USING MAXENT MODELING TO PREDICT HABITAT OF MOUNTAIN PINE BEETLE IN RESPONSE TO CLIMATE CHANGE

by

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LIST OF ABBREVIATIONS

AUC	Area Under the ROC Curve
GIST	Geographic Information Science and Technology
IDS	Insect and Disease Detection Survey
MPB	Mountain Pine Beetle
RCP	Representative Concentration Pathways
ROC	Receiver Operating Characteristic
SSI	Spatial Sciences Institute
USC	University of Southern California

ABSTRACT

The Mountain Pine Beetle (*Dendroctonus ponderosae*) is a unique indicator species in the face of climate change. Since the beginning of this century, it has expanded from its historic territory in the Rocky Mountains at an unprecedented rate. As climate variables continue to change, it is uncertain how the MPB will spread throughout the continental United States. Existing habitat models have studied the current MPB territory, but have not yet been expanded to look at how a changing climate might influence the habitable range for the MPB. In response to recent climate shifts, host tree species have become increasingly susceptible to MPB attack. As their historical habitat is consumed the MPB may also be expanding into new host species. This study applied Maximum Entropy modeling (Maxent) processes to look at habitat suitability for the Mountain Pine Beetle under future climate scenarios. Results for two different emissions scenarios for 2050 and 2070 both showed a change in the MPB's range across the United States. Habitable areas became more concentrated to cooler areas, typically at higher elevations. These models show that as climate change progresses, the Mountain Pine Beetle will be a dynamic variable in forest management across the country as it alters not only its distribution, but also impacted species. Maxent modeling techniques allow a look into the future under varying scenarios to effectively predict the impacts of climate change on the Mountain Pine Beetle and its presence in our forest system.

CHAPTER ONE: INTRODUCTION

The mountain pine beetle (*Dendroctonus ponderosae)* (MPB) is a small dark beetle that burrows into mature pine trees in Western North America. In the twentieth century, MPB habitat spanned from the Black Hills of South Dakota to the West Coast (Wood 1982). With climate change shifting potential beetle habitat, this study looks at prospective new habitats for the pine beetle within the continental United States of America. In determining what areas could be suitable beetle habitat, forest caretakers can plan for the impeding beetle arrival and develop an appropriate management strategy. GIS can be used to refine predictions of the areas of U.S. forests at risk from pine beetle infestation under climate change scenarios.

1.1 Description of Species

The MPB is one of many bark beetle species that have been part of a healthy forest cycle for thousands of years. In addition to the fossil record of bark beetles preserved in tree resin (Nikiforuk 2011, 44 - 45) studies of tree rings in Alaska and Canada show that beetle outbreaks have been a part of a natural cycle to thin forests (Berg *et al.* 2006, 22). It is hard to view the life cycle of a forest within the life span of a human, which makes the MPB seem as a destructive agent. Andrew Delmar Hopkins (1857 – 1948), considered the “father of North American entomology” (Nikiforuk 2011, 56) studied the MPB in the late 19th century and deemed it “the enemy of pine forests.” Stephen Lane Wood (1924 – 2009) of Brigham Young University was considered the premier expert on bark beetles. He authored and co-authored over 100 publications and categorized over 1000 of the world’s beetles (Cognato and Knizek 2010). In his *The*

Bark and Ambrosia Beetles of North and Central America (Coleoptera: Scolytidae): A Taxonomic Monograph, he calls the MPB "the most destructive species of *Dendroctonus*."

The MPB's life cycle typically takes one full year to complete. However, in colder climates this cycle can take up to two years to complete, while warmer areas may see two to three cycles per year (Logan and Bentz 1999, 925). Adult MPBs take flight in early summer, traveling anywhere from the next tree to over 200 miles to find new trees to infest (Nikiforuk 2011, 73). They then burrow into the tree, eating the phloem of the tree. During this process they also deposit funguses such as the Blue Stain Fungus (*grosmannia clavigera*) which they carry in their mycangia, or pouches within their cheeks (Halter 2011, 58). After laying their eggs, which develop into larva, the pulp created by the fungus then feeds the growing larva into adulthood, in which the cycle starts again. Adult MPB are 1/8 to 1/3 of an inch, while larva are 1/8 to1/4 of an inch, depicted in Figure 1.

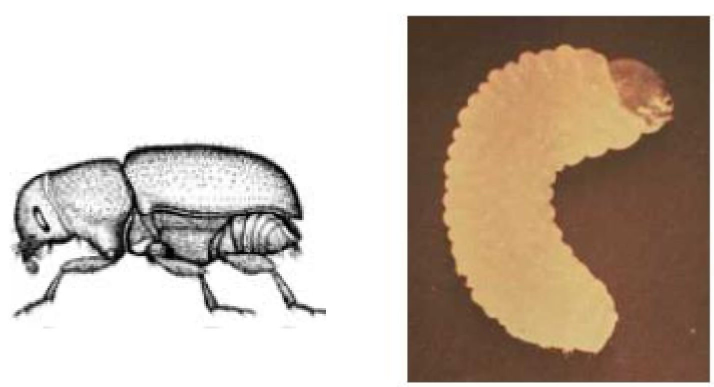


Figure 1 Left, Adult Mountain Pine Beetle; Right, Mountain Pine Beetle Larva (Colorado State University 2011)

1.2 Description of Mountain Pine Beetle Habitat

The MPB is naturally found in the Rocky Mountain region, from the Black Hills of South Dakota to the west coast (Wood 1982). Figure 2 depicts the span of the MPB range from 1997 to 2014. The pine (*Pinaceae*) family represents a range of trees susceptible to the MPB. The MPB predominantly attacks the Lodgepole Pine (*Pinus contorta*), typically trees over 10 inches in diameter, 85 to 100 years old. During large outbreaks, the MPB will attack trees as small as 4 inches in diameter (Logan and Powell 2011). However, they can infest up to 22 different species of pine (Safranyik *et al*. 2010, 416).

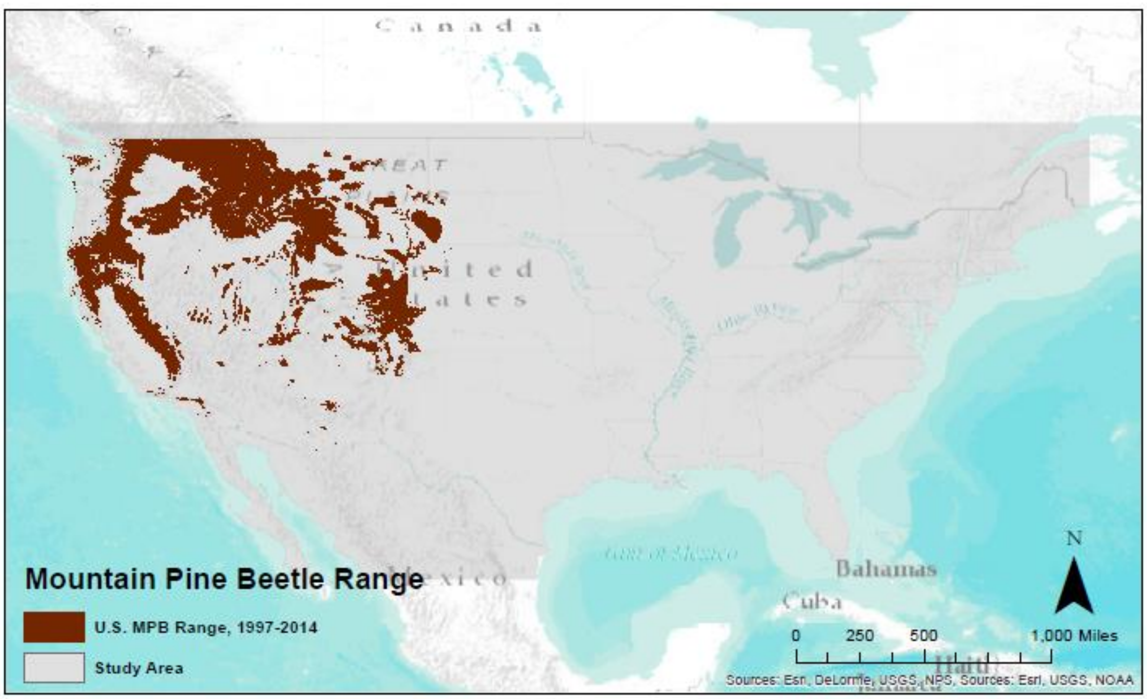


Figure 2 Forest Service IDS Mountain Pine Beetle Survey Data from 1997 to 2014

Several telltale signs can detect the MPB's presence in a tree. As MPBs burrow into a tree, they leave ample sawdust at the base of the tree (Figure 3). Trees with natural defenses against the MPB, such as the Lodgepole Pine, produce resin to block additional beetles from entering the tree and attempts to suffocate the ones that have already entered the tree (Figure 34).

Figure 3 Sawdust at the base of a tree is residue from the MPB burrowing into the tree (British Columbia 2013)

Figure 4 Lodgepole Pine produce resin in an attempt to keep the beetle out. While this can sometimes be successful, 'pitching out' the beetle, often the beetle overcomes the resin and leaves behind pitch tubes (NPS 2011).

After a successful attack, trees are broken down into three classifications; green attack (the tree is infested but still photosynthesizing, keeping the needles green), red attack (one year after a successful attack, 90% of all killed trees will have red needles), and gray attack (three years after a successful attack, a tree has lost all of its needles) (Wulder 2005, 18-41). Remote sensing can identify areas of red attack trees. While Landsat TM/ETM+ data can only identify large areas of red attack trees, multispectral IKONOS data can detect small patches of red attack trees due to the pixel size being approximately the size of a pine crown (White *et al.* 2005, 7).

Being able to identify small outcroppings of infestation is one of the most successful forms of preventing further outbreaks, as once an infestation has reached a certain size little can be done to stop it (White *et al.* 2005, 4). However, remote sensing can only be used to identify infested trees a full year after an attack has started, as there is currently no method to remotely identify green attack trees (Wulder and Dymond 2003, 2). This makes accurate prediction models of what areas would be suitable habitat for the MPB important in order for forest managers to be on high alert for the first signs of a MPB attack. Additionally, areas predicted to have a high possibility of a MPB attack can create a response plan to implement at the first sign of the MPB.

Pine forests naturally maintain a symbiotic relationship with both the MPB and wildfires. The MPB would enter a forest, leaving conditions ripe for forest fires, which would clear the underbrush and open the pinecones of old growth Lodgepole Pines (Nikiforuk 2011, 58). America's stance on wildfire suppression was to extinguish all fires no matter the size or the cause until the 1960s, when a more holistic approach was taken. It was realized that fire is a necessary part of the forest lifecycle to retain a balance between old growth and new growth vegetation. Significant damage had already been done, and many of the pine forests of North America are full of dense old growth trees. This has upset the natural relationship between the MPB, trees and wildfires, which historically had worked together to renew forests.

The presence of densely packed, old growth pine leaves forests susceptible to both wildfire and epidemic levels of beetle infestations. The MPB can travel great distances to infest a forest, and can spread over thousands of acres in a few short years (Nikiforuk 2011, 73). While an overly dense forest can in itself create a higher fire hazard, the presence of the MPB can drastically change the condition of the forest as a fuel source (Jenkins 2013, 2). In some cases, if a bark beetle is carrying the blue stain fungus, the dead forest dramatically drops in susceptibility to fire, as seen after the spruce beetle (*Dendroctonus rufipennis*) infestation on the Kenai Peninsula, Alaska (Berg *et al.* 2006). This is due to the fungus speeding up the rate of decomposition in the tree, leaving the dead trees soft rather than dry. In other cases, the MPB can leave forests as ready fuel for a fire. This is due to the MPB leaving behind dry, brittle trees when the fungus is not present. The relationship grows more complex as firefighters rely on predicting the movement and severity of a wildfire based on the known vegetation present in a forest. Each level of attacked trees, even green attack trees, presents a different level of fire susceptibility (Jenkins 2013, 6). This makes the identification of potential new MPB outbreak areas highly important for effective fire management, including the safety of surrounding communities and the fire fighters themselves.

There is debate over whether the relationship between the blue stain fungus and the MPB is traditional symbiotic or parasitic on behalf of the fungus. MPBs can successfully kill a tree without the presence of the blue stain fungus, and trees can survive with the fungus (Six 2011, 6-9). However, when trees are already stressed by higher temperatures and lower precipitation their defense system is compromised (Chapman *et al*. 2012, 2176). This can result in the presence of the fungus increasing their mortality rate (Halter 2011, 59). MPB larva cannot survive below -40 degrees F, which limits its available habitat (Carroll *et al.* 2006, 2). In the past 30 years, increasingly fewer areas in North America reach this temperature during winter. Longer, warmer summers have extended the season which adult MPB can emerge from their trees and take flight, attacking new trees. Additionally, a combination of higher temperatures and lower precipitation have left trees stressed, increasing their susceptibility to a beetle attack (Carroll *et al*. 2006, 2).

1.3 Study Area

This study looks at the contiguous United States as potential habitat for the MPB. The data sets used are nation wide data sets, although MPB presence has historically appeared in the western United States. The study boundaries (Figure 5) are set by the extent of the rasters used as the environmental variables and future climate variables. These rasters are clipped to the same coordinates NASA NEX uses for their downscaled model of the continental United States: -125.02083333, 49.9375, -66.47916667, 24.0625. Moving beyond the immediate boarder of the United States to a slightly larger rectangular prevents error along the borders of the result where the raster results may be skewed.

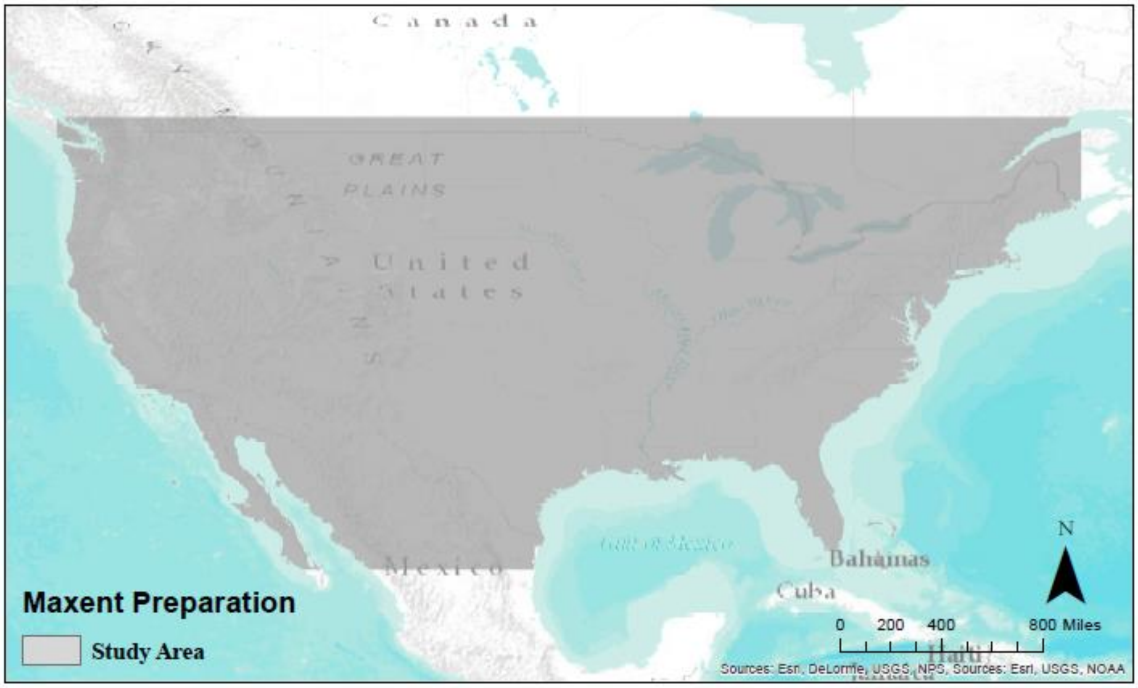


Figure 5 Study Area

This study will look beyond the western United States, as the MPB has recently been identified in Michigan, where it has attacked the Jack Pine (*Pinus banksiana*) (Klutsch and Erbilgin 2012). Additionally, studies in Canada have modeled how the MPB may move across the boreal forest, which contains significant amounts of Jack Pine (Safranyik *et al*. 2010.) Study participant Allan Carroll has stated he believes the MPB would continue to move across the continent (National Geographic 2015.) The Jack Pine does not have natural defenses against the MPB such as the Lodgepole Pine. As suitable habitat shifts, the vegetation the MPB occupies may shift as well. This study will expand the range typically used to examine MPB habitat to determine if new areas are likely to become suitable habitat under climate change scenarios. The western states where the MPB has historically inhabited are also included however, as an increase in temperatures may change their habitat boundaries there as well.

1.4 Study

The MPB has been the subject of many scientific studies. The literature review section covers the various work that have defined what variables the MPB does or does not thrive under, including climate and vegetation. How Maxent can be used as a Species Distribution Model is then explained, along with why the MPB is a good candidate for Maxent. The methods section explains what data will be used for the Maxent Models. The results show the output of the Maxent runs, while the discussion explains the modeling process, the results and their application. This study hopes to answer what areas may be suitable habitat for the MPB in the future, and the variables that determine this. By using Maxent to create future habitat models, GIS modeling allows for the prediction of suitable habitat into 2050 and 2070.

CHAPTER TWO: RELATED WORK

Starting in the early 2000s, the dramatic outbreak of MPB across the country spurred an increase in research efforts focusing on the species. These studies are generally composed of two categories; variables affecting the MPB, and how those factors will affect the MPB in the future.

2.1 Variables affecting the Mountain Pine Beetle

The Logan *et al* model looks into how univoltine seasonality (one brood a season) is related to epidemics (Logan and Bentz 1999, 925). The Regniere and Bentz model studies at what temperatures MPB larva survive verses succumb to cold temperatures (Regniere and Bentz 2007, 559-72). The Safranyik *et al* model focuses on a collection of climate variables for predicting MPB spread through Lodgepole Pine (Carroll *et al*. 2006, 1). Dr. Les Safranyik and Allan Carroll have been major players in the Canadian Forest Service's research into the MPB. Together they have worked to modify the model, and apply it to predicting range expansion into the Canadian boreal forest (Safranyik *et al.* 2010, 415-442).

The Safranyik *et al* model focuses on identifying areas that are climatically suitable for the MPB, considering temperature, length of growing season and precipitation. For this, they developed a series of true/false statements based off the original model from the 1970s, shown in Table 1.

Table 1 Safranyik Climate Factors effecting the MPB

Criteria	Description	Rationale
P1	> 350 degree-days above 5.5 degree Celsius from August 1st to end of growing season (Boughner 1964) *and* >833 degree-days from August 1st to July 31st	A univoltine lifecycle synchronized with critical seasonal events is essential for MPB survival (Logan and Powell 2001). 305 degree-days is the minimum heat requirement from peak flight to 50% egg hatch, and 833 degree-days is the minimum required for a population to be univoltine (adapted from Reid 1962)
P2	Minimum winter temperatures >-40 degrees Celsius	Under-bark temperature at or below -40 degree causes 100% morality within a population (Safranyik and Linton 1998)
P3	Mean Maximum August temperatures >/= 18.3 degrees Celsius	The lower threshold for MPB flight is ~18.3 degrees Celsius (McCambridge 1971). It is assumed that when the frequency of maximum daily temperatures >/= 18.3 degrees Celsius is <=5% during August, the peak of MPB emergence and flight will be protracted and mass attack success reduced.
P4	Sum of precipitation from April to June < long-term average	Significant increases in MPB population have been correlated with periods of two or more consecutive years of below-average precipitation over large areas of western Canada)Thomson and Shrimpton 1984)
Y1	Variability of growing season precipitation	Since P4 is defined in terms of a deviation from average, the coefficient of variation of precipitation was included. Its numerical values were converted to a relative sale from 0 to 1.
Y2	Index of water deficit (the index of water deficit replaces the water deficit approximation (National Atlas of Canada 1970) in the original model of Safranyik *et al*. (1975).	Water deficit affects the resistance of lodgepole pine to MPB, as well as subsequent development and survival of larvae and associated blue-stain fungi. Water deficit is the yearly sum of (rainfall-evapotranspiration) in months with mean air temperature >0)

Source: Adapted from Safranyik *et al.* 2010, 439

Although in close proximity to Canada, the contiguous United States possess different climate regions and vegetation types than that of Canada. However, these studies developed the variables which subsequent studies have deemed particularly important when studying the MPB. Two dominant factors from the Safrayik *et al.* model: winter temperature above -40 degrees Fahrenheit and the mean maximum temperature for August over 65 degrees Fahrenheit (Safranyik *et al.* 2010, 439) are important benchmarks for the beetle. MPB larva cannot survive below -40 degrees F, and optimum emergence occurs at a 65 degree mean August temperature. Precipitation is also an important variable, as precipitation during the growing season greatly affects the ability for trees to defend themselves during a MPB attack.

2.2 Vegetation

Throughout the contiguous United States the MPB has predominantly infested Lodgepole Pine (*Pinus contorta*), yet can also inhabit 21 other species of Pine. The Jack Pine (*Pinus banksiana*), found east of the Rocky Mountains, is predicted to be the second most suitable tree for the MPB due to its biological similarities and ecological niche (Safranyik *et al.* 2010, 419). Unlike the Lodgepole, the Jack Pine does not produce the same protective resin to resist MPB infestation by "pitching out" the beetle. Research in Canada has shown that naïve hosts (forests that have not gone through a beetle attack in the past) are more susceptible to attacks (Cudmore *et al.* 2010). As the MPB has spread into the western edge of the Jack Pine range of Alberta, Canada, research into how native pathogens would affect the Jack Pine's defense against the MPB have begun (Klutsch and Erbilgin 2012). Hydration requirements are also an important factor, but so far have only been used when evaluating Lodgepole Pine; other species are still untested

(Safranyik *et al*. 2010, 421). As such, it is unknown how the Jack Pine's defenses to the MPB may be affected by drought.

2.3 Presence/Absence or Presence-Only Data

One of the most powerful new tools in predicting MPB impacts is habitat modeling through GIS tools such as Maxent. Maxent is a type of Species Distribution Model (SDM) that uses presence only data to predict the habitat of a given species. Typically, SDMs will look at both presence and absence data to give a more complete picture of the species habitat. However, historic data is often given only as presence data; a particular species is known to exist at this location, but cannot be confirmed to be absent at a nearby location. Because of this, Maxent has become increasingly popular as large presence only datasets become more widely available and concern over climate change grows (Phillips and Dudik 2007).

Maxent can be used to determine the density of a species within its' habitat, or to predict what area may be suitable for a species outside of its current habitat. To create a model, Maxent randomly generates background points to compare against observed presence data; all locations are equally likely to be sampled. The range of your background points should be based on your ecological interests – the current habitat extent or a wider range (Merow *et al.* 2013). In addition to presence data for your species of interest, Maxent models also require importing raster layers that describe the environmental conditions intended to measure against the study species. The WorldClim BioClim 19 climatic variables are frequently used as the environmental variables, as they contain variables such as temperature and precipitation.

2.4 Past Maxent study of the Mountain Pine Beetle

In 2011, Maxent was used to evaluate three different bark beetles' habitat, including the MPB habitat under current and future climate scenarios in eight Rocky Mountain states in the western United Sates (Evangelista *et al*. 2011). These states are currently habited by the MPB. The parameters used are detailed below, followed by an analysis.

2.4.1 Biological Data

The United States Forest Service annually conducts aerial surveys and publishes Insect and Disease Detection Survey (IDS) data for their survey areas, including the acreage damaged by the MPB that year. This dataset is "the most accurate representation of Mountain Pine beetle damage" (USDA Forest Service). After a successful attack, trees are broken down into three classifications; green attack, red attack, and gray attack (Wulder 2005, 18-41). Trees are not easily identifiable from the air until the red attack phase, a year after the attack has begun. Evangelista *et al*. relied on a range of data from this Forest Service data set, dating from 1991 to 2008, the most current species presence data at the time.

2.4.2 Environmental Variables

The WorldClim's 19 bioclimatic variables were used to conduct this analysis are detailed in Table 2. This dataset is available as individual rasters spanning the inhabited continents, presented as latitude/longitude coordinates in WGS84 with approximately 1km^2 cell size.

Table 2 WorldClim Bioclimatic Variables

BIO1 =	Annual Mean Temperature
BIO2 =	Mean Diurnal Range (Mean of monthly (max temp - min temp))
BIO3 =	Isothermality (BIO2/BIO7) (* 100)
BIO4 =	Temperature Seasonality (standard deviation *100)
BIO5 =	Max Temperature of Warmest Month
BIO6 =	Min Temperature of Coldest Month
BIO7 =	Temperature Annual Range (BIO5-BIO6)
BIO8 =	Mean Temperature of Wettest Quarter
BIO9 =	Mean Temperature of Driest Quarter
BIO10 =	Mean Temperature of Warmest Quarter
BIO11 =	Mean Temperature of Coldest Quarter
BIO12 =	Annual Precipitation
BIO13 =	Precipitation of Wettest Month
BIO14 =	Precipitation of Driest Month
BIO15 =	Precipitation Seasonality (Coefficient of Variation)
BIO16 =	Precipitation of Wettest Quarter
BIO17 =	Precipitation of Driest Quarter
BIO18 =	Precipitation of Warmest Quarter
BIO19 =	Precipitation of Coldest Quarter

Source: WorldClim - Global Climate Data

For the future climate models, three were used under two different carbon emission scenarios for both 2020 and 2050. These models were the Canadian Centre for Climate Modeling and Analysis (CCMA), the Hadley Centre Coupled Model x3 (HadCM3), and the Commonwealth Scientific and Industrial Research Organization (CSIRO). The emission scenarios represented a conservative (a2a) and liberal (b2a) estimation of carbon levels. This resulted in six different possibilities for both 2020 and 2050. Additionally, they averaged the three models for each emissions scenario for both 2020 and 2050.

2.4.3 Analysis

The Maxent model was considered to work reasonably well for current climate scenarios with an average AUC of 0.898 (+- 0.003). Precipitation during the warmest quarter (Bio18) was shown to be the best predicting variable, followed by the mean temperature of the warmest quarter (Bio10). The Maxent internal jackknife test, (another method of testing the importance of each variable) showed that Bio18 and Bio12 (precipitation in the warmest quarter) as the best predictors for range.

All three climate models, CCMA, HadCM3, and CSIRO, predicted a decrease in habitat suitability for the MPB. Taking the Maxent results, they then compared them to the LANDFIRE Vegetation Type maps (Table 3). This method was chosen as vegetation is not homogenous in growth, and the MPB have begun infesting urban forests beyond what is represented by the vegetation level. As such, the results are shown both before and after being overlaid with the vegetation layer.

Table 3 Percent Habitat Change

Year	Emission Scenario	Total Habitat Decrease	% Current Habitat Suitable	% New Habitat	% Previous Habitat Decrease
2020	a2a	16%	74%	9%	26%
2020	b2a	27%	64%	9%	36%
2050	a2a	28%	58%	11%	42%
2050	b2a	28%	57%	15%	43%

Source: Evangelista *et al*. 2011

Between 1990 and 2001 the MPB infested less than 400,000 ha in the United States, or 4,000 Square Kilometers. In 2008, 25,000 Square Kilometers were infested, a 625% increase. Modeled results for 2020 and 2050 range greatly (

Table 4).

Table 4 Square Kilometers

Year	Model	Square Kilometers	Model	Square Kilometers
2020	CCCMA b2a	208,400	HadCM3 b2a	158,600
2050	CCCMA b2a	226,700	HadCM3 b2a	132,700

Source: Evangelista *et al*. 2011

The results showed an overall shift in regions hospitable to the MPB. However, the results are to be viewed as possible hypothesis for beetle habitat (Evangelista *et al*. 2011, 314). Uncertainties in the study did arise, such as contrasting predictions between models for the Western Pine Beetle (*Dendroctonus brevicomis*). Additionally, the results for the MPB indicate that it currently inhabits only a small portion of its potential range. "…results for current climate conditions suggest that an area of 244,800 km^2 is suitable for the Mountain pine beetle. In 2008, mountain pine beetle infestation reached approximately 25,000 km^2 (USDA, 2009) or one-tenth of the predicted suitable habitat" (Evangelista *et al.* 2011).

Evangelista *et al*. concluded that additional studies at different scales for bark beetle infestation would be necessary. Additionally, the climate models that they used were from the CMIP3 (Coupled Model Intercomparison Project), developed in 2001, were almost out dated at the time, and they believed the new models should be tested once available.

2.5 Maxent with CMIP5

In 1995, the Working Group on Coupled Modelling under the World Climate Research Programme started studying and standardizing atmosphere-ocean general circulation models as the Coupled Model Intercomparison Project (CMIP). New models are continuously developed and fine-tuned, with the most recent set released in 2013. These models, the CMIP5 General Circulation models, were released alongside research evaluating the models to be used for future climate scenario studies.

As the transition from CMIP3 to CMIP5 models progresses, research using the CMIP5 climate models is starting to be published. A Maxent study, *Forecasting Distributional Responses of Limber Pine to Climate Change at Management-Relevant Scales in Rocky Mountain National Park* (Monahan *et al.* 2013) was published December 31, 2013 using the CMIP5 models. In addition to the 19 BioClimatic variables for the current climate conditions, this study used a downscaled version of 31 different climate models under two different emission scenarios. When looking at a regional issue, it has been determined that a downscaled version of global climate models provide the necessary resolution needed for the smaller scale and eliminates error that would be present using a global model for a regional study (Thrasher *et al*. 2013) This study looked at a broad range of variables, yet most notably found an increase in elevation for limber pine under both emission scenarios.

CHAPTER THREE: METHODS

In the face of a changing climate around the world, many unique biological responses are beginning to appear. As climate change progresses, the areas habitable for the Mountain Pine Beetle are predicted to change. As new areas become hospitable, the MPB is predicted to expand beyond its historical habitat due to amenable climate variables such as warmer winters and weaker target species, in addition to a depletion of their traditional host forests (Evangalista *et al.* 2011). Evaluating the continental 48 states of America as a whole will provide a broader look at areas hospitable to the MPB. Previous studies have looked at the MPBs historical habitat within the western US and Canada, however have not yet focused on the eastern United States or California. Specifically, the area around the states of Michigan, New York and California will be of interest as possible new territory for the MPB.

3.2 Research Design

In this study, Maxent (Maximum Entropy Modeling) will be used to create a Species Distribution Model for the MPB across the United States. Maxent Software Version number 3.3.3K is available for free online (Phillips *et al*. 2006). The creators of the Maxent software provide a tutorial guiding the user through the features and capabilities of Maxent. Their tutorial has downloadable data for use in following the lessons. Additionally, several university professors have tutorials posted online that are useful in gaining a broader understanding of Maxent. These tutorials also explain how to use ArcGIS to prepare data for Maxent and to view and interpret results.

Maxent results are displayed as an html file, with additional capability to edit results. Several charts are produced, including the Area Under the Receiver Operating Characteristic (ROC) Curve, or the ACU. This shows how well the model preforms, with a value of .5 indicating the results could be random and confidence increasing the nearer to 1.0. Two different results test the contribution of the environmental variables. The Analysis of Variable Contributions shows the percent predictive contribution each variable contributes to the model, while the Jackknife tests identify the most important variables by running a test for each variable in isolation and comparing it to all of the variables.

Maxent produces a raster that automatically displays habitat suitability as a 0 – 1 range, with a habitat suitability threshold defined by the user. A 90% sensitivity criterion will be used to distinguish suitable from unsuitable habitat. These graphic images will then be transferred to ArcGIS, using the ASCII to Raster tool. The results can then be compared to past results to further analyze MPB habitat suitability.

3.3 Research Data

Multiple types of data are needed for this Maxent study. The data includes biological data for the species of interest, in this case the presence data for the MPB. Current environmental data is needed to train Maxent on what conditions the MPB lives in. Lastly, future climatic data is needed to then project a prediction of where the MPB may reside in the future.

3.3.1 Biological Data

The United States Forest Service's IDS data for 2014 is currently available for download. This includes damage identified in the year 2014 only; however it is not necessarily unique to 2014. Some of this area may overlap with damage identified in previous years. This data is downloadable through a database created for each region, with the damage shapefiles related to a descriptive table. To receive only the MPB data, the shapefile attribute table is joined with the connected table, and *Select by Attribute* is used to select only areas damaged by the Mountain Pine Beetle. No unknown values where included. The selected attributes where then exported into a MPB shapefile for each region, and merged to show MPB presence polygon data for the continental United States. Shown in Figure 6, this data shows the 1,781,025.4 acres of damage inflicted by the MPB across 12 states in 2015, or 7,207.5 km².

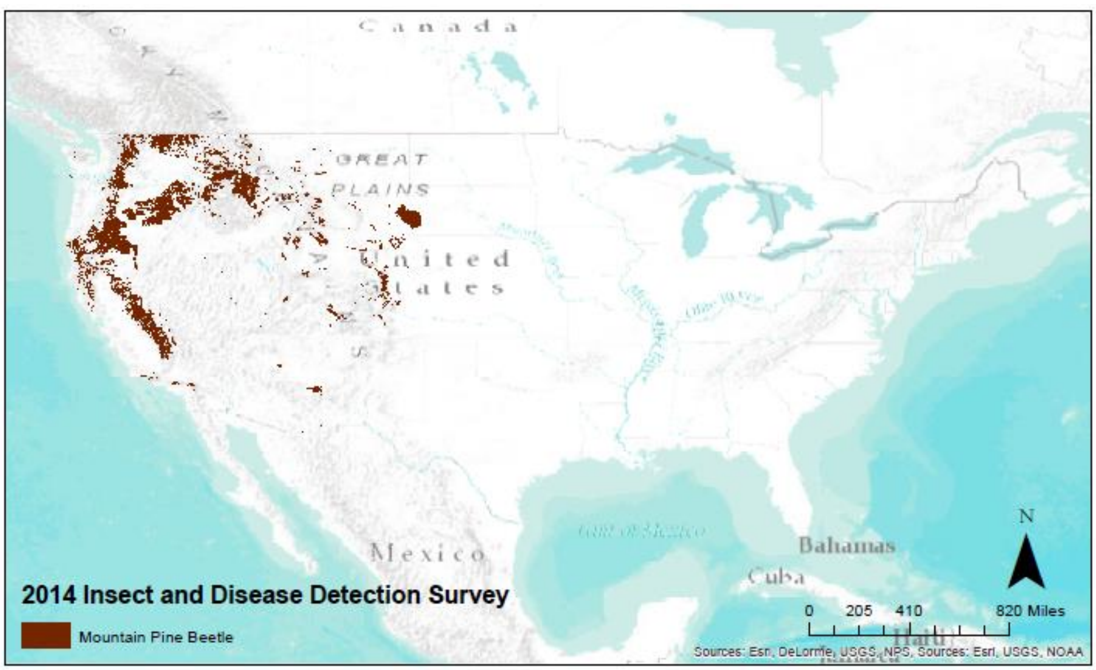


Figure 6 2014 MPB Survey Data (Forest Service 2014)

In contrast to the MPB data obtained, Maxent models rely on point data to identify species occurrence. While appropriate for modeling, most species' habitat is not confined to one XY location. MPBs can cover significant territory, and are capable of traveling many miles to infest a forest (Nikiforuk 2011). As such, this polygon data collected by the USDA Forest Service must be transformed into point data that accurately represents the breadth of infestation without overestimating spread.

After querying the dataset to extract MPB data, the polygons where ready for the next step. A bioclimate raster layer was turned into point data, using the "*Raster to Point*" tool, creating a point within each raster cell. The raster used was geographically projected in WGS 84, but the cell size had been standardized to the smallest cell. This prevents a bias toward the northern region of the country.

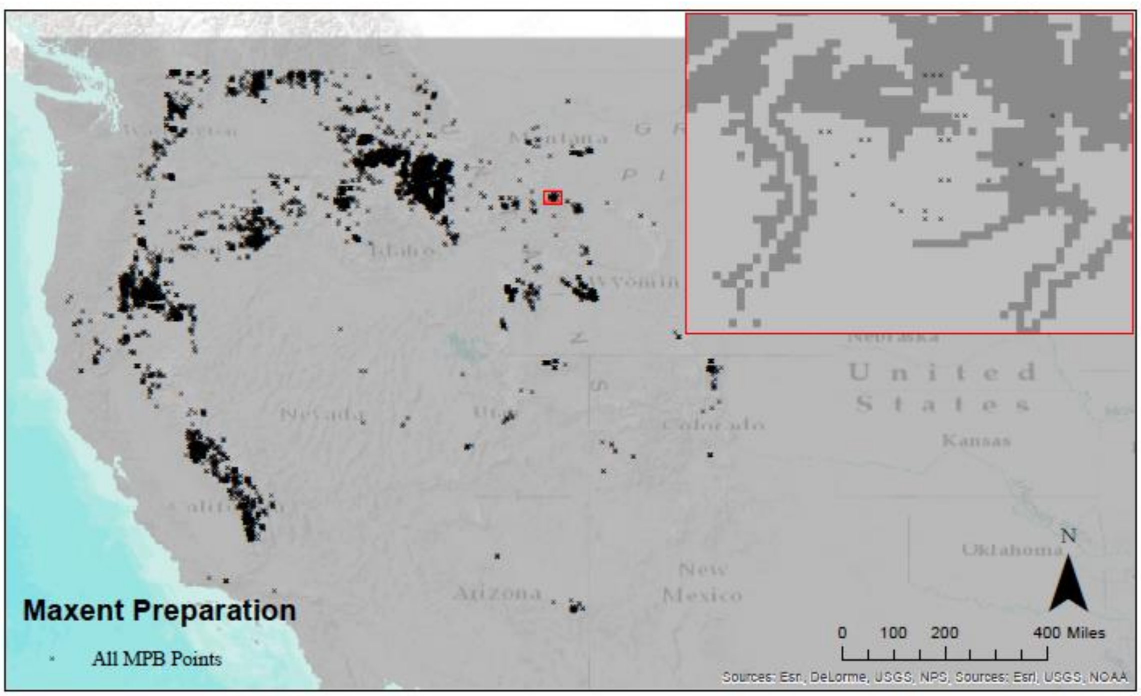


Figure 7 The raster grid cells are 30 arc-seconds: 0.008333333333333 degrees or approximately 1 kilometer squared.

The bioclimatic grid points were then clipped by the MPB presence data, with the results shown in Figure 7. This method provided a thorough sampling of points while reducing spatial autocorrelation effects.

These points will become the presence data suitable for use in Maxent. From here, the *Add XY Coordinates* tool is used to assign coordinate values for each point. The data is then saved as a database file, and is editable as an excel sheet to include the header for the Species, Longitude, and Latitude columns. The completed table is saved as a CSV file. In this study there are 11,316 points, comparable to the 10,775 points used in Evangelista's study.

3.3.2 Environmental Variables

In addition to presence data, Maxent models also require importing raster layers that describe the environmental conditions of specific interest to measure the study species against. In this case, the WorldClim's 19 bioclimatic variables were used (see Chapter 2 Table 2). These bioclimatic variables are shown to provide more meaning then monthly data alone, as insects are easily affected by changes in temperature (Kumar *et al.* 2013). Additionally, these were the environmental layers used in the previous MPB Maxent study (Evangelista *et al*. 2011, 309). However, the data set described as "current" actually includes data from approximately 1950 to 2000. This is 14 years behind the most current MPB data. The implications of this will be covered in the results.

The raster grid from these environmental layers is required for formatting species presence into the appropriate form for Maxent, as discussed above. Additionally, limited editing is required to prepare the rasters themselves for Maxent, as the layers must have the same cell size, extent and projection system (Young *et al.* 2011). This requires co-registering each layer with the same extent, and every cell size the same. This is done using the *Extract by Raster* tool within the *Spatial Analyst* toolbox. Each layer is processed to have the same extent and cell size as bio_1, the smallest cell set (Young *et al*. 2011). The rasters are then clipped to cover only the continental United States, using the coordinates NASA uses for their continental United States models as discussed in Section 1.3. These coordinates were also used as the extent for the future climate models. At this point, the rasters were converted to the necessary ASCII format. This was done with the *Raster to ASCII* tool within *Conversions* Tools. The resulting .ASC files are all sent to one new directory for use in Maxent.

Future climate models are available from WorldClim as well, already bias corrected and spatially downscaled. The 19 bioclimatic variables can be downloaded for each model and Representative Concentration Pathways (RCP.) RCP are different from the CMIP3 emission scenarios. Instead, they model how much greenhouse gas will be emitted, and at what year emissions will peak. The CMIP5 provides four different scenarios, with RCP 8.5 and RCP 4.5 comparable to A2 and B2 scenarios of CMIP3 (Maloney *et al.* 2013). RCP 4.5 predicts emissions will peak in 2040 and then stabilize, while with RCP 8.5 they will continue to grow past 2100. The Community Climate System Model, version 4 (CCSM4) was developed by the National Center for Atmospheric Research, United States. This model was chosen as its focus is the United States. The model's BioClimatic variables are downloaded as GeoTiff files. These files are then individually opened in Arc and re-projected to standardize the datum to WGS 1984. The file is then clipped to the same extent as the current bioclim variables, and saved as an ASCII using the *Raster to ASCII* conversion tool. It is important that the future variables have the same format and name as the current variables. This process was expedited after the first emission scenario was complete through the use of a model, shown in Figure 7.

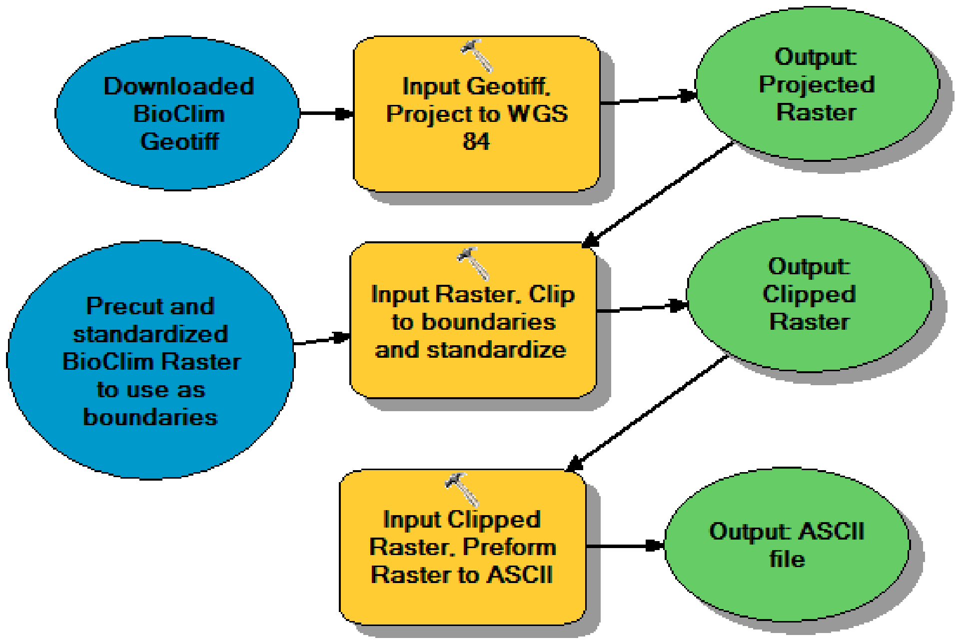


Figure 8 ArcMap model used to process GeoTIFF images for Maxent

3.4 Procedures

The Mountain Pine Beetle presence data entered is in the "samples" file, and the location of the BioClim layers folder is linked to under "Environmental Layers". Future projection data is entered under "Projection layers directory/file". An output directory is designated where results will originate. A first run with only the current data was conducted. Each climate model and emissions scenario for 2050 and 2070 are then tested independently. 30% of the points were withheld for model verification with ten replications averaged (Evangelista *et al*. 2011).

The results of the Maxent run are summarized within an HTML file in the output. This includes a graphic representation of the results. To analyze the graphic results, the averaged ASCII file was displayed as a raster in ArcGIS using Conversion tools, To Raster, *ASCII to Raster*. This has to be processed as a “Float”, as the results are a range between 0 and 1. The preset of ‘Integer” will display as empty. This produces a gray scale map of the image, that can be modified to a color ramp. To display a binary suitable/unsuitable habitat, you must reclassify the raster using the Spatial Analysis toolbox, Reclass, Reclassify. Classify the raster to have only two breaks entered manually. The threshold for suitability will be a 90% sensitivity. This information is available from the Maxent in the results CSV file under “10 percentile training presence logistic threshold.” The lowest number to this threshold is classified as zero, while above is classified as one. The results is a two coded map showing suitable versus unsuitable habitat. The area of suitable habitat can be calculated by looking at the raster count. The suitable area is calculated for the current climate along with each projection.

CHAPTER FOUR: RESULTS

The results of the Maxent models are represented both graphically and in numeric values. Numerically, there is a decrease in suitable habitat for the MPB with an increase in time and greenhouse gas. The maps can be seen below. A 90% sensitivity was set within the Maxent model for determining suitability, and that numeric threshold is also noted in the figure captions. Additionally, the models performance is evaluated, along with which variables most effect the results.

4.1 Current Species Distribution Map

When looking at current climate variables, Maxent produced 490,075 km^2 as suitable for the MPB, shown in Figure 9. This is almost 98% more land than the acreage found to be inhabited by the Forest Service's presence data.

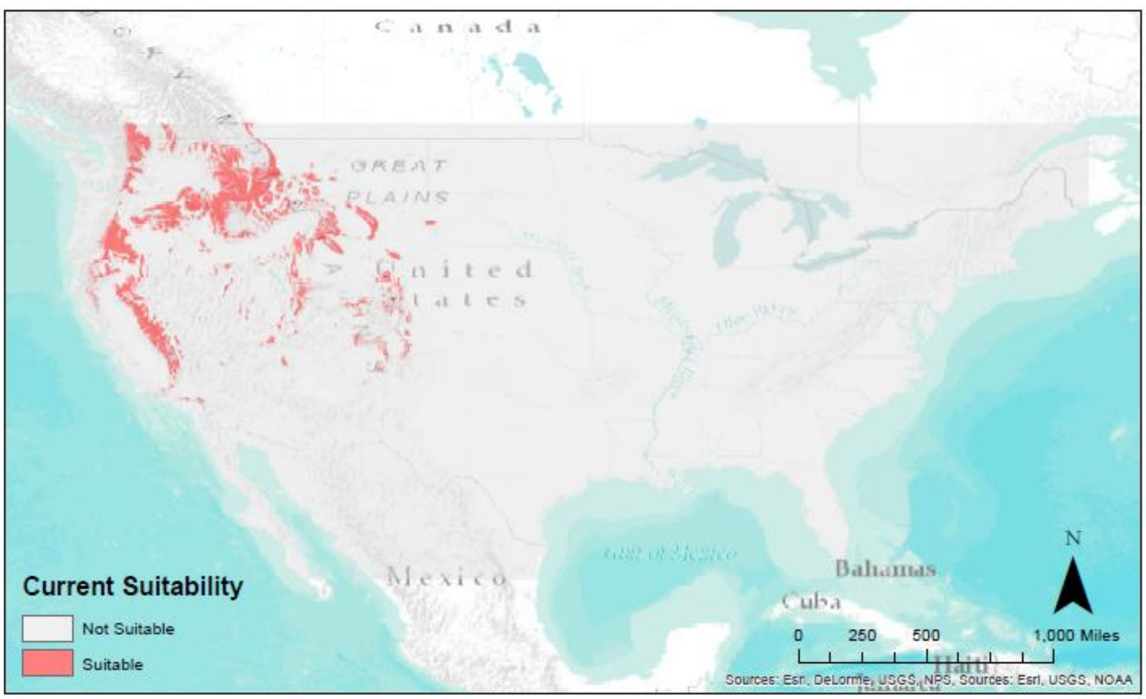


Figure 9 Current MPB Suitability (Threshold 0.4666)

The scaled maps are run with a standard deviation of 10, with the high suitability set to the same threshold as the binary maps. This result was shown to most closely match the binary results for all of the results. At this standard deviation, the MPB suitability is confined to the historic western states, as seen in Figure 10.

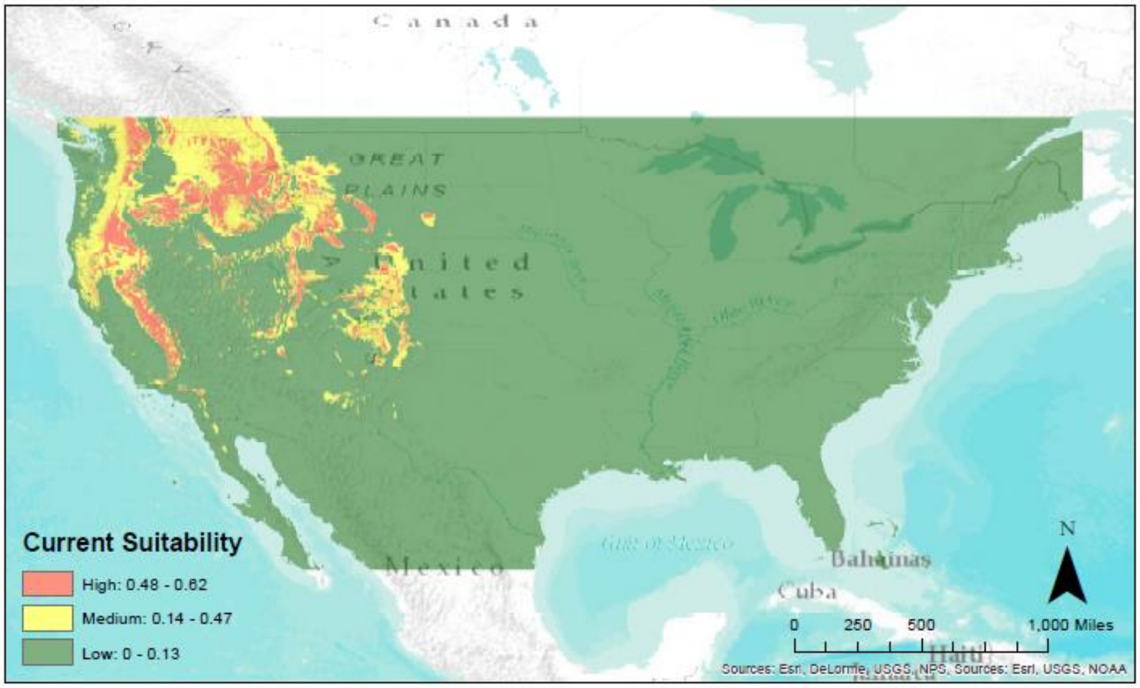


Figure 10 Current Scaled MPB Suitability

The MPN does not occupy the entire “suitable” range at all times. This is consistent with the MPB life cycle, as it continuously moves through an area as it depletes its host. While climatically it is still suitable, it no longer has a supply of host vegetation. These results are also mirrored in the Evangelista *et al.* study. However, one element to consider is the temporal gap between the MPB data set and the current Bioclimatic variables. The MPB data is from 2014, while the current bioclimatic data ends in 2000. When looking at MPB presence data ranging from 1997 to 2014, 93,942 km^2 have been infested by the MPB. This data set overlaid with the area currently deemed suitable is depicted in Figure 12. While still 80% more land is deemed suitable then inhabited in the 17 year time span, there is significant overlap between these two layers.

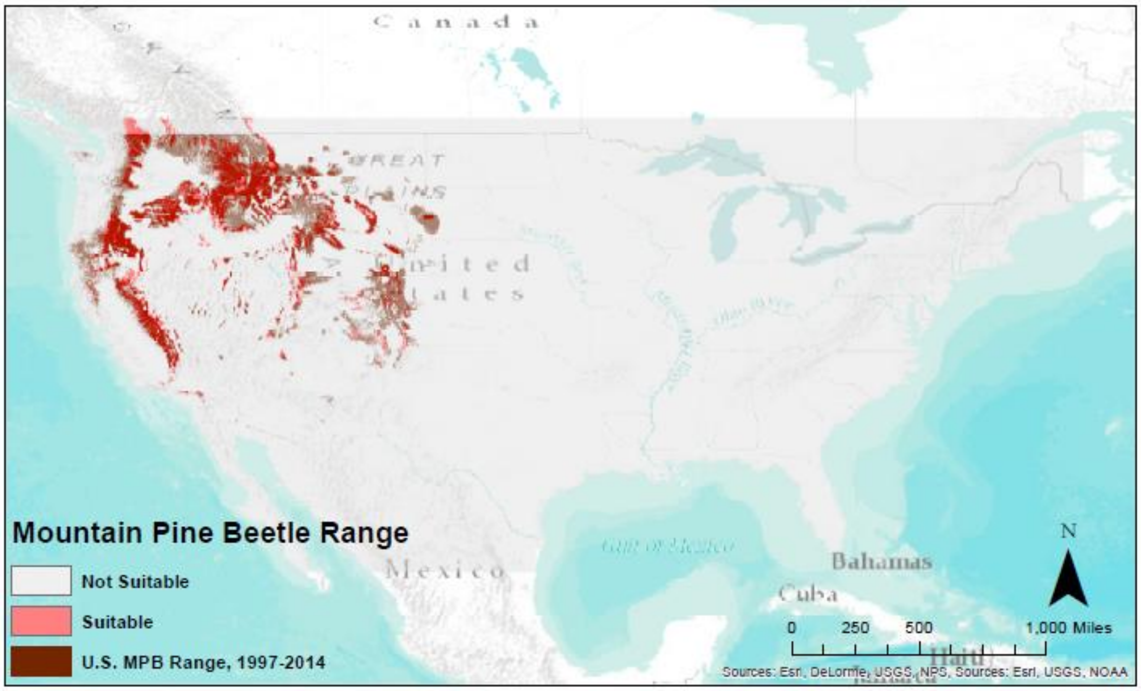


Figure 11 Current MPB Suitability compared to MPB Damage from 1997 to 2014

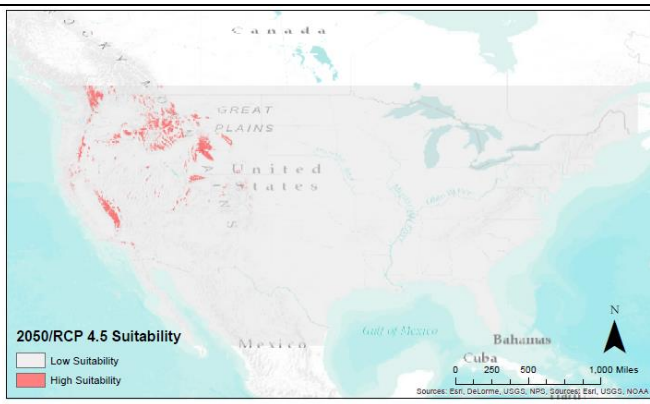
4.2 Future Species Distribution Map

When looking into the future, results were developed for both 2050 and 2070 using the two different RCPs, shown in Table 5.

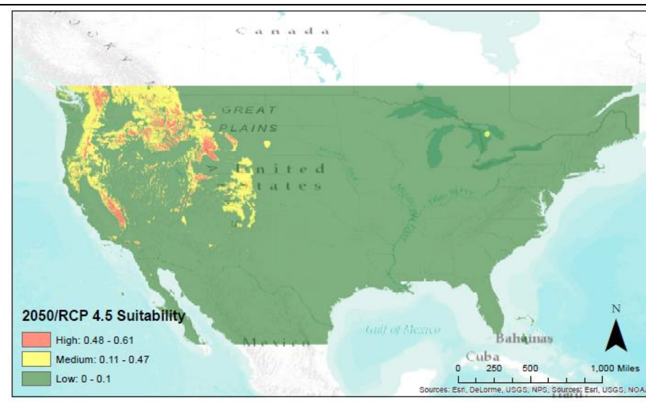
Table 5 Square Kilometers deemed suitable

	2050		2070	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
CCSM4	220,177 km^2	137,220 km^2	180,273 km^2	69,161 km^2

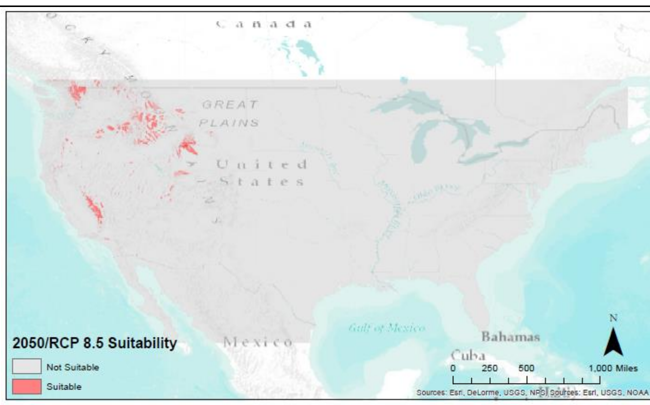
Both RCPs show a decrease in suitable habitat from now to 2050 and again in 2070. However, RCP 8.5 shows a great decrease then RCP 4.5. This decrease is visibly tracked in the maps below, Figure 12 and Figure 13.



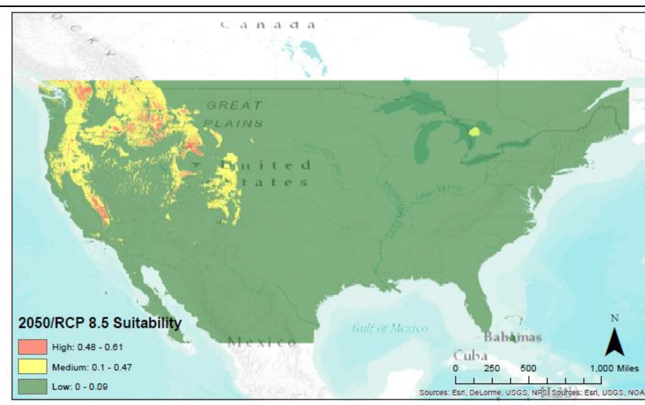
2050/RCP 4.5 Binary Results
(Threshold .4701)



2050/RCP 4.5 Scaled Results

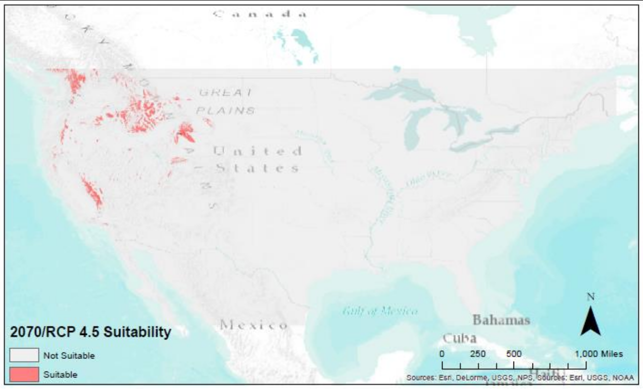


2050/RCP 8.5 Binary Results
(Threshold .4674)

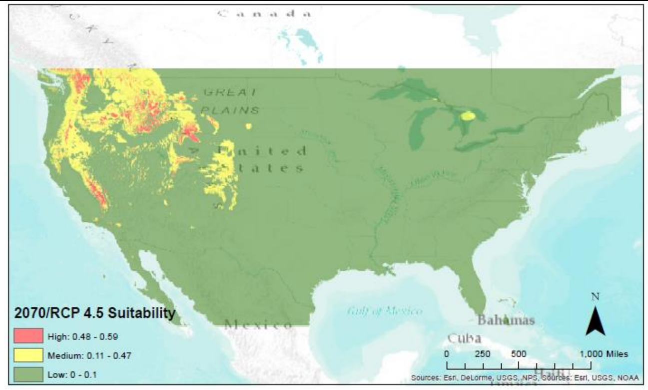


2050/RCP 8.5 Scaled Results

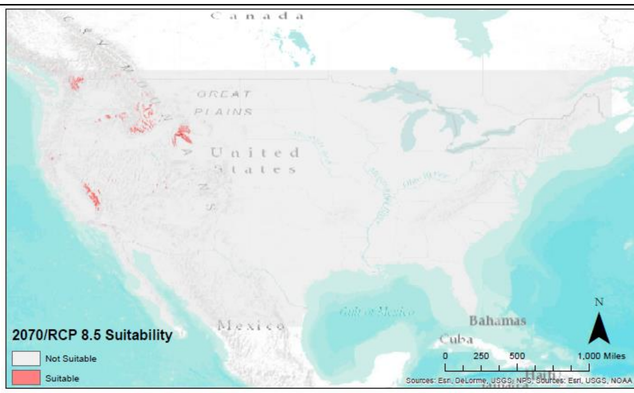
Figure 12 Binary and Scaled Results for 2050



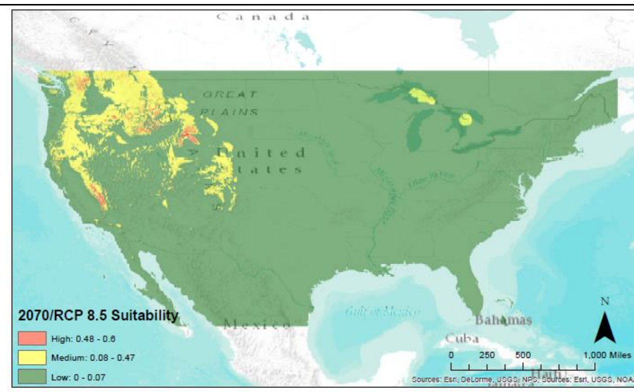
2070/RCP 4.5 Binary Results (Threshold .4722)



2070/RCP 4.5 Scaled Results



2070/RCP 8.5 Binary Results (Threshold .4685)



2070/RCP 8.5 Scaled Results

Figure 13 Binary and Scaled Results for 2070

When compared to the area Maxent determined to currently be suitable for the MPB, this is a significant decrease. The percent decrease is shown in Table 6.

Table 6 Percent decrease from current suitable area, 490,075 km^2

	2050		2070	
CCSM4	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Percent Decrease	55%	72%	63%	86%

4.3 Model Performance

Model Performance can be measured by looking at the AUC in the Maxent results. A result of .5 is believed to be the result of a random sampling, while a score of 1 is considered perfect. All of the results were found to be significant.

4.3.1 Current

The AUC for the current climate is 0.772 with a standard deviation of 0.003, proving the model is significant. The graphic depiction of this is shown in Figure 14.

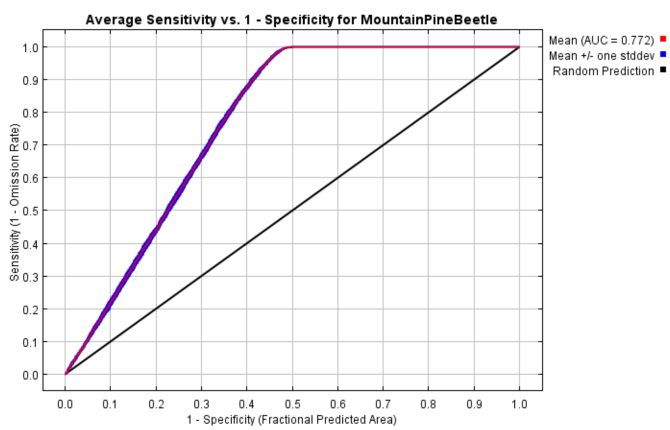


Figure 14 Area Under ROC (Receiver operating characteristic) Curve (AUC), Current Climate

4.3.2 Future

For the four future models, the AUC results were very similar. This similarity is to be expected with similar data. The results, graphically similar in appearance to Figure 14, are shown in Table 7.

Table 7 Future AUC Results

Model	AUC	Standard Deviation
2050/RCP 4.5	0.772	0.002
2050/RCP 8.5	0.773	.002
2070/RCP 4.5	0.774	.003
2070/RCP 8.5	0.774	.002

4.4 Variable Importance

Maxent produces several outputs that address each variables importance in the results. First, the variables are ranked by variable contribution. Second, the variable importance are represented through the jackknife test; each model is run eliminating one variable at a time, and then by running each variable independently. This shows if there are variables less important than others in the final result.

4.4.1 Current

When analyzing the variable contribution of the 19 Bio Climatic variables for the current climate model, Bio 8, mean temperature for the wettest quarter, is ranked as having the highest contribution of 39.5%. This is followed by Bio 10, mean temperature of the warmest quarter, with 33.8%. Previous studies also showed Bio 10 as the second leading predictor (Evangelista *et al.* 309, 2011.)

The results of the jackknife test show that Bio 10 had the highest gain when run independently for all three jackknife tests- training gain, test gain, and AUC on test data.

4.4.2 Future

Results for all four future models closely resembled the variable importance for the current model. Bio 8 is always the highest contribution, followed by Bio 10. The percent contribution for each is depicted in Table 8.

Table 8 Most Influential Variables

Model	**Most Influential Variable; %**	**Second Most Influential; %**
2050/RCP 4.5	Bio 8; 39.5%.	Bio 10; 33.2%.
2050/RCP 8.5	Bio 8; 41.8%	Bio 10; 30.1%
2070/RCP 4.5	Bio 8; 39.7%	Bio 10; 34.4%
2070/RCP 8.5	Bio 8; 40.5%	Bio 10; 32.4%.

Bio 8, mean temperature for the wettest quarter, is ranked as having the highest contribution This is followed by Bio 10, mean temperature of the warmest quarter

The results of the jackknife test show that Bio 10 also had the highest gain when run independently for all three jackknife tests- training gain, test gain, and AUC on test data. This held true for all four future models. When looking at the Jackknife test for the AUC test data, Bio 10 results in .76, close to the .78 total for all 19 variables combined. Bio 8 was ranked as having the second most useful information, while Bio 4 has the most information not present in other variables.

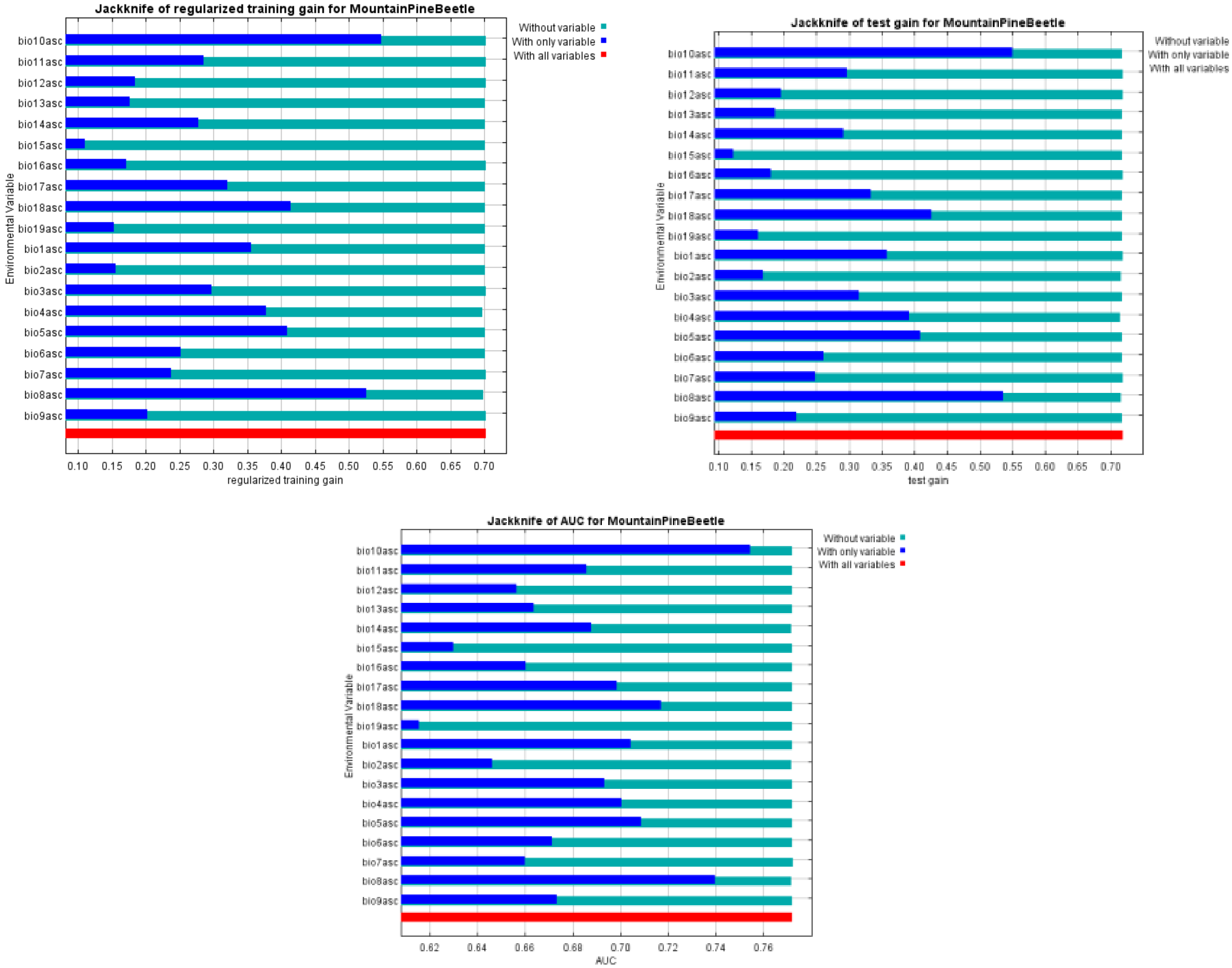


Figure 15 These Jackknife results for 2050/RCP 4.5 serve as representative Jackknife results for the future models. Results for each individual model are available in Appendix B.

CHAPTER FIVE: DISCUSSION

The Maxent results show that a changing climate will have a profound effect on the MPB. However, spatially the amount of suitable land for the MPB is predicted to *decrease* rather than increase. While this goes against early worries that the beetle epidemic would continue to increase with climate change, it does follow the trend documented by the US Forest Service IDS data (Forest Service 2014). The climatic variables that were of most importance to the Maxent models are variables that are commonly looked at in past MPB research as well. As these variables have a profound effect on the MPB, they will likely also affect the vegetation the MPB infests, leaving many questions as to how exactly climate change will affect the MPB ecosystem.

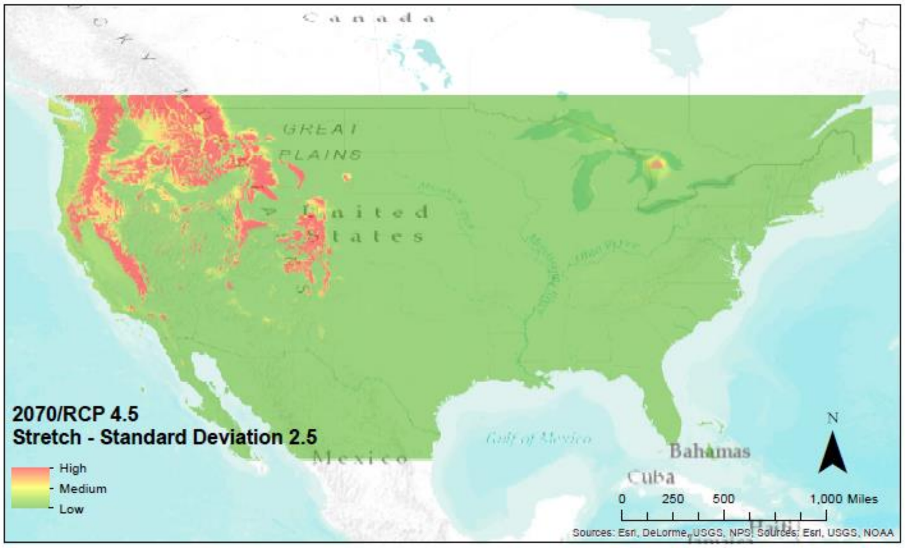
5.1 Model Strengths and Weaknesses

Maxent was an appropriate tool to evaluate the MPB habitat over a large area. The ability to only use presence data is important, as absence data would be difficult, if not impossible to produce due to the large study area and the difficulty in detecting green attack trees. All of the models proved to be statistically significant with an AUC of .77, rounded. While there is debate over the reliability of the AUC, the resulting variable importance ranking falls in line with the variables known to be most important to the MPB. Additionally, a clear pattern between RCP's is evident, further confirming the models were significant.

There were difficulties in working with data sets that cover the span of the United States. Preparing the data was difficult. The MPB data did not initially contain only the location of the MPB, but of all pests the Forest Service surveyed. This made the data set even larger then it needed to be, and it was not immediately apparent how to separate the MPB data from the rest of the data. Once the table connection was identified, this was no longer a problem. On a simpler level, the climate layers took time to load with pyramid structures and significant storage space to process, requiring enough space to store both the raw data and the processed data. For instance, the future climate variables were downloaded, then processed in groups of three while the 19 GeoTiffs were accessible from the temporary download folder. Additionally, three GB of available space was necessary for a Maxent run to be completed.

5.2 Geographic Results

When looking at the binary suitable/unsuitable results, no major geographic shifts were evident. However, when the default 2.5 standard deviation is used for the scaled results, the maps showed high probability in the Great Lakes region. A subtle “medium” suitability is seen in the results for 2050. By 2070, RCP 4.5 has a patch of high suitability on the Canadian side of the Great Lakes across from Michigan. When looking at RCP 8.5 for 2070, the patch of high suitability has decreased from where it was with RCP 4.5 and increased closer to Minnesota, as seen in Figure 16. These results border the Great Lakes and may be in error, due to the lakes mimicking variables favorable to the MPB. However, it is worth further research to determine if these anomalies are caused by the lakes or if they are the direct results of favorable conditions for the MPB.



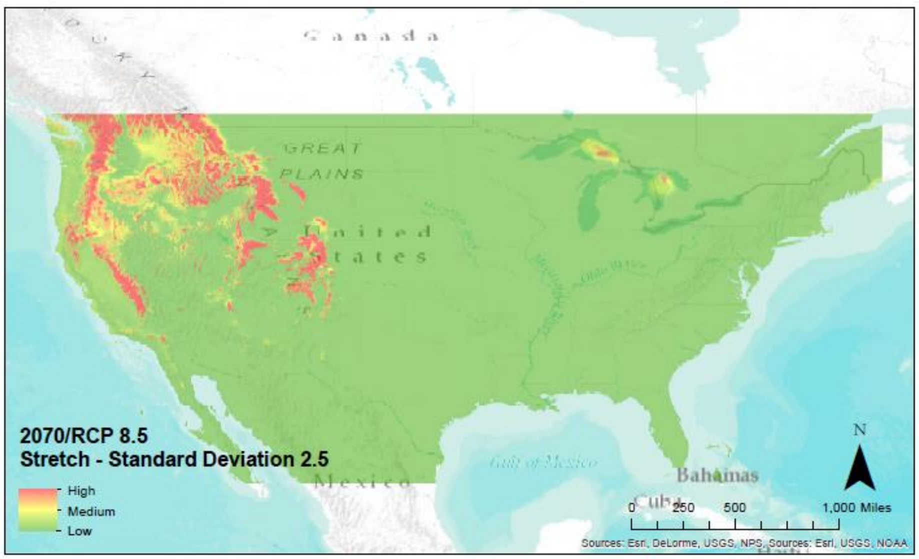


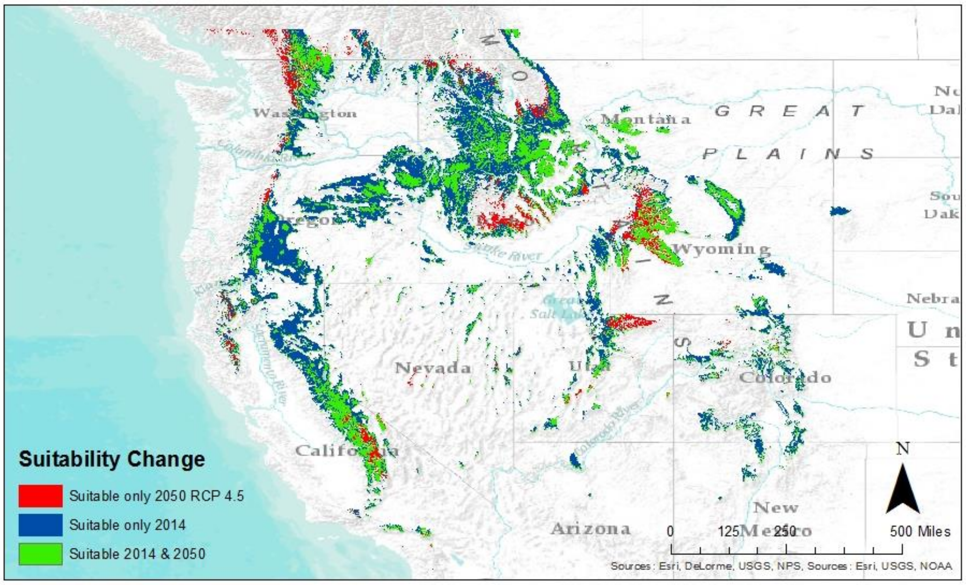
Figure 16 By 2070, both RCP 4.5 and RCP 8.5 show high suitability for the MPB near the Great Lakes. Maps showing all results with a 2.5 Standard Deviation are available in Appendix B.

While the results all showed the MPB remaining in the western United States, there were major shifts in the amount of area deemed suitable. Under the most extreme scenario, RCP 8.5, if emission continue to increase, only 69,161 km^2 would be suitable for the MPB by 2070, an 86% decrease for the amount of land suitable currently. It would be, however, still significantly greater by 89% then the 7,207 km^2 currently inhabited by the MPB in 2014.

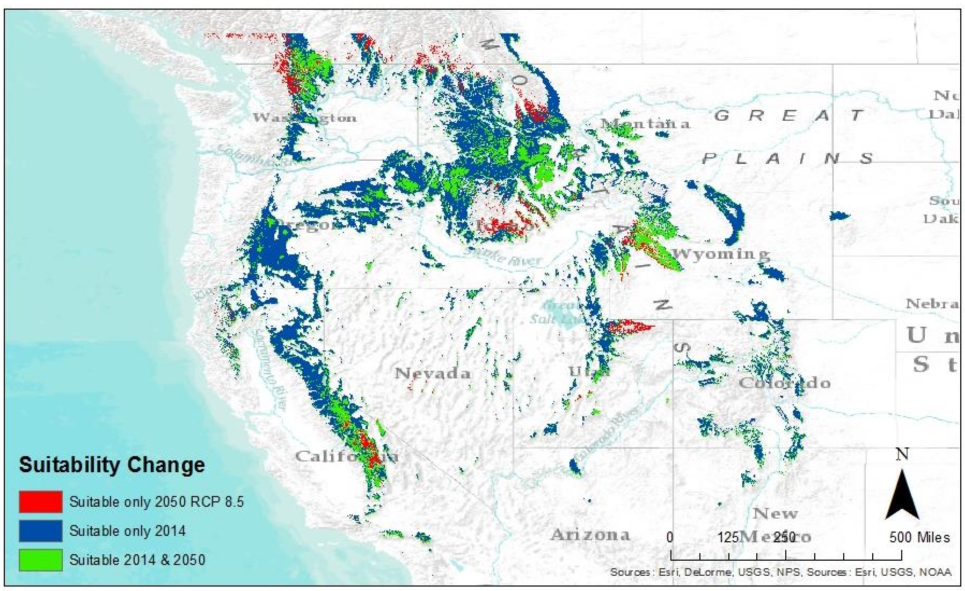
While no huge shifts where documented, the results do indicate a shift in elevation for the MPB into higher elevations. This is still a notable change in territory for the MPB, as higher elevations have different vegetation that often have not had to defend themselves from a MPB attack before. These shifts were also echoed in the Maxent study of Limber Pine in Rocky Mountain National Park (Monahan *et al.* 2013.) Further research into how these results would affect each other would provide a clearer picture as to what the higher elevations of the Rocky Mountains will look like throughout the next century.

5.3 Current to 2050 and 2070 Changes

The movement from what land is currently suitable for the MPB to what land may be suitable in the future can be depicted by comparing the rasters. The *Raster Calculator* tool can be used to subtract each future projection from the current suitability. These results are seen in Figure 17 and 18.

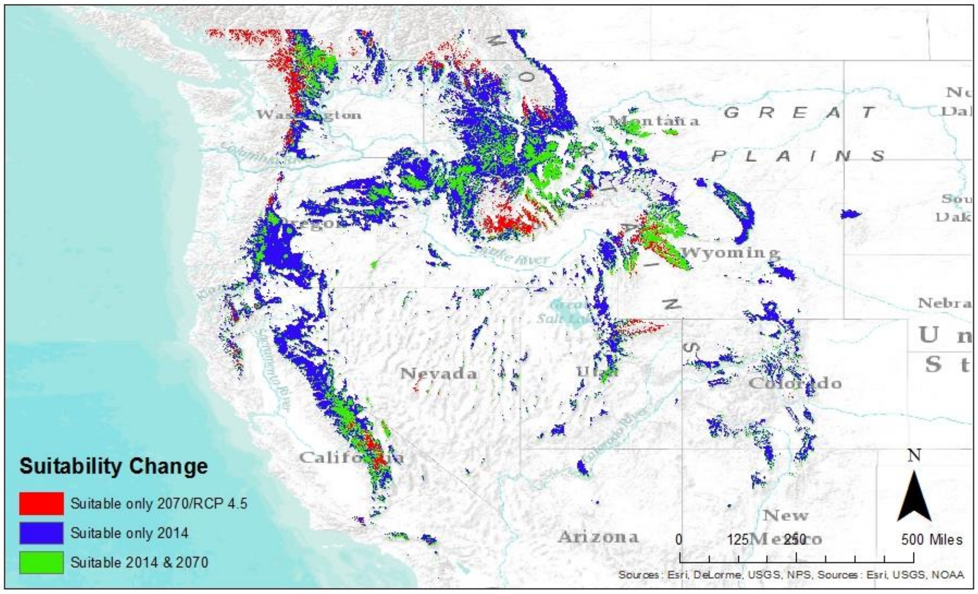


Suitable only in 2014	Suitable only in 2050/RCP 4.5	Suitable in 2014 and 2050/RCP 4.5
322,350 km²	52,452 km²	167,725 km²

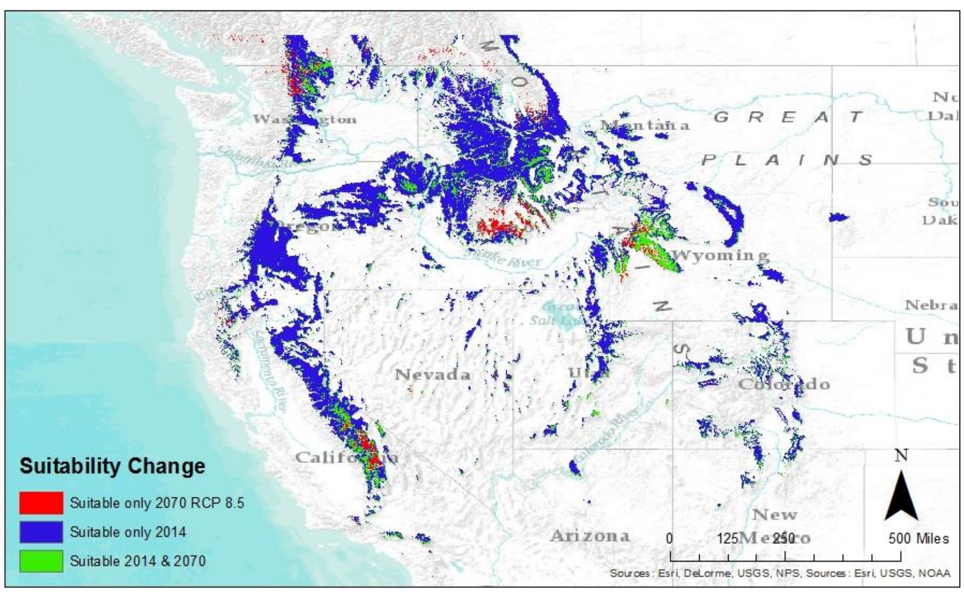


Suitable only in 2014	Suitable only in 2050/RCP 8.5	Suitable in 2014 and 2050/RCP 8.5
388,987 km²	36,132 km²	101,088 km²

Figure 17 The change in suitability for 2050



Suitable only in 2014	Suitable only in 2070/RCP 4.5	Suitable in 2014 and 2070/RCP 4.5
358,397 km²	48,595 km²	131,678 km²



Suitable only in 2014	Suitable only in 2070/RCP 8.5	Suitable in 2014 and 200/RCP 8.5
443,228 km²	22,314 km²	46,847 km²

Figure 18 The change in suitability for 2070

5.4 Variable Results

The climatic variables important to this study are echoed throughout MPB research. The Safrayik model indicates mean maximum temperature for August over 65 degrees Fahrenheit (Safranyik *et al.* 2010, 439) are important benchmarks for the beetle. The longer, warmer a summer, the more time a beetle has to propagate. This is reflected in the variables Maxent found most important in this study – Bio8, Mean Temperature of the Wettest Quarter, and Bio 10, Mean Temperature of the Warmest Quarter.

Evangelista *et al*. found Bio18, Precipitation of the Warmest Quarter, as the most important, followed by Bio 10 as well. Bio 8 and 18 are similar, both having to do with precipitation during the growing season. This is an important variable, as precipitation during the growing season greatly affects the ability for trees to defend themselves during a MPB attack. While these variables have the most effect on the MPB, they likely would affect the surrounding vegetation as well, potentially leading to even more favorable conditions for the MPB.

5.5 Future Research

This study is the beginning of applying the CMIP5 climate models to the MPB. As Evangelista *et al*. stated, "We view our models as hypotheses: possible future scenarios of ecological change." There are many opportunities for future studies to build upon this process, with a variety of ecological and spatial variables possible. Future studies should apply additional climate models to a similar process. Which climate models are favored will continue to evolve as additional research is published using the CMIP5 models. Additionally, this study did not include vegetation as an environmental variable within Maxent as vegetation is also expected to change with climate change. However, a larger study may apply a two-step process that models climate change's effect on the vegetation, and then applies those results to the MPB.

This study did not apply a sampling bias as the MPB has been recorded outside of the sampling area (such as in Michigan) and in areas not sampled by the Forest Service, such as metropolitan areas. Results could be compared to a study where a sampling bias is applied under the Maxent Bias field. Similarly, this study only incorporated MPB presence data from 2014 for the models. While this narrows in on where the MPB currently is, the results could be compared to the data set containing survey data from 1997 to 2014. This larger data set could also be paired down further to only include data before the start of the outbreak in 2000, which would also align with the "Current" Bioclimatic variables that end in 2000. This option would allow for testing of the model to see if it could accurately predict current MPB habitat.

Further, there is room for scaling in both directions. Research into individual states and ecosystems is likely more useful for forest managers to assess the probability of a MPB attack within their management area. However, a study into the span of North America including both Canada and the United States may be able to give a more complete picture to how the MPB may move in elevation and direction. A larger presence data set that covered the United States and Canada would be necessary. Differences in survey data would need to be accounted for, and a longer temporal range for the presence data would likely give a more complete picture of the MPB presence by eliminating error caused by a gap in survey method.

This study aimed to look at potential habitat for the MPB under climate change scenarios. As the results show, possible implications of climate change may have unexpected results on the expansion or contraction of species such as the MPB. The application of this modeling can give forest managers a look at what the landscape may look like in the future and plan accordingly. There are many possible ways Maxent and GIS can continue to be used to model how the MPB's habitat may change under developing climate change scenarios.

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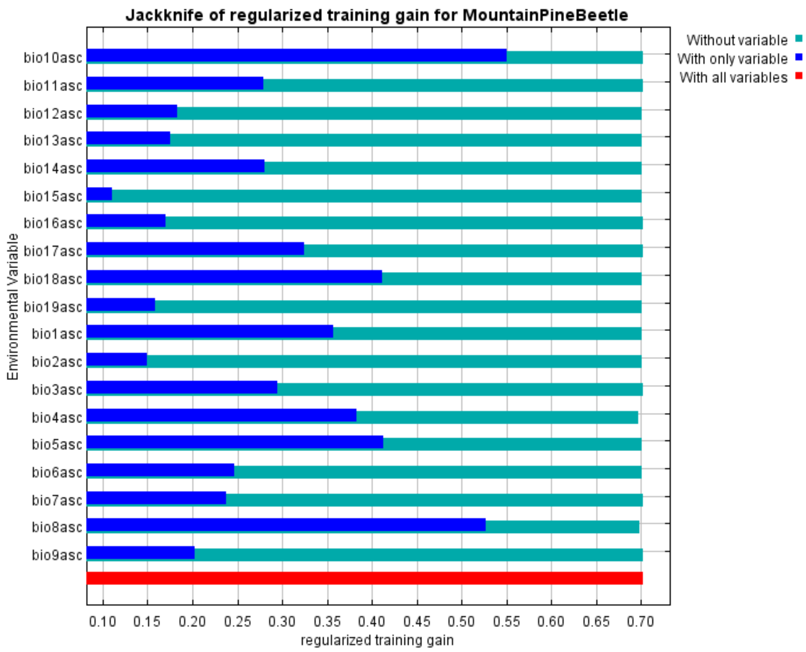
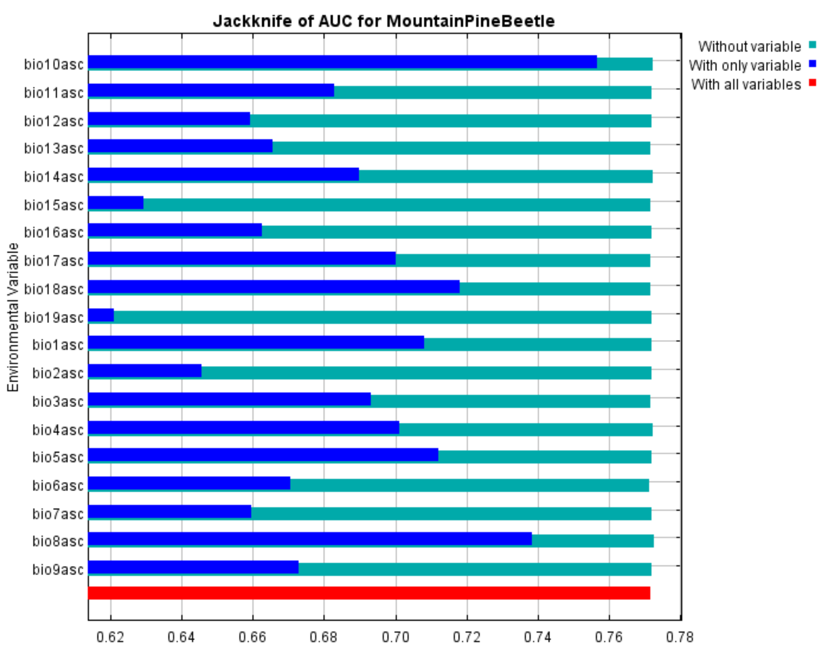
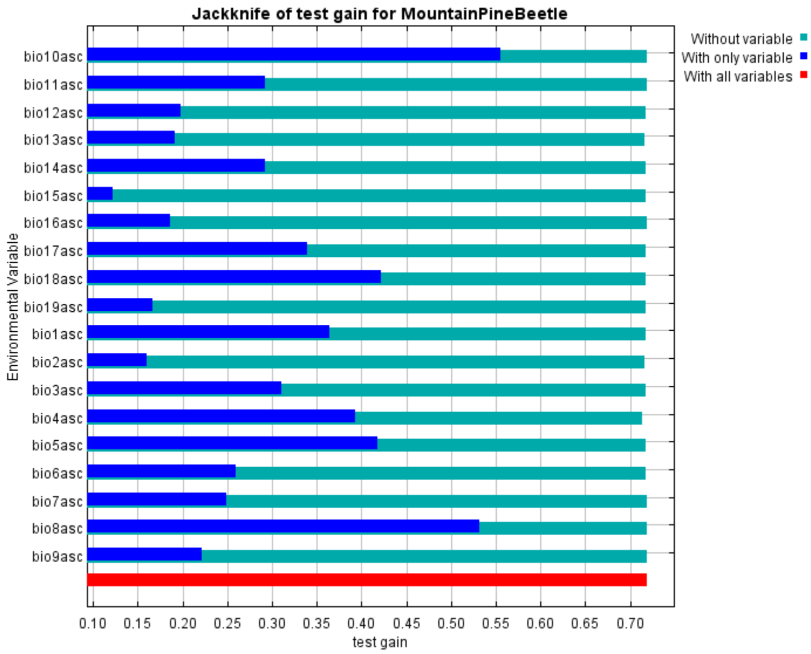
APPENDICES

Appendix A – Jackknife Tests

Current






Jackknife of test gain for MountainPineBeetle
Without variable
With only variable
With all variables
bio10asc
bio11asc
bio12asc
bio13asc
bio14asc
bio15asc
bio16asc
bio17asc
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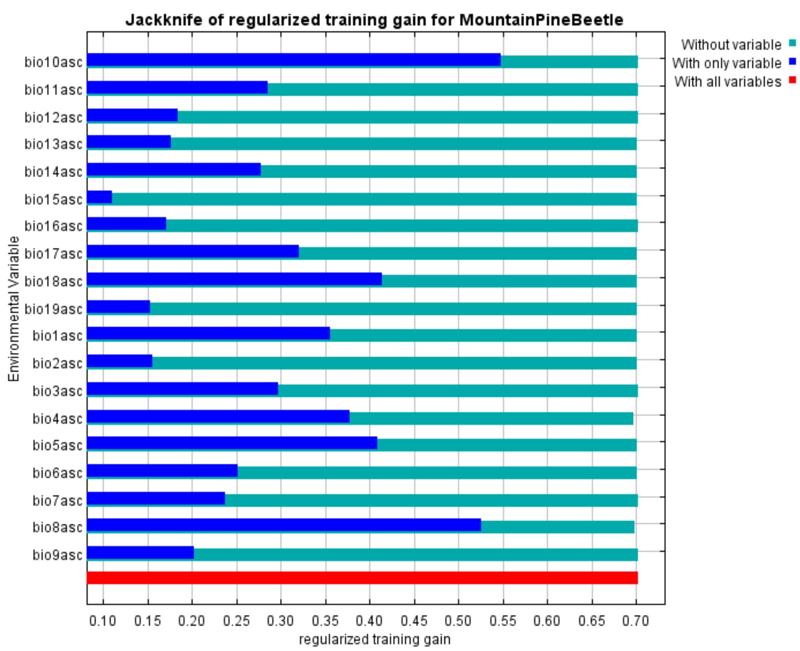
bio9asc
Environmental Variable
0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70
test gain

2050, RCP 4.5


Jackknife of regularized training gain for MountainPineBeetle
Without variable
With only variable
With all variables
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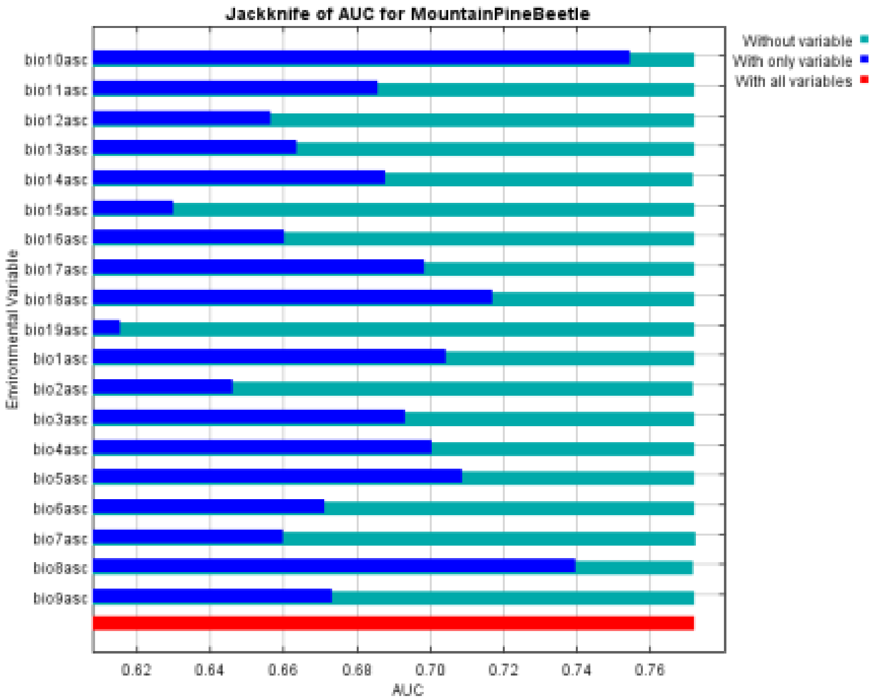
Environmental Variable
0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70
regularized training gain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bio8asc
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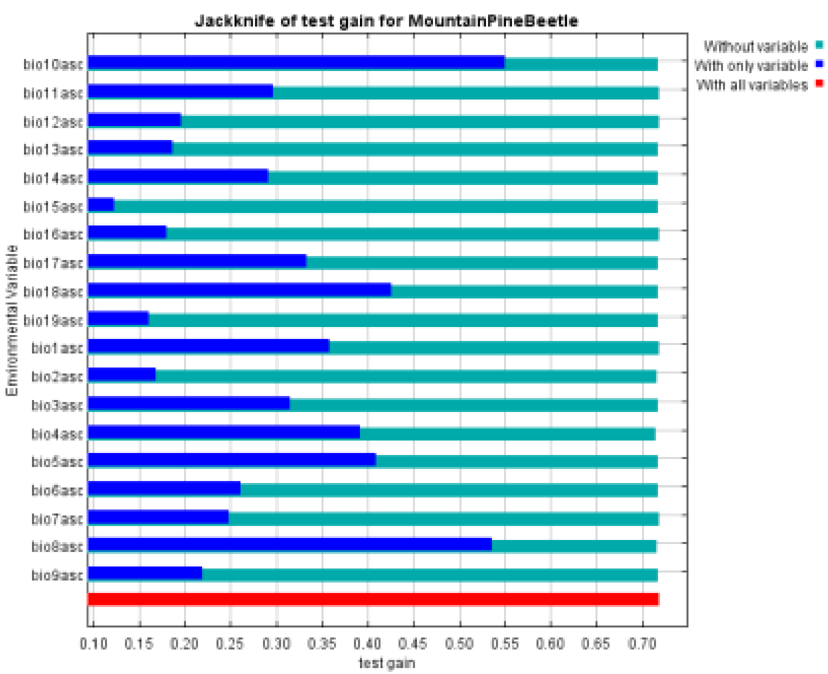
Environmental Variable
0.62 0.64 0.66 0.68 0.70 0.72 0.74 0.76
AUC


Jackknife of test gain for MountainPineBeetle
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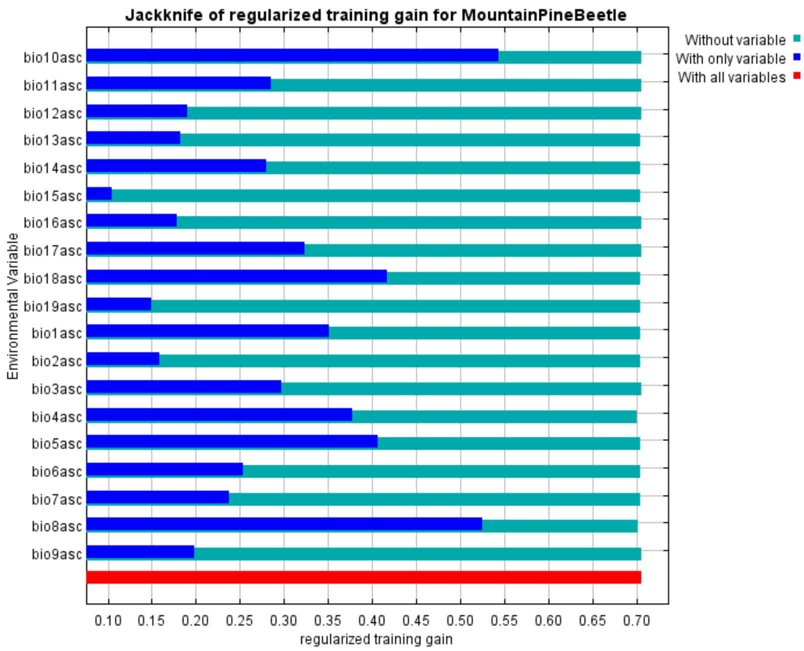
Environmental Variable
0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70
test gain

2050, RCP 8.5



Jackknife of regularized training gain for MountainPineBeetle
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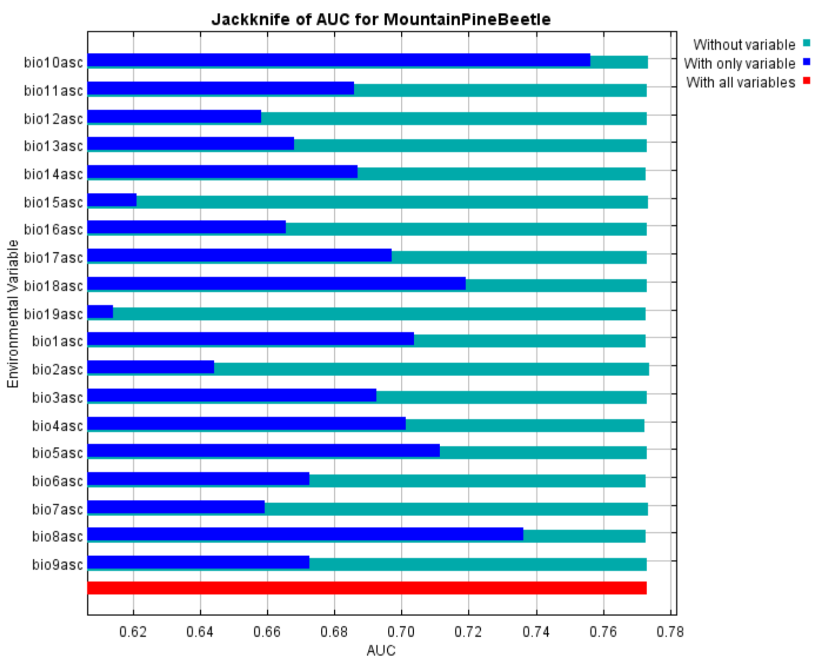
Environmental Variable
0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70
regularized training gain



Jackknife of AUC for MountainPineBeetle
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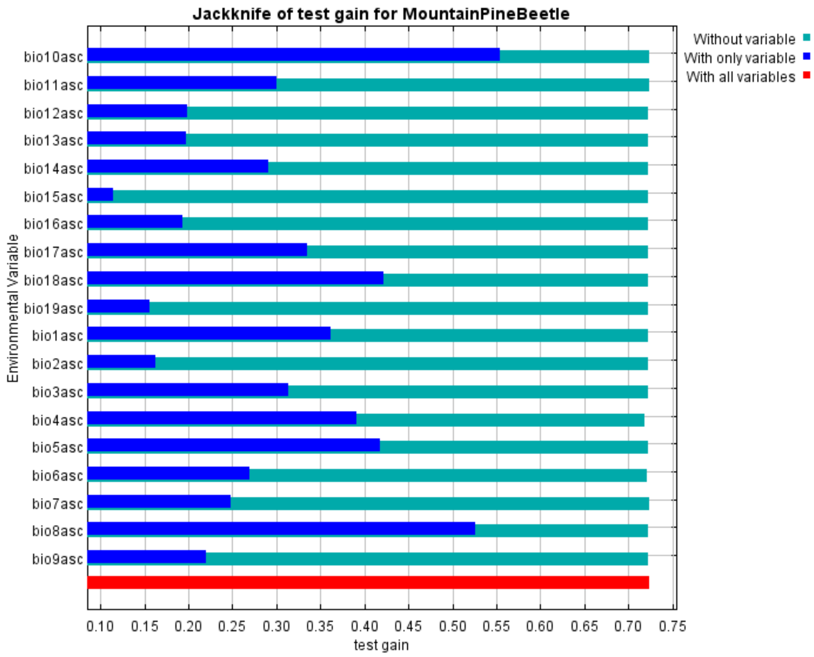
bio8asc
bio9asc
Environmental Variable
0.62 0.64 0.66 0.68 0.70 0.72 0.74 0.76 0.78
AUC


Jackknife of test gain for MountainPineBeetle
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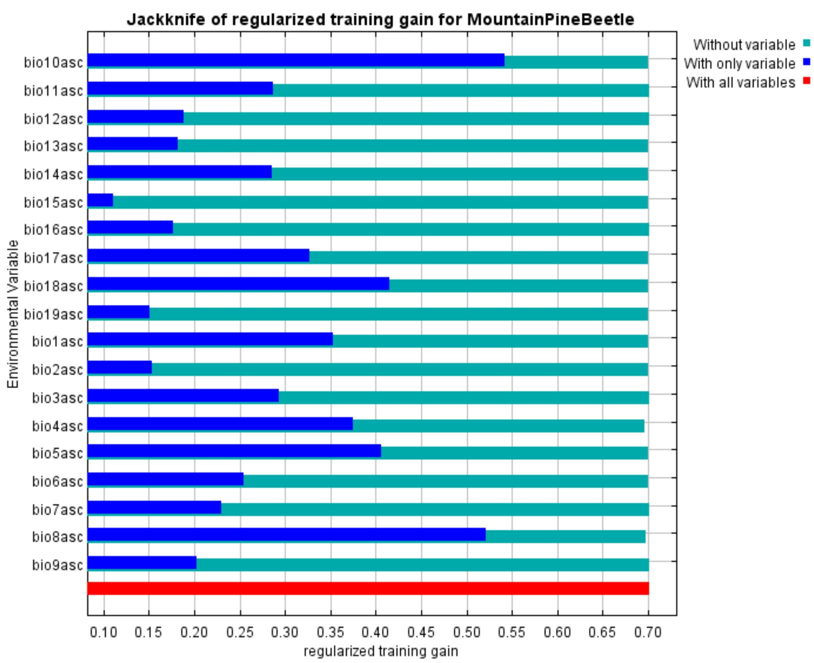
bio7asc
bio8asc
bio9asc
Environmental Variable
0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75
test gain

2070 RCP 4.5


Jackknife of regularized training gain for MountainPineBeetle
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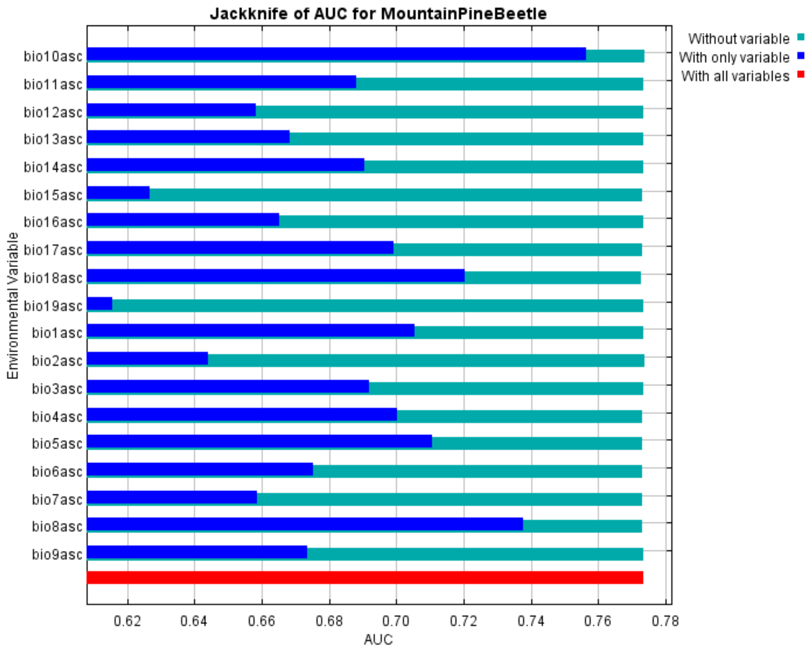
Environmental Variable
0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70
regularized training gain


Jackknife of AUC for MountainPineBeetle
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Environmental Variable
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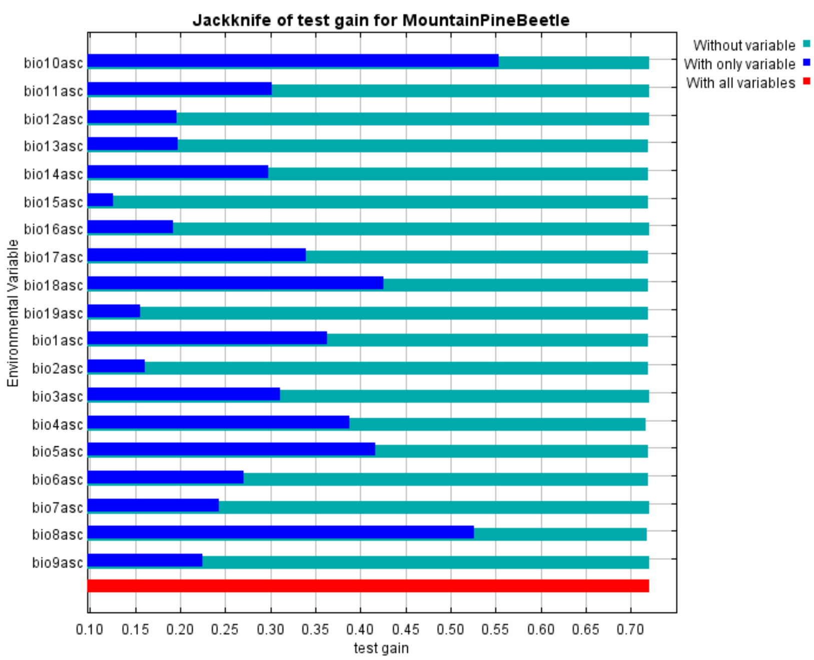
0.62 0.64 0.66 0.68 0.70 0.72 0.74 0.76 0.78
AUC


Jackknife of test gain for MountainPineBeetle
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Environmental Variable
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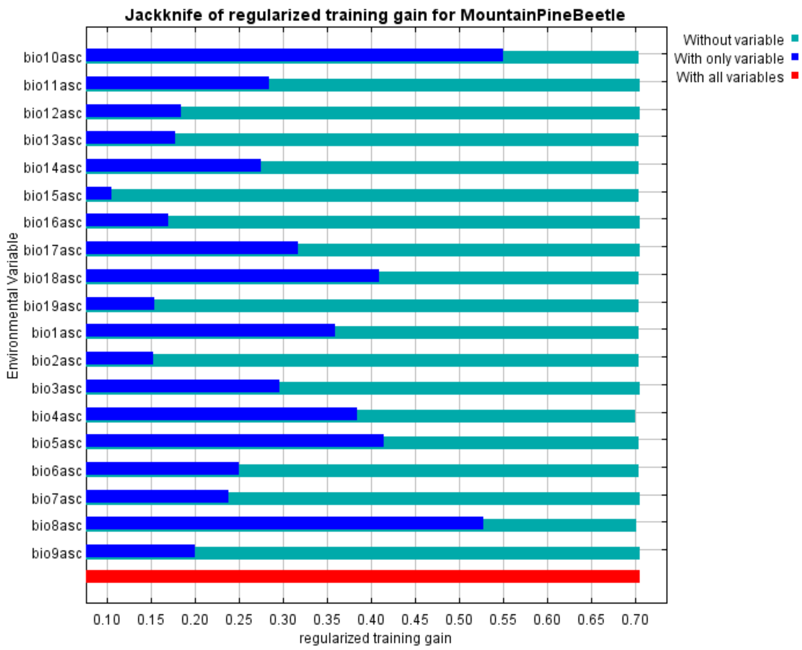
test gain

2070 RCP 8.5


Jackknife of regularized training gain for MountainPineBeetle
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Environmental Variable
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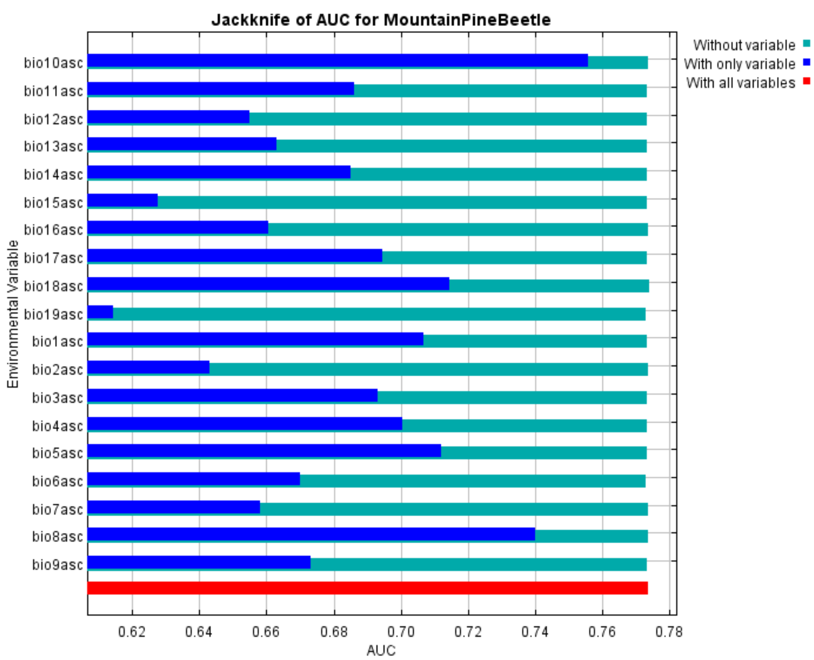
regularized training gain


Jackknife of AUC for MountainPineBeetle
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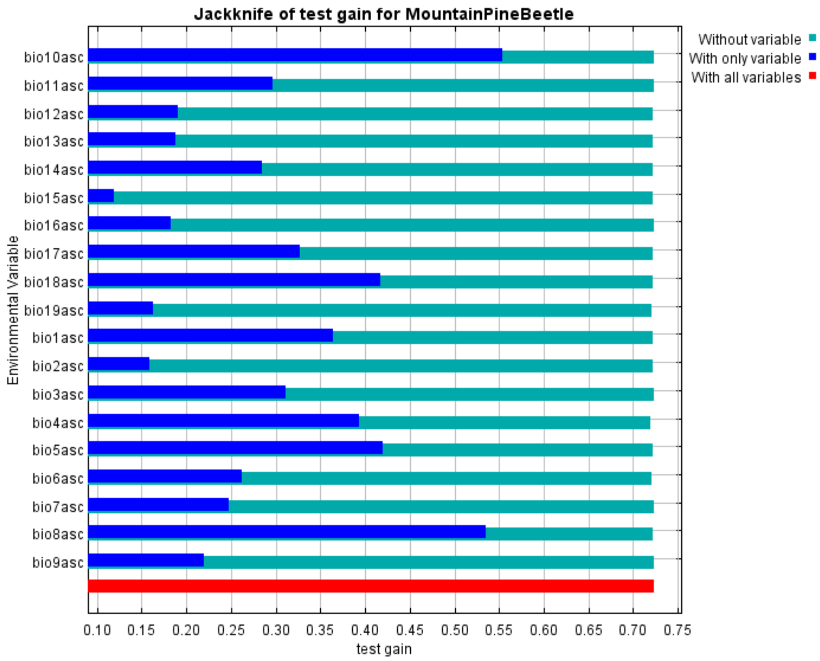
Environmental Variable
0.62 0.64 0.66 0.68 0.70 0.72 0.74 0.76 0.78
AUC


Jackknife of test gain for MountainPineBeetle
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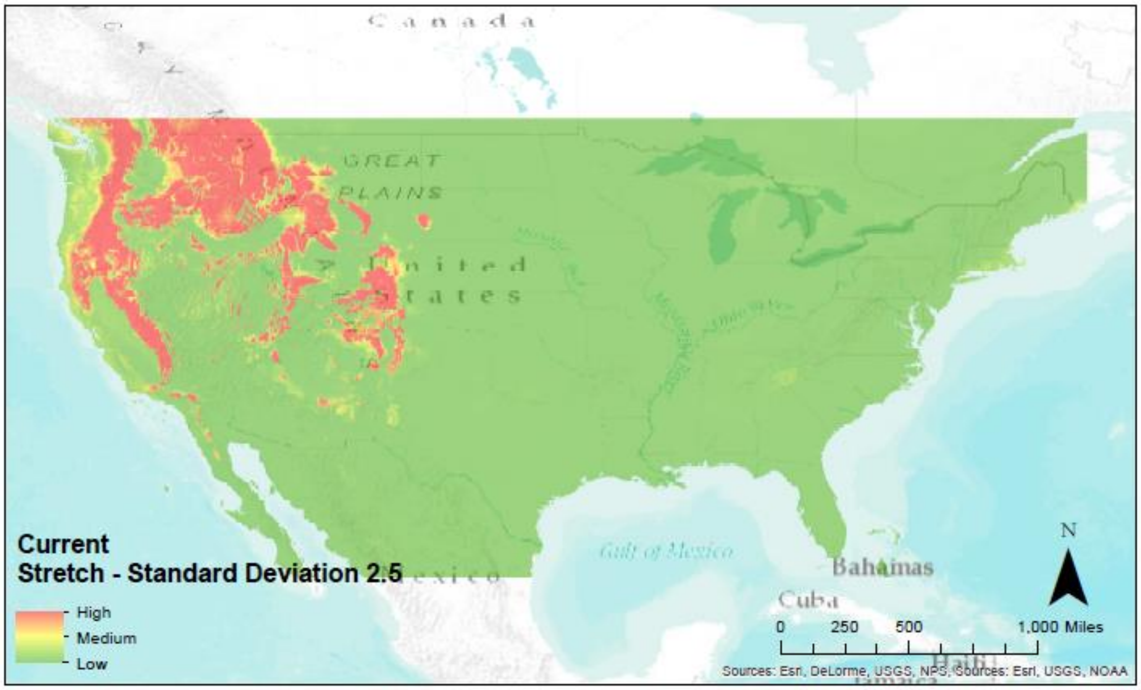
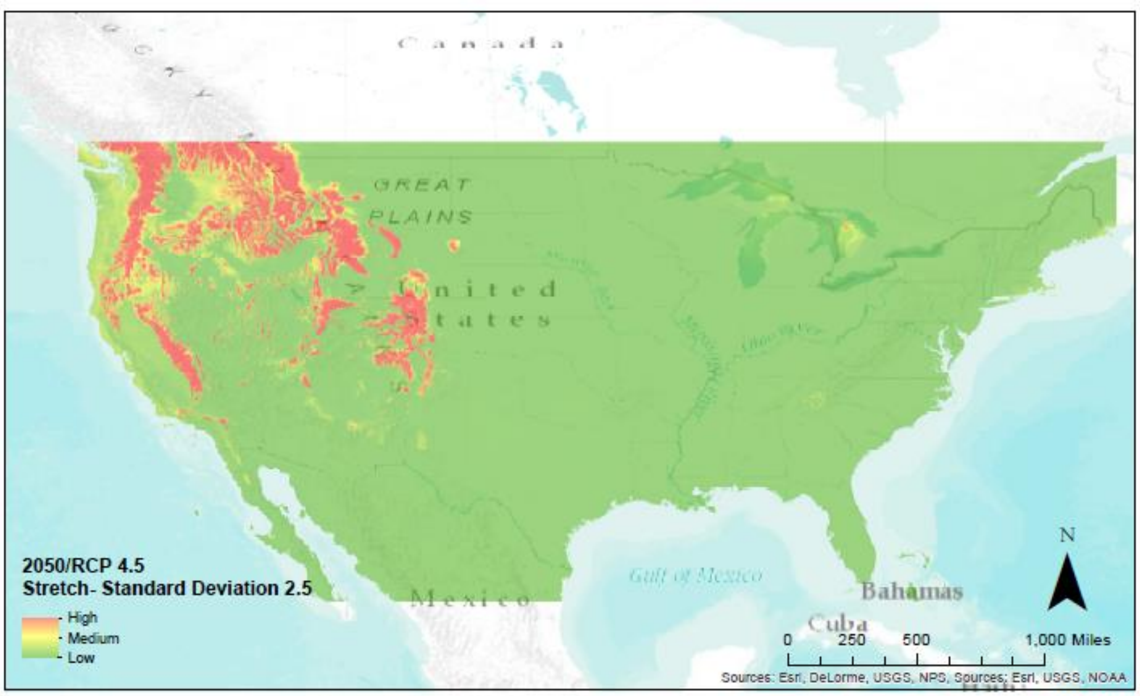
bio9asc
Environmental Variable
0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75
test gain

Appendix B – Stretch Maps with 2.5 Standard Deviation

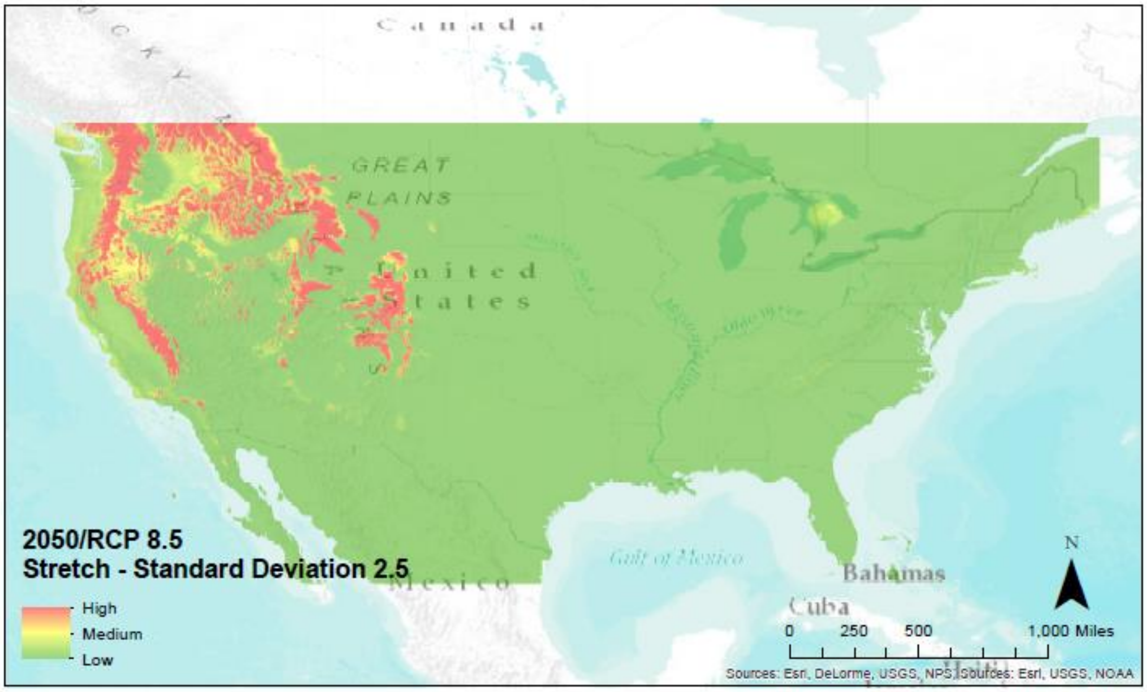
Current



2050 RCP 4.5



2050 RCP 8.5


Canada
GREAT
PLAINS
United
States
Mexico
Gulf of Mexico
Bahamas
Cuba
2050/RCP 8.5
Stretch - Standard Deviation 2.5
High
Medium
Low
N
0 250 500 1,000 Miles
Sources: Esri, DeLorme, USGS, NPS, Sources: Esri, USGS, NOAA