THE EFFECT OF CLIMATE CHANGE ON MOUNTAIN PINE BEETLE (*Dendroctonus ponderosae* Hopkins) IN WESTERN CANADA

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By

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# ABSTRACT

The mountain pine beetle, *Dendroctonus ponderosae*, (MPB) is the largest forest disturbance factor throughout its range in North America. The most recent MPB outbreak began in the 1990s and has resulted in an approximate loss of 723 million cubic meters of timber. The current global warming trends have seen global temperatures increase by approximately 1°C and are forecasted to rise by an additional 0.5-1.5°C over the preceding decades. These temperature increases are having a large impact on the MPB range, biology, and physiology. The range of MPB has expanded significantly in recent decades and is forecasted to continue to increase significantly in all directions as well as an increase in elevation. With further climate warming, there is a possibility of the MPB invading the boreal forest and using jack pine as host trees. MPB oviposition time, development, and winter survivability rates have been altered due to rising temperatures.

# ACKNOWLEDGEMENTS

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# INTRODUCTION

The mountain pine beetle (hereinafter referred to as MPB) has always been a part of the coniferous forest ecosystem of western North America, but with warming temperatures associated with climate change, the MPB's biology may change drastically. Human-caused climate change has led to an increase in global temperatures at a rate much faster than would occur naturally. This increase in global temperature has allowed for the expansion of MPB distribution and increased overwintering survivability (Logan and Bentz 1999, Carroll *et al.* 2004). The rising temperature of the climate creates many changes in the MPB's life cycle (Carroll *et al.* 2004). Warmer summer months are creating environments where the beetle can have more than one generation per year (Logan and Powell 2001, Carroll *et al.* 2004).

With warming temperatures, there are many changes to how the MPB interacts with the environment. These changes can have great implications on both the forest industry as well as society as a whole. The current epidemic of MPB in Canada peaked in 2005, leading to a cumulative loss of 753 million cubic metres of pine volume (Natural Resources Canada 2013). There are many factors that affect an outbreak of an insect, including the availability of host species and temperature (Carroll *et al.* 2004). Not only will changes to the MPB's interactions have the potential to lower wood volume, but it also increases the amount of dead standing timber, which increases fire risk.

This paper will explore how aspects of the MPB's biology, physiology, and habitat will change with increasing global temperatures. It will begin with a background description of the mountain pine beetle, including its current range, its susceptibility to cold, its biology and physiology, its life cycle, and the current outbreak in BC. It will then discuss climate change, its current trends, the climate of the past, and future climate predictions. It will then discuss what the changing climate means for the MPB and how it will be affected. It will then go on to discuss the impact of MPB on forest conditions and the associated impact on the economy. The objective of this paper is to determine the effects of climate change on the MPB regarding its biology, physiology, and its effect on coniferous forests.

## MATERIALS AND METHODS

As this thesis is a literature review, the materials and methods describe where I searched for the information used in writing this thesis.

I began with a search in Google Scholar. This led me to many peer-reviewed journal articles. I used the relevant journal articles and their references cited pages as a starting point to locate other important journals and books. I also used the online Lakehead University library to locate other sources.

The biggest challenge of finding the proper sources is finding more recent sources. It was easier to find references about the MPB from the 1990s, but it is more difficult to locate more modern sources. This is not impossible though as I have found many recent and relevant journal entries.

Government websites release plenty of information about the beetle but are compiled in format that is intended for the general public to utilize. I will be staying away from this information and associated fact sheets on MPB and focusing on peer-reviewed sources.

# LITERATURE REVIEW

## 1.0 Mountain Pine Beetle

### 1.1 Background Information

The MPB is a mostly univoltine species, meaning it has one generation per year, but is occasionally semivoltine in a colder climate, meaning more than one year to complete a generation (Mitton and Ferrenberg 2012). The MPB does not undergo diapause, or a time of decreased activity; the beetle remains active over the winter, continuing to feed and grow (Mitton and Ferrenberg 2012). Without diapause, the beetle's synchronous emergence relies solely on seasonal temperature patterns (Logan and Powell 2001). Currently, The MPB inhabits western North America, from northern British Columbia and extending as far south as Mexico (Cullingham *et al.* 2011, Mitton and Ferrenberg 2012). In Canada, MPB inhabits the temperate forests of BC (Natural Resources Canada 2013). Figure 1 shows the current range of the MPB. The main host of MPB is lodgepole pine, *Pinus contorta* Douglas, but they have the ability to attack any pine tree species, including introduced pines (Cullingham *et al.* 2011, Mitton and Ferrenberg 2012, Natural Resources Canada 2013).

Beetle species belonging to the genus *Dendroctonus* (Coleoptera: Scolytidae) are required to kill their host tree to successfully reproduce (Williams and Liebhold 2002). For the MPB this involves a mass attack strategy in which adult beetles swarm host trees in large enough numbers to overwhelm the tree's defences of producing large amounts of pitch to trap and stop the beetles, in order to kill the host tree (Cullingham *et al.* 2011, Natural Resources Canada 2013,). This attack strategy starts with a female MPB releasing aggregation pheromones while at a host tree (Pureswaran *et al.*, 2000, Cullingham *et al.* 2011, Mitton and Ferrenberg 2012). Males that are attracted then release additional pheromones and the newly created mixture is a strong pheromone that attracts MPB males and females in large numbers, and which females proceed to all bore into the tree and lay eggs (Pureswaran *et al.* 2000, Cullingham *et al.* 2011). Once attacking in these large numbers, the tree's defences are overwhelmed, and the tree dies and becomes a food source for the larva (Safranyik and Carroll 2006, Cullingham *et al.* 2011). MPB is also a vector for blue stain fungi which both assist in lowering the defences of the attacked tree by blocking the vascular system of the tree, and it also serves as a food source for the larva (Mitton and Ferrenberg 2012).


Figure 1. Current range of the mountain pine beetle (Safranyik and Carroll 2006)

## 1.2 Life Cycle

The MPB's life cycle consists of four stages: egg, larva, pupa, and adult (Logan and Powell 2001, Safranyik and Carroll 2006). All life stages of the MPB occur inside the subcortical tissues of the host tree (Safranyik and Carroll 2006). During the dispersal phase of the adult's life, the beetle must leave the host tree (Safranyik and Carroll 2006).

The female MPB deposits 60 eggs, on average, into the host tree after mating has occurred (Safranyik and Carroll 2006). The eggs are deposited into niches cut into the sides of the mating gallery and are covered in the sawdust left over from the creation of the gallery (Safranyik and Carroll 2006). Egg colour is white and egg size is approximately 1 mm in diameter, but egg size changes in relation to the size of the beetle (McGhehey 1971, Safranyik and Carroll 2006). Eggs have four stages of development that are based on their appearance (Safranyik and Carroll 2006). Stage one generally is between one and two days old and the eggs are homogenously opaque, stage two the eggs are two to three days old and are clear at one end, stage three is three to four days old and have become clear at both ends, and stage four the eggs are four to five days old and have a clearly developed and visible head capsule (McGhehey 1971, Reid 1962, Safranyik and Carroll 2006). Figure 2 shows the eggs of the MPB in the parental galleries (Safranyik and Carroll 2006).


Figure 2. MPB eggs in the niches of the parental gallery (Safranyik and Carroll 2006)

During the larval stage, there are four instars, or growth stages, in which the larva grow larger with each stage (Safranyik and Carroll 2006). Larvae feed on the phloem tissue of the host tree (Reid 1962, Safranyik and Carroll 2006). As their size increases with each instar, the feeding gallery becomes wider (Reid 1962, Safranyik and Carroll 2006). In the fourth instar, the larva clears an area of all debris to create an area for the pupal stage to occur (Reid 1962, Safranyik and Carroll 2006). At the end of the fourth instar stage, the larva will enter its pupal stage where the wings and legs are folded beneath the body (Safranyik and Carroll 2006). Figure 3 shows the fourth larval instar stage of the MPB (Safranyik and Carroll 2006).

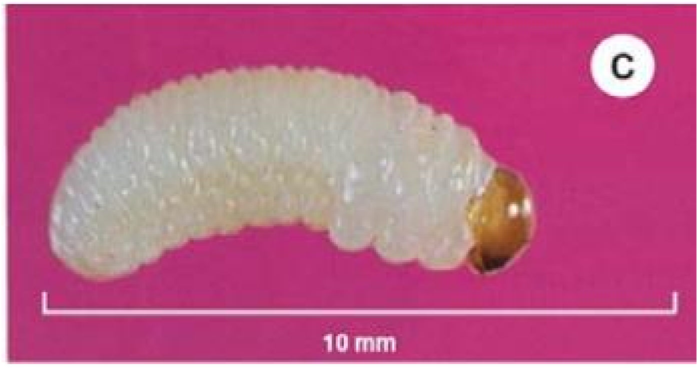


Figure 3. MPB fourth larval instar stage (Safranyik and Carroll 2006)

When the adults emerge from their pupae they are soft and pale, but before emerging from the host tree their bodies harden and become a black or dark brown colour (Safranyik and Carroll 2006). The adults range in size from 3.7 mm-7.5 mm, with females generally being larger than the males (Safranyik and Carroll 2006). Figure 4 pictures a mature adult MPB (Safranyik and Carroll 2006).


Figure 4. Mature adult mountain pine beetle (Safranyik and Carroll 2006)

## 1.3 Cold Susceptibility

The MPB overwinters in the host tree in its larval stage, typically the third and fourth instar stages (Safranyik and Carroll 2006). During the winter months, the larva is able to withstand low winter temperatures of -40°C for extended periods of time (Wygant 1940, Yuill 1941, Safranyik and Carroll 2006)

# 2.0 Climate Change

Data for climate change has been sourced from the International Panel on Climate Change's (IPCC) most recent published document from 2018. Increasing $CO_2$ levels are causing global temperature to rise (IPCC 2018). Currently, the climate has warmed by 0.8-1.2°C since pre-industrial times due to anthropogenic activities (IPCC 2018). From the year 2000 to 2018 human-induced climate change has raised global temperatures by approximately 0.87°C (IPCC 2018). With continued emissions of $CO_2$, the global temperature is expected to rise another 1.5°C (IPCC 2018). An anthropogenic warming timeline and predicted trend line can be viewed in figure 5. It illustrates the current 1°C increase in temperature and a rough timeline of when the temperature increase will reach 1.5°C (IPCC 2018). This greater increase in temperature will have impacts on many aspects of the environment, including forest and insect interactions (Williams and Liebhold 2002, IPCC 2018). Further increases in global temperature are likely to occur without an international effort to reduce carbon emissions immediately (IPCC 2018). In the event that carbon emissions are not slowed, the global temperature will continue to rise and damage may become permanent due to a feedback loop creating a perpetual state of warming (IPCC 2018). This increase in temperature to a 2.5°C rise or more will have additional adverse effects on many aspects of life, including the interactions of many plant and animal species

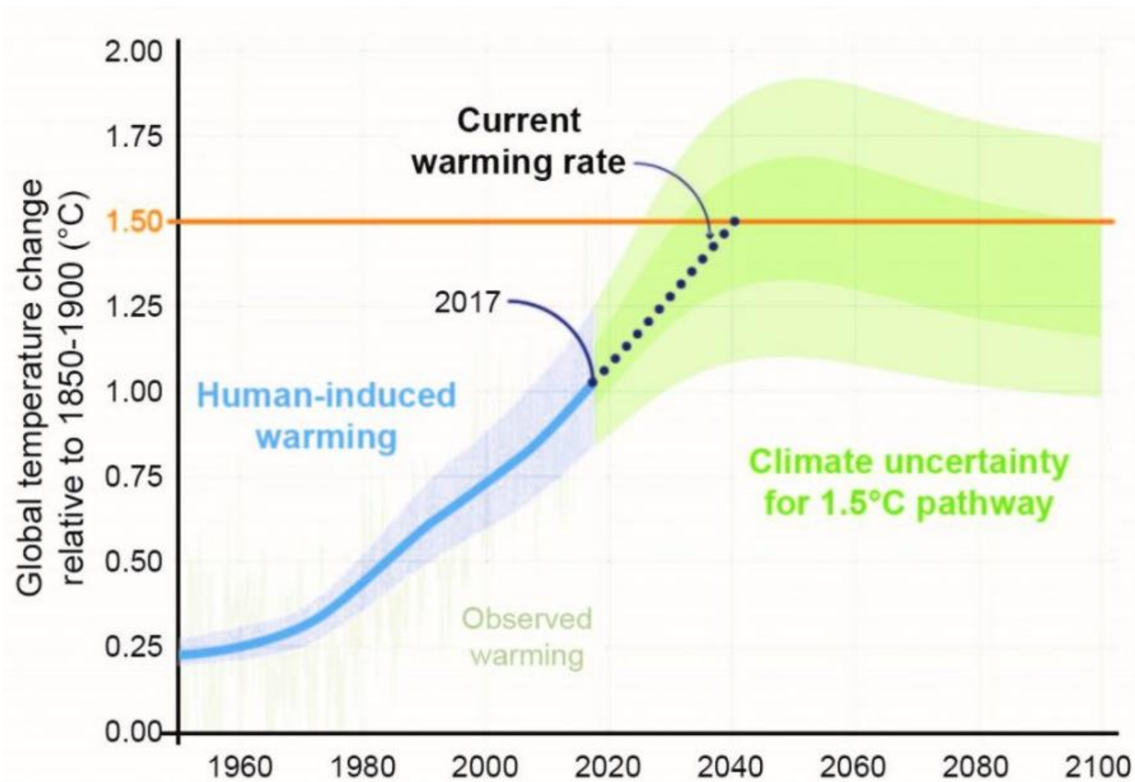


Figure 5. Human-induced warming graphed from 1950-2017 with future trend line of warming to 2040 (IPCC 2018)

It is uncertain how precipitation will be affected by climate change (Shine *et al.* 2015, IPCC 2018,). Shine *et al.* (2015) predict precipitation rate changes will vary depending on the geographic area, but precipitation increases and decreases are predicted. One study found that precipitation in some areas within the MPB range is predicted to increase as global temperatures increase (Williams and Liebhold 2002). Uncertainty on what precipitation rates show could be considered while continuing to read this literature review. Any results relating to precipitation changes are only models and/or predictions, and therefore, should be considered as such when predicting effects on the MPB.

## 3.0 Climatic Effects on MPB

### 3.1 Effects on Biology and Physiology

There is much evidence to support that with the warming climate MPB abundance and epidemic severity will increase, but there is also evidence that suggests that warmer temperatures can be detrimental to the species (Logan and Powell 2001, Carroll *et al.* 2004, Hicke *et al.* 2006, Bentz *et al.* 2010, Mitton and Ferrenberg 2012). Studies from Logan and Bentz (1999), Logan and Powell (2001), and Carroll *et al.* (2004) have found evidence that areas with ideal temperatures for MPB can become warmer to the point where the MPB will experience partial multivoltinism. This means that some parts of the population are having more than one generation per season. (Logan and Bentz 1999, Carroll *et al.* 2004). This can lead to the MPB overwintering in life stages such as eggs, pupae, or adults that are more susceptible to extreme cold

(Logan and Bentz 1999, Carroll *et al.* 2004, Taylor and Carroll 2004). A climate suitability model created by Taylor and Carroll (2004) shows the current and near-future state of the warming climate is creating environmental conditions for some MPB populations that create more time to develop and grow within a growing season, but not enough time to complete two complete life cycles (Taylor and Carroll 2004). This creates a semi-bivoltine MPB population which has a significant negative impact on the synchronous emergence of beetle populations in the following spring (Taylor and Carroll 2004). This dissynchronous emergence, combined with more beetle mortality over winter due to the beetle overwintering as less cold-tolerant life stages, will both lower the overall population of the beetle as well as decrease the effectiveness of the MPB's mass attack strategy (Taylor and Carroll 2004). This same climatic model has shown evidence that warmer spring and fall temperatures have the ability to positively impact the synchronous emergence of adult beetles even if semi-voltinism is occurring in a given population (Taylor and Carroll 2004). Warm spring and fall temperatures give the early instars of second-generation beetle time to develop further than they otherwise could under previously colder climatic conditions (Taylor and Carroll 2004). Even though the second generation should be at a less developed stage at the time of emergence, the majority of beetles emerge synchronously (Bentz *et al.* 1991, Taylor and Carroll 2004).

There is evidence to contradict the claim of negative effects on the MPB from a warming climate from Mitton and Ferrenberg (2012) who found that MPB has continued to be successful in more northern regions and higher elevations even with changing emergence times. The study also observed late summer adults in the parental chambers in the host trees with no adverse effects occurring with this advanced growth speed (Mitton and Ferrenberg 2012).

In addition to these contradicting claims there is a third theory, which says that as temperatures increase there will be a period of time where favorable environmental conditions for the MPB will decrease, but if temperatures continue to increase past a certain threshold of unfavorable environmental condition, MPB will greatly increase and surpass the current conditions (Logan and Powell 2001). This possibility of even more intense MPB epidemics creates a situation where beetle populations will expand into areas where different hosts may be used, such as whitebark pine (*Pinus albicailis* Engelm), which will begin to be greatly affected by MPB (Logan and Powell 2001). This hypothesis will be further explored in section 3.3.

MPB populations in the greater Yellowstone ecosystem have traditionally been semivoltine but have recently been observed shifting to a univoltine life cycle (Mitton and Ferrenberg 2012). This has been explained by an increase in winter temperatures of 3.4°C from the year 1960 to the year 2004 (Tran *et al.* 2007, Mitton and Ferrenberg 2012).

Table 1 shows the results of Mitton and Ferrenberg's 2012 study that shows the air temperature from 1970-2008. The table also shows the number of degree days the MPB experienced during those decades (Mitton and Ferrenberg 2012). Since the 1970s, the number of degree days has increased from 570 to 820 (Mitton and Ferrenberg 2012). That is a large increase that indicates the beetles are able to develop at a rate much faster in 2008 when compared to 1970 (Mitton and Ferrenberg 2012).

Table 1. Mountain Pine Beetle Degree days and Air Temperature over Several Decades (Mitton and Ferrenberg 2012)

| Variable | 1970–1979 | 1980–1989 | 1990–1999 | 2000–2008 | *P* |
|---|---|---|---|---|---|
| Annual temperature (°C) | 1.07 (.1)[A] | 1.05 (.1)[A] | 2.32 (.1)[B] | 2.70 (.2)[B] | <.0001 |
| Days with mean temperature >0°C | 78.3 (3.6)[A] | 80.0 (5.0)[AB] | 93.1 (3.9)[AB] | 95.4 (3.1)[B] | <.01 |
| Accumulated temperature (°C) to July 1 | −260.1 (51.0)[A] | −252.7 (79.7)[A] | 17.7 (50.1)[B] | 61.7 (53.8)[B] | <.001 |
| Total annual DDs | 570.6 (26.2)[A] | 584.8 (53.0)[AB] | 722.6 (25.5)[BC] | 820.1 (36.4)[C] | <.0001 |
| DDs before July 1 | 128.4 (10.7)[A] | 135.0 (22.9)[A] | 175.5 (16.8)[AB] | 202.7 (16.5)[B] | <.02 |

This increase in degree days affects different populations of MPB in different ways (Mitton and Ferrenberg 2012). The degree day temperature for MPB used by Mitton and Ferrenberg (2012) was found by Safranyik *et al.* (1975) to be 5.5°C. Degree days being more abundant allows for faster development and growth of the MPB, but evidence suggests that effects of increased degree-days on beetle populations would vary greatly based on intraspecific genetic variation (Bentz *et al.* 2001, 2011; Carroll *et al.* 2006; Mitton and Ferrenberg 2012). Genetic differences in beetle populations across the large range they inhabit create varying developmental rates (Bentz *et al.* 2001, 2011;

Carroll *et al.* 2006; Mitton and Ferrenberg 2012). Additionally, high elevation populations have a faster development rate compared to lower elevation populations (Mitton and Ferrenberg 2012). This is partially due to genetic variation, but evidence suggests that host tree growth defences, by means of resin production, are hindered by the high elevation and lack of water (Cates and Alexander 1982, Mitton and Ferrenberg 2012). Warming temperatures at higher elevations will increase the beetle's amount of degree days without increasing drought resistance in the host trees, creating an environment where the already fast-developing beetles will be able to grow and develop even faster (Mitton and Ferrenberg 2012). Preliminary evidence shows that this may lead to multivoltinism in high elevation MPB populations (Logan and Powell 2001, Mitton and Ferrenberg 2012). A study by Logan and Powel1 (2001) suggests a similar situation where high elevation MPB populations will move from semi-voltinism to a more synchronous univoltinism reproduction method. This more synchronous emergence of the MPB will allow for more successful mass attacks on host trees, and therefore, an increase in population for the following year (Logan and Powell 2001, Mitton and Ferrenberg 2012).

A higher number of degree days may not necessarily mean faster growth and development at the same rate (Mitton and Ferrenberg 2012). Studies of other insects have shown that growth is less temperature-dependent than development (Michel *et al.* 2010). This means at all life stages of the MPB, warming temperatures will have a greater impact on beetle growth than development (Michel *et al.* 2010). The development will still be affected by increased degree days (Michel *et al.* 2010, Mitton and Ferrenberg 2012). This evidence is not concrete, however, as this assumes that the MPB follows the results found on other ectothermic species (Michel *et al.* 2010, Mitton and Ferrenberg 2012).

MPB populations inhabiting warming climates need to adapt moderately quickly to warming temperatures in order to continue successfully occupying the same space (Taylor and Carroll 2004). The MPB is an adaptable species with a strong adaptive phenology (Taylor and Carroll 2004). Under the warming climate conditions, the MPB will likely have no problem making short-term individual adaptations to temperature changes (Taylor and Carroll 2004). Over longer time periods, many generations will eventually give the beetle a chance to genetically adapt to the warming climate (Taylor and Carroll 2004). In the event that a population of MPB is negatively affected by warming temperatures, the MPB's high genotypic adaptation in addition to its large influx of new individuals per generation will give the beetle ample time to adapt to the changing climate (Taylor and Carroll 2004). If theories of negative effects on MPB due to climate change are true, the MPB will likely remain as a natural disturbance to the same extent that it always has been (Taylor and Carroll 2004).

### 3.2 Effects on MPB Range

With an overall increase in temperature, the range at which the MPB can survive will expand (Logan and Bentz 1999, Williams and Liebhold 2002). This expansion will continue northward into areas that have traditionally been too cold for the MPB to inhabit (Logan and Bentz 1999, Williams and Liebhold 2002). It is likely that, with increasing temperatures, northern MPB populations will move to higher elevations whereas southern beetle populations will move northward (Williams and Liebhold 2002, Logan *et al.* 2003, Mitton and Ferrenberg 2012).

Williams and Liebhold's (2002) study found that, with every 8-degree Celsius increase, the northern boundary of pine trees will shift 183 km northward. This will allow the MPB's range to expand along with the pine trees (Williams and Liebhold 2002). These findings are similar to other results showing that various pine tree's ranges will expand 40-190 km northward with increased global temperatures (Hansen *et al.* 1983, Manabe and Wetherald 1987, Williams and Liebhold 2002). This movement of tree ranges, and therefore MPB range, will be a slow process of approximately 10-45 km per century, but varying by pine species (Davis and Zabinski 1992, Williams and Liebhold 2002). With human interference, this migration progress will be significantly increased (Franklin *et al.* 1992, Williams and Liebhold 2002). Availability of host trees alone will not increase the MPB's range (Safranyik *et al.* 1975, Carroll *et al.* 2004, Taylor and Carroll 2004)

Climate stress on pine trees may create favorable conditions for MPB movement (Williams and Liebhold 2002). Due to warmer temperatures, stressed trees are the perfect target for the MPB (Williams and Liebhold 2002). Stressed trees that may have been outside of the MPB's natural range may now be at risk because of easier access due to tree stress (Williams and Liebhold 2002). This will likely be seen as a shift of the beetle's range to the south (Williams and Liebhold 2002). This will expand the southern range of MPB in the short term, but this will likely decrease over time as warming temperatures change the tree species composition into an area populated by unfavourable trees for the MPB (Franklin *et al.* 1992, Williams and Liebhold 2002).

MPB range expansion brings on a new concern of beetle expansion into the boreal forest (Cullingham *et al.* 2011). Traditionally, the MPB has been restricted to BC lowlands because temperatures are too cold and variable for the beetle to successfully live in the high elevations of the Rocky Mountains (Logan and Powell 2001, Bentz *et al.* 2010, Cullingham *et al.* 2011). However, with warming temperatures, the beetle has expanded eastward over the mountains towards the boreal forest in which the main pine species is jack pine, *Pinus banksiana,* Lamb. (Cullingham *et al.* 2011). Figure 6 shows a map that depicts this crossover area into which the MPB has expanded to. (Cullingham *et al.* 2011). Beetle expansion into the boreal has the potential of extreme range expansion for the beetle. This expansion into the boreal forest could cause the MPB to expand into areas from the Northwest Territories to the upper Midwest US (Cullingham *et al.* 2011). Expansion of this magnitude could have grave consequences for the ecology of the entire boreal forest (Logan *et al.* 2003, Cullingham *et al.* 2011). There is evidence of MPB attacking naturally occurring jack pine stands or hybrid jack pine and lodgepole pine, and there is further evidence to suggest that jack pine is a suitable host for the MPB through nursery experiments (Safranyik *et al.* 2010, Cullingham *et al.* 2011). In the event that the MPB is unable to use jack pine as a host tree the hybrid zone between jack pine and lodgepole pine, seen in figure 6, gives the MPB the opportunity to slowly adapt to using jack pine as a host species (Cullingham *et al.* 2011). The Cullingham *et al.* (2011) study found MPB infesting a small number of both jack pine and hybrid jack and lodgepole pine. These infestations prove that jack pine can be used as a host, but also raised the question of whether jack pine can sustain an outbreak of MPB (Cullingham *et al.* 2011). There is still uncertainty about jack pine's susceptibility to MPB, but this preliminary evidence does indicate a threat of MPB to the boreal forest but, with current data, it is unclear if MPB can sustain itself in the boreal forest (Cullingham *et al.* 2011).

In the past, Alberta's climate has not been warm enough to sustain MPB populations over a long period of time (Carroll *et al.* 2004, Cullingham *et al.* 2011). Additionally, temperatures throughout the boreal forest have been too cold for MPB establishment and sustainability (Regniere & Bentz 2007, Cooke 2009, Cullingham *et al.* 2011). Current climate trends are making both Alberta and the boreal forest warmer and thus increasing the habitat suitability for the MPB in these regions for both the summer and winter months (Logan and Powell 2001, Carroll *et al.* 2004, Cullingham *et al.* 2011).

In addition to jack pine becoming a novel host species, high elevation pines such as whitebark pine, bristlecone pine (*Pinus longaeva* D.K. Bailey), and other five-needle pines will likely become hosts for the MPB (Logan and Powell 2001). Like jack pine, these species have not co-evolved with the MPB and do not have the same level of defences against MPB attacks (Logan and Powell 2001). These high elevation pine forests serve a crucial role in water retention and distribution, and as a food source for many animal species such as birds and bears (Logan and Powell 2001). In the case of an MPB epidemic in these forests, there is a potential for their ecosystems to break down and, over the long term, possibly disappear completely (Logan and Powell 2001). Loss of biodiversity at this scale would be detrimental for one of western North America's oldest ecosystems (Logan and Powell 2001).

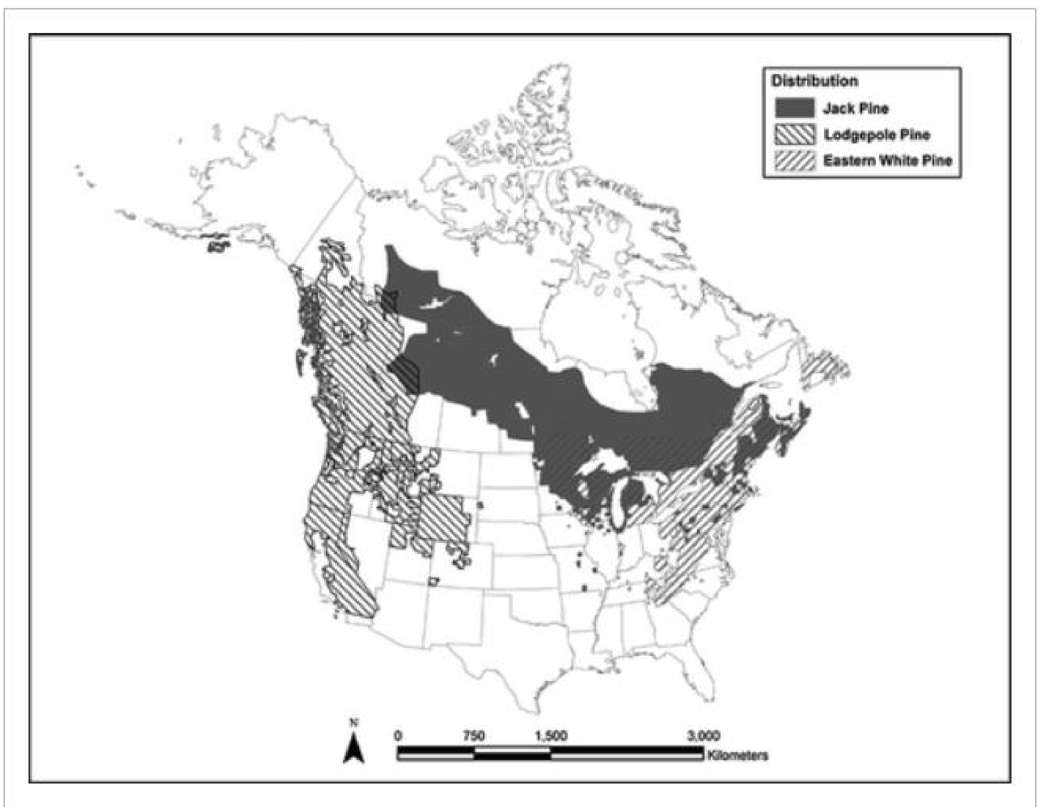


Figure 6. North American pine tree ranges and connectivity to visual a path for the MPB expansion (Cullingham *et al.* 2011)

Figure 7 shows the MPB climate suitability index as described by Carroll *et al.* in their 2004 study of MPB range expansion. The extreme sections mean the climate in that area is optimal for the MPB and very low means the climate is unsuitable (Carroll *et al.* 2004). This figure shows that habitat suitable for the MPB has expanded greatly over the past century (Carroll *et al.* 2004). The southern portions of BC have been affected the most by this suitability expansion because the most optimal habitat has expanded greatly into the southern and central areas of BC (Carroll *et al.* 2004). In the Carroll *et al.* (2004) study they also found that the MPB's range in northern sections of BC are not expanding, but rather the previously low suitability of the areas is changing to now be a more suitable habitat for the MPB. The same study found that MPB infestation rates have increased over time from the 1950s to the 2000s in areas that had, in the past, been less optimal habitat (Carroll *et al.* 2004). The only explanation for this is that climate change is expanding the range of the MPB (Carroll *et al.* 2004). Some arguments have been made that increases in host species by forest operations have increased the range of the MPB, but this cannot be strictly true as an expanding host species range will not in itself make the area climatically inhabitable for the MPB, only a warming climate will do so (Carroll *et al.* 2004, Safranyik *et al.* 1975). Other studies show that MPB range expansion is inevitable with increasing temperatures, but the most affected MPB populations will be the northern populations (Carroll *et al.* 2004, Mitton and Ferrenberg 2012)

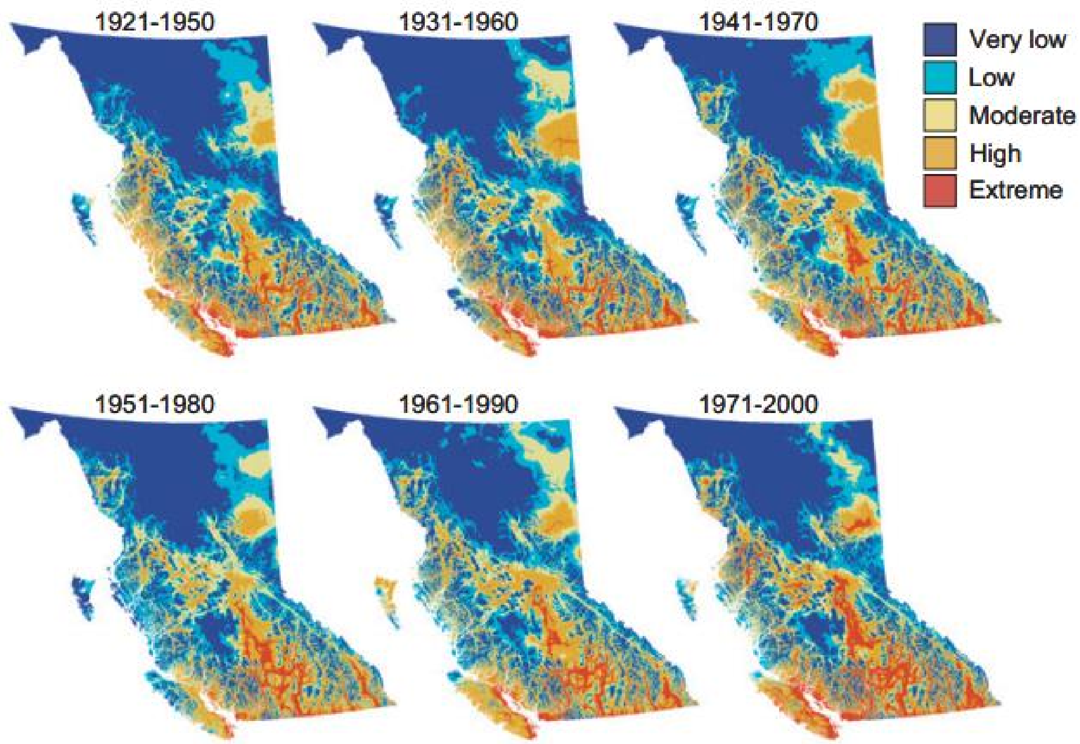


Figure 7. Historic Distribution of BC Climates Suitable for MPB Habitat (Carroll *et al.* 2004)

Mitton and Ferrenberg (2012) examined annual climate patterns and MPB range from 1970-2008 and found that with the warming temperatures the MPB has migrated to higher elevations. It was also found that MPB populations in Colorado moved from 2740 m to 3350 m in elevation (Mitton and Ferrenberg 2012). That is, a 610 m elevation increase in habitable areas for the MPB (Mitton and Ferrenberg 2012). Results from Mitton and Ferrenberg (2012) also show that multivoltinism in high elevation beetle populations will increase the rate at which the MPB range expansion into higher elevations will occur.

## CONCLUSION

With the past global temperatures rising by 1°C and continued increases in global temperature predicted to reach 1.5-2.5°C, environmental interactions between the MPB and its host species will be altered (Williams and Liebhold 2002, IPCC 2018). Certain populations of the MPB may experience a modified reproductive cycle because of climate change (Logan and Bentz 1999, Logan and Powell 2001, Carroll *et al.* 2004, Taylor and Carroll 2004). These MPB populations face the potential of reduced success due to desynchronized emergence and life stage development with partial multi-voltinism (Logan and Bentz 1999, Logan and Powell 2001, Carroll *et al.* 2004, Taylor and Carroll 2004). Contrarily, there is a possibility that an opportunity for bivoltinism or multivoltinism could increase MPB populations as well as the effectiveness of the MPB's mass attack strategy (Mitton and Ferrenberg 2012). A warming climate will also create a more climatically suitable area for the MPB to inhabit (Safranyik *et al.* 1975, Carroll *et al.* 2004, Mitton and Ferrenberg 2012). Additionally, warming temperatures will alter habitat already within the range of MPB to a more optimal habitat (Carroll *et al.* 2004, Mitton and Ferrenberg 2012). The most affected range expansion will occur with MPB populations in the far north and at high elevations (Mitton and Ferrenberg

2012). Expansion of high elevation MPB populations creates the possibility of range expansion into the boreal forest (Bentz *et al.* 2010, Cullingham *et al.* 2011, Logan and Powell 2001). MPB has the ability to use all pine species as a host tree, thus if MPB were to begin to infest jack pines in the boreal forest, MPB expansion could reach the east coast of North America given enough time (Logan *et al.* 2003, Cullingham *et al.* 2011).

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