GIS Analysis of Mountain Pine Beetle Mitigation Policy in the Northern Rockies and Pacific Northwest

By

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Abstract

Mountain pine beetle (MPB) populations experienced rapid increase in the early 2000s for a variety of reasons, with management policy implementation by the United States Forest Service and the British Columbia Ministry of Forests shortly after. These policies use a variety of control methods to protect their region's forests, and through annual aerial detection surveys, data has been collected for the last two decades on where MPB have impacted forested areas. Through analyzing total area, mean size, and mean center of each region's yearly surveyed MPB areas, we can assess how the characteristics of these areas have changed after the new policy was implemented. I found that after policy implementation there was a decrease in total area in subsequent years, with some regions also showing a decrease in average area size during this period. Centroids of yearly impacted areas in British Columbia began to shift northward in 2009.

Introduction

Up until the mid 1990s, the mountain pine beetle was considered an essential part of the lodgepole pine forest ecosystem, providing food for birds and other insectivores, while keeping the pine tree population under control. Since about 2000, three major factors have changed the way beetles are spreading throughout the Northern Rocky Mountain region. First, drier, drought-like conditions are becoming more prevalent, which stresses the tree's primary functions, decreasing its ability to fight off a pine beetle attack. Second, warmer winter temperatures allow the beetles to survive longer into the winter than before, as the freezing temperatures are a primary mortality agent of the pine beetle (US Forest Service 2005). Third, there are older, larger pine trees for beetles to feed on, as there are now more restrictions on logging old growth forest, contributing to the 42% decrease in old growth harvesting since 2015 (Government of British Columbia 2018). These three conditions have created the so-called “perfect storm” for creating epidemic conditions of mountain pine beetle spread. The British Columbia Ministry of Forests (BCMF) estimated that nearly 20% of the province’s total forested area was affected by MPB by 2006 (Government of British Columbia 2006).

The importance of this issue can be seen primarily in the loss of habitat in these areas. The decaying lodgepole pine ecosystems leave dead trees which are inhabitable by other organisms, and a decreased leaf area index means less protection for animals lower in the food chain. Mud and landslides are also more common due to decaying root structures and added water content (B.C. Ministry of Forests).

Affected stands also pose a higher wildfire risk than unaffected stands. Since part of the beetle infection destroys a tree’s ability to transport water and nutrients, these stands are left incredibly dry, altering the fuel structure of forests (Harvey 2014). Without pine beetle infestation, old growth forests are more resistant to wildfire than newer forests. (Center for Biological Diversity 2022). A combination of these factors allow wildfires to burn hotter and for longer periods of time in stands affected by pine beetles.

Pine beetle outbreaks affect the natural resource economy, especially in areas whose economy is very dependent on forestry and logging. Affected trees are less suitable for logging, and in 2012 the BC government increased the annual allowable cut (AAC) to account for the loss of profit for companies harvesting the low valued wood (Corbett 2016). However, profits are slow to catch up, even with intense replanting programs, simply because pine stands need a decade to develop into harvestable wood.

The differences in forestry management techniques and policy between different states and provinces in the United States and Canada to better understand pine beetle damage mitigation efforts and strategies used by natural resource management agencies to protect the resources in these areas. The differences between these different states and provinces will provide insight into some industry best practices and how other areas can adopt similar techniques and policies. Current mitigation strategies include semiochemicals, insecticide spraying, prescribed burning, forest thinning and predator encouragement and introduction.

Each government agency has a slightly different pine beetle management strategy, so I will compare the US Forest Service and British Columbia Ministry of Forests' collected aerial GIS data to answer the question: How has the implementation of the new MPB management policy changed the characteristics of the total impact area in these regions?

Background:

What are pine beetles and where did they come from?

Although the mountain pine beetle has brought devastation to much of the Northern American pine stands, up until recently, they played a critical role in the ecosystems where they reside. Mountain Pine beetles play an important role in the forest ecosystem, as they attack older, weakened trees, which allows young trees to develop, while simultaneously providing a food source to the many species of insectivores, such as woodpeckers. The beetle, Dendroctonus ponderosae, is native to the Northern Rocky Mountain region, but due to climate change and human activity, many of the processes that have kept the populations stable have been ineffective. Due to decades of fire depression and aged-managed forests with increased tree density, the likelihood of a MPB outbreak has increased (Taylor et al 2006). Dense, even-aged stands are more susceptible to MPB attacks than open grown forests (Mitchell et. al 1983). Lodgepole pine stands in Western North America are in general more susceptible than other species of pine due to their tendency to grow in denser distribution and more even age structure (Schoennagel et al. 2012). Lodgepole pine has been shown to be considerably more susceptible to MPB attack than Ponderosa Pine, the other main pine species in the area of study (Chapman et. al. 2012). Ponderosa pine is characterized by many low intensity and high intensity fires, allowing for a more diverse range of tree age, which is less ideal for an MBP outbreak (Sherriff and Veblen 2007).

Why is the problem so bad now?

Increasing regional temperatures due to climate change are a primary factor in the expansion of the MPB territory and population growth. In Colorado, it has been shown that MPB habitat elevation has increased from 2740m (8990 ft) to 3350m (10991 ft) in recent decades while not showing decreased populations at historically populated elevations (Mitton and Ferrenberg 2012). Flight season has been earlier, (Bentz and Schen-Langenheim 2007) and doubled in length; historically the flight season was from early August to mid-September (Negrón, et al 2011) while as of 2010, researchers have found a first flight date of June 21st, and a last observed flight in October 4th (Mitton and Ferrenberg 2012). Early spawning allows more trees to be populated, and eggs to be laid sooner in the year to develop into adults by July, decreasing winter mortality. (Mitton and Ferrenberg 2012).

Overview of Control Methods

In general, there are two types of mitigation strategies used: active mitigation and preventative treatments. Active mitigation strategies are used when some host trees are already populated, but the stand as a whole is not majorly infected. Preventative treatments are used in areas that are characteristically susceptible to a pine beetle invasion but have not been infected yet. Preventative treatments are more common, as active treatments have a higher cost-to-saved-tree ratio.

Active treatment strategies include pesticides application, prescribed fire, and mechanical processes. Spraying trees with pesticides is not a solution to kill all beetles in an area but can be used as a holding action until highly susceptible trees are removed. The overall stand susceptibility does not decrease after spraying, so reinfestation will occur without proper preventative measures (Cole and Amman 1980). Pesticide use is most suitable for treating spot infestations in areas where physically removing trees is difficult. Pesticides used against mountain pine beetles include organophosphate carbaryl, pyrethroids permethrin and bifenthrin (USFS). Although effective, these three pesticides do not successfully prevent tree mortality after a tree becomes a host for MPB. Prescribed fire has also been shown to decrease beetle populations, with a 50% reduction in beetles in burned areas, and 100% reduction in individual heavily burned trees (Safranyik et al 2001). Stock and Gorley (1989) found that only intense wildfire was able to kill large populations of MPB in individual trees, and that areas with only moderate wildfire still saw MPB resilience.

Preventative treatments for MPB attack attempt to reduce susceptibility of stands in danger of an infestation and include silvicultural alternatives and pheromone baiting as the most prevalent methods. Silviculture is the science of forest management, and these methods refer to a variety of tree removal practices to decrease the possibility of MPB infection.

For even aged lodgepole pine stands, which are characteristically the most susceptible to attack, three different methods are used: type conversion, salvage cutting, and stocking control. Type conversion refers to introducing other species of tree, mainly ponderosa pine, and cutting some trees to get a more age diverse stand, to discourage rapid MPB population growth. It has been shown that clearcutting small areas creates a mosaic of tree age within large previously even aged stands which has a positive effect on forest health (Amman 1976). Salvage cutting refers to the removal of infected trees by logging companies. This method is preferred to individual tree controls as it is more cost effective, and the logging company is still able to profit from the salvage cuts. The stocking control method attempts to control the average phylum and tree diameter thickness of a stand to become unfavorable for MPB. Stocking control combined with other managed practices, such as thinning, genetic improvements, and fertilization, help increase individual tree health, so current age and size standards for MPB may not be as important to tree susceptibility.

In areas with uneven aged, species diverse pine stands, salvage cutting, and stocking control is used, in addition to species discrimination and partial cutting. Species discrimination is a method of choosing which trees in a susceptible area to cut down. In the case of MPB large lodgepole pine will be cut under this method but can only be used in healthy well managed forests. Partial cutting can be used in place of clearcutting or salvage cutting when dealing with nonhomogeneous forests and is only really used when clearcutting is not an option due to environmental or visual impacts.

In conjunction with silvicultural methods of control, semiochemicals or “message” bearing chemicals can be effectively used to deter MPB to reduce overall stand susceptibility. Semiochemicals are naturally produced by attacking beetles, to let other individuals know which trees are being attacked as a message to not join populated host trees. In 1987, private industry started to synthesize an artificial semiochemical for MPB which is used as a tree bait (PheroTech 1987). Semiochemicals can be used to either confuse beetles enough to prevent them entering host trees or applied to certain trees to control which trees the beetles inhabit. Semichemical applications have been used to deter beetles in stands scheduled for harvest. Spot baiting is a method where 2-3 susceptible trees in the center of the stand are baited prior to beetle flight, and then after the flight period has ended, dying previous host trees and the baited trees are removed. Depending on the size of the infestation, different baiting patterns and practices are used.

Methods

Objectives

In this analysis, I evaluated and visualized the efficacy of outbreak mitigation strategies. Geographic Information Systems, or GIS, is a powerful analysis tool for visualizing spatial relationships, and working with spatial data. Spatial distribution of outbreak areas in relation to provincial and national boundaries provide an interesting setting for GIS analysis.

Data

Vector layers of mountain pine beetle damage areas were taken from aerial surveys conducted by the United States Forest Service (USFS 2023) and the British Columbia Ministry of Forests (BCMF 2023). Both datasets track overall forest damage with various causes, including wildfires, avalanches, and other insect species damage, however the data are organized differently, so the methods of analysis differ slightly between the two datasets. Yearly detection surveys are the primary method for understanding forest health, and the data collected is used to write Forest Insect and Disease Conditions in the United States. The aerial surveys are completed in early July through mid-September, to coincide with the highest level of visibility of all forest damage factors surveyed. The flight path of surveying aircraft is determined by the topology and visibility of the ground. Flight paths over flat areas are uniform, while flight paths over mountainous regions tend to follow ridgelines, so the surveyor can assess conditions in each valley or region of interest (Figure 1).

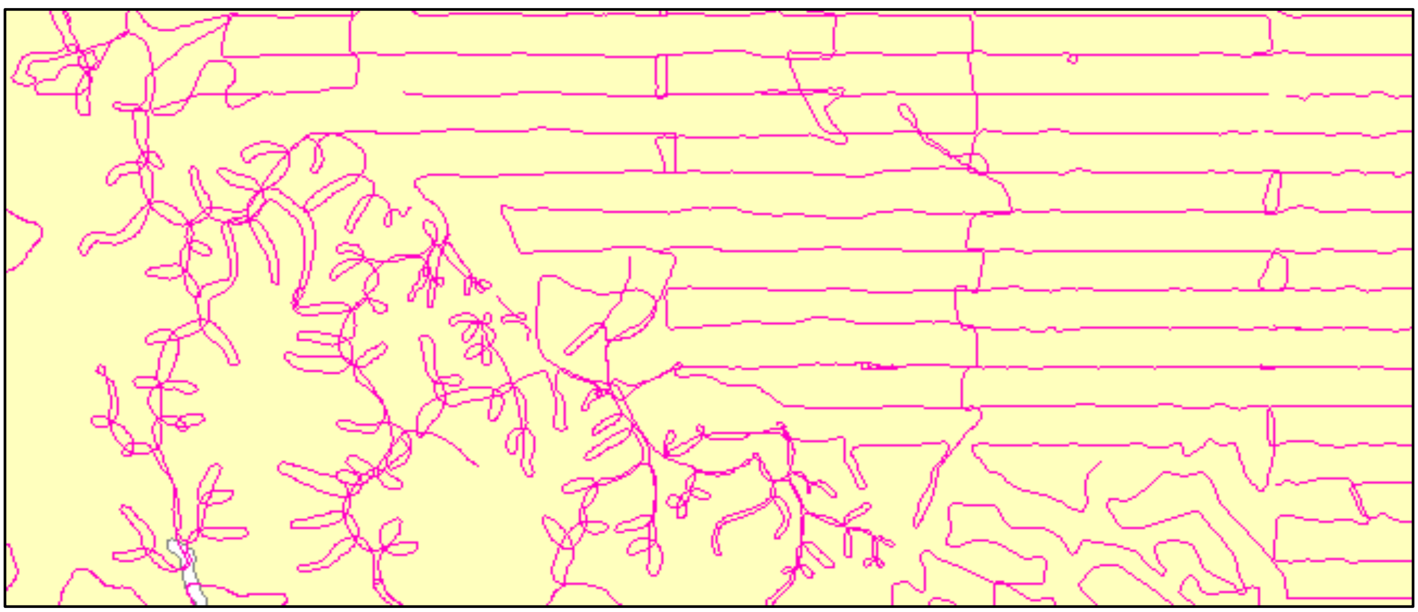


Figure 1: Aerial survey flight paths over mountainous regions versus flat areas. Mountainous regions can be seen in the southwest side of the map and follow ridgelines and natural topography. Flat areas are surveyed in a grid like pattern, present in the northeastern side of the map. This flight path is a screenshot from the southwest corner of British Columbia in 2011.

USFS Data Cleaning

To analyze mountain pine beetle damage in USFS Region 1 and Region 6 (Figure 2) I downloaded a folder that contained shapefiles of all flight paths, spot damage, and polygons of damaged areas from all surveys done by USFS representatives from 1999 through 2021. The data also contained different problem causes and types of damage. The first step to cleaning my data was to filter for damage type, specifically "Mortality", and filter for the cause as 'mountain pine beetle'. For the purposes of my analysis, I was only interested in seeing data from 2004 through 2015, as USFS implemented a new management policy in 2009 (USFS). I recorded how many polygons were observed each year for each region, as well as calculated the total area affected each year, and the percent change from previous years. I calculated the percent change from 2004-2009 as a measure of how the outbreak was before policy and calculated the percent change from 2010-2015 to measure how the outbreak reacted to the new policy. I recognize that some changes to aerial survey observed outbreaks are not solely caused by changes in policy. Shapefiles were also created showing the maximum extent of the damage from these two time periods for each region.

British Columbia Data Cleaning

To analyze mountain pine beetle damage in British Columbia I downloaded shapefiles from the BCMF that contained all flight paths, and polygons of damaged areas from surveys done by Ministry of Forests representatives from 2001 through 2010. I used the Select by Attribute tool to filter the Forestry Health Factor (FHF) for mountain pine beetle damage for each year. For the purposes of this analysis, I was only interested in seeing data from 2001 through 2010, as USFS implemented a new management policy in 2005 (BC Ministry of Forests). I calculated the percent change from 2001-2005 as a measure of how the outbreak was before policy and calculated the percent change from 2006-2010 to measure how the outbreak progressed during the new policy regime. Shapefiles were also created showing the visible extent of the damage from these two time periods. The data before 2002 did not have a coordinate system declared in the GIS data, although Albers 1983 was used according to metadata files, so I used the Define Projection tool to be able to continue my analysis.

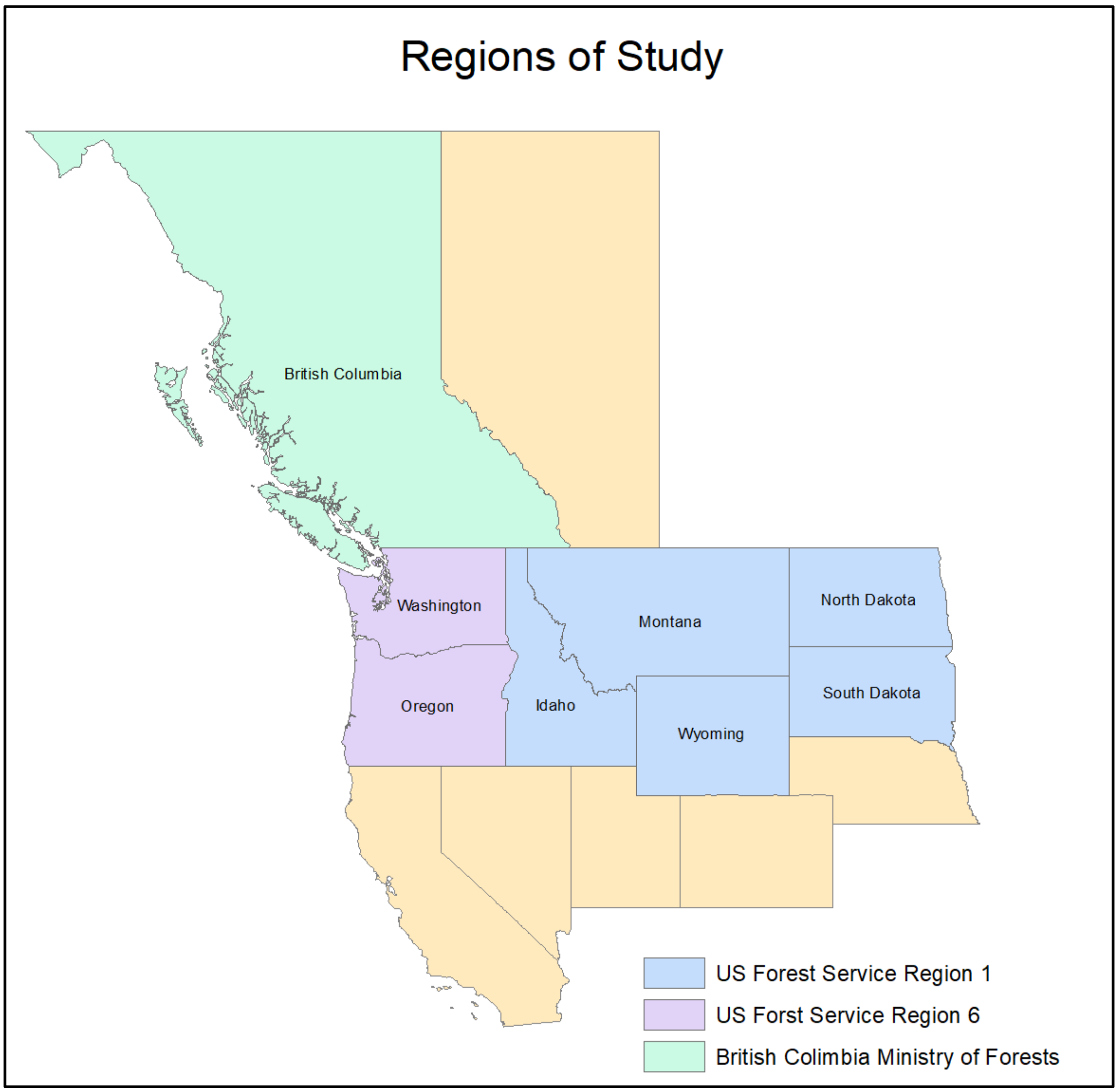


Figure 2: Map detailing extent of US Forest Service Region 1, US Forest Service Region 6, and British Columbia Ministry of Forests areas. Regions of study are surrounded by other state and provincial boundaries for spatial context.

Data Methods

To control for differences in climatology in the southern regions of USFS and Northern Regions of BCMF, 50-mile, 100-mile, and 200-mile buffers were created along the US-Canada border and data within those buffers was isolated for specific analysis at each buffer distance (Figure 3). In this analysis, the 200-mile buffer includes all area from the US-Canada border to the buffer's edge. The data was extracted by clipping each year's data to each buffer. This was done to see spillover effects from neighboring policy, and to control for climatological and other ecological factors. For creating maps of before policy and after policy impacted areas, data from 2004-2009 and 2010-2015 in USFS and 2000-2011 in BCMF were dissolved together to cut down on processing time. Total area and mean polygon area were calculated and recorded for each year for each of the three buffer distances for USFS Region 1, USFS Region 6, and BCMF. A comparison was made between years, calculating percentage change in total area from year to year.

Buffer Regions

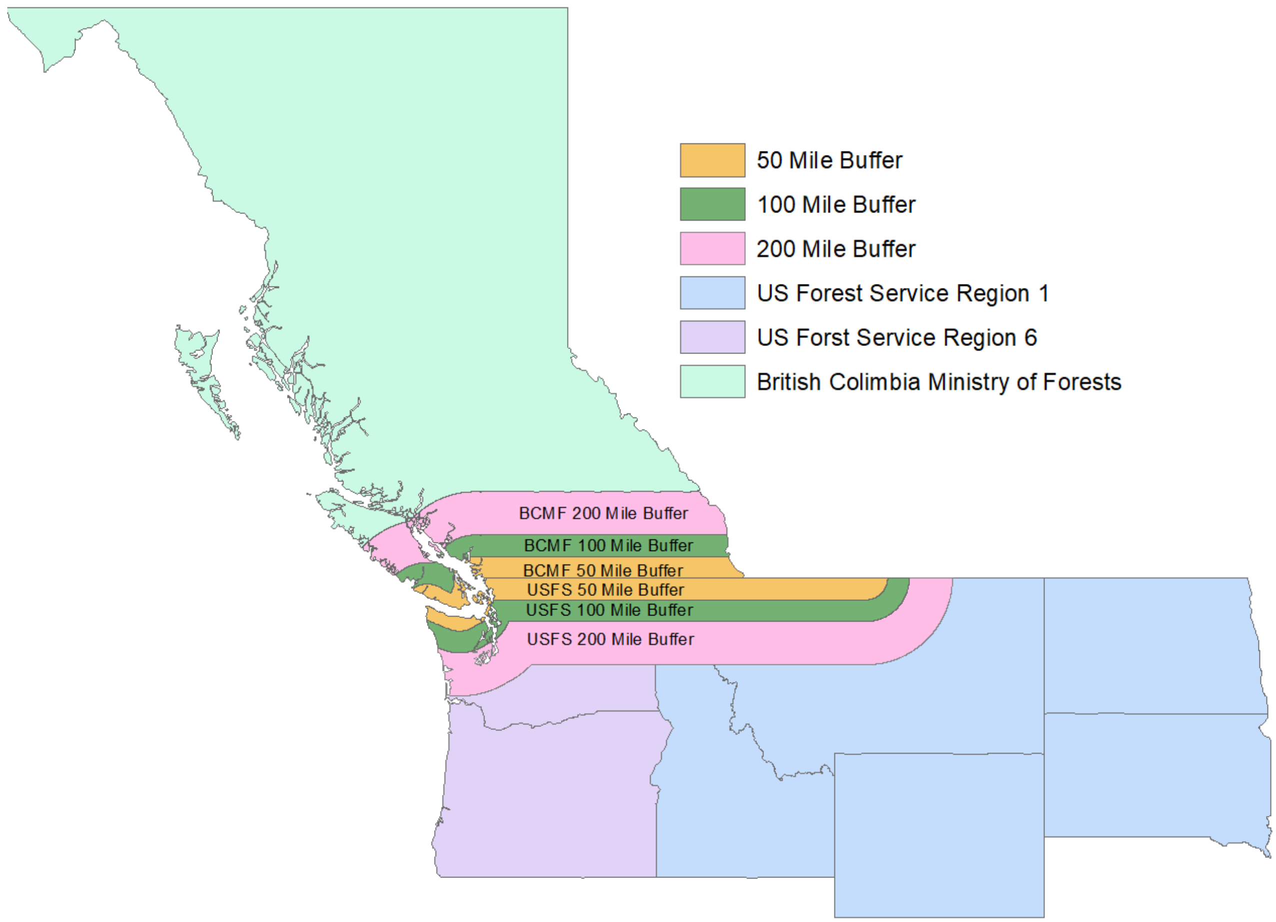


Figure 3: Visualization of 50-mile, 100-mile, and 200-mile border buffer regions within USFS and BCMF managed forests. The 200-mile and 100-mile buffer includes all area between the US-Canada border and the buffer's edge. These buffers are created to help control for outside factors.

An area centroid analysis was also performed to show how MPB populations move over time. Each year's polygon data were converted to points, while keeping their attributes. For every year's data, the mean center tool was used to calculate the centroid of all the points. This tool takes the average latitude and longitude of each year's polygons, and along with the total area attribute of each polygon, computes a weighted mean center for each year in each region.

Weighted Mean Center

$$\bar{X}_W = \frac{\sum_{i=1}^{n} w_i X_i}{\sum_{i=1}^{n} w_i} \qquad \bar{Y}_W = \frac{\sum_{i=1}^{n} w_i Y_i}{\sum_{i=1}^{n} w_i}$$

The data for MPB impacted areas in British Columbia also contained a severity attribute with each observed polygon; either light, medium, or severe. Light Mortality is defined as discolored foliage, with some branch tip and upper crown defoliation, while Medium Mortality is defined as pronounced discoloration, top third of many trees severely defoliated, and Severe Mortality is defined as severe bare branch tips and completely defoliated tops, with most trees sustaining more than 50% total defoliation (BCMF 2000).

Results

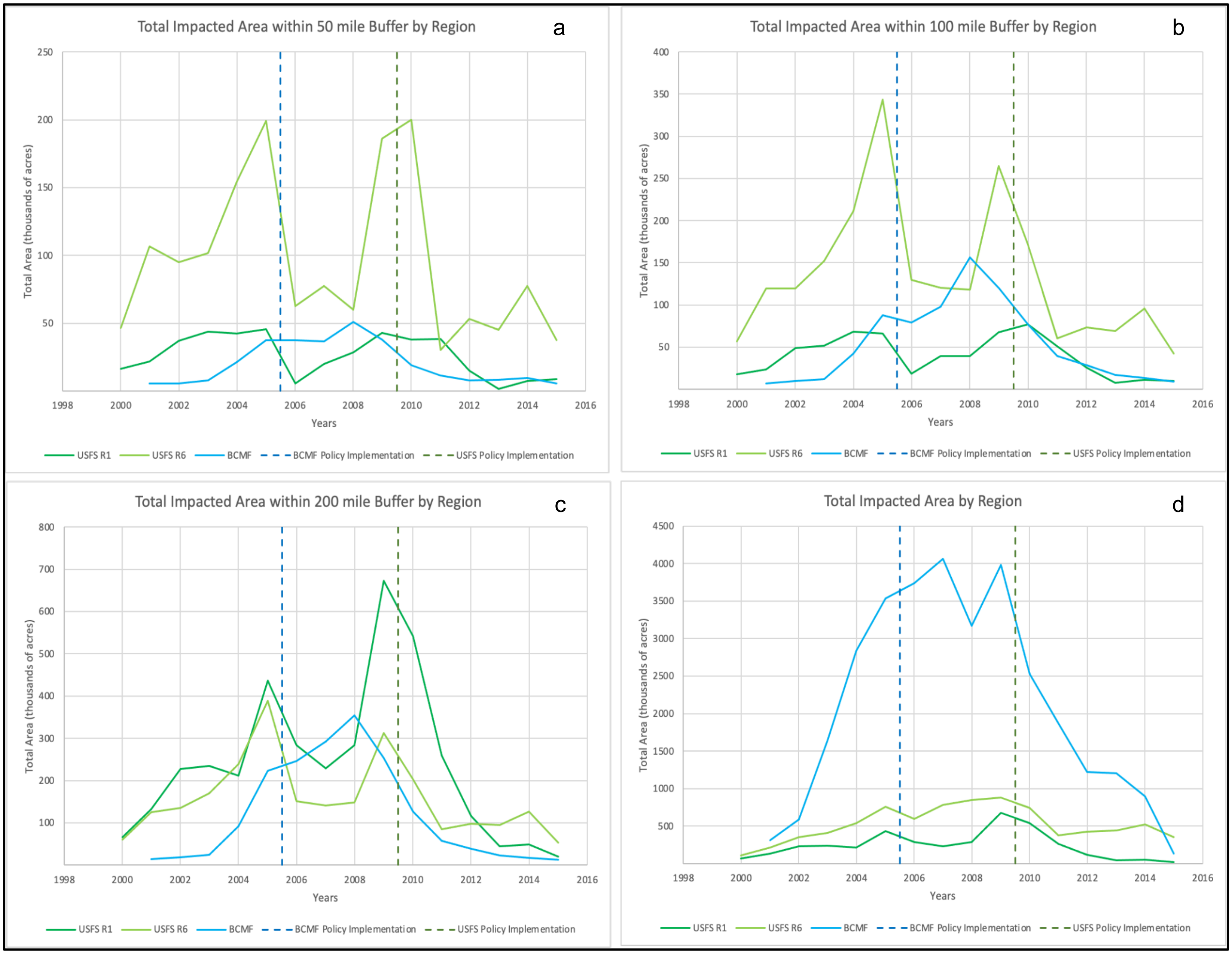


Figure 4: Total Impacted Area by buffer for USFS Region 1, USFS Region 6, and BCMF. Dashed lines represent different policy implementation dates. Image (a) shows the total impacted area within a 50-mile buffer for the US-Canada border by region. Image (b) shows the total impacted area within a 100-mile buffer for the US-Canada border by region. Image (c) shows the total impacted area within a 200-mile buffer for the US-Canada border by region. Image (d) shows the total impacted area within the entire area for the US-Canada border by region.

Figure 5: Mean Impacted Polygon Area by buffer for USFS Region 1, USFS Region 6, and BCMF. Dashed lines represent different policy implementation dates. Image (a) shows the average area size within a 50-mile buffer for the US-Canada border by region. Image (b) shows the average area size within a 100-mile buffer for the US-Canada border by region. Image (c) shows the average area size within a 200-mile buffer for the US-Canada border by region. Image (d) shows the average area size within the entire area for the US-Canada border by region.

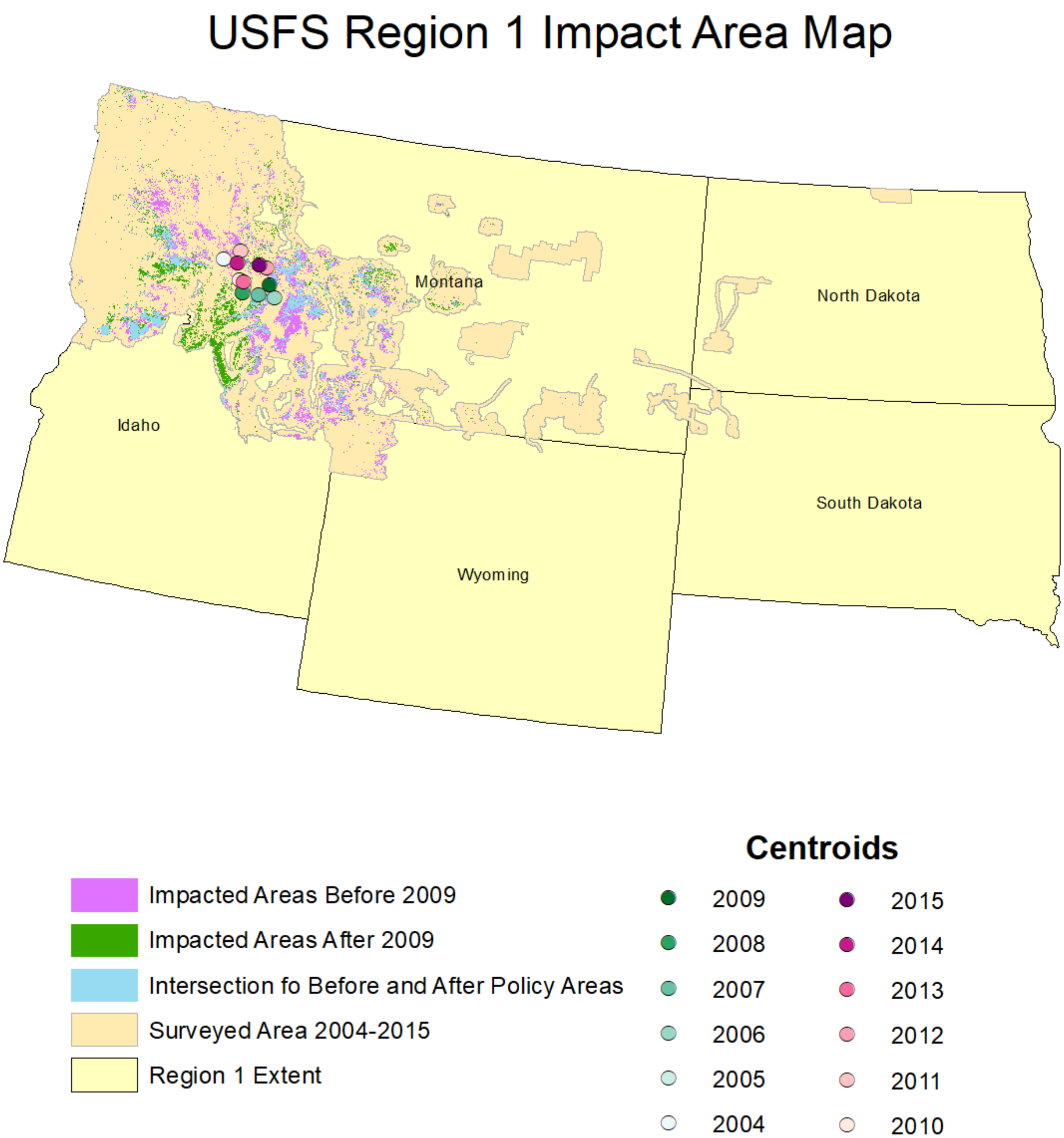


Figure 6: US Forest Service Region 1 Impact Area Map 2004-2015. Impact Area Before 2009 begins shows MPB impact areas from 2004-2009. Impact Area After 2009 shows MPB impact area from 2010-2015. Centroids depict weighted mean center of all MPB impacted area each year.

USFS Region 1 Results

In the USFS Region 1, MPB impacted areas increased prior to policy implementation in 2009, and decreased afterward (Figure 6). From 2004 to 2009, the total area of MPB affected areas increased by 549%, from 675,360 acres in 2004 to 4,387,947 acres in 2009. From 2010 to 2015 the total area of MPB affected areas decreased by 93.2%, from 3,152,418 acres in 2010 to 295,506 acres in 2015. From 2004 to 2009, the affected areas in the 50-mile buffer decreased by 43%, the 100-mile buffer increased by 77.8%, and the 200-mile buffer increased by 154.4%. From 2010 to 2015, the affected areas in the 50-mile buffer increased by 42.7%, the 100-mile buffer decreased by 25.2% and the 200-mile buffer decreased by 49.2% (Figure 4).

From 2004-2009, the mean MPB impacted area increased by 240%, from 52.34 acres in 2001 to 178.28 acres in 2005. From 2010-2015, the mean MPB impacted area decreased by 9.0%, from 88.56 acres in 2006 to 80.55 acres in 2010. From 2004 to 2009, the mean size of impacted areas in the 50-mile buffer decreased by 67.6%, the 100-mile buffer decreased by 60.7%, and the 200-mile buffer increased by 27.8%. From 2006 to 2010, the mean size of impacted areas in the 50-mile buffer increased by 9.7%, the 100-mile buffer decreased by 3.7%, and the 200-mile buffer decreased by 62.0% (Figure 5).

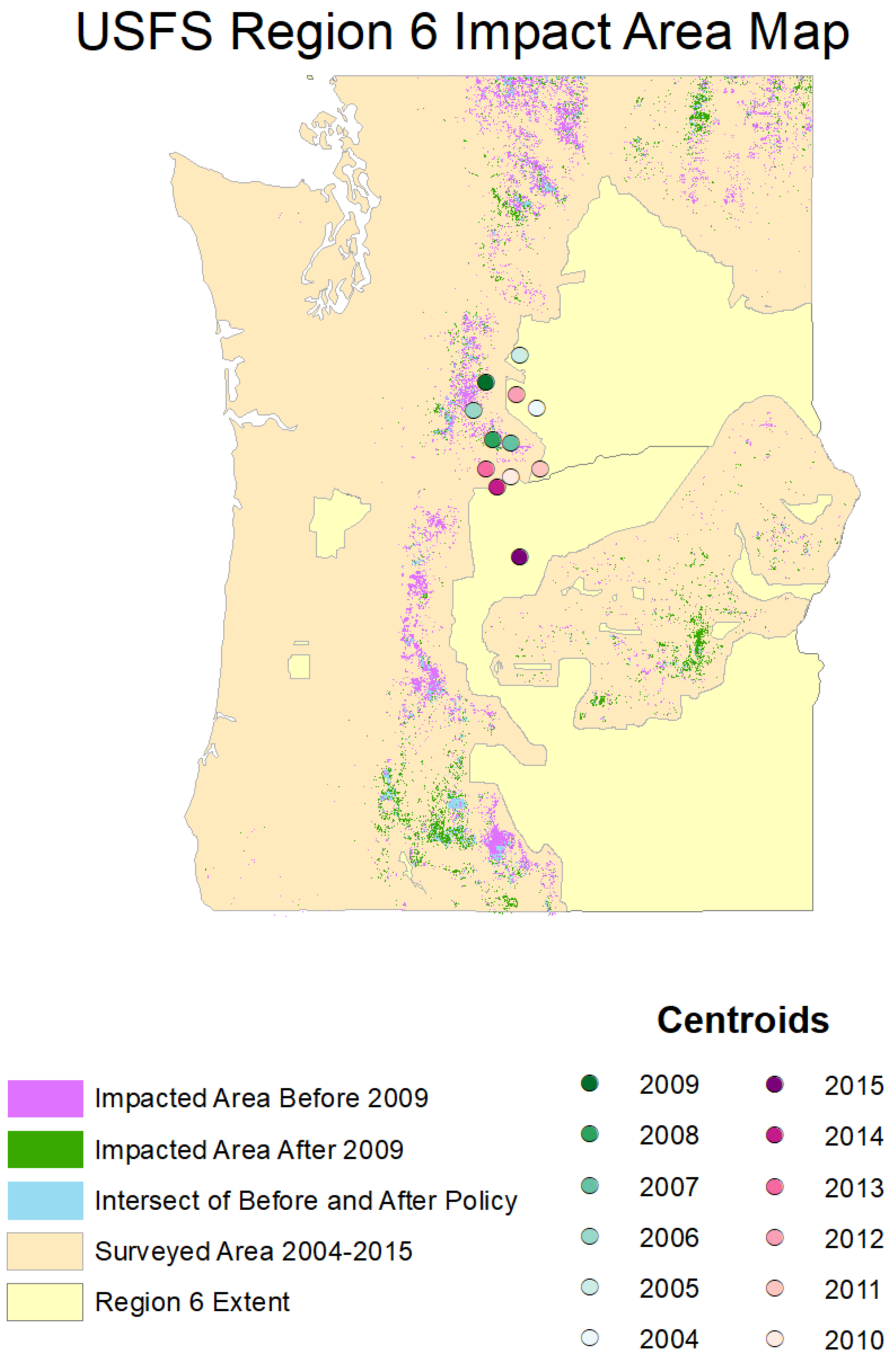


Figure 7: US Forest Service Region 6 Impact Area Map 2004-2015. Impact Area Before 2009 begins shows MPB impact areas from 2004-2009. Impact Area After 2009 shows MPB impact area from 2010-2015. Centroids depict weighted mean center of all MPB impacted area each year.

USFS Region 6 Results

In the USFS Region 6, MPB impacted areas increased prior to policy implementation in 2009, and decreased afterward (Figure 7). From 2004 to 2009, the total area of MPB affected areas increased by 64.2%, from 537,365 acres in 2004 to 882,574 acres in 2009. From 2010 to 2015 the total area of MPB affected areas decreased by 60.3%, from 745,438 acres in 2010 to 350,334 acres in 2015. From 2004 to 2009, the affected areas in the 50-mile buffer increased by 20.6%, the 100-mile buffer increased by 25.2%, and the 200-mile buffer increased by 30.9%. From 2010 to 2015, the affected areas in the 50-mile buffer decreased by 81.2%, the 100-mile buffer decreased by 75.3% and the 200-mile buffer decreased by 73.9% (Figure 4).

From 2004-2009, the mean MPB impacted area decreased by 7.5%, from 64.91 acres in 2004 to 60.04 acres in 2009. From 2010-2015, the mean MPB impacted area decreased by 36.7%, from 37.53 acres in 2010 to 23.77 acres in 2015. From 2004 to 2009, the mean size of impacted areas in the 50-mile buffer increased by 17.4%, the 100-mile buffer decreased by 0.7%, and the 200-mile buffer decreased by 9.7%. From 2006 to 2010, the mean size of impacted areas in the 50-mile buffer increased by 48.9%, the 100-mile buffer increased by 19.4%, and the 200-mile buffer increased by 2.8% (Figure 5).

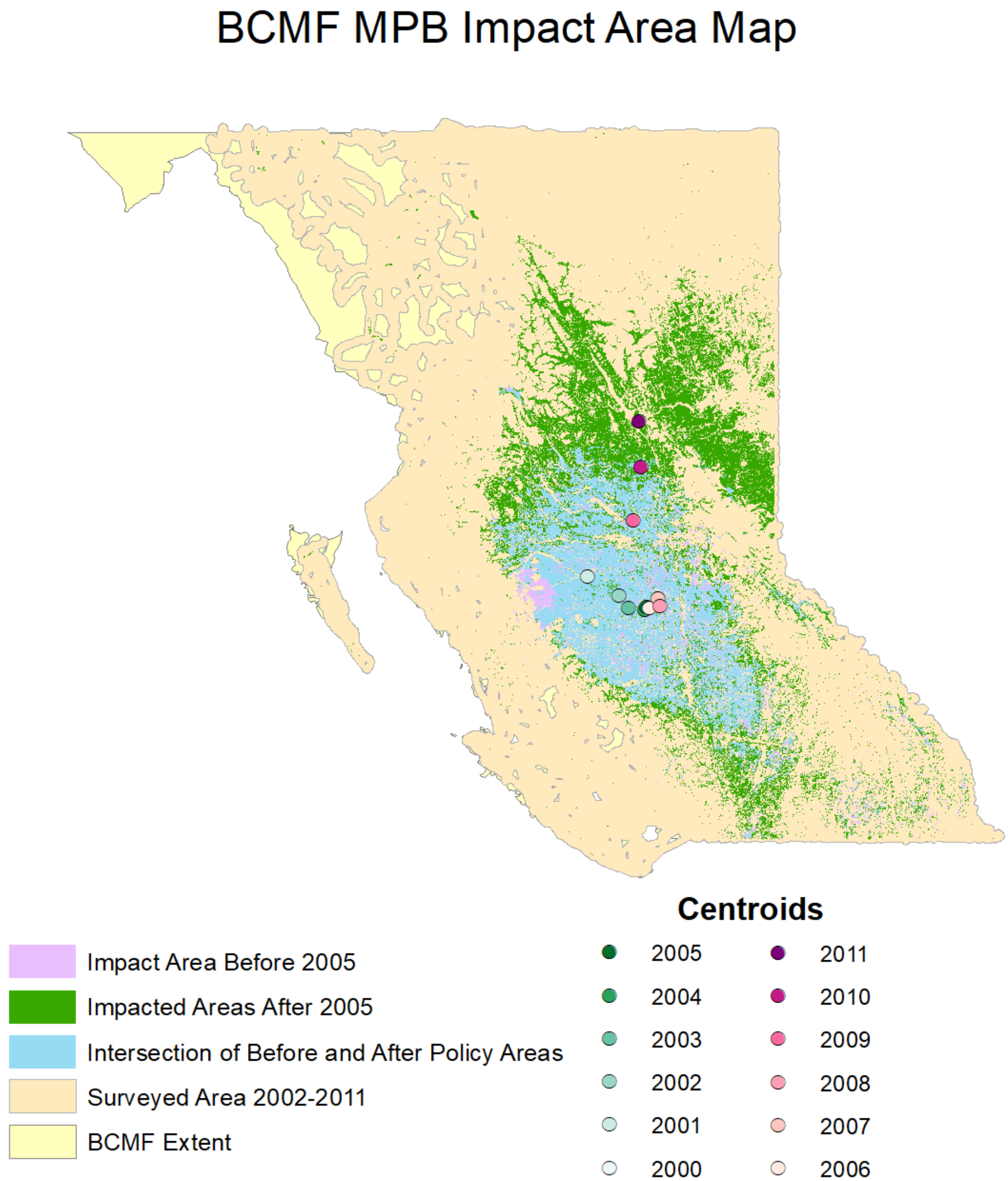


Figure 8: British Columbia Ministry of Forests Impact Area Map 2000-2011. Impact Area Before 2005 begins shows MPB impact areas from 2000-2005. Impact Area After 2005 shows MPB impact area from 2006-2011. Centroids depict weighted mean center of all MPB impacted area each year.

British Columbia Results

In British Columbia, MPB impacted areas increased prior to policy implementation in 2005, and decreased afterward (Figure 8). From 2001 to 2005, the total area of MPB affected areas increased by 1024%, from 776,931 hectares in 2001 to 8,735,007 hectares in 2005. Following policy implementation, from 2006 to 2010 the total area of MPB affected areas decreased by 32.4%, from 9,241,071 hectares in 2006 to 6,247,713 hectares in 2010. From 2001 to 2005, the affected areas in the 50-mile buffer increased by 578%, the 100-mile buffer increased by 1212%, and the 200-mile buffer increased by 1537%. From 2006 to 2010, the affected areas in the 50-mile buffer decreased by 48.4%, the 100-mile buffer decreased by 3.1%, and the 200-mile buffer decreased by 48.4% (Figure 4).

From 2001-2005, the mean MPB impacted area increased by 53.3%, from 41.37 acres in 2001 to 63.47 acres in 2005. From 2006-2010, the mean MPB impacted area increased by 30.9%, from 54.21 acres in 2006 to 70.97 acres in 2010. From 2001 to 2005, the mean size of impacted areas in the 50-mile buffer increased by 106%, the 100-mile buffer increased by 198%, and the 200-mile buffer increased by 176%. From 2006 to 2010, the mean size of impacted areas in the 50-mile buffer decreased by 45.5%, the 100-mile buffer decreased by 19.8%, and the 200-mile buffer decreased by 50.5% (Figure 5).

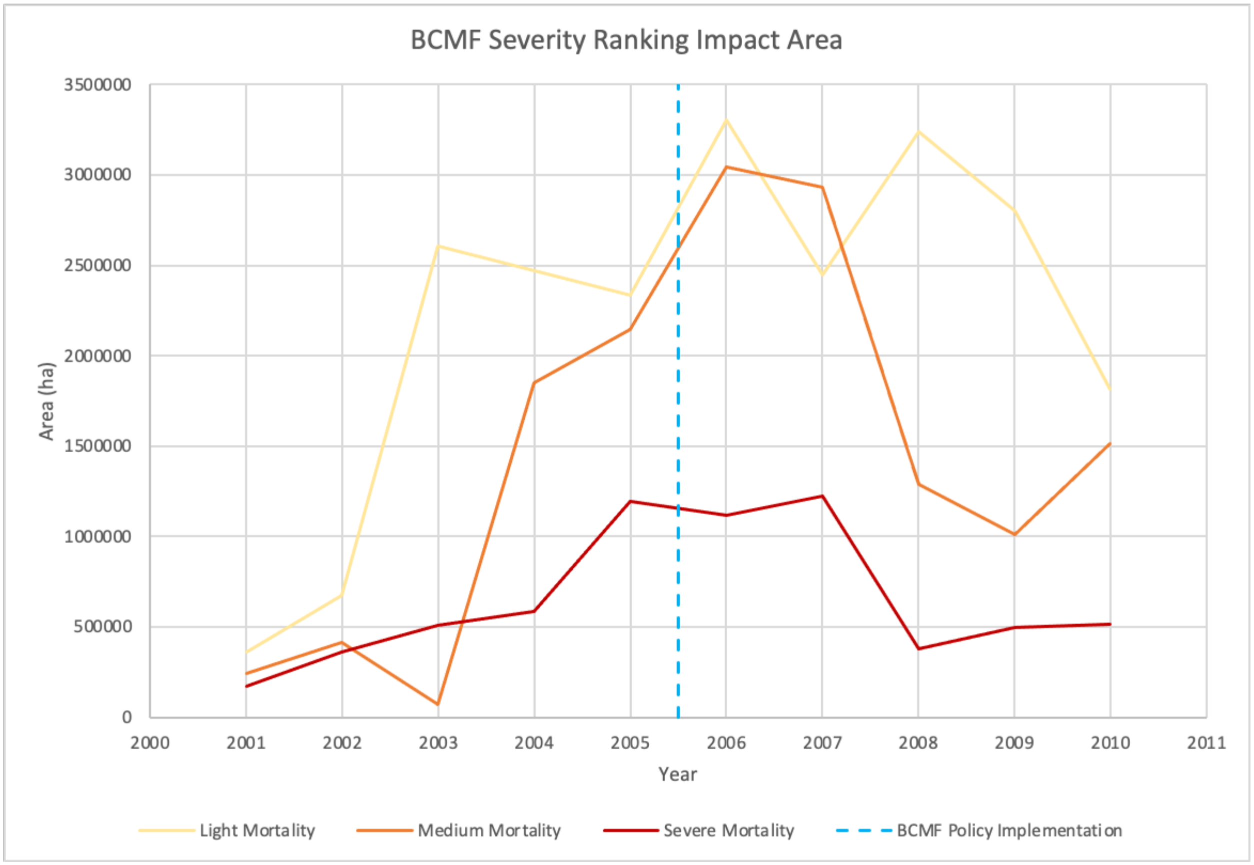


Figure 9: British Columbia Ministry of Forests Severity Ranking Area per Year. Light Mortality is defined as discolored foliage, with some branch tip and upper crown defoliation, while Medium Mortality is defined as pronounced discoloration, top third of many trees severely defoliated, and Severe Mortality is defined as severe bare branch tips and completely defoliated tops, with most trees sustaining more than 50% total defoliation.

From 2001 to 2005, severe mortality areas increased by 597%, medium mortality increased by 790% and low severity increased by 549%. After policy implementation, from 2006 to 2010, severe mortality areas decreased by 53.8%, medium mortality decreased by 50.2% and low severity decreased by 45.0% (Figure 9).

Discussion

The buffer regions provided predictable results based on policy implementation timing. All three regions of study experienced a decrease in total area of MPB impact zones after policy implementation in the 50-mile, 100-mile and 200-mile buffer regions, and total area. In the 50-mile buffer comparison, we can see a decrease in total area of USFS regions around the time of BCMF policy implementation. In the 100-mile and 200-mile buffers this decrease is still apparent, but not at the same magnitude as the 50-mile buffer. Within the three buffer distances, the differences between each region are marginal, while the total area around the time of policy implementation was more than three times as large in British Columbia. There was much more surveyed area in British Columbia compared to either USFS regions, or much more of BC's land cover is pine forest.

Within the 50-mile, 100-mile, and 200-mile buffer regions, there is a downward trend in average polygon size after 2005 when BCMF implemented their policy. The large increase in BC seen after 2012 is likely due to increased flight surveying in the northern British Columbia area after 2010. Infected areas in the remote northern part of the province may not be seen until they are very large or are not treated as heavily as stands in more economically beneficial areas in terms of logging or tourism. A combination of these factors likely accounts for some of the increase in average polygon size after 2010.

In USFS Regions 1 and 6, the centroids of annual infected areas did not have a significant directionality over time. Since Region 1 and Region 6 are up against the Canadian border, there is a limit to how far north a centroid of all infected areas can be. The unchanging latitude of the centroids does show that warmer temperatures are not forcing MPB out of their previously populated habitats. In BC, the centroid of impacted areas began a dramatic northern shift in 2009. There was not more survey flight area farther north in the province starting in 2010, suggesting that MPB suitable habitat range has shifted north. A map of MPB impacted area centroids with matching yearly survey centroids can be found at Appendix A. With a changing climate, and warmer winters, the areas that were too cold for MPB to survive the winter in 2000 are now suitable habitats.

From 2000 to 2006, we see an increase in all three mortality ratings, with the highest increases being in Light and Medium mortality. After 2006, we see a general decrease, again mainly affecting the Light and Medium Mortality. The mortality rate lagged behind policy implementation, which makes sense since it may take up to a year for trees to show signs of mortality and decay.

Limitations of Analysis

The first limitation of this study is inconsistent flight paths for aerial detection surveys. A standardized flight path would allow for more rigorous analysis, as consistent total flight area would provide a better comparison between years. None of the data for this project had consistent flight paths year to year, which makes sense as additional survey flights would be done over areas where infections are known to have spread. Due to the nature of data collection, aerial detection surveys are not the most accurate method of area estimation, as impacted areas are recorded by hand by technician in an airplane. An analysis of British Columbia of intersecting before policy impact areas and after policy impact areas was not possible with this data due to the computational power needed to compare over one hundred thousand polygons. I started this process but was not able to join attribute tables and was only able to show spatial intersects on maps.

Potential Problems with Solutions

Repeated use of insecticides in areas such as resort developments, campgrounds, and wildland-urban areas can have adverse effects on nontarget organisms such as fish, birds, and aquatic organisms (Devine and Furlong 2007). The most popular insecticide for MPB, organophosphate carbaryl, is known to cause headaches, memory loss, muscle weakness and cramps, and anorexia in humans even in low levels of exposure (EPA 2000). Sanitation methods, which include debarking and other mechanical treatments of infested trees pose little risk to forest hydrologic values and reduce mechanical damage to the residual stand compared to other silvicultural operations such as fully removing trees. Fully removing infected trees can have negative effects on the geology and hydrological characteristics of a stand, since tree roots play a large part in erosion prevention, weed control, and plant biodiversity (Gillette 2014). Semiochemical treatments, which are safe and effective at low to moderate beetle population densities, do not have nontarget effects but may result in the killing of the most susceptible trees by bark beetles and other parasitic invertebrates (Campbell and Borden 2006).

Effect on Economy

In 2020 the forestry sector made up 29% of British Columbia's total commodity exports, valued at about $11.5 billion CAD, or $8.36 billion USD. (Canada Action 2022) Therefore, MPB negatively impacts the economy in BC, as many people depend on forestry and logging for their livelihood. According to the British Columbia Provincial Government, 193,000 hectares of forest were logged in 2020, totaling 75 million cubic meters of timber.

When infected areas encroach on planned harvest areas, forest managers are faced with important decisions about whether to salvage log beetle-killed forests. Salvage logging removes dead and weakened trees, either previously or actively populated by MPB. Salvage logging has been shown to exacerbate the negative impacts of MPB on landscape structure and wildlife populations, while also contributing to the spread of MPB to new areas after infected trees are transported (Saab et.al. 2014). Land managers face challenges when implementing policy for beetle or fire damaged forests, while continuing to provide stewardship for the remaining wildlife species in the area.

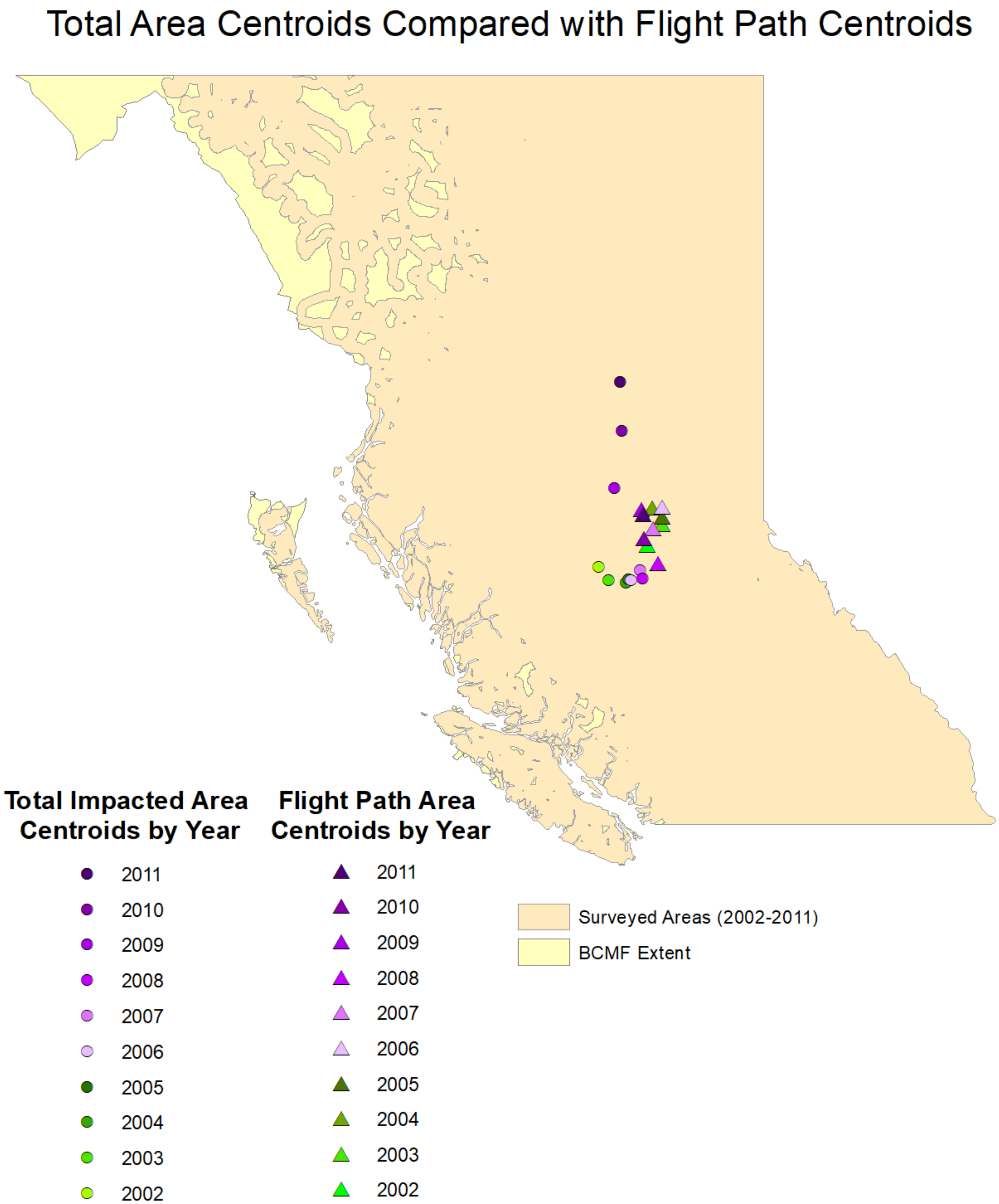
Questions for Further Research

Due to the vast amount of information contained in both the USFS and BCMF datasets, many other analyses could be done. The data contains information about a variety of forest health indicators, including wildfire, fungal diseases, and other species of parasitic invertebrates. Analyzing spatial relationships between different factors could help expand knowledge of how different species interact with their environment or compete for host trees. Additionally, a study of treated areas could provide more insight on efficacy of specific treatment methods, rather than only studying a multifaceted policy. This would need to be done either by compiling spatial treatment data, which I was unable to find, or do a case study on multiple areas with similar ecology with different control methods.

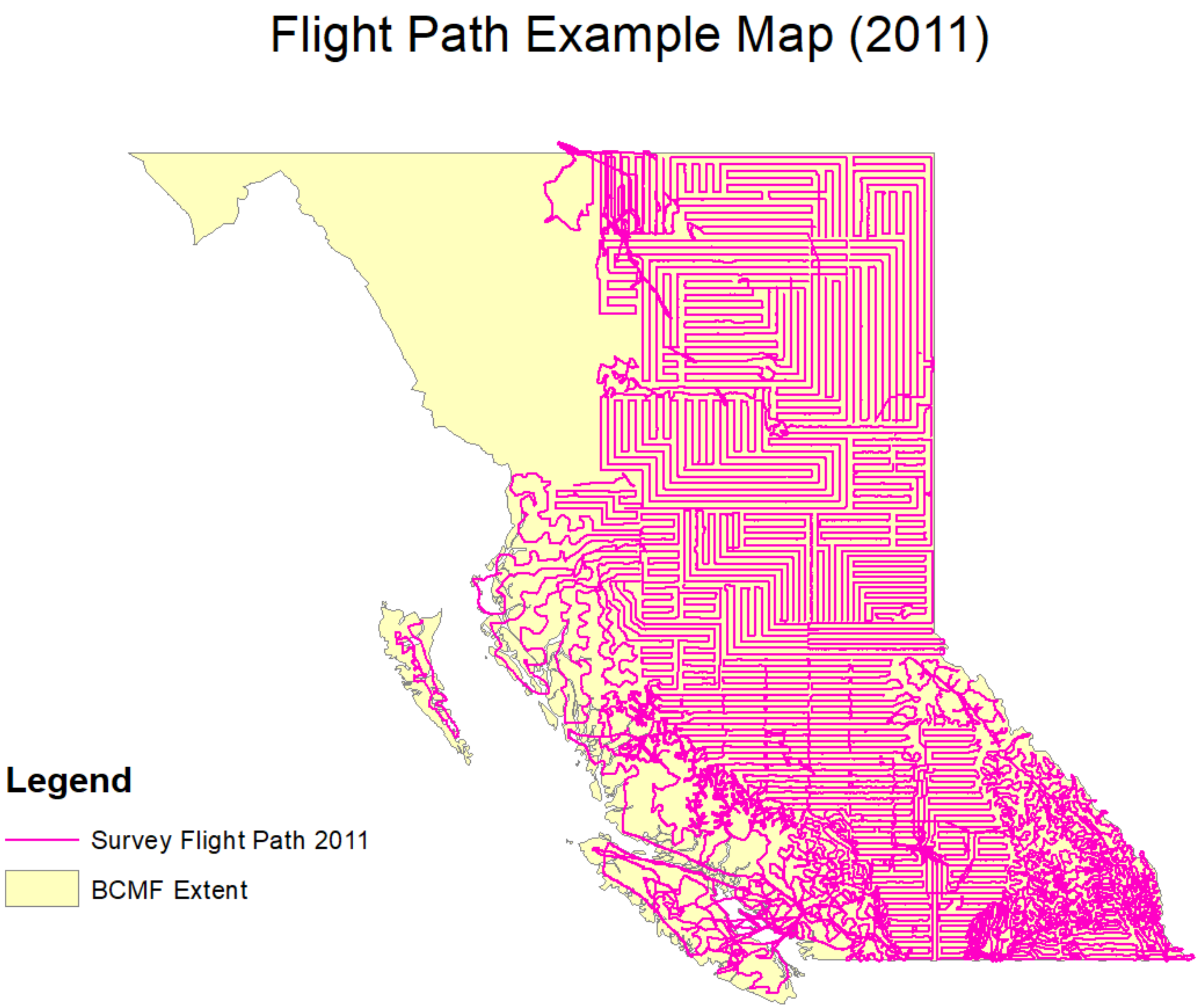
Acknowledgements

First and foremost, I would like to thank my lead advisor, Steve Miller, for helping me develop my methodology and being a fantastic support system throughout this project. I would also like to thank my ENVS representative, Cassandra Brooks for getting me interested in a project of this magnitude and leading an incredibly helpful seminar class. I would like to thank Sarah Kelly for her help with various GIS problems I encountered, and issues with my data. I would like to thank the University of Colorado Undergraduate Research Opportunities Program for funding my research. Also, Jeffery Kaiden from USFS who helped me find data for Region 1 and Region 6, and Rob Thompson, who connected me to David Tellier who sent me MPB data for Alberta, which I unfortunately did not end up using for this project.

Appendix A: Comparison of Annual Surveyed Area Centroids and Total MPB Area Centroids



Appendix B: Example of Aerial Survey Flight Path in British Columbia in 2011



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