the landscape and mainly breed in weakened trees.[19,31] Surveillance for infestations is typically carried out by the federal forestry agencies, the US Forest Service and the Canadian Forest Service. These agencies also coordinate containment using additional federal funding and the assistance of private landowners. Despite the practical emphasis on early infestation detection, there is little research on the role of surveillance and the added value of early detection in outbreak containment.

The efficacy of direct control measures has not been well evaluated, and more research is needed to determine the most effective strategies.[32] Forest managers and researchers are acutely aware that pine beetles can reproduce and spread rapidly. High temperatures, drought, and processes that homogenize forest age, population genetics, and reduce species diversity can synchronize pine beetle populations such that they overcome the eruptive threshold, generating epiphytotics.[15,25]

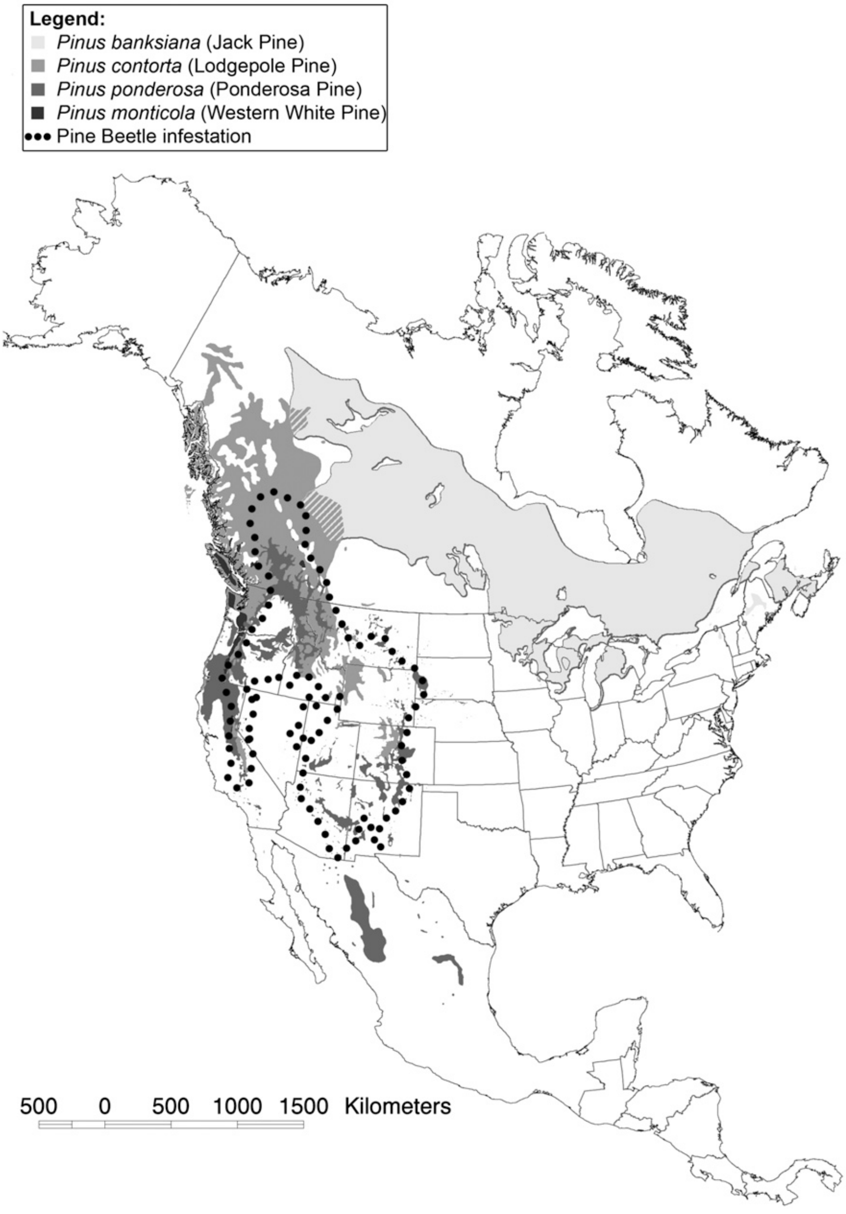
IMPACTS OF THE CURRENT EPIPHYTOTIC ON ECOSYSTEM SERVICES

Coniferous forests of North America, dominated by pine and spruce species susceptible to *Dendroctonus* species, provide a wide range of important ecosystem services.[33] Ecosystem services provided by pine forests can be classified as regulating, provisioning, cultural, and supporting,[34] and pine beetles can disrupt each of these service classes (Table 1). In economic terms, the forests of the United States contribute services valued at approximately $63 billion, with climate regulation, waste treatment, and food production accounting for approximately 75% of the estimated value.[35] There is an emerging literature on the role of ecosystems in protecting human health, with several studies of health impacts associated with ecosystem change and degradation and reviews of the health impacts of ecosystem disruption.[5,34,35] We review the specific ecosystem services provided by intact North American pine forests and the ecosystem service disruptions of the pine beetle epiphytotic.

Regulating and Supporting Services

Regulating services are the benefits obtained from an ecosystem's capacity to regulate air, water, and soil quality; supporting services are necessary for the production of other ecosystem services like nutrient regulation, climate stabilization, and biomass production.[36] Pine beetle infestations affect pine forests' ability to regulate water quality and flows and to maintain their role as an important carbon sink.

Pine beetle infestation has complex interactions with the hydrologic cycle both within and outside areas of significant tree mortality. Tree death leads to decreased tree density and canopy cover, resulting in increased ground snow accumulation. This decreases evaporation rates as less snow is held in the canopy; it also results in higher rates of snowmelt and precipitation runoff. [37,38]



Source. Data for distribution of the mountain pine beetle infestation are from Amman et al.,[10] and data for the host trees are from Little.[11]

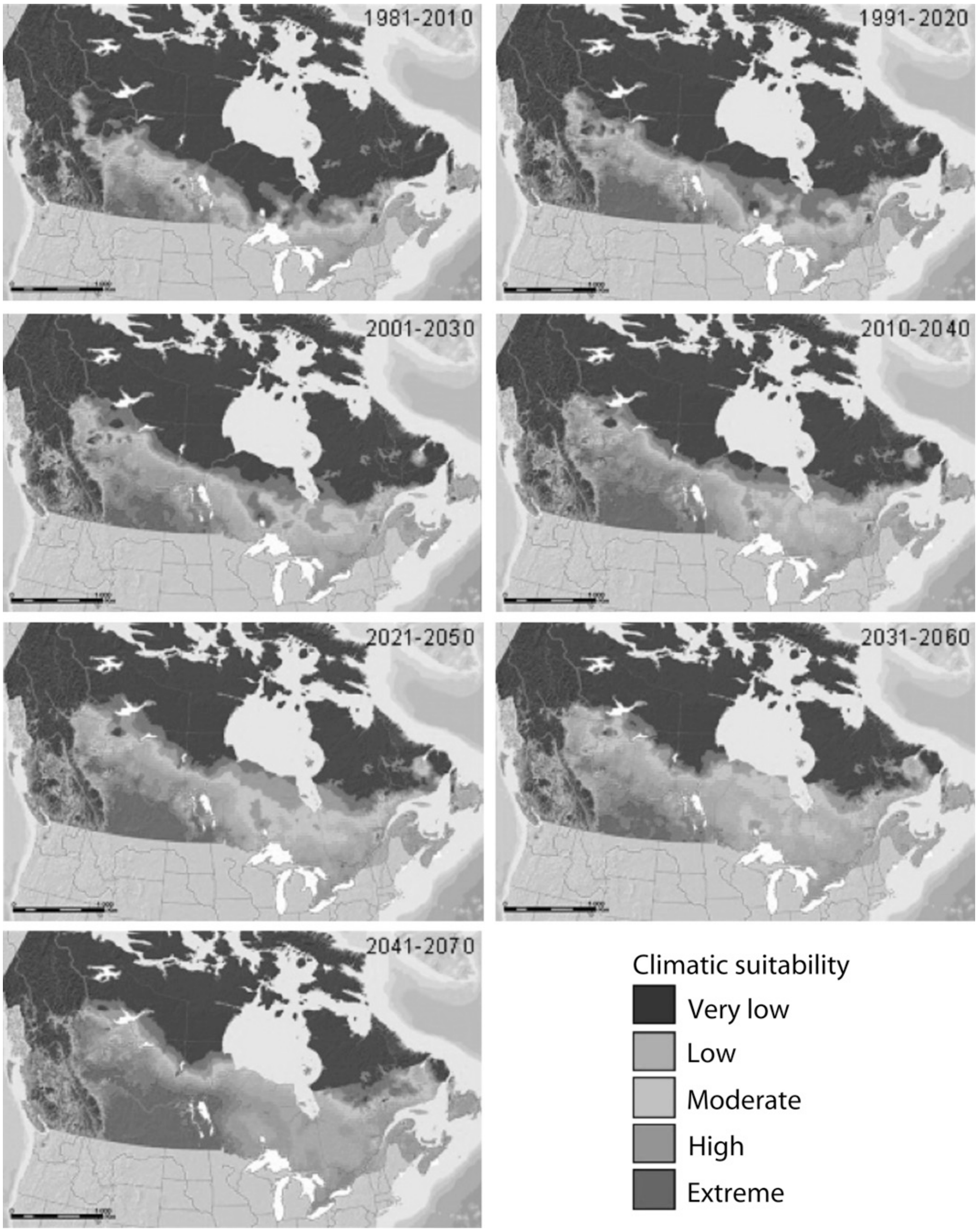
FIGURE 1—Current distribution of the mountain pine beetle infestation, the host trees lodgepole pine, ponderosa limber pine, and whitebark, and the potential host jack pine.

Generally, pine beetle infestations result in increased surface water yields within watersheds in the late spring and early summer and decreases in later summer months. This increases water stress for human populations that depend on snowmelt in the late summer as a water supply.[39,40] Moreover, the increased runoff, coupled with the reduced number of trees available for nutrient uptake from surrounding soils, can alter nutrient cycling and increase erosion and sediment delivery to watercourses.[41,42] These changes can necessitate increased water purification before human consumption[43] and can also affect downstream ecosystems.[42,44]

Forests often act as a carbon sink, reducing the concentrations of atmospheric greenhouse gases; high tree mortality halts this service and can even reverse it. It is estimated that the current pine beetle epiphytotic alone will release as much as 270 megatons of carbon dioxide by 2020 from decomposition of tree matter.[21] Together, the loss of carbon sequestration and this direct release will result in carbon dioxide emissions that will likely transform Canada's managed forests from a net carbon sink to a net source of carbon in the near future.[21,45] The timing of this turning point is poorly understood, and similar projections for US forests are unavailable. Increases in greenhouse gas emissions (or decreases in carbon uptake) will induce further global climate change, increasing risks to public health, as has been extensively documented elsewhere.[2,46] Importantly, declines in carbon sequestration capacity from forest die-off are likely to become increasingly important for Annex I countries as emission reduction targets loom and national greenhouse gas emission inventories are highly sensitive to these changes.

Provisioning and Cultural Services

Provisioning services are the commodities, such as timber and pulp, obtained from forest ecosystems, whereas cultural services are nonmaterial benefits obtained through recreation or aesthetics.[36] Pine forests provide a range of such services for local communities, and losses of provisional services, although varying with local economic drivers, can result in decreased property values[47] and a possible decrease in tourism income through declining aesthetic appeal and fewer recreational visitors.[48,49] An economic analysis of residential property values in Grand County, Colorado, a tourism- and recreation-dependent area hit hard by the current pine beetle epiphytotic, estimated that property values declined by $648, $43, and $17 for every tree killed by infestation within 0.1, 0.5, and 1.0 kilometers of the property, respectively.[47] It is difficult to tease apart the effect of beetle infestation and macroeconomic trends, such as recession, in tourism-dependent areas, and there are few studies evaluating the beetle's



Note. Distributions are derived from a conservative climate change scenario[26] and the Safranyik model of climatic suitability.[27] Areas with "very low" suitability are unlikely to support mountain pine beetle populations, whereas "extreme" areas are those considered climatically optimal.
Source. Reprinted with permission from Her Majesty the Queen in right of Canada, Natural Resources Canada, Canadian Forest Service.

FIGURE 2—Future distributions of climatically suitable habitats for the mountain pine beetle in Canada.

impact. However, one study found that there is public agreement that pine beetle infestation has resulted in decreased revenue and greater unemployment within infested communities.[50]

Communities that are dependent on the timber industry face their own unique set of difficulties. Immediately following pine beetle infestation, timber harvests increase to clear dead trees. This creates a small economic windfall that quickly dissipates once the dead timber has been harvested and no new growth is available.[51,52] This can lead to a rise in unemployment and decline in socioeconomic status, with outmigration further depressing tax revenues.[52]

TABLE 1—Ecosystem Services of Forests and Impacts on Human Health

Class of Ecosystem Services	Examples of Services Provided by Forest Ecosystems	Changes in Forests Induced by Pine Beetle Infestation	Examples of Economic, Environmental, and Human Health Impacts Caused by Forest Change
Regulating	Air purification	Increased sedimentation into streams	Increased gastrointestinal disorders with increased turbidity
	Control of water quality	Increased turbidity	
	Control of water quantity		
	Nutrient cycles		
Provisioning	Providing lumber and pulp	Decreased lumber production	Loss of tax revenue
	Providing game and tourism		Unemployment
Cultural	Creation of recreational area	Public-perceived decrease in aesthetic value	Fewer recreational visitors
	Aesthetic beauty		Decreased property values
	Value of nature		Possible loss of tax revenue
	Intellectual stimulation		
Supporting	Climate stabilization	Decreased ability to sequester carbon	Increased greenhouse gas emissions
	Nutrient regulation		Temperature fluctuations resulting in heat-related mortality and morbidity
	Soil stabilization		
	Maintenance of biodiversity		

PUBLIC HEALTH IMPACTS BY EXPOSURE

Ecosystem disruption can have a wide range of human health impacts. The pine beetle infestation is associated with exposures ranging from forest fires to loss of the ecosystem services described in the previous section. Potential health effects of these exposures can be mediated through decreases in economic activity, employment, tax revenue, and community services relevant to public health, yet there have been no studies to date directly linking the current epiphytotic with health impacts.

Fire

Increased fire risk poses one of the most immediate human health concerns stemming from pine beetle infestation. Massive forest die-off increases fuel loads, thus escalating the risk of fire. Additionally, pine beetle outbreaks often coincide with prolonged periods of drought,[53] which itself contributes to increased risk and severity of forest fires. Those living directly within burn areas face loss of property and livelihood as well as physical injury. They can also experience displacement often lasting months to years, lowered socioeconomic status, the need for alternative water supplies, increased water quality control (processes aimed at management of the physical, chemical, and biological characteristics of a watershed to meet standards for ecosystem health, human exposure, and human consumption) and purification costs, and increased soil erosion.[54–56] For example, various wildfires near water reservoirs in Australia increased turbidity in drinking water to unsafe levels. Dependent populations were required to boil drinking water for up to 6 months, and one population had to switch to an alternative water supply for one year.[57]

One study examining fire risk associated with pine beetle infestation suggests an increased risk of 10%,[58] but many studies note that risk depends largely on the stage of forest mortality after the beetle attack.[53,59] Recently attacked trees retain their dead needles and contribute to an increased risk of crown fire in the short term. Approximately 2 years following an attack, the needles fall and there is a possible temporary decreased risk of fire because of lower crown fuel load. Approximately a decade after attack, the trees fall and provide more fuel at ground level, again increasing fire risk.[53,60,61]

Human health impacts of forest fires extend hundreds of kilometers beyond the burn zone as inhalation of windblown smoke can compromise the respiratory function of those exposed.[62] Especially vulnerable to the health effects associated with smoke inhalation include those with preexisting cardiopulmonary-related health diseases, a prevalent preexisting condition that resulted in an estimated 223 of 100 000 mortalities annually in the western United States between 1999 and 2007.[63] Exposure to smoke and particulate matter associated with wildfire can exacerbate bronchitis and increase the risk of asthmatic episodes, heat exhaustion, and dehydration.[64,65] The particles making up wood smoke can cause inflammation, oxidative stress, and irritation, and some particles are carcinogenic.[62] Further research is needed that examines the effects of high exposures of particulate matter smaller than 2.5 micrometers in diameter ($PM_{2.5}$) during forest fires.

Few analyses have focused on the cost of human health impacts from smoke exposure, and none directly on the increased risk of smoke exposure that may result from pine beetle infestations. Health-related costs of smoke exposure are high; one study of the 2001 fire in the Canadian province of Alberta estimated the health-related costs resulting from the fire at Can $9 million to $12 million for an affected population of 1.1 million. The cost analysis included premature mortality, emergency department visits, respiratory and cardiac hospital admissions, asthma symptoms days, restricted activity days, and acute respiratory symptom days. Non–health-related costs of the fire, including property loss, timber loss, and firefighter costs, totaled $33 million; thus, the human health costs accounted for approximately 25% of the total.[66]

Shifts in Water Quantity and Quality

Pine beetle infestations can cause significant loss of ecosystem services by altering local and regional hydrologic dynamics. It is estimated that 33 million people dependent on the Colorado River for tap water could be affected by more rapid snowmelts and enhanced annual stream flows—and associated changes to water quality and quantity— resulting from tree loss.[67] Increased turbidity has been associated within increases in gastrointestinal illness,[68,69] although this has not been demonstrated for drainages affected by pine beetle infestations specifically. Other toxins, heavy metals, and noxious chemicals are also found in runoff from fires, although the health impacts of these exposures are unclear. Further research is needed to evaluate the effects of increased turbidity and other adverse impacts associated with forest fires on water quality, treatment costs, and health in ecosystems specifically affected by infestations.

Loss of Economic Activity, Cultural and Aesthetic Value, and Biodiversity

Although the total value of the ecosystem services of North American temperate and boreal forests is unknown, Costanza et al.[33] and Krieger[35] estimate that globally, these forest types provide $894 billion in ecosystem services annually. As North American forests are approximately a third of the world total, the value of their ecosystem services is probably in the neighborhood of $300 billion annually. The pine beetle has caused serious timber supply problems resulting in billion-dollar economic losses. A simplified calculation of the economic impact of the pine beetle in British Columbia estimated a Can $2.5 billion decrease in manufacturing activity, a loss of 27 000 direct jobs, and a loss of $250 million in government stumpage (the price charged by government to companies or operators for the right to harvest timber on public land) and royalty revenues.[70,71] These estimates, which were based on loss of available timber fiber, were made prior to the current global recession. Similar economic data for timber-related losses in the United States and for losses from tourist industries are not available.

It is difficult to assess the impact of pine beetles on the psychosocial health of populations because of varying perceptions of forest values and lack of consensus regarding valuation metrics. However, areas of aesthetic quality where people experience contact with nature and pursue outdoor recreation have been shown to be a resource for physical activity and to contribute positively to mental and physical health.[72,73] In a survey of visitors (not forest industry employees) to Pinery Provincial Park, Ontario, it was found that their definitions of a healthy forest depended on whether it was pristine, contained diverse flora and fauna, and was part of a larger ecosystem. Many survey respondents recognized that the forest contributed to both physical and psychosocial health.[74] Nearby residents and visitors to national parks affected by the pine beetle report negative attitudes toward the beetle's presence.[75,76] An increase in perceived risk of forest fire has also been reported, negatively affecting mental health by increasing public worry and concern.[77]

MANAGING PUBLIC HEALTH IMPACTS

In order to assess the public health impacts, we examine pine beetle infestation from a traditional prevention standpoint.

Primary Prevention

Primary prevention averts contact between human hosts and adverse exposures. To prevent human host contact with adverse exposures associated with ecosystem disruption from pine beetle infestation, primary prevention would involve preventing forest infestation through multiple methods, including creating a barrier between infected and uninfected areas to minimize the probability that enphytotic areas expand and new epiphytotics develop. Because the pine beetle has few significant natural predators during severe infestations, possible barriers are limited to pesticide applications and selective logging.[32] Widespread primary prevention is likely to be neither economically feasible nor practicable, particularly as the projected area of vulnerable forest is set to increase substantially under future climates. Limited, targeted primary prevention is a reasonable goal, especially for an individual community. Targeted primary prevention would be enhanced by early warning systems capable of assisting communities in monitoring their risk of infestation.

Aspen, Colorado, faces a pine beetle infestation advancing from the northeast, and is currently engaging in primary prevention activities. The community established For the Forest in collaboration with the US Forest Service and several nonprofit organizations. The group has worked to protect forested open space, and since 2009 they have worked to remove beetle-infested trees to prevent larval maturation and thus reduce subsequent infection of healthy trees. Their primary prevention activities have also included application of the pesticide verbenone around healthy trees to further protect them from infestation.[78] In addition to saving open space, the group has made special efforts to protect Smuggler Mountain in order to create a barrier between the established pine beetle populations northeast of town and the Aspen community. Although this focused prevention is proving to be effective in its early stages, further research is needed to examine the long-term effectiveness of such barriers.

Secondary Prevention

Secondary prevention includes interventions that will prevent harm to human health after adverse exposures occur—that is, after ecosystem disruption has occurred but before significant population health impacts are manifest. Secondary prevention includes activities intended to prevent impacts from secondary exposures such as forest fires and declining water quality. These activities include maintenance of ecosystem services to the degree possible after the ecosystem is disturbed, as well as water treatment and strategies to prevent forest fires. Once pine beetle infestation has affected an area, secondary prevention should aim to control further spread and establishment of the beetle to prevent widespread tree die-off and to minimize ecosystem disruption as a result of the infestation.

To facilitate containment, the same principles used in the Smuggler Mountain Project can be applied, but with the goal of minimizing establishment and further spread rather than preventing entry into the area. Steps to contain an infestation are similar to primary prevention efforts, and are again expensive and time-consuming.[30] Although the strategies used are similar to those used for primary prevention, they serve a different purpose, similar to the ways in which vaccination can support both primary and secondary prevention in vaccine-preventable disease outbreaks. Education on identifying infected trees, selective logging, and pesticide use are essential. To minimize adverse secondary impacts, local public health officials should be involved in assessing the risk of applying pesticides on a large scale, with the goal of minimizing pesticide exposures, especially among sensitive populations. There is historical precedent for integration of forest pesticide application with ongoing assessment of potential environmental health impacts into an iterative, ongoing process.[79]

Merritt, British Columbia, has had some success applying principles of secondary prevention. Unlike Aspen, the town is completely surrounded by pine beetle–infested forest and unable to create a barrier to prevent beetle entry. The resident landowners are instead encouraged to cut down infested trees and use verbenone pouches on healthy trees. Also unlike in Aspen, pine beetles have entered the town proper and Merritt estimates it has lost approximately 35% to 40% of its ponderosa pines. By comparison, a nearby town that took no action had 98% ponderosa mortality.[80] Merritt has been funded by provincial fire safety initiatives, but exact costs are unknown. The secondary prevention efforts are believed to have decreased forest fire risk within the community but have not decreased overall economic losses, particularly the substantial losses from unemployment in the timber industry. To decrease the economic risk, national and provincial funding has been directed toward job diversification and training.[81]

Tertiary Prevention

Tertiary prevention includes symptom treatment and palliation. In the case of pine beetle infestation, it includes medical treatment of symptoms resulting from hazardous exposures such as forest fires. The need for tertiary prevention represents a public health failure to the extent that hazardous exposures were not prevented. However, although there is evidence that pine beetle infestations and associated hazardous exposures can be minimized, their incidence cannot be reduced completely; as health impacts are likely, provisions for tertiary prevention will be necessary.

Areas already in the throes of a pine beetle epiphytotic, areas that are unable to prevent new infestations, or those that cannot afford to prevent infestations must invest disproportionately in tertiary prevention. This strategy is relatively expensive, even compared with the costly interventions associated with primary and secondary prevention. These areas must be prepared for the associated ecological impacts of forest die-off such as increased risk of fire. The community should have a fire response plan that addresses prefire and postfire management (prefire management would technically be secondary prevention). To prepare for a fire, efforts should be made to reduce the extent and severity of fires through the removal of dead and downed trees. If a fire occurs, the plan needs to include actions for a coordinated emergency services response of both firefighters and hospital services, evacuation of those within the burn area, and protection of smoke-susceptible populations by the distribution of masks or air purifiers. After the fire, the plan must address relocation of the displaced, possible interruption of the water supply, erosion prevention efforts, and financial aid for those affected economically by loss of business or loss of residency. Canada's federal Mountain Pine Beetle Program (MPBP) pledged Can $200 million to assist communities at reducing their wildfire risk after pine beetle attacks, increase economic diversity, and control the spread of the infestation within the affected community.[82] In addition to the MPBP, tertiary prevention is largely taken on by existing public health and medical infrastructure.

ECOLOGICAL DISRUPTION, PUBLIC HEALTH, AND CLIMATE CHANGE ADAPTATION

That the current mountain pine beetle infestation has public health implications does not make it, first and foremost, a public health problem. But it does highlight the need for 2 important shifts in public health practice vis-à-vis climate change adaptation.

The first is a shift in the scope and nature of public health practice to acknowledge the systemic threats posed by climate change and the need for a more integrated, systems-based approach. Ultimately, climate change is a rapidly emerging ecological stressor; when the baseline climate dynamics of natural or managed ecosystems are shifted, multiple ecosystem components may shift in response,[83] often in nonlinear fashion.[84] As a result, the resilience of many ecosystems, particularly those with a high degree of precariousness, is likely to be fundamentally challenged,[85] and there is the possibility of environmental shifts at particular tipping points with subsequent health impacts.[86] To understand these dynamics and their impacts on human health, a systems-based analysis is called for. Systems analysis focuses on interactions between the climate system, environmental states, and ecological systems, while including the influence of external inputs such as human behavior or technology. In other sectors, such an approach has deepened understanding of impacts and the formation of adaptation strategies.[87] A systems approach can yield powerful insights and, coupled with dynamic models of managed systems, set the stage for adaptive management[88]; however, it also complicates conventional approaches, including those employed in the protection of public health.[89] The health sector has not historically focused on natural resource management, but is being both pushed and pulled to expand the scope of its practice as climate change threatens the integrity of a variety of systems that sustain public health.[90,91] Although public health should remain true to its key mission, the increasing need for substantial interdisciplinary cooperation in pursuit of this goal cannot be denied.

The second is a shift to recognize the limits of technological responses in the process of containing and managing many climate-sensitive public health threats, particularly those mediated through loss of ecosystem services. In many instances, technological interventions can serve as adjuncts but not as solutions or replacements for ecosystem services.[92] Replacing these services is often infeasible,[93] and even when partial substitutes are available, replacements are imperfect, expensive, and prone to unanticipated complications that can exacerbate impacts down the line.[4] The failure of control measures to contain the climate-driven pine beetle infestation described here serves as one cautionary example. Even large-scale, well-funded efforts in 2 affluent countries have not prevented this infestation from growing many times larger than any previous recorded event,[7,21] leading to billions of dollars in economic losses[51,94] and leaving the public more vulnerable to adverse health impacts despite (and, in the case of pesticide use, potentially as a result of) adaptation decisions. Indeed, some human interventions that previously governed the extent of ecological damages (and associated harm to public health) may be less effective under future climate conditions. As a result, public health and other involved disciplines must either focus on innovation to develop iterative management strategies applicable to the shifting dynamics of such settings, or acknowledge that in future there may be less leverage in primary and secondary prevention measures and emphasize the need to invest more heavily in tertiary prevention in the context of significant ecosystem disruption.

CONCLUSIONS

The pine beetle epiphytotic's impacts on human health are expected to be broad and reach far beyond the initial site of infestation; however, the exact effects remain unknown and require further research and understanding. Populations living within infestation zones face an increased risk of forest fires, decreased water quality, lower socioeconomic status from job and tourism losses, possible displacement, and other losses associated with compromised ecosystem services. Changes in carbon sequestration dynamics will accelerate health impacts from climate change mitigation efforts across the globe and hobble Annex I countries' efforts to reduce their greenhouse gas emissions. The epiphytotic's potential human health impacts have gone largely unrecognized, unquantified, and unstudied by public health experts and researchers. Methods for preventing the spread of pine beetles are needed to decrease the burden of these impacts as the infestation spreads; yet such efforts are likely to be costly and time-consuming and, to date, have met with only mixed success. Without increased attention, pine beetle infestation within the North American West is likely to stand as a cautionary example of the need for public health to take a more interdisciplinary perspective and to recognize the limited options available for replacing ecosystem services lost as a result of global change. ■

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