

AN EVALUATION OF MOUNTAIN PINE BEETLE OUTBREAKS IN COLORADO AND  
WYOMING UNDER CLIMATE CHANGE USING GEOSPATIAL ANALYSIS

by

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## Abstract

In the past two decades, the native mountain pine beetle (*Dendroctonus ponderosae*) has decimated the pine forests of Colorado and Wyoming. These infestations are an issue for local communities because of the loss of ecosystem services that these forests provide, the potential for increased fire risk in the dead stands, and the unattractive appearance of these dead trees, which result in lower property values and is an eyesore for the local population. Previous research has linked climate change to increased outbreak levels and the range expansion of this beetle. In my study, a geospatial analysis was used to identify susceptible forests under current and future climate conditions based on the mountain pine beetle's temperature tolerance and host vegetation requirements. A climate envelope model was used, and thus the results determine the potential for mountain pine beetle attack but do not evaluate the results of future attacks. Historically, cold winter temperatures limited the range and magnitude of outbreaks; however, under the IPCC's A1B climate scenario, nearly all of the pine forests in the study area will be susceptible by 2050. Under this scenario, some 400,000 additional acres of forest will become susceptible to outbreaks by 2050, an increase of about 8.5%. The new areas that will become at risk include the San Isabel National Forest, Gunnison National Forest, Grand Mesa National Forest, and Uncompahgre National Forest. Forested areas just to the west of Colorado Springs that were once protected by cold winter temperatures will become increasingly susceptible to outbreaks. Under future conditions, climate change adaptation mechanisms such as forest restoration will be increasingly important. Because of a lack of resources for large-scale management operations, small-scale suppression strategies, such as the use of pheromones, insecticides, and thinning, will be particularly important at the wildlands-urban interface and other sites of local importance. The lessons from this beetle can be used to direct future forest and climate change policies, and highlight the need to increase resources for adaptation in order to protect natural areas, improve landscape-level management, reduce other stresses to the environment, and enhance the natural resilience of forest ecosystems.

## Introduction

Native bark beetles are capable of destroying vast areas of forest, and as temperatures have risen due to anthropogenic climate change, these outbreaks have spiraled out of control (Logan et al. 2003). The Colorado and Wyoming front range, where the plains meet the Rocky Mountains, has been devastated by mountain pine beetle (*Dendroctonus ponderosae*) outbreaks in the past two decades. Outbreaks levels have greatly surpassed historic levels, and this forest pest has infested millions of acres of forest. These changes in outbreak levels have been linked to climate change, which has already increased the magnitude, frequency, and range of mountain pine beetle outbreaks (Logan and Powell 2001; Logan et al. 2003). Since the industrial revolution, the summer and winter temperatures of the study region have become several degrees warmer, and this trend is expected to worsen in the coming years (IPCC 2007). A geospatial analysis was conducted to identify areas that are currently susceptible to mountain pine beetle outbreaks as well as those areas that will likely be at risk in 2050 because of climate change. A climate envelope model that considered temperature and host vegetation was used to identify these areas. Such information can be used to direct future management strategies.

### *Mountain Pine Beetle Life History & Spread*

In the past two decades, the forests of the western United States and southwest Canada have been decimated by the native mountain pine beetle. The current range of this pest includes most of the western United States, including Arizona, California, Colorado, Idaho, Montana, New Mexico, Nevada, Utah, Oregon, South Dakota, Washington, and Wyoming, as well as parts of Canada, including British Columbia and Alberta (Figure 1). Millions of acres of forest have already been destroyed in the western United States, including 3.7 million acres in Colorado alone (U.S. Forest Service and Colorado State Forest Service 2010). As of 2008, more than 34 million acres of forest have been impacted in British Columbia and northwestern Alberta (Kurz et al. 2008).

Most western pine species can serve as suitable hosts for the mountain pine beetle, although lodgepole pine (*Pinus contorta*) and ponderosa pine (*Pinus ponderosae*) are the most important (Logan and Powell 2001). Recently, whitebark pine trees (*Pinus albicaulis*), a long-lived high-elevation species, have become infected and destroyed by the mountain pine beetle; although the mountain pine beetle has occasionally infected whitebark pine before, beetle populations were never large enough to cause any substantial damage (Logan et al. 2003).

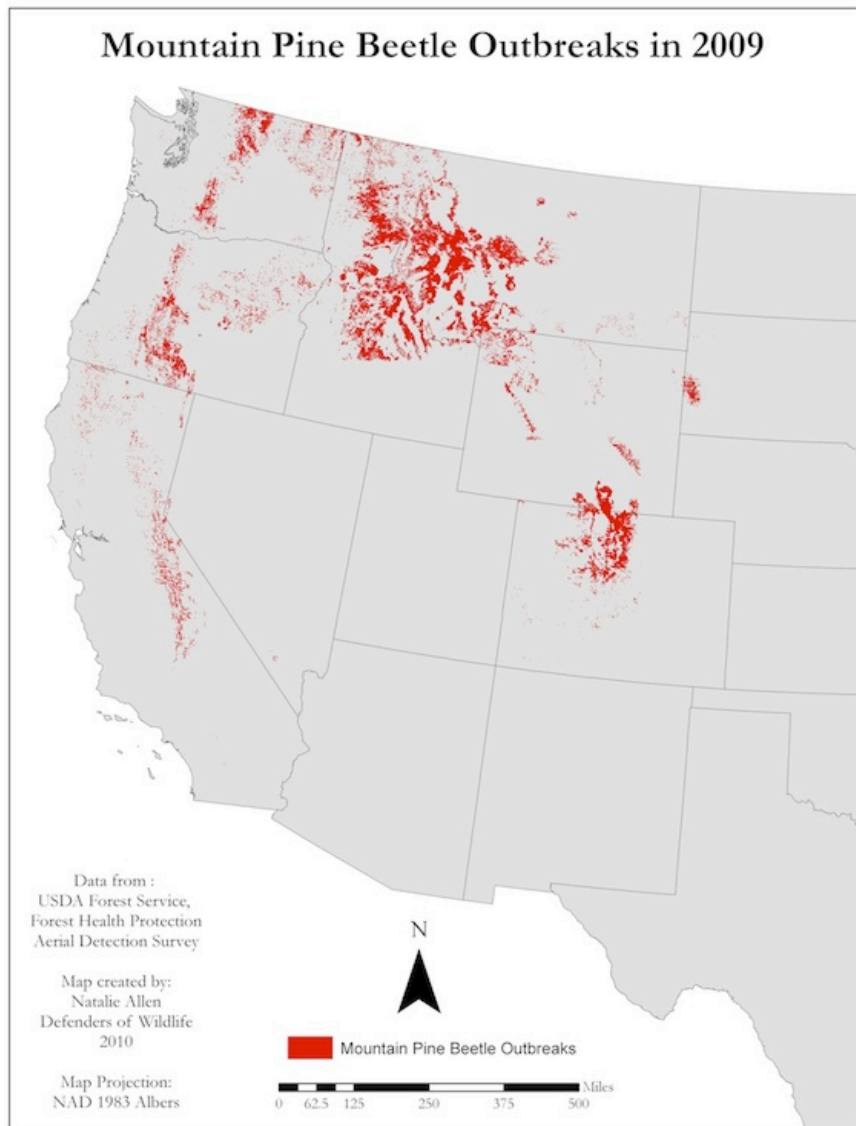
Timing and synchrony are the two major ecological factors contributing to the success of the mountain pine beetle. As described by Samman and Logan (2000), the typical life cycle of the mountain pine beetle centers around a female-initiated attack, during which the females emit a pheromone to attract males to the host tree. These males in turn release other pheromones to bring other mountain pine beetles to the site, resulting in the “mass attack” that the mountain pine beetle requires to successfully reproduce (Samman and Logan 2000; Logan and Powell 2001). The females lay eggs in the tree, and the resulting larvae then create feeding galleries in the phloem, causing the tree to die from a lack of nutrient exchange within the tree. Under normal circumstances, one generation of mountain pine beetles is produced per year, and the entire population goes through the life cycle stages at the same time; without this synchrony, the mass attack would be impossible. Adaptive timing also plays a major role in the successful development and reproduction of the mountain pine beetle, as adults must emerge early enough to allow the most amount of time possible for reproduction but late enough to avoid lethal freezing temperatures (Logan and Powell 2001).

When the mountain pine beetles are synchronized in their development during the appropriate time of year under the right environmental conditions, they are able to reach outbreak levels.

As a native insect, the mountain pine beetle historically played an important ecological role in these western pine forests until their recent population increase altered the dynamics of this ecosystem. Specifically, the mountain pine beetle is naturally an important component of the relationship between fire and the lodgepole pine (Logan and Powell 2001). After mountain pine beetle outbreaks, the dead needles and trees left behind allow the stand-replacing crown fires to develop

that are needed for successful lodgepole pine reproduction. Under normal levels, these insect outbreaks have a positive impact on these forest ecosystems, as they contribute to nutrient cycling and provide coarse woody debris for streams (Samman and Logan 2000). Furthermore, a number of woodpecker species, including the black-backed, downy, hairy, pileated, three-toed, and white-headed woodpeckers, depend on bark beetles for food and use the dead trees for nesting. These patterns have only begun to change relatively recently.

A number of compounding factors have led to this unprecedented outbreak in mountain pine beetle populations. Human-induced land change has had a



*Figure 1: Mountain Pine Beetle Outbreaks in 2009. Data compiled from the USDA Forest Service Forest Health Protection Aerial Detection Surveys. Not all portions of each state are examined every year with the Aerial Detection Survey, and outbreak areas depicted here are based only on the areas surveyed for 2009.*

large impact on forest ecosystems, creating conditions that allow for massive outbreaks to occur (Samman and Logan 2000). By mining, suppressing fires, grazing, logging, and restocking, these pine forests have become increasingly homogeneous in age and species composition. Simultaneously, the vegetation has become much denser than it would have been naturally. One of the main triggers of these and other bark beetle outbreaks appears to be related to the recent temperature rises that have been occurring due to climate change (Logan and Powell 2009). Ultimately, climate change in conjunction with reduced habitat heterogeneity has increased the chances that a devastating mountain pine beetle outbreak will occur, thus leading to the recent increases in the frequency, impacts, and ranges of mountain pine beetle outbreaks (Raffa et al. 2008). Under typical levels, the mountain pine beetles would remove the older and weaker trees, resulting in mortality rates of about two percent (Samman and Logan 2000). Now mortality rates far exceed the natural levels, ranging from 38 to 86 percent (Lewis 2009).

### *Ecological Impacts of the Mountain Pine Beetle*

The mountain beetle is different from most insect pests in that they almost always kill their host tree during reproduction (Logan and Powell 2009). Because of this life history trait, mountain pine beetles are able to destroy huge forest areas to the detriment of both the biotic and abiotic environment. The mountain pine beetle has been directly responsible for tree deaths and altered forest stand densities (Samman and Logan 2000). Furthermore, these tree deaths have resulted in changes to the coarse woody debris, the forest floor litter, and the amount of light reaching the forest floor. These changes have indirectly led to changes in the fire regime, water quality, wildlife, and forest composition. The species, age, size, and distribution of the forests have been altered by these outbreaks, and wildlife are losing important hiding cover and older tree habitat. Overall, these outbreaks have destroyed important habitat within protected and recreational areas, as well as valuable timber production sites.

In contrast to smaller outbreaks, large-scale mountain pine beetle induced mortality tends to result in sparse and patchy recruitment. In British Columbia, lodgepole pines were unable to recruit following an outbreak; they had difficulties reestablishing on the moss-dominated forest floor in the absence of other forms of forest disturbances such as fire, and thus subalpine fir comprised the majority of recruitment following an outbreak (Astrup et al. 2008). Furthermore, for the ten years following the outbreak, the forest experienced no pulse of regeneration, and thus recruitment levels after mountain pine beetle disturbances were far below that of recruitment levels following natural fire events. When natural fires occur or when smaller-scale mountain pine beetle outbreaks occur in conjunction with fire, the substrate undergoes changes that allow for increased recruitment. In contrast, bark beetle disturbances alone do not result in changes to the moss-dominated forest floor that are needed for many tree species to successfully recruit. Overall, it appears that many forests disturbed by mountain pine beetles are undergoing large shifts in landscape level species composition.

The whitebark pine is a classic example of a k-selected species (Schwandt 2006). They are longer lived, with slower development, delayed reproduction, and limited dispersal. These traits make this species particularly at risk of the mountain pine beetle. Because they are slow-growing and often live for 1,500 years, their recovery from bark beetle infestations is especially difficult. Clark's nutcracker (*Nucifraga Columbiana*) and whitebark pine are strongly connected; this bird requires the highly nutritious whitebark pine seeds as a primary food source, and in return, the whitebark pine is completely dependent on Clark's nutcracker for seed dispersal (Logan and Powell 2001). As

whitebark pine trees are destroyed, Clark's nutcracker must struggle to survive on a limited food supply, and if their numbers then decline, it will become increasingly difficult for the whitebark pine to successfully reproduce and recover from the outbreak. Red squirrels (*Tamiasciurus hudsonicus*) and grizzly bears (*Ursus arctos*) both also rely on the whitebark pine seeds for survival, and may be unable to survive in their absence.

### *Climate Change and the Mountain Pine Beetle*

Climate change is expected to result in the shift of insect populations toward higher latitudes and higher elevations (Logan and Powell 2001; Williams and Liebhold 2002; Logan et al. 2003). Evidence of this has already been seen as the mountain pine beetle expanded to higher elevations and farther east than ever before (Logan and Powell 2001). As the mountain pine beetle shifts its range, it has the potential to encounter new host species (Williams and Liebhold 2002). Evidence indicates that changing growth rates in beetle populations are largely the result of rising temperatures in the regions occupied by the mountain pine beetle (Logan et al. 2003). When combined with management practices that have favored homogeneous stands of host pine species, the elevated temperatures and increased droughts brought on by climate change have increased the frequency and magnitude of outbreaks (Raffa et al. 2008). Not only are mountain pine beetle outbreaks occurring in areas that had previously only had small beetle populations, but mountain pine beetles are shifting their range to new areas as well. Fire suppression has certainly made western forests more susceptible to outbreaks by altering the natural species composition and distribution, and climate change is exacerbating the situation.

Overall, temperature is the most important climatic factor in determining the outbreak patterns of the mountain pine beetle, as it affects flight, colonization, and larval development (Aukena et al. 2007). Current distributions of mountain pine beetles appear to be restricted primarily by climate conditions that prevent successful brood development rather than by pine tree host availability (Carroll et al. 2003); furthermore, because mountain pine beetles are ectothermic, they tend to respond rapidly in response to changing temperature by altering their distribution and behavior. Warmer temperatures in August lead to a shorter and more synchronized flight period, and thus more successful mass-attacks while simultaneously weakening host trees with water-stress (Aukena et al. 2007). Fewer extremely cold days in the winter also increase the survival rates of larvae, leading to greater population levels throughout the rest of the year. As temperatures rise, these trends could become increasingly prevalent. In addition to climate change's direct impacts on mountain pine beetle physiology, climate change can also indirectly impact these populations through changes to their host trees and the fungi they carry (Williams and Liebhold 2002).

A comparison of climatically suitable historic habitat and current habitat indicates that the range of the mountain pine beetle has been increasing (Carroll et al. 2003). Infestations are becoming more common in areas that were once climatically unsuitable, and the continued warming of this region that is anticipated with climate change will allow the mountain pine beetle to continue their range expansion northward, eastward, and to higher elevations. Thus far, the mountain pine beetle has experienced extremely rapid range shifts in southeastern and south-central British Columbia due to climatic changes. Furthermore, some areas such as the Sawtooth Valley in Idaho have undergone a shift from a marginally to a highly favorable habitat due to changing temperatures (Logan and Powell 2009).

The projected outbreak areas for the mountain pine beetle are expected to shift towards higher elevations, with potential decreases in overall infestation area as temperatures rise (Williams and Liebhold 2002). Based on a 2.5°C increase in temperature, modeling indicates that a latitudinal shift of more than 7° N will occur, moving mountain pine beetle populations even farther into Canada (Logan and Powell 2001). This is already occurring, and the mountain pine beetle has shifted far beyond its historic range (Logan and Powell 2009). Under a carbon dioxide doubling scenario, this model predicts the range expansion of the mountain pine beetle into Canadian jack pine trees (*Pinus banksiana*), an ecosystem that the mountain pine beetle has not been exposed to historically (Logan and Powell 2001). Previously, the Great Plains had always served as a barrier that prevented the mountain pine beetle from migrating eastward. If this barrier is breached to the north through the jack pine forests of Canada, there is then a continuous connection of suitable pine tree hosts down the entire east coast of the United States, including through Texas. Under such a scenario, infected areas could more than double. The barrier was recently breached in the Peace River Valley of British Columbia, putting pine trees on the east coast at risk from the mountain pine beetle (Logan and Powell 2009). As the mountain pine beetles have moved into lodgepole-jack pine hybrids (*Pinus contorta* var. *latifolia*-*Pinus banksiana*) in British Columbia and Alberta, the mountain pine beetles will infest the jack pine trees of Canada's boreal forests, spreading along a corridor that takes the mountain pine beetle closer to the red pine (*Pinus resinosa*) and white pine (*Pinus strobus*) forests around the Great Lakes (Raffa et al. 2008). Such a range expansion would have both economic and ecological consequences (Logan et al. 2003).

The invasion of high elevation pine ecosystems has become an increasingly important issue, and the elevational shifts in the mountain pine beetle distributions are expected to occur quite rapidly because the mountain pine beetle is so strongly influenced by temperature (Williams and Liebhold 2002). As the mountain pine beetle has spread to higher elevations, the rates of whitebark pine infestations have drastically risen (Penderson et al. 2010). Whitebark pine trees are long-lived, and are not adapted to such insect disturbances the way lower elevation pine trees are in the West (Logan and Powell 2009). Previously, these areas were cool enough that it took two years for mountain pine beetles to complete their life cycle. As such, issues with timing and synchrony prevented large outbreaks from occurring. As the temperature increase reached 3°C in some regions, these beetle populations shifted from completing their life cycles in one year instead of two, thus allowing the large outbreaks to occur, further decimating whitebark pine trees that were already suffering from white pine blister rust. This has occurred in areas such as Railroad Ridge and the Snow Bank Mountain in Idaho, thus emphasizing the fragile nature of the whitebark pine ecosystem. The summer of 2003 had an especially high rate of whitebark pine mortality, with a subsequent loss in the biodiversity of the region by animals that depended upon the whitebark pine (Schwandt 2006).

As explained by Carroll et al. (2003), since the mid-1980s, the level of infestations experienced in those areas that were historically the most climatically suited to mountain pine beetles have been declining rapidly. This could be the result of reductions in the numbers of mature pine trees due to fire, harvesting, or past mountain pine beetle outbreaks. It is also more likely that this is the result of such areas becoming too warm for successful mountain pine beetle infestations. As summer temperatures warm past a certain level, portions of the mountain pine beetle population switch to having more than one generation per year (Logan and Bentz 1999; Logan and Powell 2001). This forces eggs, pupae, and adults to overwinter, and these life stages are much more susceptible to the cold than larvae, leading to decreased populations from winter mortality; simultaneously, this partial multivoltinism can also disrupt flight synchrony and the mass attack during the following year

because parts of the beetle population are at different life stages. Essentially, as temperatures become too warm in the southern range of the mountain pine beetle, there will be a loss in the adaptive seasonality and synchrony required for the beetle to successfully reproduce. Thus, although range expansion is expected to the north and at higher elevations, areas to the south and at lower elevations will likely become less suitable for mountain pine beetles.

Massive mountain pine beetle outbreaks are also impacting the global carbon cycle, as the widespread tree mortality increases emissions from the decay of the dead trees and reduces the ability of forests to uptake carbon (Kurtz et al. 2008). This causes the forests to switch from a small net carbon sink to a large net carbon source during the infestation as well as afterwards. The emissions from the recent outbreaks in British Columbia alone are equivalent to 75% of the average annual forest fire emissions for all of Canada. These mountain pine beetle outbreaks may change the manner in which these northern forests store carbon, thus further exacerbating the issues associated with climate change.

### *Economic Impacts of the Mountain Pine Beetle*

Although mountain pine beetle outbreaks have ecological benefits when they occur on a smaller-scale, they can be extremely detrimental from an economic perspective when they occur on a larger scale. They can disrupt and destroy logging industries, and have large negative impacts on tourism and outdoor recreation (Negrón et al. 2008). Beetle-killed trees tend to be significantly less valuable than trees harvested under regular conditions because of a reduction in structural quality (Samman and Logan 2000). Mountain pine beetle damage can also significantly reduce property values; for every tree killed by mountain pine beetles within 0.1 km, property values decline by approximated \$648 (Price et al. 2010). This is particularly important at the wildlands-urban interface. Dead trees further away can also lower property values, although to a lesser extent than closer outbreaks.

A mountain pine beetle outbreak in British Columbia, Canada had an initial high positive economic impact followed by a high negative impact (Flint et al. 2009). There was a short-term boom in the economy due to increased logging of beetle-killed trees, followed by a long-term decline due to the large decrease in the timber supply. A loss of income from tourism is also expected as trails were closed for safety reasons, and the aesthetics of the areas declined. The economic impact of the mountain pine beetle outbreak in Colorado remains uncertain, although it is likely to have a similar negative impact on tourism and recreation (Flint et al. 2009). Those areas with luxury resorts and natural recreation will experience economic impacts as a result in the declines in aesthetics.

Local communities must often bear the costs of mitigation efforts during any sort of forest pest outbreak (Flint et al. 2008). Local residents also have to clear their personal property of dead trees following an outbreak, which can be quite costly; beyond a purely aesthetic standpoint, this is especially important to reduce the risk of dead trees falling on homes (Flint 2006). More than 90% of people surveyed following a mountain pine beetle outbreak in Colorado indicated that they had experienced tree clearing costs (Flint et al. 2008).

### *Mountain Pine Beetle Management Strategies*

Managers do not aim for a complete elimination because of the important role the mountain pine beetle plays under normal conditions within the forest ecosystems of the West (Amman and Logan 1998). Although no method is known for completely suppressing mountain pine beetle epidemics, a

number of management approaches exist for controlling the issue to varying degrees, largely depending on the size of the outbreak, the conditions of the site, and the sizes and ages of the trees (Coops et al. 2008). The most effective approach to managing mountain pine beetle infestations is largely scale-dependent, ranging from attractants, repellants, and insecticides for smaller-scale operations; harvesting and thinning for medium-scale operations; and prescribed burning for larger-scale operations. Beyond a no-action approach, which is often most appropriate in wilderness areas, management strategies can also be grouped into three different approaches including prevention, suppression, and restoration (Samman and Logan 2000).

The prevention strategy involves altering forest conditions to make the pine trees less susceptible to outbreaks by using different silviculture techniques and prescribed fire in order to create vegetative mosaics (Samman and Logan 2000). Such an approach tends to be more long-term, large-scale, and cheaper in the long run. Thinning operations have long been promoted as a solution to the mountain pine beetle epidemic, as this method was assumed to increase tree vigor, thus allowing the trees to better withstand invasion (Coops et al. 2008); however, changes in microclimate immediately following thinning are also responsible for the decreased beetle mortality rates (Amman and Logan 1998). Alterations to the temperature, light intensity, and wind speed influence mountain pine beetle behavior, making forests less susceptible to mountain pine beetle invasions. Such an approach does appear to be relatively effective, as such stands tend to have a lower number of attacked trees, a lower density of attacked trees, and lower tree mortality (Coops et al. 2008).

Fire is another prevention approach that can be used to address mountain pine beetle infestations. Prescribed burning can be used to restore fire-adapted forests to a more natural state, thus making them more resistant to major mountain pine beetle outbreaks (Coops et al. 2008). During such burns, care must be taken to not weaken stands and tree tissues to the point that they are unable to withstand invasions. Under some circumstances, infected trees can be cut and burned to kill existing mountain pine beetle populations and prevent them from spreading. Such an approach is useful in small patches of infested trees or when infested trees are patchily distributed.

The suppression approach is aimed at controlling existing populations of the mountain pine beetle in the short-term and on a smaller-scale. It tends to be more expensive and often involves multiple applications. This approach includes activities such as sanitation cuts, salvage cuts, pheromone traps, and pesticide treatments. The most common management approach involves the use of attractants, repellents, and insecticides. Anti-aggregation pheromones such as Verbenone alone are often inconsistent, and a combination of attractants and repellents is often more effective, although all of these approaches are time-consuming and impractical on a larger scale (Coops et al. 2008). Sanitation harvesting is aimed at removing trees in areas that are currently infested in order to reduce outbreaks whereas salvage logging is aimed at removing dead trees purely for economic purposes. In some areas such as British Columbia, the scale of salvage logging in response to the mountain pine beetle is unprecedented, after which these areas are replanted, typically leading to even-aged stands of lodgepole pine (Lewis 2009). This approach often leaves inadequate snag habitats, which are needed for a number of woodpecker species. Salvage logging must be carefully planned in order to maintain and recruit live trees and deadwood habitat to support wildlife populations. Such operations also have the potential to increase the vulnerability of forests to future attacks due to decreases in the heterogeneity of the vegetation.

Lodgepole pine areas that have recently experienced mountain pine beetle outbreaks and have since been replanted after salvage harvesting are at elevated risk from the Warren root collar weevil

(*Hylobius warren*) (Klingenberg et al. 2010.) Warren root collar weevils tend to migrate from unsalvaged mature stands into the replanted juvenile stands. Although the Warren root collar weevil was not an especially significant pest previously, it often becomes one in areas dominated by replanted lodgepole pine juveniles. Current mitigation approaches aimed at addressing mountain pine beetle outbreaks such as salvage harvesting followed by replanting can inadvertently create additional pest challenges. In order to address this new pest issue, other non-host trees need to be included in the planting mixes in to reduce tree mortality.

The restoration approach is aimed at reestablishing the entire forest ecosystem's ecological integrity by creating a landscape mosaic of forest types that are more similar to the historical landscape (Samman and Logan 2000). This in turn would restore the important ecological role of the mountain pine beetle while keeping the beetle populations at a reasonable level. Clerid beetles (family Cleridae) can also serve as a natural predator of the mountain pine beetle, and a more intact ecosystem will likely involve a greater degree of natural controls such as these.

Bark beetles outbreaks have been assumed to increase the flammability of coniferous forest for a number of years following an outbreak (Hopkins 1909; McCullough et al. 1998). Certainly the reduction of hazardous fuels is vital in areas with adjacent human communities, and thus the priority for bark beetle, fuel, and fire management should be at wildland-urban interfaces as well as in watersheds that supply drinking water. In such areas, the thinning of brush and small trees would be appropriate to protect the safety of human communities. In contrast, it is impractical to build roads and cut trees in remote roadless areas in order to simply reduce wildfires; this approach is more appropriate in areas with homes, commercial properties, recreational value, or critical wildlife habitat (Dombeck et al. 2004; Jenkins et al. 2008). Neither thinning nor extensive logging strategies will completely reduce catastrophic fires, and instead the focus should be on restoring a more natural fire regime while simultaneously reducing risks to local communities (Dombeck et al. 2004).

### *Objective*

The objective of this study was to identify areas in Colorado and Wyoming that are currently susceptible to mountain pine beetle outbreaks as well as those areas that will likely be at risk in 2050 because of climate change. Specific objectives included:

- Building a climate envelope model based on current climate.
- Generating a current climate map of areas susceptible to outbreaks.
- Generating a future climate map based on the A1B IPCC scenario.
- Projecting future distributions to highlight places potentially at risk in the future. The future climate projections indicate location for more focused monitoring and management.

## **Methods**

### *Scenario*

A thorough literature review was conducted to examine the relationship between mountain pine beetle outbreaks and climate. The study area was the Colorado and Wyoming front range, where the plains meet the Rocky Mountains. This area has been devastated by the mountain pine beetle in recent years, and a geospatial analysis was conducted to identify areas that are currently susceptible to mountain pine beetle outbreaks as well as those areas that will likely be at risk in 2050 because of climate change.

### *Climate Data*

The climate data were retrieved from [www.worldclim.org](http://www.worldclim.org), and included information on both minimum and maximum temperatures for 2009. This year was selected because the MPB outbreak data was also from this year. The minimum January temperatures for the study area ranged from  $-23.0^{\circ}\text{C}$  to  $-7.9^{\circ}\text{C}$ . The maximum July temperatures for the study area ranged from  $10.6^{\circ}\text{C}$  to  $34.6^{\circ}\text{C}$ . In comparison to average winter and spring temperatures, these years were among the top fifteen warmest years since 1990 in Colorado (NOAA, 2009). In Wyoming, these temperatures were also warmer than normal, but not to the same extent as in Colorado. Data were at the 30-arcsec resolution, the equivalent of about 1km.

Future climate projections for this region for 2050 were retrieved from [www.worldclim.org](http://www.worldclim.org). Data were available as a raster dataset for minimum January and maximum July temperatures at a 30 arcsec resolution (about 1km). These projections are based on the IPCC's A1B climate change scenario, which assumes very rapid economic growth, a global population that peaks mid-century, substantial reductions in regional differences in per capita income, and a balance between fossil fuels and alternative energy sources (IPCC 2007). Unlike the A2 and B2 projections, this scenario predicts that carbon dioxide emissions will fall by 2100. Of a number of potential model runs, the A1B scenario posits a more modest climate change overall, but slightly higher temperature increases by 2050 (see Figure 2). Thus, it was chosen as an overall intermediate temperature scenario.

This future climate dataset is from the Canadian Centre for Climate Modeling and Analysis's third generation coupled global climate model (CCCMA-CGCM31), which includes updated atmospheric circulation information. The original results of this model were downscaled for regional and local scaled analysis. As part of this process, a statistical relationship was developed between local climate variables such as surface air temperature and large-scale predictors such as pressure fields. This relationship was then applied to the coarse scale dataset in order to simulate local climate characteristics under future climate conditions.

### MULTI-MODEL AVERAGES AND ASSESSED RANGES FOR SURFACE WARMING

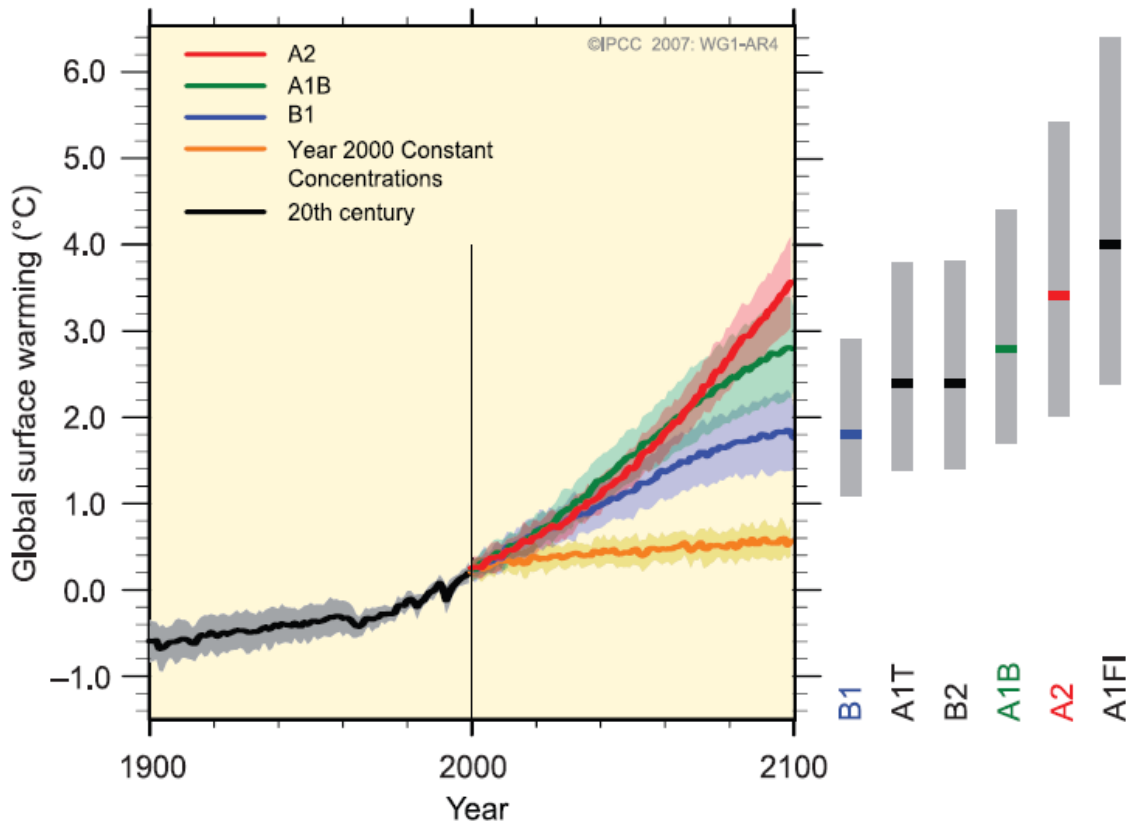


Figure 2: Solid lines are multi-modeled global averages of surface warming relative to 1980-1999 for the A2, A1B, and B1 scenarios. Shading denotes the  $\pm 1$  standard deviation range of individual model annual averages. The orange line represents a scenario in which concentrations were held constant at year 2000 values. The grey bars at the right indicate the best estimate (solid line within each bar) and the likely range associated for these scenarios. (IPCC 2007).

### Pine Beetle Data

The mountain pine beetle outbreak data were compiled from the USDA Forest Service Forest Health Protection Aerial Detection Surveys for Region 2 from 2009 (USDA Forest Service, 2010). Not all portions of each state are examined every year with the Aerial Detection Survey, and outbreak areas depicted here are based only on the areas surveyed for 2009, and thus it is possible that some outbreaks went undetected. Survey areas are prioritized based on historical outbreaks and those areas most likely to be infested with new outbreaks. Still, these data area assumed to be sufficiently accurate for the purposes of this analysis because of the analysis focuses on representative occurrences.

## *Vegetation and Landcover Data*

The vegetation data were from the LANDFIRE Data Distribution Site ([www.landfire.cr.usgs.gov](http://www.landfire.cr.usgs.gov)). The specific dataset used was LF\_1.0.2, which included information of existing vegetation cover based on imagery from 1999 to 2003. Vegetation types of interest were extracted, and included lodgepole pine, ponderosa pine, and whitebark pine. Urban development was also extracted from this dataset to highlight the relationship between susceptible areas and urban areas. All data were at the 30m by 30m resolution size. These data only indicate forest presence and do not adequately depict forest health. In reality, those forests that have been altered, be it through fire suppression, land-use change, habitat fragmentation, or logging practices, are most at risk. However, for the purposes of this analysis, lodgepole pine, ponderosa pine, and whitebark pine forests were treated equally when identifying susceptible areas because all are at risk to a certain degree.

## *Analysis*

A climate envelope model was developed to identify the current temperature tolerances of the mountain pine beetle (Hijman and Graham 2006). The results of this model identify areas that are susceptible to mountain pine beetle attack but does not indicate the potential results of the attack. As part of this model, the climate data was sampled with the mountain pine beetle to determine the temperature range where mountain pine beetles were present, and thus what climate conditions are associated with any outbreaks. The climate data used was minimum January temperature and maximum July temperature. This assumes that these maximum and minimum temperatures serve as the primary control over mountain pine beetle outbreaks. From this information, areas that are currently susceptible to mountain pine beetle outbreaks based on present temperatures only were identified. Those areas that fell within the mountain pine beetle's temperature tolerance as well as contained the host trees of the mountain pine beetle (lodgepole, ponderosa, and whitebark pine) were then identified. Because these are the two factors that most strongly influence mountain pine beetle distribution and outbreak levels, these areas that are currently most threatened by the mountain pine beetle.

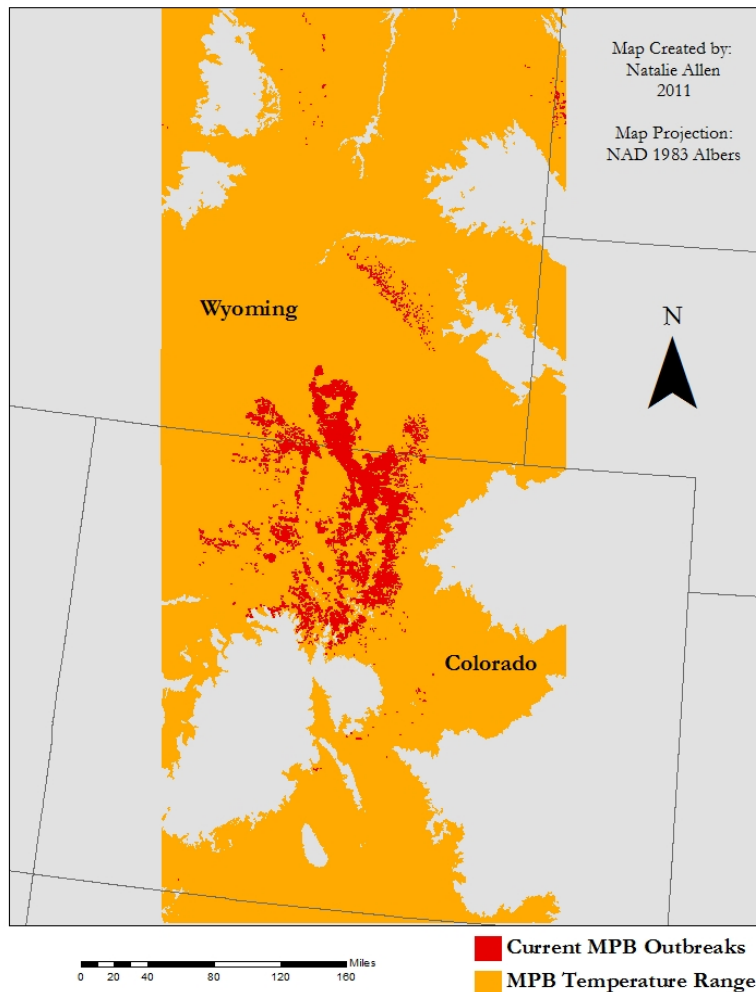
The same analysis was conducted using the IPCC's average A1B scenario (IPCC 2007). Those areas that meet the mountain pine beetles' temperature tolerances and host vegetation requirements under future climate conditions were identified. Because forests are unlikely to drastically change their distribution in the next forty years due to climate change because of their slow response time, the assumption was made that current vegetation distribution served as an adequate estimate of future vegetation conditions in 2050. Thus, the current forest distribution dataset was used for this portion of the analysis as well.

Areas currently susceptible to outbreaks were compared to areas that will be susceptible to outbreaks under future climate conditions in terms of distribution and area. Urban development data was then added in order to evaluate how these outbreaks might impact residential areas. With mountain pine beetles, connectivity is less important in identifying susceptible areas due to the long transport range of the mountain pine beetle, and was not considered (Jackson and Murphy 2003). All GIS analysis was conducted with ArcGIS 10.0 (ESRI, Redlands, CA). All data were projected to NAD 1983 Albers Equal Area Conic, and were masked to include the Colorado and Wyoming study region. A script of the full ArcGIS analysis is located in Appendix 1.

## Results

### *Areas Susceptible to Mountain Pine Beetle Outbreaks*

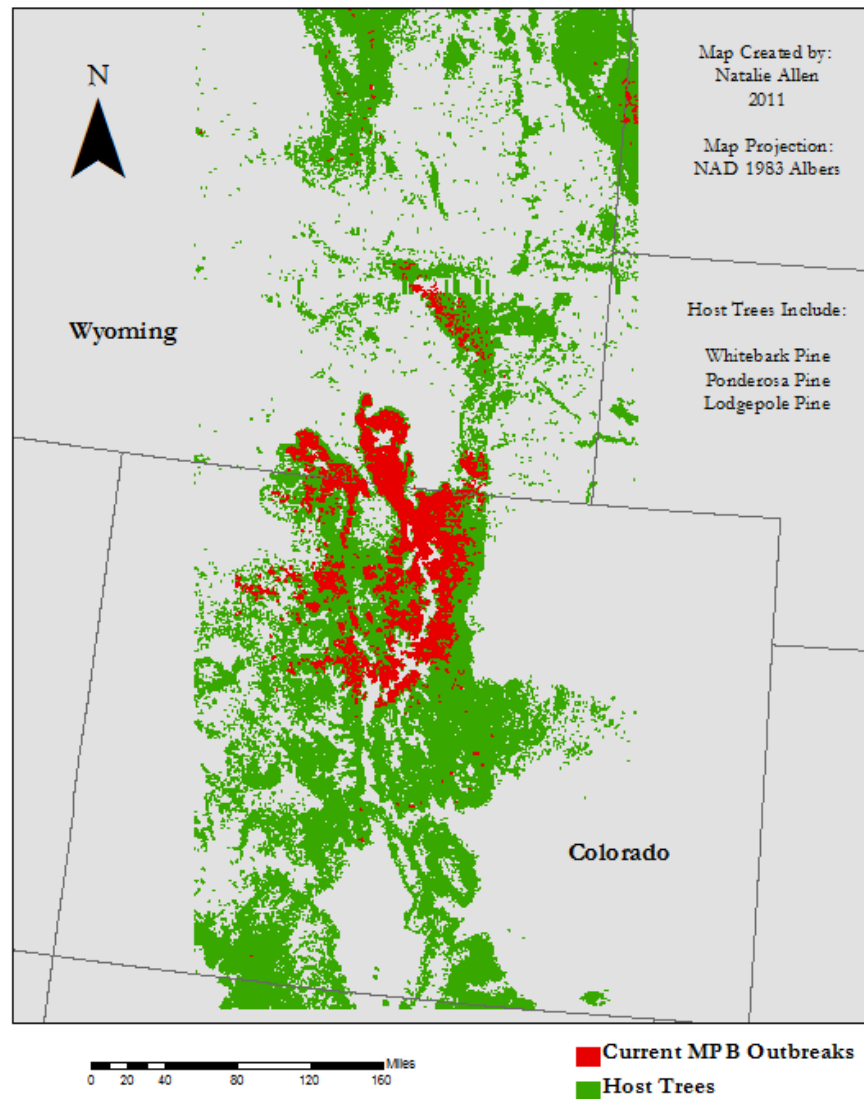
Based on this analysis, the mountain pine beetle infestations occur between a minimum January temperature of  $-18.1^{\circ}\text{C}$  and a maximum July temperature of  $31.1^{\circ}\text{C}$ . Based on temperature alone, much of the study area of Colorado and Wyoming is susceptible to mountain pine beetle outbreaks if sufficient host vegetation is present. Under current (2009) conditions, most of the northern front range of Colorado has experienced outbreaks, but the areas further to the south have not. Many of these more southern areas are higher in elevation, and thus fall outside of the temperature tolerance of the mountain pine beetle (Figure 3).



*Figure 3: Areas Susceptible to Future Mountain Pine Beetle Outbreaks Based on Temperature Tolerance under Current Climate.*

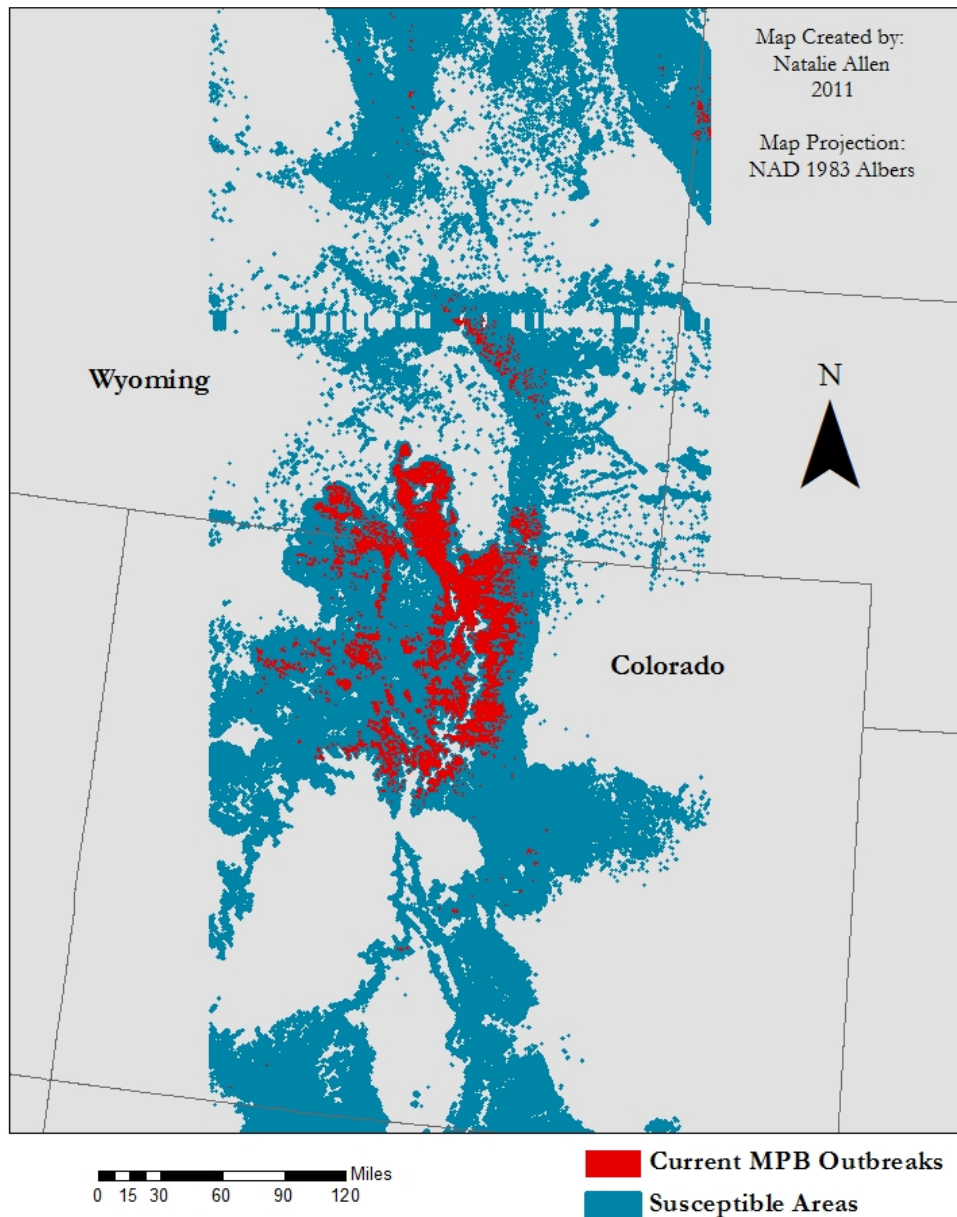
Much of the front range of Colorado and Wyoming contain whitebark pine, ponderosa pine, and lodgepole pine, all of which serve as host trees for the mountain pine beetle (Figure 4). Although habitat connectivity does not strongly influence mountain pine beetle dispersal, its host vegetation is much more connected to the south of the current outbreaks than to the north (Jackson and Murphy 2003). Much of the viable habitat in northern Wyoming is somewhat disconnected from the current outbreaks, and thus these areas may be slightly more protected from future outbreaks than the southern portions of Colorado.

Temperature and host tree presence are the two primary factors controlling mountain pine beetle outbreaks, and in the absence of human intervention, such as the use of insecticides, these two factors can be used to predict areas susceptible to future outbreaks. When host vegetation data is combined with the mountain pine beetle's temperature tolerance information, sites in the region that are susceptible to outbreaks under current climate conditions can be identified. Those areas most susceptible to future mountain pine beetle outbreaks based on temperature tolerance and the presence of host trees under the current climate are present throughout much of the front range of Colorado and Wyoming (Figure 5). There is a large area in the southwest portion of the study area that is not at risk under the current climate because the area is too high in elevation, and thus temperatures are



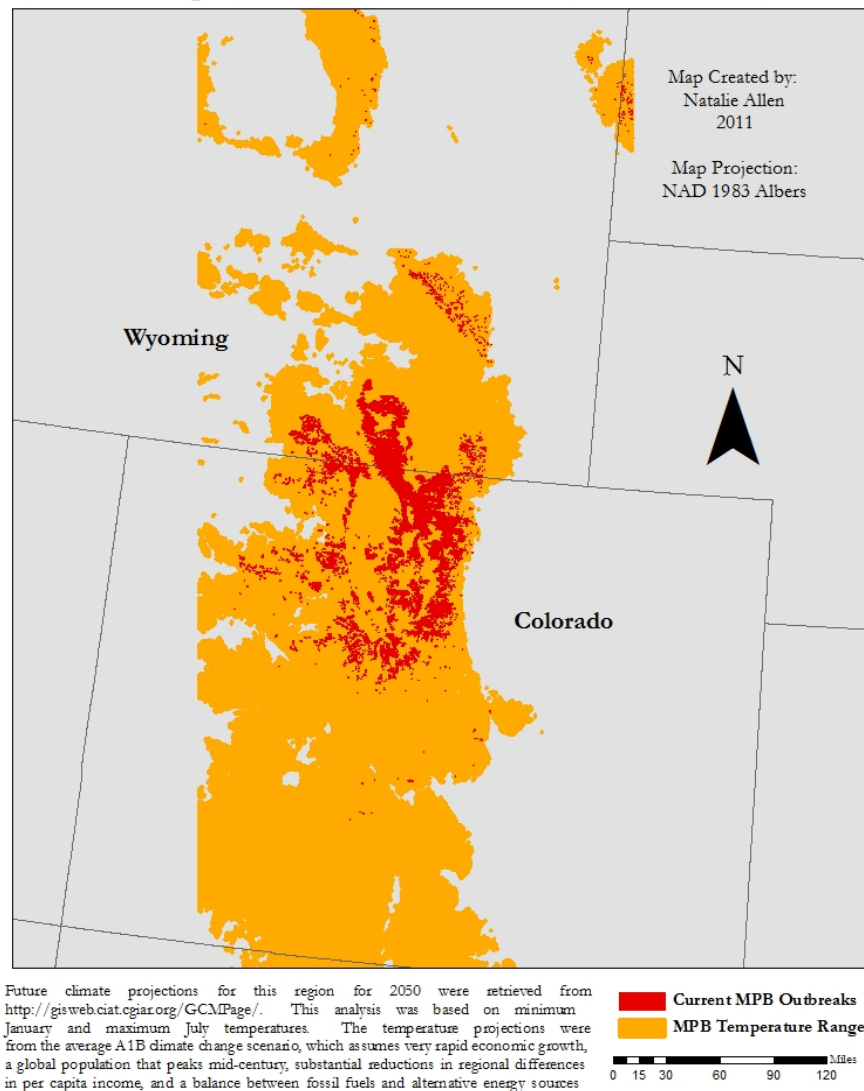
*Figure 4: Areas Susceptible to Future Mountain Pine Beetle Outbreaks Based on Host Tree Presence under Current Climate Conditions. Host trees include Whitebark Pine, Ponderosa Pine, and Lodgepole Pine. Vegetation data are based on 1999 to 2003 aerial surveys from the LANDFIRE Data Distribution Site.*

too cold in the winter for mountain pine beetle survival despite the presence of host vegetation. In contrast, a large continuous area just to the west of the current outbreaks looks suitable as habitat based on the data. Because small pockets of outbreaks are already present in this area, these outbreaks could easily spread to these adjacent regions. Similarly, although most of the susceptible areas in Wyoming are to the north, susceptible areas to the south are closer to current outbreaks, and thus most at risk.



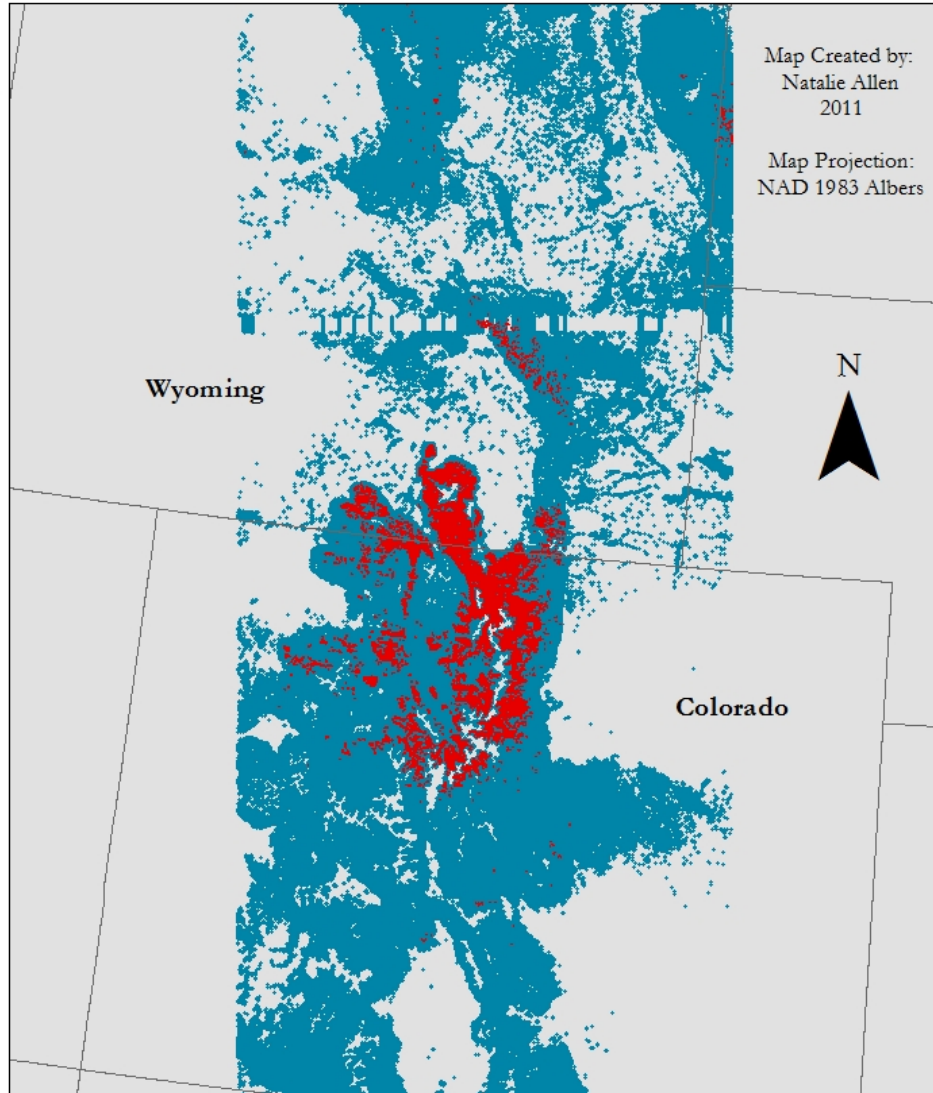
*Figure 5: Areas Susceptible to Future Mountain Pine Beetle Outbreaks Based on Temperature Tolerance and Presence of Host Trees under Current Climate.*

Under these 2050 climate projections, more of the western portion of the study region will be within the mountain pine beetle's temperature tolerances, primarily due to increasingly warm winter temperatures (Figure 6). Historically, low winter temperatures kept most outbreaks in check, but under future climate conditions, winter temperatures will no longer serve as a major restriction on mountain pine beetle survival and reproduction in these areas. Many areas of northeastern Wyoming still fall within the temperature tolerance of the mountain pine beetle, although these areas are now more patchily distributed and thus not clear in Figure 6. Several areas to the east that were once within the mountain pine beetle's temperature tolerance no longer are as summer temperatures become too warm.

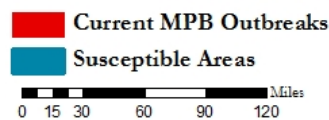


*Figure 6: Areas Susceptible to Future Mountain Pine Beetle Outbreaks Based on Temperature Tolerance in 2050 under the IPCC's Average B1 Scenario.*

Because of the long lifespan of these pine trees and developmental pressure, it is unlikely that the distribution of these pine forests will drastically shift in the next forty years. As such, the current vegetation distribution was used to evaluate the forests most susceptible to outbreaks in 2050. When considering both temperature tolerance and host vegetation presence under future climate conditions, areas in eastern Wyoming will open up to mountain pine beetle infestations, as will areas



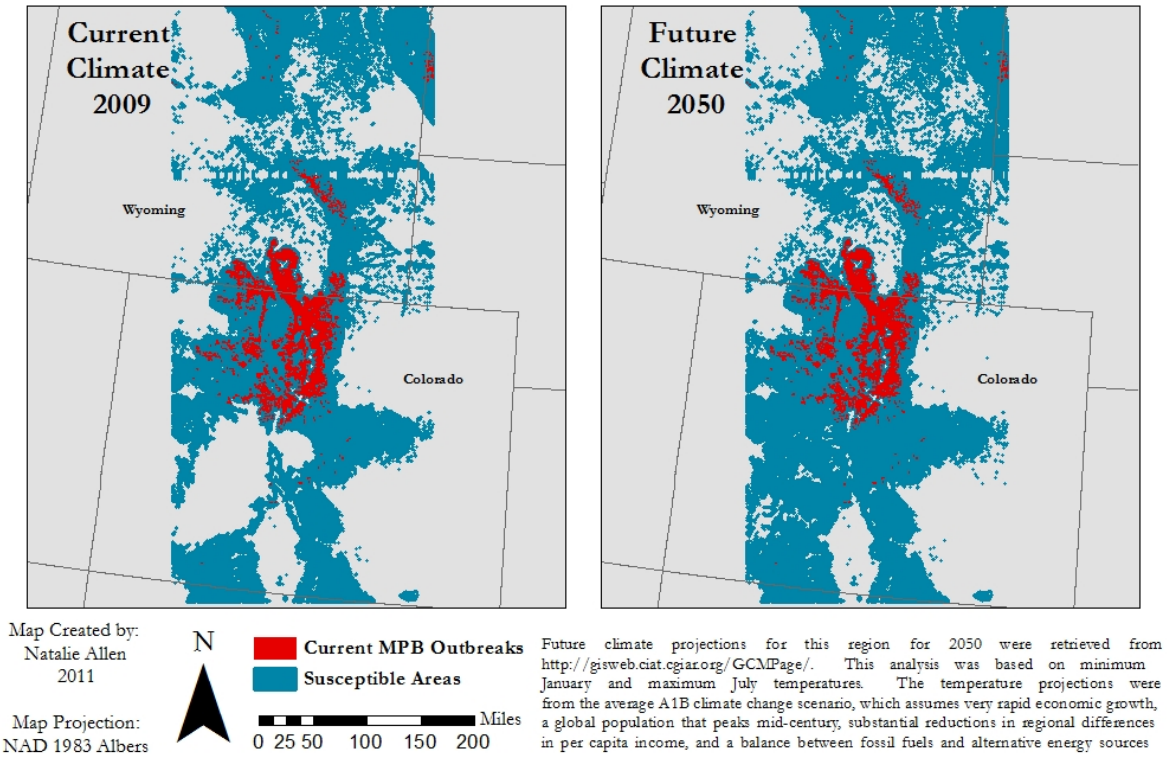
*Figure 7: Areas Susceptible to Future Mountain Pine Beetle Outbreaks Based on Temperature Tolerance and the Presence of Host Trees in 2050 under the IPCC's Average A1B Scenario.*



of the western portion of the study region in Colorado (Figure 7).

When comparing the areas that are currently susceptible to the areas that will be susceptible under the A1B Scenario for 2050, many additional areas in Colorado and Wyoming become susceptible under future climate conditions (Figure 8). The warmer winter temperatures will increase the susceptibility of many of the areas that contain suitable host vegetation but were historically

protected from outbreaks by harsh winter temperatures. Although several areas to the east are no longer suitable for the mountain pine beetle from a temperature perspective, because these areas do not contain the required host vegetation, very few additional areas become excluded from outbreaks under future climate conditions as temperatures become too warm in the summer. This was surprising because previous research indicated that multivoltinism would occur in many areas as temperatures became too high, thus resulting in some areas becoming less susceptible to outbreaks (Logan and Bentz 1999; Logan and Powell 2001).

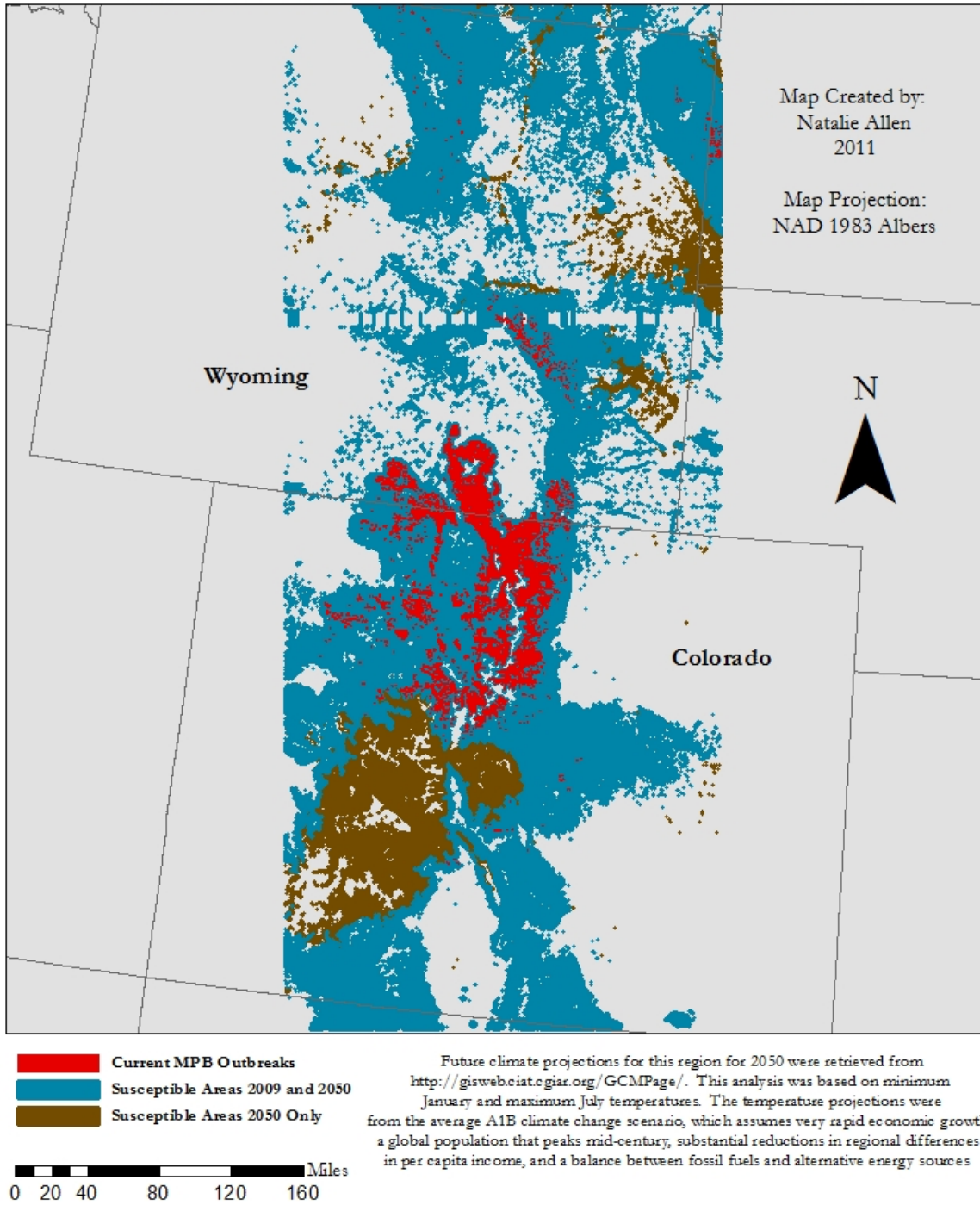


*Figure 8: Areas Susceptible to Future Mountain Pine Beetle Outbreaks Based on Temperature Tolerance and Presence of Host Trees in Current Climate vs. Future Climate under the IPCC's A1B*

Figure 9 highlights the additional areas that will become susceptible in 2050 under this scenario. Many of the additional areas in Wyoming are patchy in their spatial distribution. However, the biggest change is again just southwest of central Colorado. The San Isabel National Forest, Gunnison National Forest, Grand Mesa National Forest, and Uncompahgre National Forest are all located in this part of Colorado, which will become more susceptible to mountain pine beetle outbreaks. Because these areas are large continuous forests and are further from urban development, increasing resilience on the large-scale through forest restoration will be especially important in these ecosystems. Prescribed burns to increase forest heterogeneity is one method that should be emphasized because it is feasible on a larger scale. Overall, outbreak levels are expected to increase within the study area by 398,315 acres (1,611 km<sup>2</sup>), primarily in this region (Table 1).

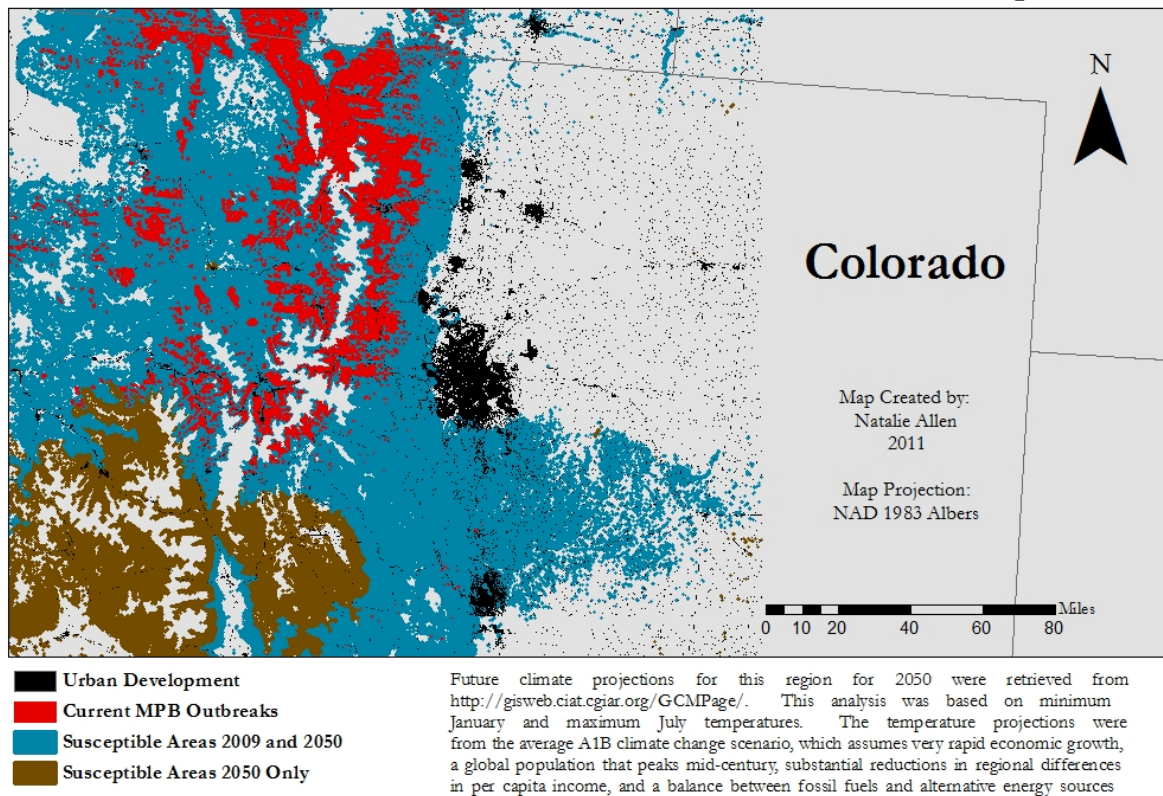
*Table 1: Increase in Susceptible Area Under Future Climate Conditions*

	Area (km <sup>2</sup> )	Area (acres)
Current Climate	19,059.07	4,709,597.99
Future Climate (2050)	20,670.99	5,107,912.86
Increase in Susceptible Area	1,611.92	398,314.87
% Increase in Susceptible Area	8.46%	8.46%



*Figure 9: Areas Susceptible to Future Mountain Pine Beetle Outbreaks Based on Temperature Tolerance and Presence of Host Trees in Current Climate vs. Future Climate under the IPCC's A1B Scenario in 2050.*

The outbreaks of greatest concern to local populations are often those near urban areas. Although the forests just to the west and south of Denver are greatly at risk of infestation even under current climate conditions, they have not experienced as severe of outbreaks as many of the more mountainous regions of Colorado (Figure 10). Similarly, those areas just to the west of Boulder and Fort Collins are also greatly at risk of infestation. Although the shift in the mountain pine beetle's range does not strongly impact these urban areas, these areas will still be at a greater risk under future climate conditions because the magnitude of mountain pine beetle outbreaks will continue to increase as temperatures warm. Forests just to the west of Colorado Springs will become susceptible to outbreaks under future climate conditions. Management efforts on the local level such as the use of insecticides, pheromones, and even tree thinning, will be especially important in the areas near these communities..



*Figure 10: Areas Susceptible to Future Mountain Pine Beetle Outbreaks Based on Temperature Tolerance and Presence of Host Trees in Current Climate vs. Future Climate under the IPCC's A1B Scenario in 2050 in the Denver Region*

## Discussion

### *Data Limitations*

The nature of the datasets used result in a number of limitations with these results. The mountain pine beetle outbreaks data was compiled from the USDA Forest Service Forest Health Protection Aerial Detection Surveys from 2009. Because not all portions of each state are examined every year with the Aerial Detection Survey, and the outbreak areas depicted here are based only on the areas surveyed for 2009, it is possible that some outbreaks went undetected. This dataset also does not adequately account for areas that were once infested and were then abandoned by the mountain pine beetles because all potential hosts had been killed. The forest vegetation dataset was based off of aerial surveys from 1999 to 2003, and there may have been some changes in the distribution of forest types because of logging and previous outbreaks. Furthermore, this dataset does not differentiate between those forests that are completely intact and those that have become less resilient to withstanding outbreaks because of fire suppression and logging practices.

The climate envelope model approach was used in this analysis, which predicts the potential for future mountain pine beetle attack, but does not evaluate what the results of an attack would be. As a result, this could result in an overestimate of potential outbreaks.

Current and future temperature data were at a 30 arcsec resolution, equivalent to about 1km. As a result, these data may not adequately account for specific mountain peaks and valleys. These data still show general mountain range trends, and were considered sufficient for the size of this study area.

### *Outbreaks*

Forest pest outbreaks are a major visual public impact of climate change that is occurring throughout the United States. Colorado and Wyoming have been especially hard hit. Mountain pine beetle outbreaks do not have a clear solution because although they are native and natural, the current outbreak levels are abnormal. Complete eradication is neither possible nor desirable, and instead such forest pests should be returned to a more natural population level throughout Colorado and Wyoming. The focus should be on preventing forest pest outbreaks before they occur in those areas currently susceptible to outbreaks and those areas predicted to be susceptible to outbreaks in 2050, such as through forest and climate change adaptation policy. In particular, the San Isabel National Forest, Gunnison National Forest, Grand Mesa National Forest, and Uncompahgre National Forest will all likely become susceptible to outbreaks under future climate conditions. These forests are located to the west of Colorado Springs, and thus these local communities will be particularly affected by the impacts of climate change on mountain pine beetle outbreaks.

Many current suppression strategies are less useful for large-scale application, and should be emphasized primarily at the wildlands-urban interface, such as to the west of Boulder, Fort Collins, Denver, and Colorado Springs. Ultimately, in order to address the mountain pine beetle situation, future policies should focus on restoring forest ecosystems, increasing resilience, and limiting climate change. Attempting to restore forest ecosystems throughout the entire study area is not a practical solution because of limited resources. As a result, the wildlands-urban interface should be prioritized over remote forest locations, as is the case in current forest fire policy.

Mountain pine beetle outbreaks are largely controlled by temperature, and are thus strongly impacted by climate change. From a climate policy standpoint, the forest pest issue highlights the importance of mitigation and the need to decrease greenhouse gas emissions to stop climate change. Even with reductions, temperatures will continue to rise, and both native and nonnative forest pest outbreaks will continue to increase in both magnitude and range. The stress of increased forest pest outbreaks combined with temperature and precipitation changes may result in even higher levels of tree mortality.

The climate associated with the A1B scenario used in this study is unlikely unless the United States and other nations take major steps towards mitigation and the replacement of some fossil fuels with alternative sources. Because the mountain pine beetle situation is extremely dire even under the A1B scenario, adaptation mechanisms will be extremely important in the coming years. Even major changes in the world's attitude towards the environment will not be enough to save these forests unless management strategies are made to make these forests more resilient to climate change are heavily emphasized. New climate policies that increase resources for adaptation should be implemented in order to protect natural areas, improve landscape-level management, reduce other stresses to the environment, and enhance the natural resilience of the ecosystem. Such policies will help to prevent new outbreaks from occurring and will allow forests to better withstand existing outbreaks. Without an emphasis on adaptation strategies, the mountain pine beetle will continue to destroy the pine forests of Colorado and Wyoming, perhaps past the point of recovery. Such outbreaks have the potential to completely change these forest ecosystems forever.

The exact manner in which these current outbreaks are addressed primarily depends on the management objectives for the region. From a timber production standpoint, bark beetle outbreaks are considered to be negative, and in areas where that is the primary management objective, short-term control efforts will likely take precedent over long-term ecological restoration. Such areas will also provide managers with an opportunity to experiment with methods of replanting designed to return tree composition and density to more natural levels. In wilderness areas, a no treatment option is usually the most appropriate because these outbreaks are somewhat a natural process. At the wildlands-urban interface, short-term or small-scale strategies such as thinning or the use of chemical treatments may be more appropriate. Insecticides and thinning only work on a very small scale and do not offer a long-term solution. However, due to limited resources, such small-scale management operations are often the only practical approach. Although these strategies are inappropriate in large remote forests, they should be emphasized at the wildlands-urban interface, such as to the west of Boulder, Fort Collins, Denver, and Colorado Springs. There is much concern that bark beetle infestations increase the risk of fire by increasing fuel loads. It is important to err on the side of caution by taking measures to limit the chances of wildfire in areas where human developments exist nearby.

Land-use changes have had an impact on mountain pine beetle outbreaks for some forest types, especially ponderosa pine. Land-use change has made these forest ecosystems more susceptible to the outbreaks by changing the composition and density of the vegetation. Because of fire suppression and silviculture practices, forests have been altered from their natural state to become more dense and homogeneous. These changes are largely the result of fire suppression, which have made these forests significantly denser (Romme et al. 2006). Management practices for these ponderosa pine forests should thus focus on restoration and increasing resilience to allow these forests to better withstand the increased outbreaks that will come with increasing temperatures. Restoration has the potential to help restore the functional role of the bark beetle within the forest

while also reestablishing ecological integrity. It is important that efforts not seek to completely eliminate bark beetle populations, as they have an important natural role that should be restored. Despite how they make look, beetle-infested forests are still functioning ecosystems that provide habitat for a number of different species. Nevertheless, such restoration efforts could help reduce outbreak populations to a more natural level. In many ways, restoration is the best form of prevention. Silviculture actions and prescribed burning are useful preventative methods that can lead to the long-term restoration of the ecosystem and reduce forest susceptibility to outbreaks. Ultimately, restoration involves returning the vegetation in the landscape to a more natural state in terms of structure, species, and age, while also allowing bark beetles and other forms of wildlife to return to their historic role. By restoring historic fire regimes and stand structures, these ecosystems will be better able to withstand bark beetle outbreaks by returning the bark beetle populations to a more acceptable level.

In terms of forest policy, it is also vital that all post-infestation treatments be viewed as experimental, and that new approaches are used with caution. The appropriate post-infestation response remains uncertain, and therefore it is important to focus on monitoring, research, and adaptive management. Post-outbreak treatments should be done on a small scale until the long-term ramifications are better understood. Some practices, such as salvage logging, have the potential to exacerbate existing problems, as it removes habitat for a number of species and can slow ecosystem recovery. Such treatments should not be implemented on the large scale without further study of how these practices affect the rest of the ecosystem. Rigorous monitoring and research of ecosystem conditions both before and after any treatments must occur, and these results will help direct further management strategies.

## **Conclusions**

Mountain pine beetle outbreaks are an issue that has worsened with climate change. Currently, there are no clear solutions to this problem; temperature increases are already occurring, and cannot easily be reversed. The lessons from the mountain pine beetle can be used to direct better forest and climate change policies, which can help prevent the situation from worsening. Reducing risk and focusing on ecological restoration and climate change adaptation mechanisms will be particularly important management strategies in the coming years. It is vital to proceed with caution rather than implementing policies that worsen the situation or that are inappropriate for the particular forest system in question. Because large-scale existing outbreaks are extremely difficult to stop, the focus should be on preventing outbreaks from occurring in new forest stands. Controls of existing outbreaks should instead be emphasized at the wildlands-urban population where they are most likely to impact local communities. Furthermore, because much uncertainty exists surrounding this issue, adaptive management is vital, and should be incorporated into all policies and management strategies that are developed.

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## Appendix 1

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# import arcinfo  
  
# Import arcpy module  
import arcpy  
  
# Check out any necessary licenses  
arcpy.CheckOutExtension("spatial")  
  
# Set Geoprocessing environments  
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arcpy.env.mask = "H:\\MP\\Temperature\\tmin_cl_pr"  
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"PROJCS['NAD_1983_Albers',GEOGCS['GCS_North_American_1983',DATUM['D_North_Ame
rican_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0],UNIT[
'Degree',0.0174532925199433]],PROJECTION['Albers'],PARAMETER['False_Easting',600000.0],P
ARAMETER['False_Northing',0.0],PARAMETER['Central_Meridian',-
120.0],PARAMETER['Standard_Parallel_1',43.0],PARAMETER['Standard_Parallel_2',48.0],PARA
METER['Latitude_Of_Origin',34.0],UNIT['Meter',1.0]]", "NEAREST", "952.096922594292", "", "",
"PROJCS['NAD_1983_Albers',GEOGCS['GCS_North_American_1983',DATUM['D_North_Ame
rican_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0],UNIT[
'Degree',0.0174532925199433]],PROJECTION['Albers'],PARAMETER['False_Easting',0.0],PARA
METER['False_Northing',0.0],PARAMETER['Central_Meridian',-
96.0],PARAMETER['Standard_Parallel_1',29.5],PARAMETER['Standard_Parallel_2',45.5],PARAM
ETER['Latitude_Of_Origin',23.0],UNIT['Meter',1.0]]")
```

```
# Process: Project Raster (4)
```

```
arcpy.ProjectRaster_management(tmin_jan_cl__3_, tmin_cl_pr,
"PROJCS['NAD_1983_Albers',GEOGCS['GCS_North_American_1983',DATUM['D_North_Ame
rican_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0],UNIT[
'Degree',0.0174532925199433]],PROJECTION['Albers'],PARAMETER['False_Easting',600000.0],P
ARAMETER['False_Northing',0.0],PARAMETER['Central_Meridian',-
120.0],PARAMETER['Standard_Parallel_1',43.0],PARAMETER['Standard_Parallel_2',48.0],PARA
METER['Latitude_Of_Origin',34.0],UNIT['Meter',1.0]]", "NEAREST", "952.096922594292", "", "",
"PROJCS['NAD_1983_Albers',GEOGCS['GCS_North_American_1983',DATUM['D_North_Ame
rican_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0],UNIT[
'Degree',0.0174532925199433]],PROJECTION['Albers'],PARAMETER['False_Easting',0.0],PARA
METER['False_Northing',0.0],PARAMETER['Central_Meridian',-
96.0],PARAMETER['Standard_Parallel_1',29.5],PARAMETER['Standard_Parallel_2',45.5],PARAM
ETER['Latitude_Of_Origin',23.0],UNIT['Meter',1.0]]")
```

```
# Process: Sample
```

```
arcpy.gp.Sample_sa("H:\\MP\\Temperature\\tmax_cl_pr;H:\\MP\\Temperature\\tmin_cl_pr",
MPB_point_clip, samples6, "NEAREST")
```

```
# Process: Feature To Point
```

```
arcpy.FeatureToPoint_management(reg2_MPB_proj, MPB_point_shp, "INSIDE")
```

```
# Process: Clip
```

```
arcpy.Clip_analysis(MPB_point_shp, Metadata_shp, MPB_point_clip_shp, "")
```

```
# Process: Extract by Attributes
```

```

arcpy.gp.ExtractByAttributes_sa(us_102evt__3_, "\"SAF_SRM\" = 'SAF 208: Whitebark Pine'",
whitebark)

# Process: Extract by Attributes (2)
arcpy.gp.ExtractByAttributes_sa(us_102evt__3_, "\"SAF_SRM\" = 'SAF 237: Interior Ponderosa
Pine'", Ponderosa)

# Process: Extract by Attributes (3)
arcpy.gp.ExtractByAttributes_sa(us_102evt__3_, "\"SAF_SRM\" = 'SAF 218: Lodgepole Pine'",
lodgepole)

# Process: Extract by Attributes (4)
arcpy.gp.ExtractByAttributes_sa(us_102evt__3_, "\"SAF_SRM\" = 'LF 20: Developed' OR
\"SAF_SRM\" = 'LF 20:Developed'", developed)

# Process: Extract by Attributes (5)
arcpy.gp.ExtractByAttributes_sa(us_102evt__3_, "\"SAF_SRM\" = 'SAF 208: Whitebark Pine' OR
\"SAF_SRM\" = 'SAF 218: Lodgepole Pine' OR \"SAF_SRM\" = 'SAF 237: Interior Ponderosa
Pine'", susctrees)

# Process: Raster to Polygon (3)
arcpy.RasterToPolygon_conversion(susctrees, susctrees_poly2_shp, "SIMPLIFY", "VALUE")

# Process: Raster Calculator
arcpy.gp.RasterCalculator_sa("Con(\"%tmax_cl_pr%\" < 311,1)", tmax_31_1)

# Process: Raster to Polygon
arcpy.RasterToPolygon_conversion(tmax_31_1, tmax311_poly_shp, "SIMPLIFY", "VALUE")

# Process: Raster Calculator (2)
arcpy.gp.RasterCalculator_sa("Con(\"%tmin_cl_pr%\" > - 181,1)", tmin_neg18_1)

# Process: Raster to Polygon (2)
arcpy.RasterToPolygon_conversion(tmin_neg18_1, tmin18_poly_shp, "SIMPLIFY", "VALUE")

# Process: Intersect
arcpy.Intersect_analysis("H:\\MP\\Temperature\\tmax311_poly.shp
#;H:\\MP\\Temperature\\tmin18_poly.shp #", temp_intersect_shp, "ALL", "", "INPUT")

# Process: Clip (2)
arcpy.Clip_management(susctrees, "-1257473.19835739 1478298.18550227 -392817.193893594
2604910.6915768", temp_veget, temp_intersect_shp, "", "ClippingGeometry")

# Process: Clip (5)
arcpy.Clip_analysis(Current_MPB_Outbreaks, MPB_Temperature_Range, MPB_temp_clip_shp, "")

# -----
# Future.py

```

```

# Created on: 2011-04-01 12:14:36.00000
# (generated by ArcGIS/ModelBuilder)
# Description:
# -----

# Import arcpy module
import arcpy

# Check out any necessary licenses
arcpy.CheckOutExtension("spatial")

# Set Geoprocessing environments
arcpy.env.scratchWorkspace = "C:\\\\TEMP"
arcpy.env.cellSize = "MAXOF"
arcpy.env.mask = "tmax_cl_pr"
arcpy.env.workspace = "H:\\\\MP"

# Local variables:
tmax_7_asc = "E:\\\\Max\\tmax_7.asc"
tmin_jan_cl = "H:\\\\MP\\Temperature\\tmin_jan_cl"
tmin_1_asc = "E:\\\\Min\\tmin_1.asc"
susctrees = "susctrees"
max = "E:\\\\Max\\max"
max_3_ = "E:\\\\Max\\max"
max_proj2 = "E:\\\\Max\\max_proj2"
max_proj_clip = "E:\\\\Max\\max_proj_clip"
min = "E:\\\\Min\\min"
min_2_ = "E:\\\\Min\\min"
min_proj = "E:\\\\Min\\min_proj"
min_proj_clip = "E:\\\\Min\\min_proj_clip"
min_temp_181 = "E:\\\\Min\\min_temp_181"
max_temp_311 = "E:\\\\Max\\max_temp_311"
Temp_combined_shp = "E:\\\\TempComb\\Temp_combined.shp"
max_temp_poly_shp = "E:\\\\Max\\max_temp_poly.shp"
min_temp_poly_shp = "E:\\\\Min\\min_temp_poly.shp"
temp_veg = "E:\\\\TempComb\\temp_veg"
temp_veg_poly_shp = "E:\\\\TempComb\\temp_veg_poly.shp"
SusArea_shp = "E:\\\\TempComb\\SusArea.shp"

# Process: ASCII to Raster (2)
arcpy.ASCHIIRaster_conversion(tmin_1_asc, min, "INTEGER")

# Process: Define Projection (2)
arcpy.DefineProjection_management(min,
"GEOGCS['GCS_WGS_1984',DATUM['D_WGS_1984',SPHEROID['WGS_1984',6378137.0,298.
257223563]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]]")

```

```

# Process: Project Raster (3)
arcpy.ProjectRaster_management(min__2_, min_proj,
"PROJCS['NAD_1983_Albers',GEOGCS['GCS_North_American_1983',DATUM['D_North_Ame
rican_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0],UNIT[
'Degree',0.0174532925199433]],PROJECTION['Albers'],PARAMETER['False_Easting',0.0],PARA
METER['False_Northing',0.0],PARAMETER['Central_Meridian',-
96.0],PARAMETER['Standard_Parallel_1',29.5],PARAMETER['Standard_Parallel_2',45.5],PARAM
ETER['Latitude_Of_Origin',23.0],UNIT['Meter',1.0]]", "NEAREST", "952.096910210133",
"WGS_1984_(ITRF00)_To_NAD_1983", "",
"GEOGCS['GCS_WGS_1984',DATUM['D_WGS_1984',SPHEROID['WGS_1984',6378137.0,298.
257223563]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]]")

# Process: Clip (3)
arcpy.Clip_management(min_proj, "-1022028.03185073 1581787.93106706 -630716.196664469
2501513.55829315", min_proj_clip, tmin_jan_cl, "", "NONE")

# Process: Extract by Attributes
arcpy.gp.ExtractByAttributes_sa(min_proj_clip, "\"VALUE\" > -181", min_temp_181)

# Process: Raster to Polygon (2)
arcpy.RasterToPolygon_conversion(min_temp_181, min_temp_poly_shp, "SIMPLIFY",
"VALUE")

# Process: ASCII to Raster
arcpy.ASCIIToRaster_conversion(tmax_7_asc, max, "INTEGER")

# Process: Define Projection
arcpy.DefineProjection_management(max,
"GEOGCS['GCS_WGS_1984',DATUM['D_WGS_1984',SPHEROID['WGS_1984',6378137.0,298.
257223563]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]]")

# Process: Project Raster (2)
arcpy.ProjectRaster_management(max__3_, max_proj2,
"PROJCS['NAD_1983_Albers',GEOGCS['GCS_North_American_1983',DATUM['D_North_Ame
rican_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0],UNIT[
'Degree',0.0174532925199433]],PROJECTION['Albers'],PARAMETER['False_Easting',0.0],PARA
METER['False_Northing',0.0],PARAMETER['Central_Meridian',-
96.0],PARAMETER['Standard_Parallel_1',29.5],PARAMETER['Standard_Parallel_2',45.5],PARAM
ETER['Latitude_Of_Origin',23.0],UNIT['Meter',1.0]]", "NEAREST", "952.096922591057",
"WGS_1984_(ITRF00)_To_NAD_1983", "",
"GEOGCS['GCS_WGS_1984',DATUM['D_WGS_1984',SPHEROID['WGS_1984',6378137.0,298.
257223563]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]]")

# Process: Clip (2)
arcpy.Clip_management(max_proj2, "-1022028.03185073 1581787.93106706 -630716.196664469
2501513.55829315", max_proj_clip, tmin_jan_cl, "", "NONE")

# Process: Extract by Attributes (2)

```

```
arcpy.gp.ExtractByAttributes_sa(max_proj_clip, "\"VALUE\" <311", max_temp_311)

# Process: Raster to Polygon
arcpy.RasterToPolygon_conversion(max_temp_311, max_temp_poly_shp, "SIMPLIFY",
"VALUE")

# Process: Intersect
arcpy.Intersect_analysis("E:\\Min\\min_temp_poly.shp #;E:\\Max\\max_temp_poly.shp #",
Temp_combined_shp, "ALL", "", "INPUT")

# Process: Clip (4)
arcpy.Clip_management(susctrees, "-1022028.23124638 1581411.88928947 -630340.143645165
2501513.55833605", temp_veg, Temp_combined_shp, "", "NONE")

# Process: Raster to Polygon (3)
arcpy.RasterToPolygon_conversion(temp_veg, temp_veg_poly_shp, "SIMPLIFY", "VALUE")

# Process: Calculate Areas
arcpy.CalculateAreas_stats(temp_veg_poly_shp, SuscArea_shp)
```