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

by

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Submitted for completion of the degree Master of Science in Public Health
(MSPH)

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Abstract

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Climate change is disrupting ecosystems worldwide. This disruption can pose a significant threat to human health through direct exposures and diminished ecosystem services. In the US and Canada, the pine forest ecosystems are being dramatically disrupted by pine beetle infestation. Recent decreased frequency of extremely cold days and corresponding increase in yearly winter temperatures have led to an epiphytotic 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 precipitation runoff and water turbidity, forest fires, and loss of ecosystem services. This paper reviews these 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.

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Introduction and Background:

Globally, there is abundant evidence of accelerating ecosystem disruption associated with climate change.^{1, 2} Many of these disruptions are likely to have significant direct and indirect health effects through a variety of overlapping pathways.³⁻⁵ 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 the North American continent serves as such an example.

Mountain pine beetles have few natural predators, and historically cold winter temperatures have controlled their population growth. In recent years, unusually high proportions of beetle larvae have survived over the winter, resulting in a devastating epiphytotic in North American pine forests⁶ that is expected to continue and expand during the next century⁷. This is in sharp contrast to previous smaller outbreaks, which were stopped due to temperature fluctuations and human interventions like thinning stands and insecticides.⁸⁻¹⁰ As a result of these new dynamics, what were once sporadic epiphytotics are becoming a large epiphytotic, with periodic epiphytotics expanding beyond the beetle's northern range. With its unprecedented scale, the current infestation has diminished a range of ecosystem services provided by pine forests¹¹, and increased the risk of several direct health effects resulting from increased runoff, runoff turbidity and forest fires, and their associated waterborne disease^{12,13} and respiratory disease¹⁴ effects.

The objectives of this paper are to explore the potential human health impacts of the current pine beetle infestation and to apply a public health framework to identify interventions that may reduce future public health impacts. We begin with a review of pine bark beetle ecology, the observed impacts of a warming temperature trend on beetle

populations, and likely near-term future trends. Next, we explore the infestation's impact on ecosystem services and potential associated health impacts. Finally, we apply a public health framework and outline relevant strategies that may limit further adverse effects.

Glossary of Terms:

Term	Explanation
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 outbreak of disease suddenly and rapidly affects many plants in a specific area, similar to epidemic disease in human populations.

Mountain Pine Beetle And Blue Stain Fungus Ecology

Historical Ecological Patterns

Mountain pine beetles and related bark beetles are native, bark-burrowing insects found throughout the United States and in parts of Mexico and Canada (See Figure 1).⁷ This paper focuses on the *Dendroctonus* genus, the most destructive to the forests of the American west and western Canada. The beetles inhabit pine trees, in particular Ponderosa, Lodgepole, Whitebark, Scots, and Limber pines,^{7, 15} 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 summer¹⁰. Though 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 spp.*, *Ophiostoma spp.* and *Leptographium spp.*¹⁵ 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.¹⁶ Both the fungi and beetles are well-adapted to cold temperatures, enabling their mutual spread across the American west and western Canada.¹⁷ The average beetle life span is approximately one year, and although they have natural predators, climate typically limits beetle populations.^{18, 19}

Climatological Drivers

The *Dendroctonus* life cycle is governed strongly by temperature.²⁰ While adult and developing beetles are highly resistant to cold, larvae are unable to survive temperatures below -40°C , which cause rapid mortality.^{6, 21} Thus shifts in seasonal temperature norms, particularly extreme cold, can interact to facilitate or limit beetle development, affecting abundance and population viability.^{7, 20}

Periodic, widespread pine beetle infestations, defined in terms of beetle population size relative to the abundance of available host,²² 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.^{23, 24} 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

Recent Changes in Pine Beetle Ecology

Since the mid-1970s, winter temperature minima have increased across North America, reducing the frequency of cold events below the -40°C survival threshold.⁸ Both larval and adult stages have increased in population size and geographic extent, allowing a rapid, widespread infestation of millions of acres of pine forest²⁵⁻²⁷

The primary infestations responsible for current tree mortality began in 1996 in northern central Colorado, and 1999 in central British Columbia.²⁸ As of 2008, the pine beetle infestation in the western United States and Canada covered 35 million acres and is ten times larger than any previous recorded event.²⁷ This area of infestation is expected to increase with increased climatically suitable habitats (See Figure 2).⁷ In 2006, the US Forest Service estimated that 58 million acres of trees are at risk of dying by 2020 due to insect-related disease in the United States, and bark beetles made up seven of the top eleven etiological agents listed.²⁹

The change in temperatures has allowed the pine beetle to spread its range northward, and several projections estimate a further temperature increase will allow for a large increase in the area suitable for beetle habitation in northern latitudes.²⁶ Such a northward shift could potentially allow for infestation of the species *Pinus banksiana*, which has been historically untouched by pine beetle due to its distribution exclusively in high northern latitudes.²⁶ If the pine beetle spreads further north and attacks Canadian *P. banksiana* stands, the infestation could then move eastward across Canada and re-enter the United States in the Great Lakes region, opening up new areas at risk for infestation (Figure 1).²⁶

Pine Beetle 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.³² Aggressive containment actions are warranted until the ratio of the pine beetle population and available hosts is maintained at an equilibrium endemic level, at which beetle populations persist at low numbers across the landscape and mainly breed in weakened trees.^{22, 33} Surveillance for infestations is typically carried out by the federal forestry agencies, the United State Forest

Service and the Canadian Forest Service. These agencies also coordinate containment of infestation with additional federal funding and assistance of private land owners. 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.³⁴ Forest managers and researchers are acutely aware that pine beetles can reproduce and spread rapidly, and temperature, drought, and processes that homogenize forest age, genetic, or species structure can synchronize spatially discontinuous pine beetle populations and epiphytotics to overcome the eruptive threshold and reach epiphytotic levels.^{18, 28}

Impacts of the Current Epiphytotic on Ecosystem Services

Coniferous forests of North America, dominated by pine and spruce species susceptible to species of genus *Dendroctonus*, provide a wide range of important and highly valuable ecosystem services.³⁵ The forests of the United States contribute approximately \$63 billion to that total, with climate regulation, waste treatment and food production accounting for approximately seventy-five percent of the services based on value.³⁶ There is an emerging literature on the role of ecosystems in protecting human health, with several studies of health impacts associated with ecosystem services, ecosystem change, and degradation and reviews of the health impacts of ecosystem disruption^{5, 11, 36}.

In regards to ecosystem services, pine forests provide services that can be classified as regulating, provisioning, cultural and supporting,¹¹ and pine beetles can disrupt each of these service classes (Table 1).

Regulating and Supporting Services

Regulating services are the benefits obtained from an ecosystem's capacity to regulate air, water, and soil quality, and supporting services are necessary for the production of all other ecosystem services like nutrient regulation, climate stabilization and biomass production.³⁷ 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, rates of snowmelt, and precipitation runoff.^{49, 50} Generally, pine beetle infestations result in increased water yields within watersheds in the late spring and early summer and relative decreases in later summer months, increasing water stress for human populations that depend on snowmelt for water during this time.^{51, 52} Moreover, the increased runoff, coupled with the reduced number of trees available for nutrient uptake from surrounding soils, can alter nutrient cycling and increase sedimentation.^{53, 54} These changes can necessitate increased water purification before human consumption⁵⁵ and can also impact downstream ecosystems.^{54, 56}

Forests normally act as a carbon sink and reduce atmospheric greenhouse gas concentrations; increased tree mortality halts this service and can even reverse it. The current pine beetle epiphytotic alone will release as much as 270 megatons of CO₂ by 2020 from decomposition of tree matter. When the loss of carbon sequestration is added to this direct release, the net effect is even greater CO₂ emissions that will likely lead Canada's managed forests to act as a net carbon source in the future.^{24, 47} Similar projections are unavailable for the United States. Increases in greenhouse gas emissions (or decreases in carbon uptake) will induce further climate change, increasing the associated health risks that have been extensively documented elsewhere, including thermal stress, microbial proliferation, changes

in agricultural productivity, and displacement.^{3, 57} Importantly, these dynamics also affect a nation's greenhouse gas emission inventory, and declines in carbon sequestration capacity from forest die-off are likely to become increasingly important for Annex I countries as emission reduction targets loom.

Provisioning and Cultural Services

Provisioning services are the products obtained from ecosystems like timber and pulp in the case of forests. Cultural services are non-material benefits people can obtain from ecosystems through like recreation or aesthetic experience.³⁷ Pine forests provide a range of economically valuable services for local communities. Provisioning losses vary depending on local economic drivers, but include decreased tourism income due to declining aesthetic appeal and fewer recreational visitors⁴⁴ as well as decreased property values.⁴⁵ An economic analysis of residential property values in Grand County, CO, an area hard hit by the current pine beetle epiphytotic and highly dependent on tourism and recreation, estimated property values declined by \$648, \$43, and \$17 for *every tree* killed by infestation within a 0.1, 0.5, and 1.0 km buffer, respectively.⁴⁵ It is difficult to tease apart the effect of beetle infestation and the current economic recession within tourism-dependent areas, and there are no studies directly evaluating the beetle's impact. However, there is a public perception that pine beetle infestation has resulted in decreased revenue and greater unemployment within infested communities.⁴⁴

Communities that are dependent on the timber industry face other difficulties. Immediately following pine beetle infestation, timber harvests increase to clear dead trees. This creates a small economic boom that quickly dissipates once the dead timber has been harvested and no new growth is available.^{58, 59} This can lead to a rise in unemployment and decline in socioeconomic status, where outmigration further depresses tax revenues.⁵⁹

Public Health Impacts by Exposure

Ecosystem disruption can have a wide range of human health impacts. Exposure pathways vary in their directness and impacts vary in severity. The pine beetle infestation, specifically, is associated with exposures ranging from forest fires to loss of aforementioned ecosystem services, though there have been no studies directly linking the current epiphytotic with health impacts. These exposures have multiple potential health effects, some of which are mediated through decreases in economic activity, employment, tax revenue, and community services relevant to public health.

Fire

Increased fire risk poses one of the most immediate human health concerns from pine beetle infestation. Massive forest die-off increases fuel burdens and thereby generally increases the risk of fire and associated health effects. Additionally, pine beetle outbreaks often coincide with prolonged periods of drought.⁶⁰ Drought alone contributes to increased forest fires, suppression of which can cost over a billion dollars in the United States annually.⁶¹ Those living directly within burn areas face loss of property and livelihood as well as physical injury. After a fire, those living within burned areas can face displacement often lasting months to years, lowered socioeconomic status, the need for alternative water supplies, increased water quality control and purification costs, and increased soil erosion.⁶²⁻⁶⁴ For example, various wildfires near water reservoirs in Australia increased drinking water turbidity post-fire to unsafe levels. Dependent populations were required to boil drinking water for up to six months, and another population used an alternative water supply for one year.⁶⁵

One study examining fire risk associated with pine beetle infestation suggests an increased risk of at 10%,⁶⁶ but many studies note that risk depends largely on the stage of forest mortality post-attack.^{60, 67} recently attacked trees retain their dead needles and contribute to an increased risk of crown fire in the short term. Approximately two years following an attack, the needles fall and there is a possible decreased risk of fire due to lower crown fuel load. After approximately a decade post-attack the trees fall to the ground, providing more available ground fuels to again increase fire risk.^{60, 68, 69}

Human health impacts extend hundreds of kilometers beyond the burn zone as direct and windblown smoke inhalation can compromise respiratory function of those exposed.⁷⁰ Especially vulnerable to smoke inhalation include those with pre-existing cardiopulmonary-related health diseases, a prevalent pre-existing condition that resulted in an estimated 223/100,000 mortalities annually in the western United States between 1999-2007.⁷¹ Exposure to smoke and particulate matter associated with wildfire can exacerbate bronchitis and increase risk of asthmatic episodes, heat exhaustion, and dehydration.^{72, 73} The particles making up wood smoke can cause inflammation, oxidative stress, irritation, and some particles are carcinogenic.⁷⁰ Further research needs to be done examining acute, high PM_{2.5} exposures associated with forest fires, another pollutant known to cause harm in other settings.

Few analyses have focused on the cost of human health impacts from smoke exposure, and none directly on increased risk of smoke exposure as a result of pine beetle infestation. Morbidity is often considered a secondary concern in comparison with fire-related mortality; however, when these morbidity costs are analyzed the results are economically significant. A 2001 fire in Alberta, Canada estimated the health impact costs from the fire to be between \$9-12 million for an affected population of 1.1 million. The cost

analysis included premature mortality risks, emergency department visits, and respiratory and cardiac hospital admissions, asthma symptoms days, restricted activity days and acute respiratory symptom days. Other associated costs included property loss, timber loss, and fire fighter costs totaled \$33million, so the human health costs were approximately 30% of the total costs of the fire.⁷⁴

Shifts in Water Quantity and Quality

Previous discussion of loss of ecosystem services emphasizes the local and regional hydrologic dynamics related to pine beetle infestation. It is estimated that thirty-three million people dependent on the Colorado River for tap water could be affected by changes in water quality and quantity as a result of more rapid snowmelt and enhanced annual stream flow associated with tree loss.⁷⁵ Based on our current understanding of these dynamics, these impacts are most likely to manifest as increased water treatment costs. Additionally, increased turbidity has been associated within increases in gastrointestinal illness,^{12, 39} though this has not been demonstrated for drainages affected by pine beetle infestations specifically. Further research is needed to evaluate the impacts of increased turbidity on decreased water quality, treatment cost, and health impacts in ecosystems specifically affected by infestations.

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

The total value of ecosystem services of temperate and boreal forest ecosystem goods and services in North America is unknown. However, Costanza and Krieger estimate that global ecosystem services for these forest types provide \$894 billion of services annually^{35, 36}. As North American forests are approximately a third of the world total, the value of their ecosystem services is likely in the neighborhood of \$298 billion annually. The pine beetle has caused serious timber supply problems resulting in billion dollar economic losses as noted. A simplified calculation of the economic impact of pine beetle in British

Columbia estimated a \$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.^{41, 76} This estimate is based on loss of available timber fiber and was 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 beetle on the psychosocial health of humans due to varying perceptions of forest value and uses and lack of consensus regarding valuation metrics. However, areas of aesthetic quality where people can have nature contact and pursue outdoor recreation offer a resource for physical activity and contribute positively to residents' mental and physical health.^{77, 78} A survey of human perceptions of a forest in Pinery, Canada by people not employed by the forest industry defined a healthy forest by whether it was pristine, if it contained diverse flora and fauna and it was part of a larger ecosystem. Though many survey respondents recognized that the forest contributed to aesthetic and physical human health, the recognition of human health impacts did not have a bearing on behavior change to preserve forest health.⁷⁹ Pine beetle infestations, which visibly affect large swaths of forest with orange-leaved dead and dying trees, likely reduce perception of aesthetic quality of the forest and decrease flora-fauna diversity, which contributes to an overall negative human perception of forest health⁴⁴. Nearby residents and visitors to national parks affected by pine beetle often have negative attitudes towards toward the presence of the beetle^{80, 81}. There is also increased perceived risk of forest fire, which negatively affects mental health by increasing public worry and concern⁸².

Managing the Public Health Impacts

For the purpose of this discussion we identify humans as the hosts of potential health impacts. There are four types of prevention relevant to climate change impacts including those associated with pine beetle: zero order, primary, secondary, and tertiary. We discuss each in turn, illustrating with specific examples of prevention activities where appropriate.

Zero Order Prevention

Zero order prevention involves preventing the development of a hazardous exposure,⁸³ i.e. climate change mitigation, and is not specific to pine beetles, but instead to all climate sensitive impacts. Given that, based on past emissions, there will be further climate warming,⁸⁴ and the threshold dynamics of climatic impacts on pine beetle ecology, zero order prevention may not be possible even with immediate, aggressive mitigation. The specifics of the other types of prevention are discussed further below.

Primary Prevention

Primary prevention prevents contact between adverse exposures and human hosts, and in this case focuses on preventing human host contact with adverse exposures associated with ecosystem disruption from pine beetle infestation. This centers on preventing forest infestation with pine beetles, and entails creating a barrier between infected and uninfected areas to minimize the probability that epiphytotic areas expand and new epiphytotics develop. As the pine beetle has no significant natural predators during massive and severe infestations, possible barrier mechanisms are limited to the use of pesticide and selective logging.³⁴ 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. More targeted primary prevention is a

reasonable goal, especially for an individual community. This would require an early warning system that assists communities in monitoring their risk of infestation.

Aspen, Colorado is currently facing a pine beetle infestation from the northeast. The community responded by establishing *For the Forest*, a collaboration between the community, the United States Forest Service, and other non-profit organizations. The group has worked to protect forested open space from pine beetle infestation through the Smuggler Mountain Project, which, beginning in 2009 has removed beetle-infested trees to prevent larval maturation and thus reduce subsequent infection of healthy trees. The project also applied verbenone, a pesticide, around healthy trees to further protect them from infestation.⁸⁵ In addition to saving open space, the project specifically protects Smuggler Mountain, creating a northeast division between the pine beetles northeast of town and the Aspen community. While this focused prevention is proving to be effective in its early stages, further research is needed to examine the effectiveness of barriers, and the possible need for additional barriers to protect the town.

Secondary Prevention

Secondary prevention includes interventions that will prevent development of symptoms in human hosts after adverse exposures, i.e. 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 and need for water treatment. These activities include maintenance of ecosystem services to the degree possible after the ecosystem is disturbed as well as water treatment, strategies to prevent forest fires when fire risk is high, and other strategies for slowing the development of hazardous exposures after pine beetle infestations have substantially disturbed local forest and aquatic ecosystems.

Once pine beetle infestation has impacted an area, secondary prevention response should be aimed at controlling further spread and establishment of the beetle to prevent widespread die off of tree stands. The same principles used in the Smuggler Mountain project can be applied in secondary prevention, but with the goal of containment rather than barrier creation. Steps to contain an infestation are similar to primary prevention efforts, and are again expensive and time-consuming.³² Education on identifying infected trees, selective logging, and pesticide use are essential. 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.

Merritt, British Columbia has had some success applying principles of secondary prevention. The town is completely surrounded by pine beetle-infested forest, and resident landowners are encouraged to cut down infested trees and use verbenone pouches on healthy trees. Merritt estimates that it has lost approximately 35-40% of the ponderosa pine in comparison to a nearby town that took no action and had 98% mortality.⁸⁶ 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 timber industry unemployment. In order to decrease the economic risk, national and provincial funding has been directed towards job diversification and training.⁸⁷

Tertiary Prevention

Tertiary prevention includes symptom treatment and palliation. In the case of pine beetle infestation, tertiary prevention includes medical treatment for 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,

while 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, that are unable to prevent new infestations, or that cannot afford to prevent infestations must invest disproportionately in tertiary prevention. This strategy is relatively expensive, even in comparison 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 pre- and post-fire management (pre-fire management would technically be secondary prevention). To prepare for a fire, efforts should be made to reduce fire extent and severity via fuel load reduction. If a fire occurs, the plan needs to include actions for a coordinated emergency services response of both forest fighters and hospital services, evacuation of those within the burn area, and protection of smoke susceptible populations by mask or air purifier distribution. After the fire, the plan must address relocation of displaced, water mitigation, erosion prevention efforts and those affected economically by loss of business or loss of residency. Canada's federal Mountain Pine Beetle Program (MPBP) pledged two hundred million dollars to assist communities at reducing their wildfire risk after pine beetle attacks, increase economic diversity and control the spread of the infestation.⁸⁸ Beyond 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 two 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: in shifting baseline climate dynamics around which both natural and managed ecosystems have evolved, multiple ecosystem components may shift in response. As a result, the resilience of many ecosystems, particularly for those with a high degree of precariousness, is likely to be fundamentally challenged.⁸⁹To understand the resulting shifts and their impacts on human health, a holistic, systems-based approach is required. As such, the need to adapt to the health and other impacts of climate change is prompting a shift toward systems-based management approaches.⁹⁰While this can yield powerful insights and, coupled with dynamic models of managed systems, set the stage for adaptive management⁹¹, it also complicates conventional approaches, including those employed in the protection of public health. 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.^{92, 93}While 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 away from an optimistic faith in technical solutions* for intervening in, containing, and otherwise managing many climate-sensitive public health threats, particularly those mediated through loss of ecosystem services. Replacing these services with technology is often infeasible, and even when partial substitutes are available, replacements are

imperfect, expensive, and prone to unanticipated complications that can exacerbate impacts down the line. The failure of previously successful control measures to contain the climate-driven pine beetle infestation described here serves as one cautionary example. Even large-scale, well-funded efforts in two affluent countries have not prevented this infestation from growing many times larger than any previous recorded event,^{7, 24} leading to billions of dollars in economic losses⁴² and leaving the public more vulnerable to adverse health impacts despite (and, in the case of pesticide use, 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 novel 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.

Conclusion

The pine beetle epiphytotic's impacts on human health are broad and reach far beyond the initial site of infestation. 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 climate change mitigation efforts across the globe and hobble Annex I countries' efforts to reduce their greenhouse gas emissions. These human health impacts have gone largely unrecognized, unquantified, and unstudied by public health experts and

researchers. Methods of preventing the spread of pine beetle need to be addressed immediately to decrease the burden of these increased risks; however, the efforts are likely to be costly and time consuming and to date have met with only mixed success. Without increased attention, however, 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 toward the health impacts of global change.

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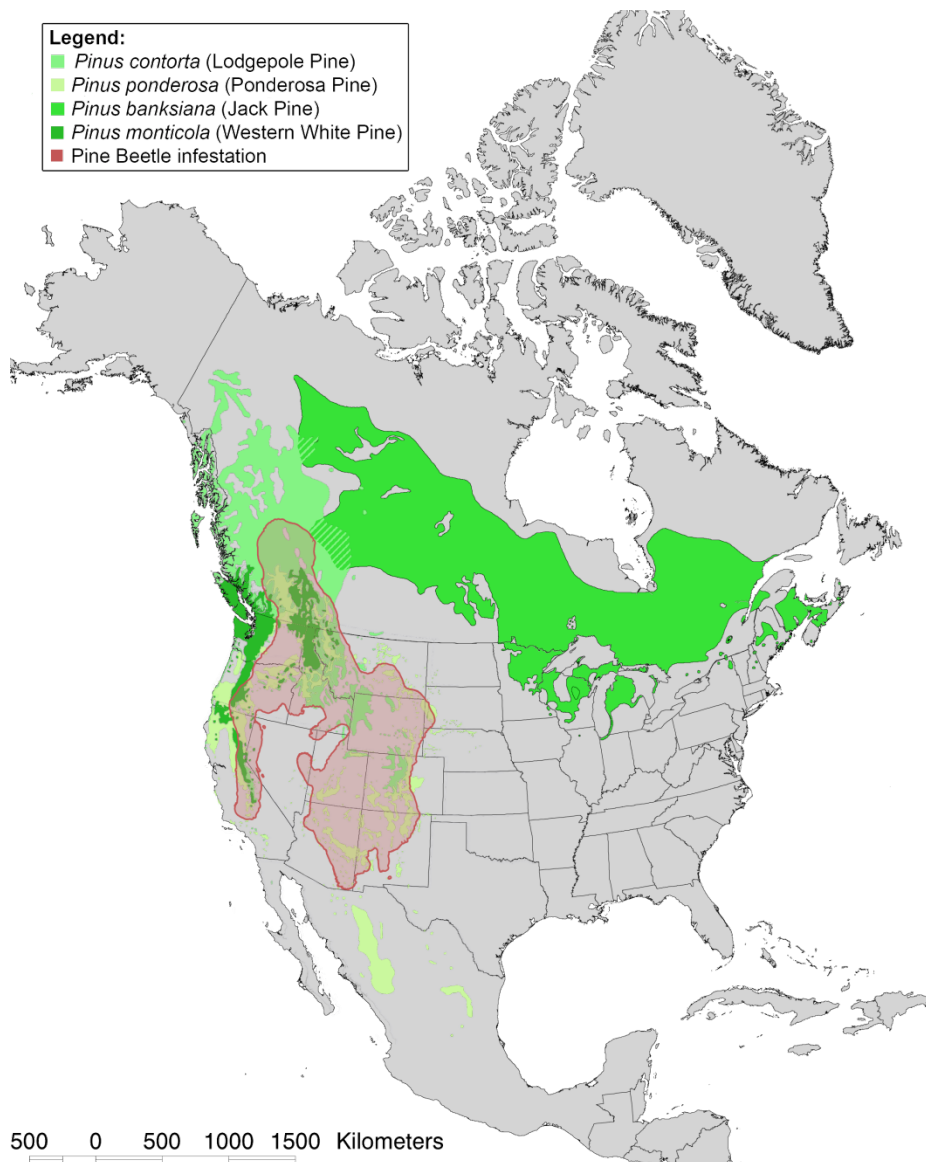


FIGURE 1 - Current distribution of the mountain pine beetle infestation (data from Amman⁹), and host species lodgepole pine, ponderosa limber pine and whitebark, and potential host jack pine (data from Little²⁰).

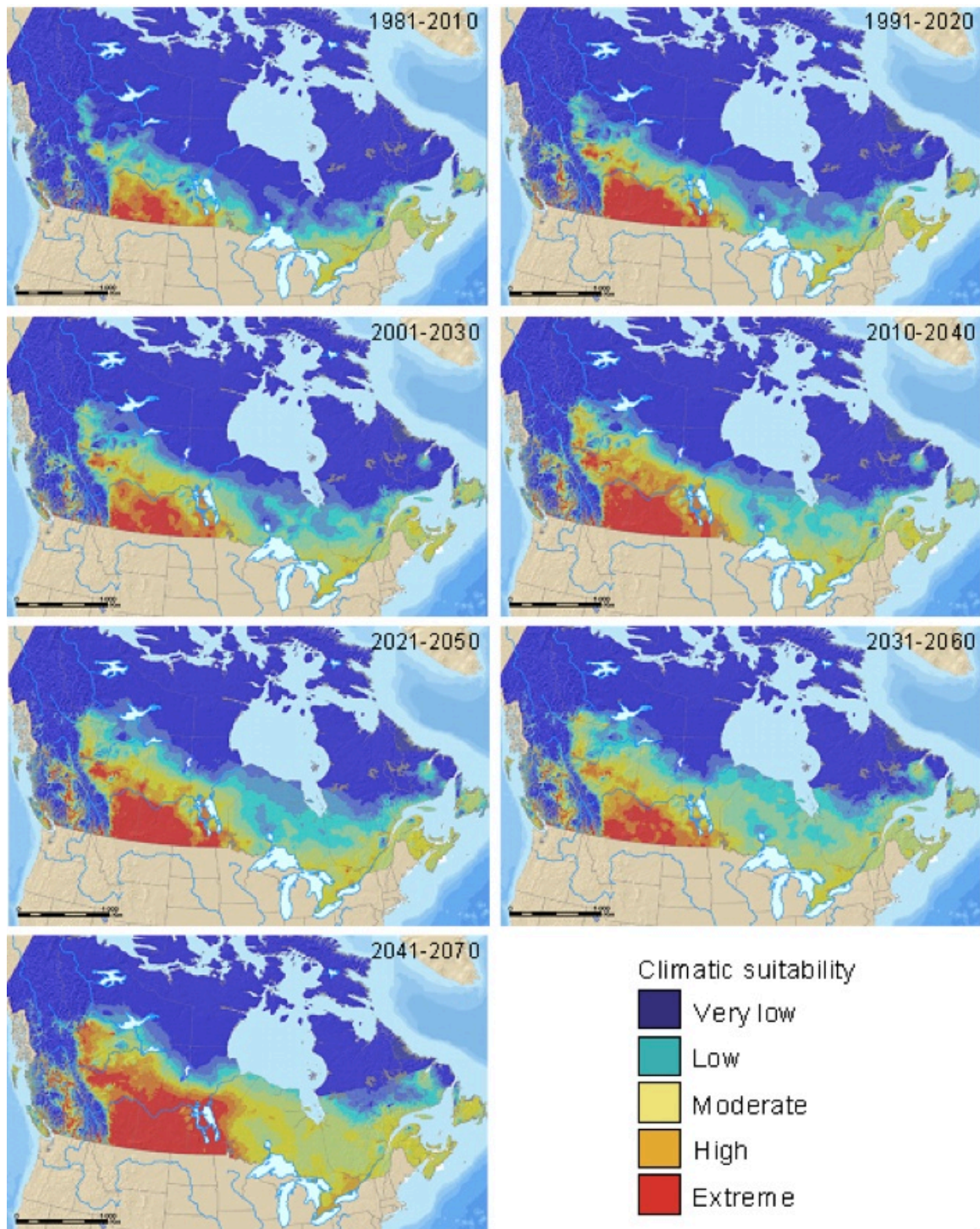


FIGURE 2 - Future distributions of climatically suitable habitats for the mountain pine beetle in Canada derived from a conservative climate change scenario³⁰ and the Safranyik model of climatic suitability.³¹ Areas with “very low” suitability are unlikely to support mountain pine beetle populations, whereas “extreme” areas are those considered climatically optimal. Reprinted with permission from Her Majesty the Queen in right of Canada, Natural Resources Canada, Canadian Forest Service.

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

Class of ecosystem services	Example services provided by forest ecosystems^{36, 37}	Forest change induced by pine beetle infestation	Some impacts of forest change
Regulating	<ul style="list-style-type: none"> - Air purification - Control of water quality - Control of water quantity - Nutrient cycles 	<ul style="list-style-type: none"> - Increased sedimentation into streams - Increased turbidity³⁸ 	<ul style="list-style-type: none"> - Increased gastrointestinal disorders with increased turbidity^{12, 39}
Provisioning	<ul style="list-style-type: none"> - Providing lumber and pulp - Providing game and tourism 	<ul style="list-style-type: none"> - Decreased lumber production⁴⁰ 	<ul style="list-style-type: none"> - Loss of tax revenue⁴¹ - Unemployment⁴²
Cultural	<ul style="list-style-type: none"> - Creation of recreational area - Aesthetic beauty - Value of nature - Intellectual stimulation 	<ul style="list-style-type: none"> - Public perceived decrease in aesthetic value⁴³ 	<ul style="list-style-type: none"> - Fewer recreational visitors⁴⁴ - Decreased property values⁴⁵ - Possible loss of tax revenue^{41, 46}
Supporting	<ul style="list-style-type: none"> - Climate stabilization - Nutrient regulation - Soil stabilization - Maintenance of biodiversity 	<ul style="list-style-type: none"> - Decreased ability to sequester carbon^{24, 47} 	<ul style="list-style-type: none"> - Increased greenhouse gas emissions²⁴ - Temperature fluctuations resulting in heat-related mortality and morbidity⁴⁸