Marshall University
Marshall Digital Scholar

Theses, Dissertations and Capstones

2009

Modeled Red Spruce Distribution Response to Climatic Change in Monongahela National Forest

James Michael Stanton

Modeled Red Spruce Distribution Response to Climatic Change in Monongahela National Forest

Thesis submitted to
the Graduate College of
Marshall University

In partial fulfillment of
the requirements for the degree of
Master of Science
in Geography

By

James Michael Stanton

Dr. Anita Walz, Ph.D., Committee Chairperson
Dr. Kevin Law, Ph.D.
Dr. James Leonard, Ph.D.

Marshall University

December 2009

Abstract

Modeled Red Spruce Distribution Response to
Climatic Change in Monongahela National Forest

By James Michael Stanton

In Monongahela National Forest of West Virginia, red spruce grows in high-elevation island ecosystems that are particularly sensitive to changes in climatic conditions. The ecological niche modeling application Maxent was used to project the distribution response of red spruce to climatic change for the purposes of conservation planning. Red spruce distribution data was acquired from the United States Forest Service. Three sets of nineteen bioclimatic variables, corresponding to present, 2050, and 2080 conditions, were derived from 1961-1990 monthly temperature and precipitation means and the IPCC A2 emissions scenario of HadCM3. The modeling revealed rapidly diminishing red spruce habitat suitability from southwest to northeast, while the border region between Randolph and Pendleton Counties displayed consistent suitability over time. Conservation efforts for red spruce should focus in the areas projected to maintain habitat suitability in the longer term, while alternative species planting may be necessary elsewhere to preserve forest integrity.

Acknowledgments

I would like to thank Dr. Anita Walz, my committee chairperson, for her assistance and patience during the completion of this project. I would also like to thank Dr. Kevin Law for his input on climatological matters, Dr. James Leonard for his guidance in GIS techniques, Dr. Joshua Hagen for his instruction in performing geographical research, and Professor Larry Jarrett for his helpful advisement. I would like to extend my gratitude to Samuel Lammie, Geographer at Monongahela National Forest, for providing the red spruce distribution data, boundary shapefiles, and essential background information. Finally, I would like to thank my parents for helping to make this achievement possible through tireless guidance and support.

Table of Contents

List of Figures

List of Tables

Chapter One: Introduction

The distribution of terrestrial plant communities is inextricably linked to factors of climate and physical landscape. Natural climatic variations have directly influenced the native ranges, biological adaptations, and extinction rates of tree and other plant species throughout the history of the planet. Additionally, alterations in vegetation typology and density, resulting from either climate-induced impacts or anthropogenic land use changes, have produced feedback effects upon the climate at multiple scales.

While still controversial, evidence exists that anthropogenic emissions of the greenhouse gases carbon dioxide and methane are significant forcing agents in the trend of global climatic warming over the past century (IPCC, 2007). These gases absorb longwave radiation and reflect it back towards the surface, increasing air temperatures and potentially altering precipitation patterns. As it has throughout geologic history, modern climatic change could alter regions of habitat suitability for tree species, causing them to shift ranges, adapt to new conditions in place, or diminish to extinction (Holt, 1990). As forest vegetation forms an important habitat for many other organisms, and plays environmental regulation roles through transpiration, carbon sequestration, soil retention, and ground shading, entire ecosystems could be impacted as well.

Biodiversity conservation efforts for forests in a changing climatic environment will be of increasing importance. The development of appropriate conservation strategies will require accurate and precise models that predict species distribution changes at regional and local scales, and will also require updated information about species range shifts already underway at specific sites (Hannah, et al., 2002).

The primary objective of this study is to utilize the Maximum Entropy Species Distribution Modeling application, or Maxent, to predict changes in the spatial distribution of red spruce in Monongahela National Forest, West Virginia, due to currently projected climatic changes. The study aims to estimate the set of environmental conditions most favorable to the growth of red spruce in the region of eastern West Virginia based on its natural distribution, and projects future distributions using altered sets of environmental conditions. The study tests potential migration rather than adaptation or extinction possibilities. Distribution changes at certain locations and in certain directions are examined. Implications of a shifting red spruce ecosystem for regional biodiversity conservation efforts are also considered.

Chapter Two: Literature Review

Monongahela National Forest

The Monongahela National Forest is comprised of approximately 917,000 acres of federally owned and managed forest land in the Appalachian Mountains of east central West Virginia. An additional 586,000 acres of land under private or other ownership exists within the National Forest proclamation boundary. The Forest is administered by the United States Department of Agriculture Forest Service, and the Forest headquarters is located in the city of Elkins, West Virginia (Figure 1). The boundary area is vast by regional standards, containing portions of ten West Virginia counties along with highly variable topography, soils, and climatic conditions. Elevations range from approximately 1,000 feet near Petersburg, Grant County, to 4,863 feet at the summit of Spruce Knob, Pendleton County (Mueller, 1992). The area is bordered by George Washington National Forest to the southeast in Virginia.

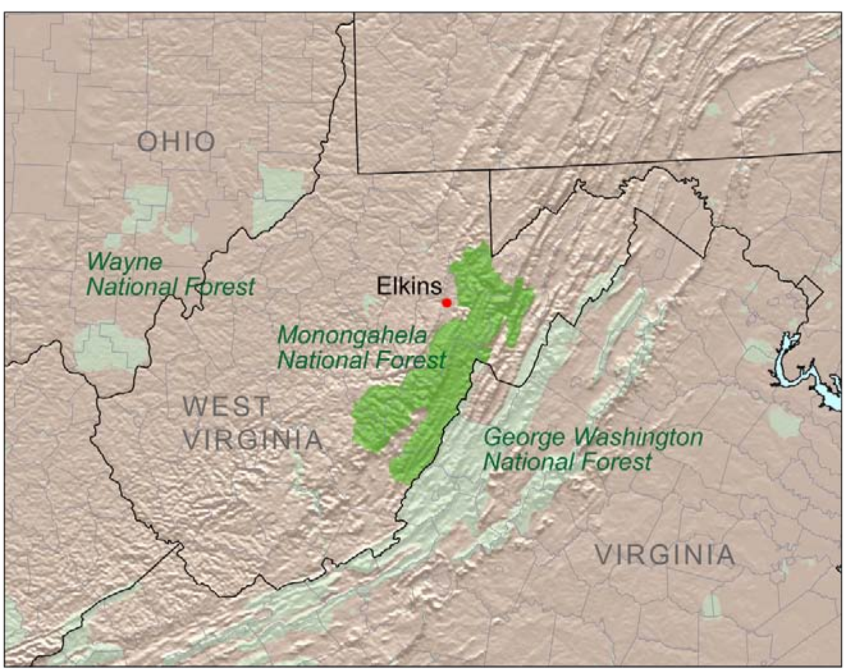


Figure 1: Location of Monongahela National Forest (Musser, 2009)

Following extensive logging of the Appalachian forests in the late 1800s and early 1900s, the 1911 Weeks Act was passed to authorize federal acquisition of land for natural resource protection and recovery. In 1915, an initial area of 7,200 acres near Parsons, Tucker County, was purchased by the federal government. The Monongahela National Forest was officially designated on April 28, 1920 (United States Forest Service, 2008). Over time, parcels of land within the 1.5 million acre proclamation boundary have been purchased by the federal government to enhance the protective value and public benefits of the Forest (Figure 2).

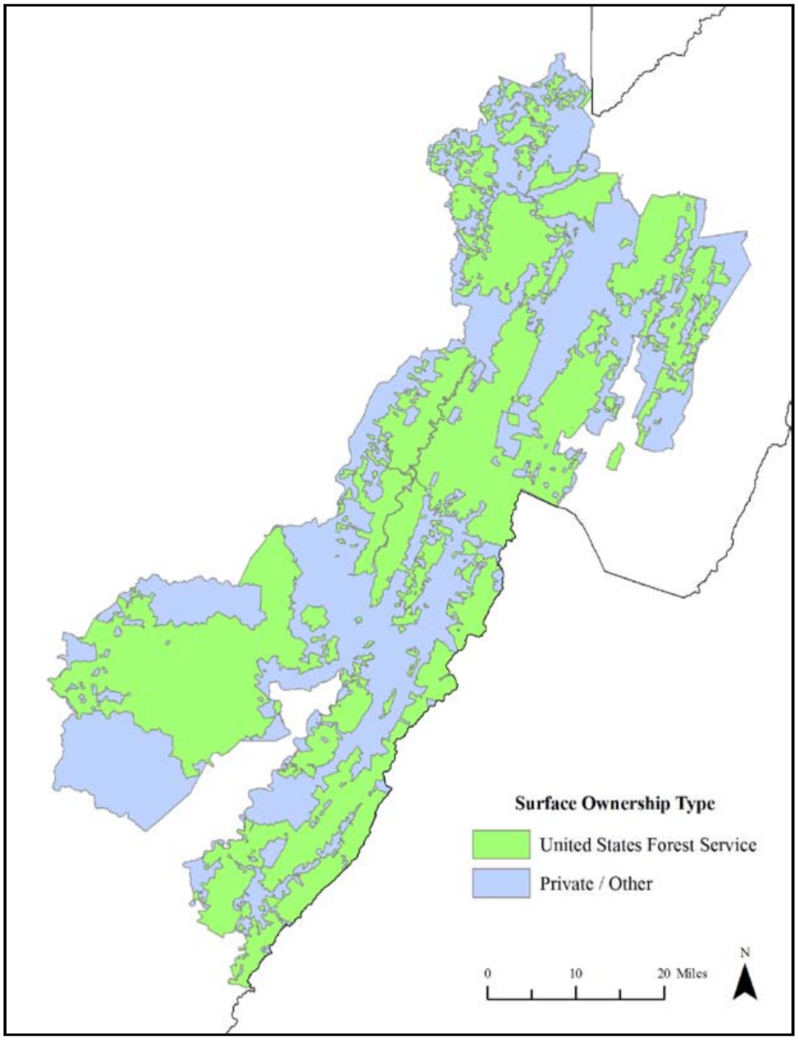


Figure 2: Surface Ownership Distribution of Monongahela National Forest (United States Forest Service, 2009)

Red Spruce

Red spruce (*Picea rubens*) is a coniferous species of tree that favors cool, moist conditions and is particularly tolerant of shade. Mature trees may reach heights of 110 feet and live as long as 400 years. Red spruce tends to grow on acidic soils with pH between 4.0 and 5.8, and has a shallow root system that spreads laterally, helping to protect top layers of soil from erosive processes. The rate of seed production depends on several factors, including forest density, sunlight access, and climatic conditions, but the best seed quality on average occurs after trees have reached an age of 30 years (Natural Resources Conservation Service, 2004).

The present range of red spruce extends from the Canadian maritime provinces westward into Quebec and southward into northern New England. The range becomes discontinuous in New York state, clustering in higher elevation areas where climatic conditions are favorable to its growth. The main clusters further south are in West Virginia, western Virginia, and western North Carolina. Significant gaps occur in Pennsylvania due to generally lower relief (Figure 3).

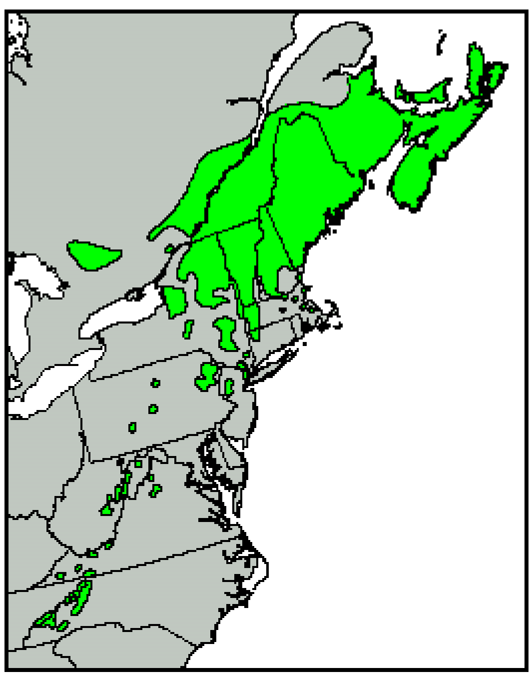


Figure 3: Red Spruce Distribution in North America (United States Geological Survey, 1999)

A montane forest community dominated by red spruce and balsam fir (*Abies balsamea*) exists as a discontinuous series of island ecosystems at the highest elevations of Monongahela National Forest (White & Cogbill, 1992). The ecotone of red spruce forests in this region is about 3,500 feet in elevation, although some red spruce is found at lower elevations in the vicinity of Canaan Valley in the northeast. These midlatitude forests are related to the vast boreal forests of eastern Canada, but contain a distinctly varied set of resident plant and animal species, including the endangered Virginia northern flying squirrel (*Glaucomys sabrinus fuscus*) and the rare Virginia varying hare (*Lepus americanus virginianus*) (Mueller, 1992).

Red spruce growth is clustered in four general geographical areas in the National Forest. The first is in a rugged plateau region in the vicinity of Cranberry Wilderness in the southwest. Another exists along the high elevation topography of the central region, following the border between Randolph and Pocahontas Counties. A third is in a collection of isolated ridge tops in the central east, including Spruce Knob. A fourth is in the vicinity of Canaan Valley and Dolly Sods Wilderness in the northeast. Mixed conifer and deciduous forests are typically located at lower elevations surrounding the conifer units. Red spruce mostly occurs there with sugar maple, beech, and birch, among others (White & Cogbill, 1992).

The red spruce forest of West Virginia is highly dependent upon and well-adapted to the consistently cool and moist climate of the high elevations. Its relative sensitivity to changes in environmental conditions, as opposed to the forest communities of lower elevations, places it in a unique position to provide early indicators of vegetation response to modern climatic change (McLaughlin, et al., 1998). The potential disappearance of this community from the region, and the invasion of different tree communities in its wake, would have profound consequences for regional wildlife habitat and biodiversity.

Species Distribution Change

Climate and climatic change are regarded as the most significant factors determining the distributions of organisms in the context of the present day and recent past (Meadows & Hill, 2002). Plant communities may respond to climatic warming either by shifting their ranges to higher elevations and latitudes, maintaining their ranges through adaptation to new environmental conditions, becoming extinct, or a combination of these processes (Holt, 1990). An evaluation of fossil and genetic data from forests of the distant past revealed that tree species extinctions have occurred primarily during periods of high climatic variability (Petit, et al., 2008).

Numerous studies have determined that certain plant and animal species are already shifting their ranges poleward and upslope due to climatic warming. A study of 58 species of North American and European butterfly revealed that two-thirds of the species have shifted their ranges northward over the preceding 70 years (Parmesan, 1996). The average range of one particular species, the Edith's Checkerspot butterfly (*Euphydryas editha*), has moved northward by 92 kilometers, and has increased its elevation by 124 meters in California's Sierra Nevada Mountains (Parmesan, 1996). The average ranges of 59 species of bird in the United Kingdom have shifted northward by 18.9 kilometers between 1979 and 1999 (Thomas & Lennon, 1999). A comparison was made between 1977 and 2007 vegetation surveys of a 2,314 meter elevation gradient in California's Santa Rosa Mountains. It was discovered that increasing surface temperatures and widening precipitation variability in the period between surveys had caused the average elevation of the dominant plant species to rise by approximately 65 meters (Kelly & Goulden, 2008).

Ecological Niche Modeling

In order to increase the accuracy and precision of projected species distributions, steady technological developments have been made in vegetation modeling methods at various scales. Ecological niche modeling programs are used to project habitat suitability and distribution changes for a single species. These models, such as GARP, Bioclim, Domain, and Maxent, relate species distribution data to the set of environmental or ecological characteristics found in its area, and to which the species is adapted (Elith, et al., 2006). Some models rely on presence-only data while others utilize both presence and absence data (Phillips, et al., 2006). Future distributions are projected based on where similar environmental conditions are likely to be found after a period of climatic change (Peterson, et al., 2005).

Alternatively, biogeography models such as BIOME, DOLY, MAPSS, and Holdridge Life Zone are used to project shifts in groupings of plant species with similar physiological and structural properties known as plant functional types (Peterson, et al., 2005).

Vegetation models have been used in numerous studies to create multiple scenarios of climatic change. A study was performed to determine the expected biological response of 130 North American tree species to climatic warming (McKenney, et al., 2007). Two scenarios were presented, in which species either migrate entirely into future climatic niches or do not migrate out of their present niches. In the migration scenario, potential ranges show decreases and increases in size, with an average decrease of 12% and northward shift of 700 kilometers. In the non-migration scenario, potential ranges decrease in size by 58% and shift northward by 330 kilometers. Another study examined the vulnerability of 34 species of oaks and pines to the effects of climatic change in Mexico (Gomez-Mendoza & Arriaga, 2007). Using the Hadley Centre general circulation model HadCM2, databases of herbaria specimens and digital covers of biophysical variables affecting oaks and pines were used to project species distributions under both severe and conservative climatic change scenarios for the year 2050. Both scenarios showed temperature increases, precipitation decreases, and reductions in the species ranges.

Maximum Entropy Species Distribution Modeling

Elith, et al. (2006) performed an analysis of 16 major species distribution modeling methods to compare their predictive performances. The study considered the distribution changes of 226 species and used three output statistics to assess each model's ability to discriminate between species presence and absence. The Maximum Entropy Species Distribution Modeling application, or Maxent, ranked among the top three predictive performers due to its complex treatment of environmental variables. Other commonly used modeling methods, including GARP, Bioclim, and Domain, performed relatively poorly (Elith, et al., 2006).

The Maxent application operates by assessing a set of environmental variables with a set of point locations where a species is known to exist. The habitat suitability of each cell in a grid is expressed as a function of the environmental variables at that cell. High values mean there is a high probability of presence for the species in those locations (Phillips & Dudik, 2008). Maxent is designed to project suitability over areas based on an incomplete set of species presence information. Maximum entropy refers to the most likely probability distribution within a set of imposed environmental constraints on that distribution (Phillips, et al., 2006).

Chapter Three: Methodology

Data Collection

A set of GIS data depicting the 1988 distribution of red spruce in Monongahela National Forest was acquired from the United States Forest Service (Figure 4). This dataset was created by the West Virginia University Department of Geography under contract by the United States Forest Service Northeast Forest Experiment Station. Although dated twenty years, it represents the most current and complete information on red spruce distribution in the National Forest.

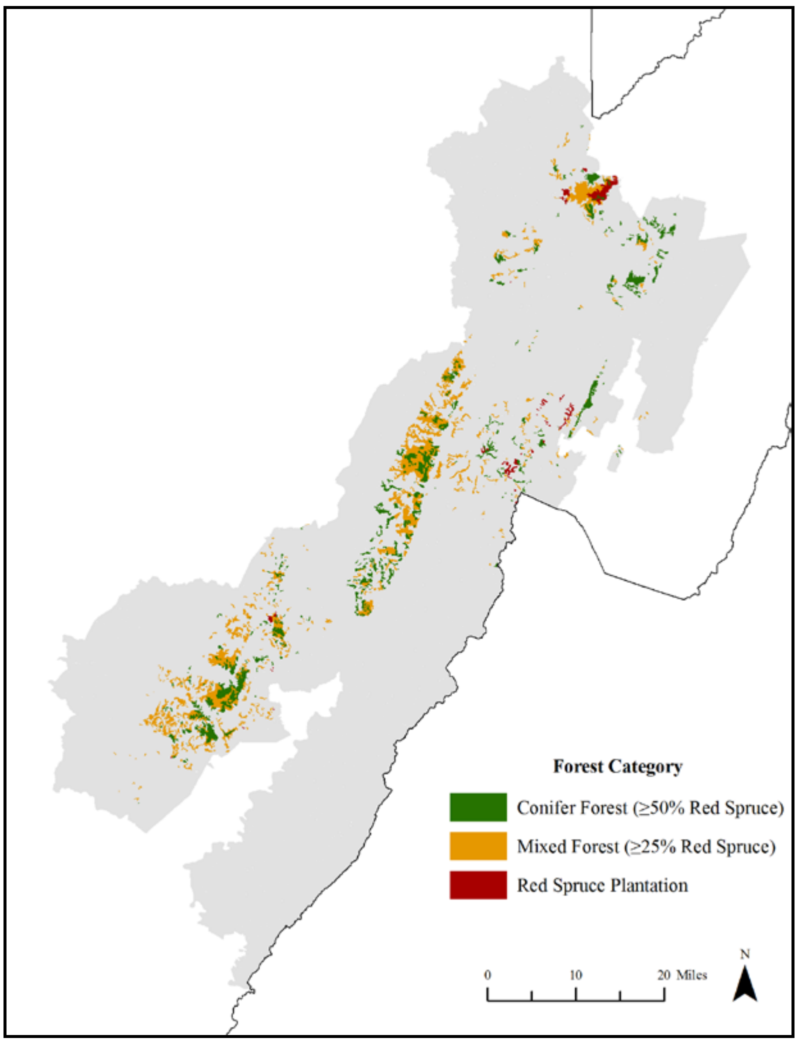


Figure 4: 1988 Red Spruce Habitat as Forest Categories (United States Forest Service, 1988)

Red spruce occurrence was identified through the interpretation and mapping of color infrared aerial photographs at a scale of 1:30000, coupled with expert opinion and identification in the field. The three criteria used in delineating presence locations were conifer stands with at least 50% of the overstory identified as red spruce, mixed conifer and deciduous stands with at least 25% of the overstory identified as red spruce, and red spruce plantation stands.

Climatic data corresponding to the 1988 distribution were acquired from the WorldClim Global Climate Data website, operated by the Museum of Vertebrate Zoology, University of California at Berkeley (WorldClim, 2005). Climatic rasters were generated through the interpolation of mean monthly temperature and precipitation data from all operational collection stations between 1961 and 1990. Interpolation was performed using the Shuttle Radar Topography Mission (SRTM) elevation database of the Jet Propulsion Laboratory, California Institute of Technology, and the ANUSPLIM software developed at The Australian National University. The interpolation was set to a resolution grid of 30 arc seconds, or approximately 1 square kilometer (Hijmans, et al., 2005).

The maximum temperature, minimum temperature, and precipitation data for each month were used by the WorldClim developers to generate 19 bioclimatic variable rasters for ecological niche modeling (Table 1). The variables were created using the ArcInfo workstation script "bioclim" and made available on the WorldClim database website (WorldClim, 2005). Bioclimatic variables are a means of isolating and working with various aspects of temperature and precipitation patterns. They are important for biogeographical applications because they represent both average annual climatic conditions and extreme or limiting conditions, which may affect species distributions, adaptations, or behaviors in different ways.

Most of the variables are self-explanatory calculations of temperature and precipitation patterns either throughout the year or in certain parts of the year. Several involve calculations between other variables. Mean diurnal range (BIO02) is equal to the overall mean of monthly maximum temperatures minus monthly minimum temperatures, and represents the mean difference between daytime and nighttime temperatures. Temperature annual range (BIO07) is the maximum temperature of the warmest month (BIO05) minus the minimum temperature of the coldest month (BIO06). Isothermality (BIO03) is the mean diurnal range (BIO02) divided by the temperature annual range (BIO07). Temperature seasonality (BIO04) and precipitation seasonality (BIO15) are coefficients of variation for their respective climate factors.

Bioclimatic Variable	**Units**	**Abbreviation**
Annual Mean Temperature	°C	BIO01
Mean Diurnal Range	°C	BIO02
Isothermality	N/A	BIO03
Temperature Seasonality	N/A	BIO04
Maximum Temperature of Warmest Month	°C	BIO05
Minimum Temperature of Coldest Month	°C	BIO06
Temperature Annual Range	°C	BIO07
Mean Temperature of Wettest Quarter	°C	BIO08
Mean Temperature of Driest Quarter	°C	BIO09
Mean Temperature of Warmest Quarter	°C	BIO10
Mean Temperature of Coldest Quarter	°C	BIO11
Annual Precipitation	mm	BIO12
Precipitation of Wettest Month	mm	BIO13
Precipitation of Driest Month	mm	BIO14
Precipitation Seasonality	N/A	BIO15
Precipitation of Wettest Quarter	mm	BIO16
Precipitation of Driest Quarter	mm	BIO17
Precipitation of Warmest Quarter	mm	BIO18
Precipitation of Coldest Quarter	mm	BIO19

Table 1: Bioclimatic Variables (WorldClim, 2005)
Temperature variables are BIO01 through BIO11 and precipitation variables are BIO12 through BIO19. Quarters refer to periods of three months during which a particular climatic factor has an extreme value compared with the rest of the year.

Future climatic data were also acquired from the WorldClim Global Climate Data website (WorldClim, 2005). Only projected data for the years 2020, 2050, and 2080 were available, and 2050 and 2080 data were selected for this study. The rasters were in the form of the same 19 bioclimatic variables, each set to a resolution grid of 30 arc seconds.

A variety of climate modeling methods are used in the IPCC assessment reports. Each method produces a different average projection of climatic warming over this century (Figure 5). Data from the Hadley Centre Coupled Model Version 3 (HadCM3), Commonwealth Scientific and Industrial Research Organisation Model (CSIRO), and Canadian Centre for Climate Modelling and Analysis Model (CCCma) were available for use through the WorldClim database. Data from the National Center for Atmospheric Research Climate System Model (NCAR CSM) was available through the NCAR GIS database.

HadCM3 was selected for this study over other available modeling methods due to its comparatively average projection of global temperature rise and widespread usage among the scientific community. HadCM3 is a coupled atmosphere-ocean general circulation model developed by the Met Office Hadley Centre for Climate Change in the United Kingdom. The model was among those utilized for both the Third and Fourth Assessment reports of the Intergovernmental Panel on Climate Change (IPCC, 2007). HadCM3 output has a spatial resolution of 2.50° latitude by 3.75° longitude. This is interpolated to a resolution of 30 arc seconds using the aforementioned methods (Hijmans, et al., 2005).

Emissions scenarios are used by IPCC to describe different economic development and globalization situations as pertaining to greenhouse gas emissions and atmospheric concentrations (Figure 6). The A2 and B2 scenarios were available for each of the modeling methods in the WorldClim database. The A2 scenario family assumes increasing economic

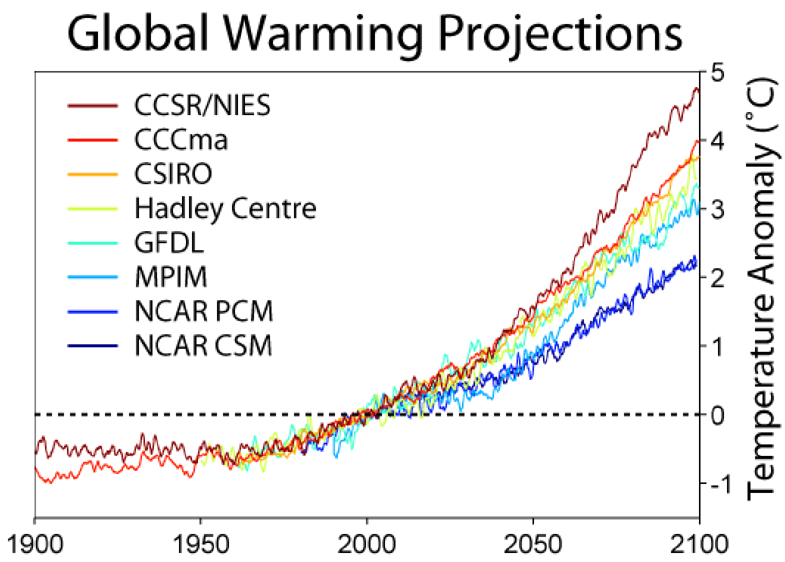


Figure 5: Global Warming Projections of Climate Modeling Methods (Rohde, 2006)
This graph shows a comparison between the global warming projections of eight major global climate models using the A2 emissions scenario. The Hadley Centre model (HadCM3) selected for this study is shown in light green.

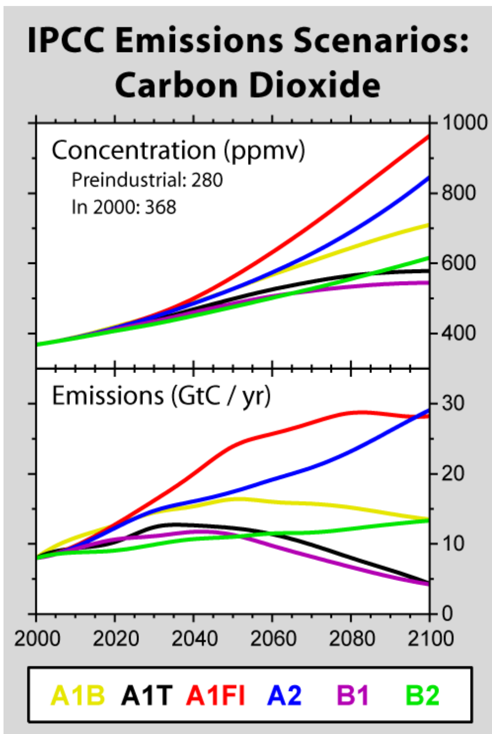


Figure 6: IPCC Carbon Dioxide Emissions Scenarios (Rohde, 2006)
The top graph shows projected atmospheric concentrations of carbon dioxide through 2100 among the various emissions scenarios. The bottom graph shows projected emissions of carbon dioxide through 2100. The A2 emissions scenario selected for this study is shown in blue. The B2 scenario shown in green was also available through the WorldClim database.

regionalization, increasing income disparities, and greater emphasis by governments on economic development than environmental protection, resulting in a relatively high continuance of carbon emissions growth (IPCC, 2000). The B2 scenario family also assumes increasing economic regionalization, but with a reduced emphasis on national economic development at the expense of the environment, resulting in reduced emissions growth (IPCC, 2000). The IPCC emissions scenario A2 was selected for this study over B2, due to its closer representation of a business-as-usual emissions situation.

An elevation raster with a resolution of 30 arc seconds was acquired from the WorldClim website. Although elevation is a static environmental variable in this study, it is an important factor in projecting migration constraints of the red spruce forest.

Model Configuration

Maxent 3.3.1 utilizes two groups of data inputs in order to project red spruce habitat suitability in 1988, 2050, and 2080 (Phillips, et al., 2006). The first group involves comma separated values files containing point coordinate information of species presence. There may be multiple species contained in a single file, or each species to be modeled may be represented by its own file. The second group involves ASCII raster grids which can describe either continuous or categorical environmental variables. Sets of environmental variable files must all have the same extent and resolution.

The polygon data in the 1988 red spruce distribution shapefile was converted to point data using the Create Random Points function of ArcGIS 9.3.1 (Figure 7). Points were created in a random spatial pattern at intervals of 10 meters within the bounds of the former polygons. This reflects an average spacing of mature red spruce trees. The conifer, mixed, and plantation categories were all included in the conversion in order to determine the favorable range of climatic conditions in which red spruce grows. Although the points do not accurately reflect the actual densities of red spruce in the field, the purpose was to distinguish regions of red spruce presence and absence to identify the ecological niche. There were 720,623 total points generated.

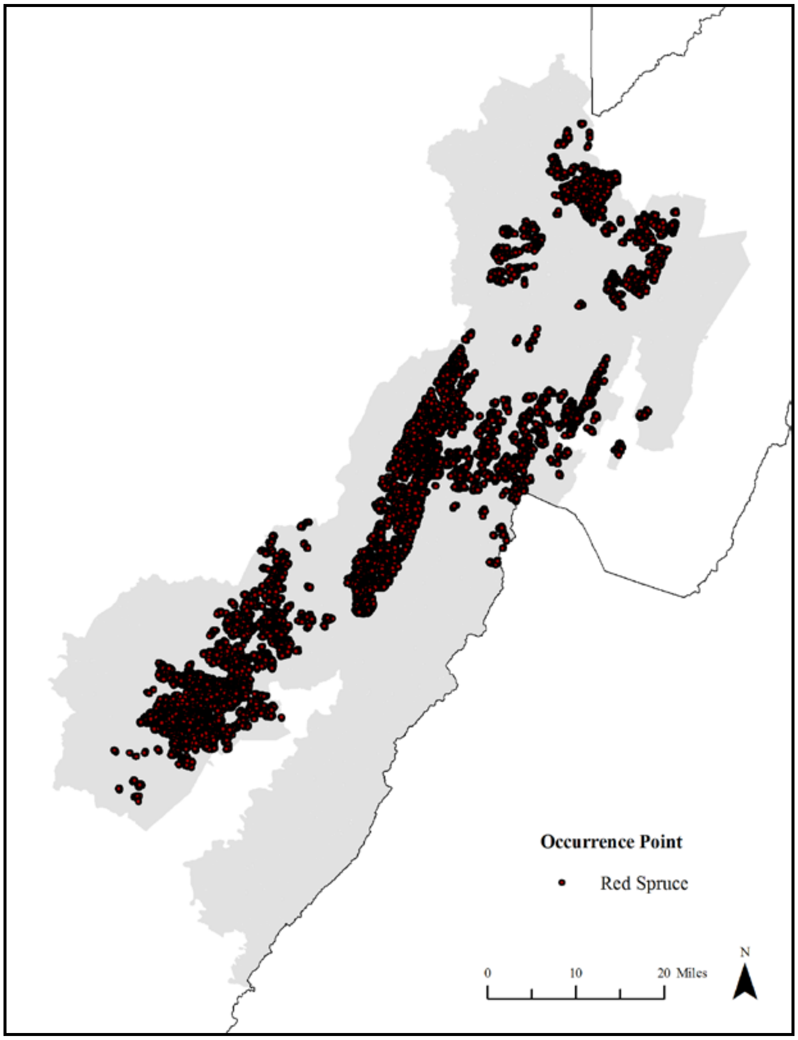


Figure 7: 1988 Red Spruce Habitat as Occurrence Points

The coordinate system of the shapefile was transformed from the original NAD83 UTM Zone 17N projected coordinate system to the WGS84 geographic coordinate system, via NAD83 to WGS84 Method 5. This was necessary as all of the climatic and elevation data files were in WGS84. The latitude and longitude coordinates of each point were then added to the shapefile's attribute table using the Add XY Coordinates function of ArcGIS. Finally, the shapefile was converted to a comma separated values file for input into Maxent.

All of the climatic rasters were cut from their global extent to a range around the outside of the National Forest boundary. The new latitude range was 37.5°N to 39.5°N and the new longitude range was 81.0°W to 79.0°W. These files were then loaded into Maxent as continuous environmental variables.

The elevation input raster is displayed below (Figure 8). On the following page, the annual mean temperature inputs (BIO 01) (Figure 9) and annual precipitation inputs (BIO12) (Figure 10) are displayed. The temperature and precipitation inputs are given the same respective scale to emphasize differences between 1961-1990 conditions and the 2050 and 2080 projections.

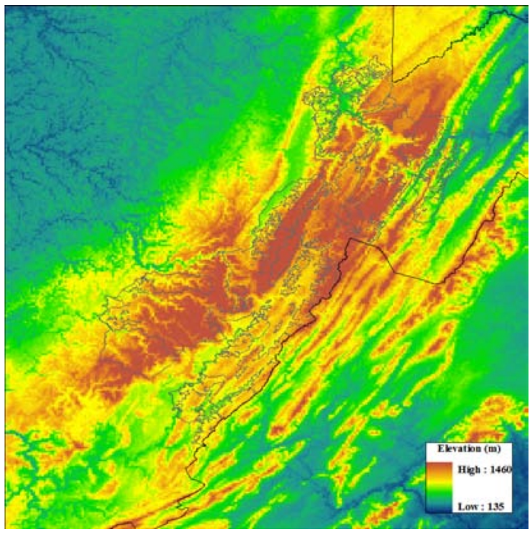


Figure 8: Elevation (WorldClim, 2005)

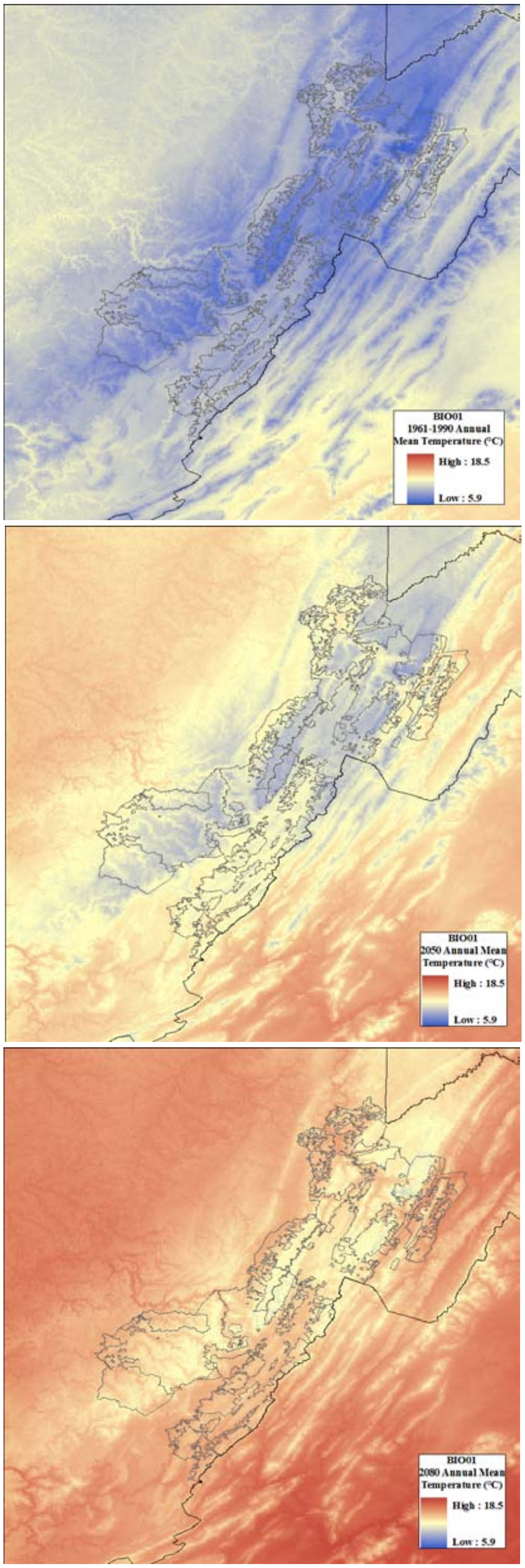


Figure 9: Annual Mean Temperature (WorldClim, 2005)
Map (a) is mean 1961-1990, (b) is 2050, and (c) is 2080.

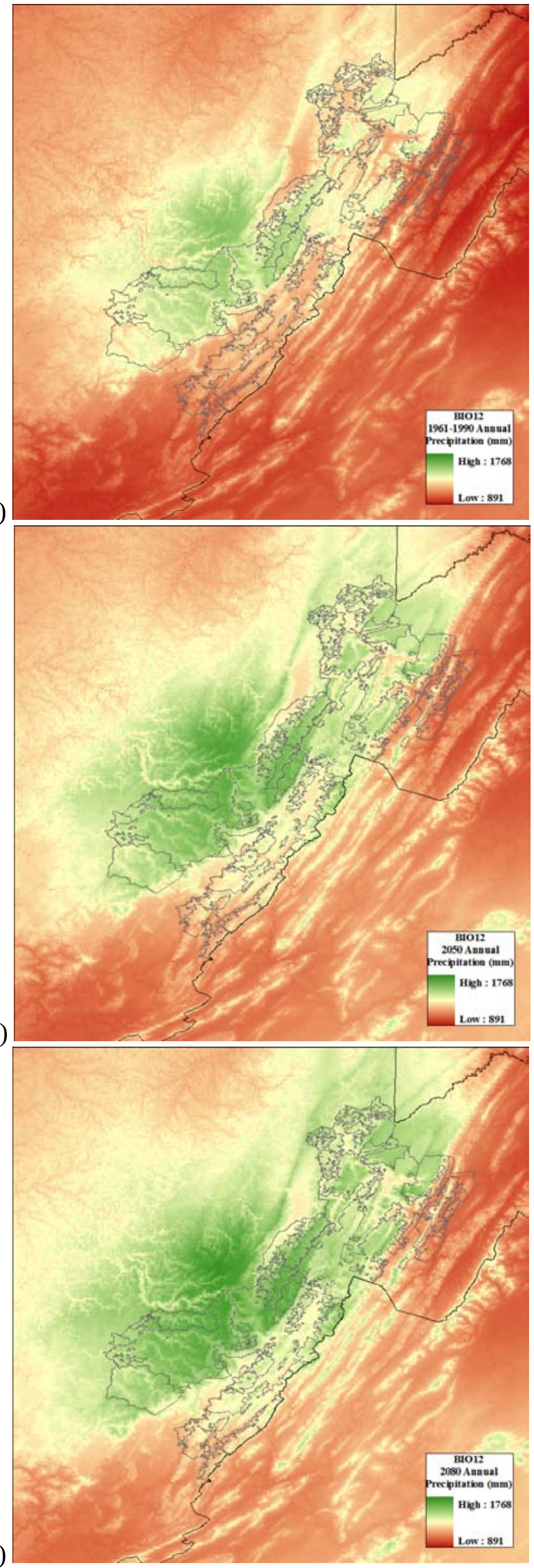


Figure 10: Annual Precipitation (WorldClim, 2005)
Map (a) is mean 1961-1990, (b) is 2050, and (c) is 2080.

According to the inputs, the 1961-1990 annual mean temperature within the raster extent is 5.9 degrees C to 13.6 degrees C. This becomes 8.6 degrees C to 16.3 degrees C in the 2050 projection, and 10.9 degrees C to 18.5 degrees C in the 2080 projection. The 1961-1900 annual precipitation within the raster extent is 89.1 cm to 159.1 cm. This becomes 97.3 cm to 171.1 cm in the 2050 projection, and 99.3 cm to 176.8 cm in the 2080 projection.

Most of the Maxent settings were kept with their default values, but several settings were adjusted for this study. The option to create response curves was enabled, which allowed the graphing of the spatial relationships between individual environmental variables and red spruce presence. The number of processor threads was set to 4, representing the number of central processor cores available for utilization when running the model. The number of random background points used in model training was adjusted from 10,000 to 50,000. Due to the very large number of species occurrence points, it was necessary to adjust this setting to attain a more accurate training of the model.

The output setting was kept in the default logistic format. In logistic output, cell values range between 0 and 1 on a scale of increasing probability of species presence, or relative suitability. Unlike the raw output, in which the sum of all cell values in the raster is 1, the logistic output scales up values in a non-linear fashion for improved comparison between the suitabilities of different areas.

Model Operation

An initial run was performed with the 1961-1990 climatic data to enable the model to evaluate the variables and map the 1988 habitat suitability for red spruce. Subsequent runs with the future climatic data projected habitat suitability for the years 2050 and 2080. An additional run for each year was performed in which the elevation files were left out of the environmental variable sets. The purpose of this was to allow the model to weight the significance of bioclimatic variables alone in influencing the red spruce distribution. The strong correlation between elevation and red spruce distribution at this relatively limited regional scale would diminish and skew the influences of climatic factors in the analysis.

The three output rasters, representing habitat suitability in the years 1988, 2050, and 2080, were cut to the extent of the Monongahela National Forest land area using the Extract by Mask feature of ArcGIS. This permitted more a focused comparison of the outputs.

Cell values between the maximum and median values in each raster represented the regions with the highest likelihood of habitat suitability. These sets of cells were extracted into three new rasters using the Extract by Attributes feature. The rasters were then layered with the later years on top to reveal the projected change in red spruce habitat suitability over time.

Each of the shapefiles and rasters appearing as images in this document were projected into WGS84 UTM Zone 17N to portray more realistic spatial relationships and usable scales.

Chapter Four: Results

Three output rasters were generated by the Maxent model. The first output (Figure 11a) is the result of model training between the 1961-1990 averaged climatic data and the 1988 red spruce occurrence data, with elevation data factored in. This is the 1988 red spruce habitat suitability according to the model.

The 1988 habitat suitability was layered with the species occurrence points for purposes of comparison (Figure 11b). While a visual correlation is strong as expected, there are a few areas of warmer color along ridge tops where red spruce is not presently found. This shows that the model is considering the environmental conditions at each locality represented by a grid cell, and not merely assigning all of the high suitability values to locations with existing red spruce growth. It is realistic that some areas favorable to red spruce growth may not have species presence, and that less favorable areas may have species presence.

The second output (Figure 11c) is the projection of red spruce habitat suitability for the year 2050. The third output (Figure 11d) is the projection for the year 2080. Colors are again assigned based on 20 equal interval classes for each respective raster, and cell values represent suitability relative to each other under the projected climatic conditions.

While cell values within each raster are scaled based on relative habitat suitability, and are able to be quantitatively compared with one another, values are not able to be quantitatively compared between separate projections. The values diminish exponentially as environmental variables move further from the training range of the model. However, the model takes this into account when assigning cell values.

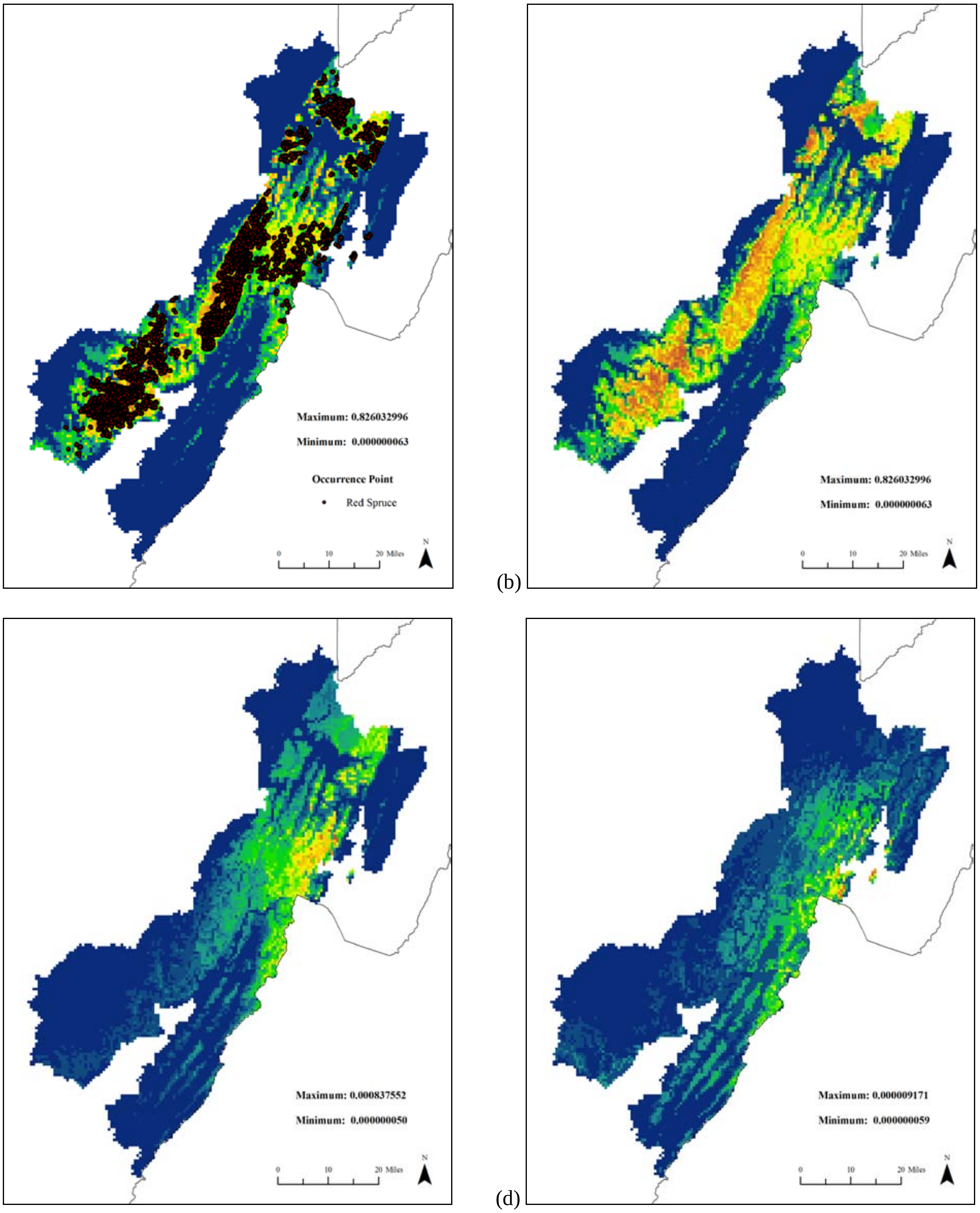


Figure 11: Modeled Red Spruce Habitat Suitability

These model outputs display (a) 1988 suitability layered with red spruce occurrence points, (b) 1988 suitability, (c) 2050 suitability, and (d) 2080 suitability. The maximum and minimum cell values in each output are given as well. Warmer colors represent areas where environmental conditions are most favorable to red spruce growth based on its 1988 distribution. Cooler colors represent areas where conditions are unfavorable to red spruce growth.

Areas with the highest habitat suitability for red spruce are represented by values between the maximum and the median value in each output. The vast majority of the 1988 species occurrence points coincide with cell values above this median threshold. When values in each output are scaled by equal intervals for display purposes, differences in the range and degree of habitat suitability for red spruce may be observed. As previously described, raster cells greater than or equal to the median threshold for each year were extracted (Figure 12). This revealed the projected change in red spruce habitat suitability over time, which will ultimately affect the actual species distribution.

The bioclimatic variable with the highest contribution in determining the red spruce ecological niche is the minimum temperature of the coldest month (BIO06) (Table 2). Other variables with significant contributions are maximum temperature of the warmest month (BIO05), mean temperature of the warmest quarter (BIO10), mean diurnal range (BIO02), and precipitation of the driest quarter (BIO17). The red spruce distribution is most strongly correlated with areas of cold annual temperature extremes as opposed to warm extremes, a minimized difference between daytime and nighttime temperatures, and a maximized amount of precipitation during the driest portion of the year.

The bioclimatic variable with the lowest contribution is precipitation of the wettest quarter (BIO16). Other variables with little contributions are precipitation of the driest month (BIO14), mean temperature of the wettest quarter (BIO08), isothermality (BIO03), and annual mean temperature (BIO01).

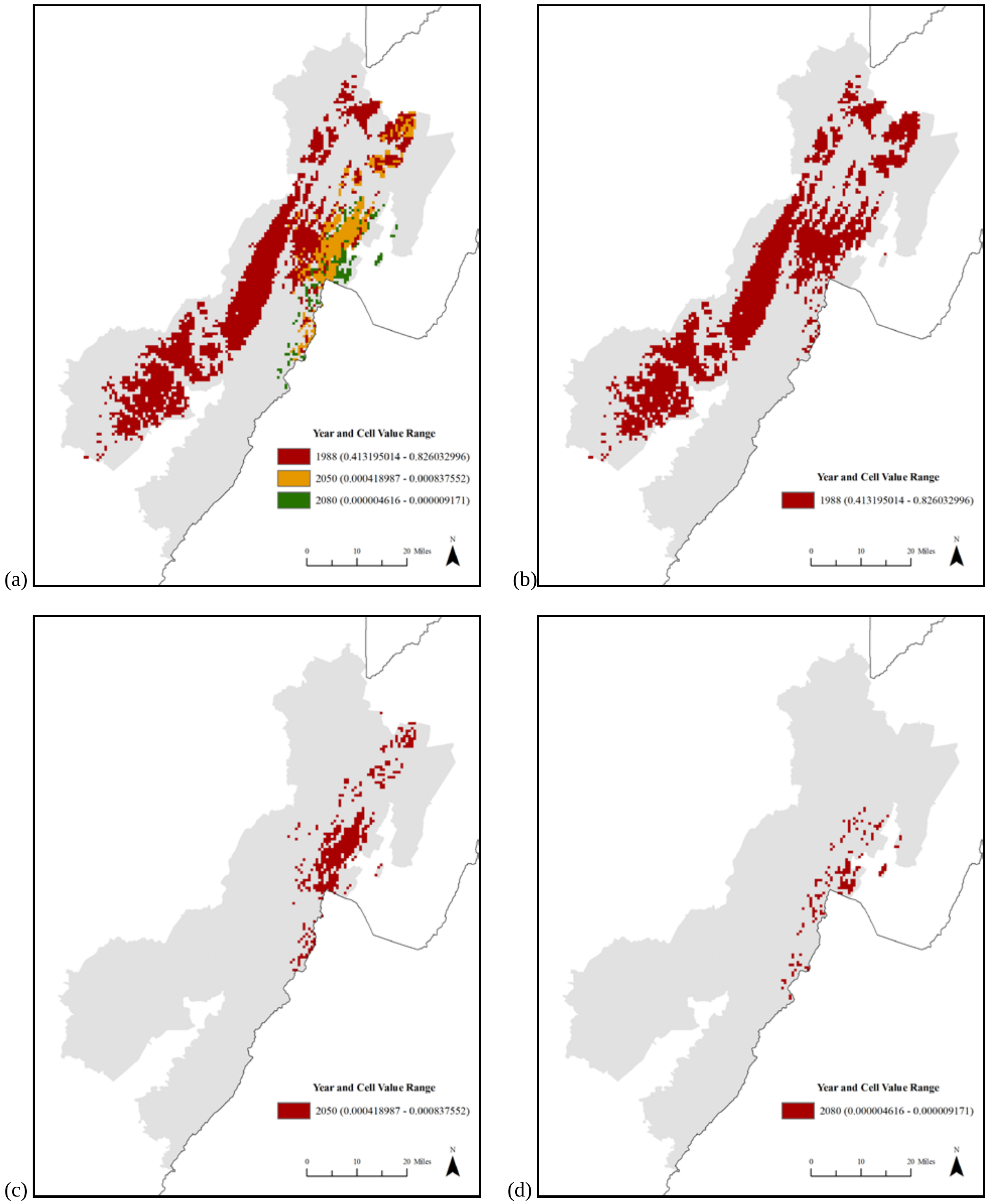


Figure 12: Extracted Red Spruce Habitat Suitability

These maps display all cells between the maximum and median values in each output, representing the locations with the most favorable habitat suitability under the projected climatic conditions. They show (a) habitat suitability change between 1988, 2050, and 2080, (b) 1988 suitability, (c) 2050 suitability, and (d) 2080 suitability.

Bioclimatic Variable	Contribution Percentage
Minimum Temperature of Coldest Month (BIO06)	43.5
Maximum Temperature of Warmest Month (BIO05)	22.3
Mean Temperature of Warmest Quarter (BIO10)	8.9
Mean Diurnal Range (BIO02)	7.9
Precipitation of Driest Quarter (BIO17)	6.9
Annual Precipitation (BIO12)	2.7
Precipitation of Coldest Quarter (BIO19)	1.3
Temperature Seasonality (BIO04)	1.2
Mean Temperature of Coldest Quarter (BIO11)	1.0
Temperature Annual Range (BIO07)	1.0
Precipitation of Wettest Month (BIO13)	0.8
Precipitation Seasonality (BIO15)	0.7
Precipitation of Warmest Quarter (BIO18)	0.6
Mean Temperature of Driest Quarter (BIO09)	0.4
Annual Mean Temperature (BIO01)	0.3
Isothermality (BIO03)	0.3
Mean Temperature of Wettest Quarter (BIO08)	0.2
Precipitation of Driest Month (BIO14)	0.1
Precipitation of Wettest Quarter (BIO16)	0.0

Table 2: Bioclimatic Variable Contribution Percentages
This output gives a ranked estimate of the relative contribution of each variable in determining the ecological niche of red spruce, along with the contribution percentage.

A set of 19 species response curves were also generated (Figures 13-15). This is a function of Maxent in which a separate species correlation model is run for each environmental variable in isolation. The graphs represent the probability of presence of red spruce as each variable is altered, and the range of the x-axis is determined by the value range of the input rasters. The graphs automatically take into account the effects of possible correlations between environmental variables, and dependencies of habitat suitability on these combinations. The response curves were used internally by the model to help project future habitat suitability.

The elevation graph reveals that red spruce probability of presence increases with increasing elevation (Figure 13). Figure 11a has a median cell value of 0.413, which corresponds to about 1,050 meters, or 3,445 feet, on the graph. This matches the ecotone data in the literature.

The graph for annual mean temperature (BIO01) shows that suitability changes little at colder temperatures, but quickly decreases as the mean temperature passes a certain threshold. This pattern is reflected in the other temperature variables graphs, signifying that red spruce favors colder temperatures and smaller annual temperature ranges (Figure 14).

The graph for annual precipitation (BIO12) shows that suitability is extremely low for over half of the precipitation values in the modeled extent. Suitability rises with increasing precipitation before trailing off at the highest values in the extent. This pattern is also reflected in the other graphs, signifying that red spruce favors areas with an abundance of precipitation (Figure 15). The graph for precipitation seasonality reveals that red spruce favors neither highly variable rates of precipitation nor periods of drought over the course of a year.

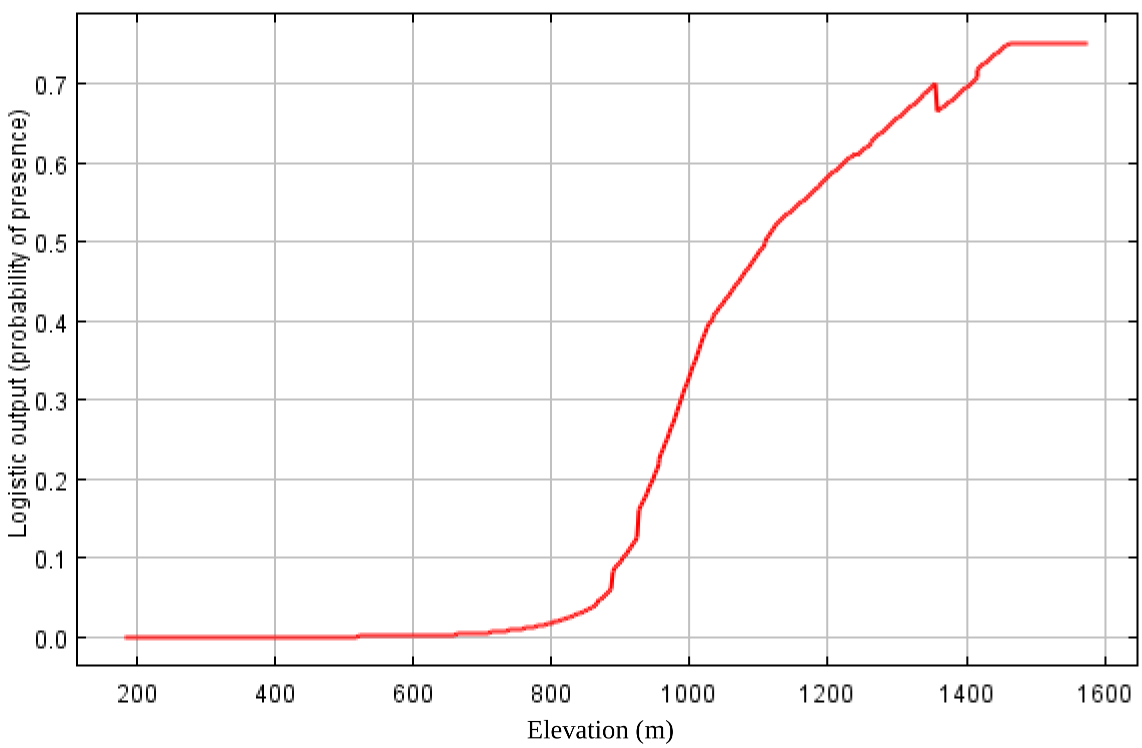
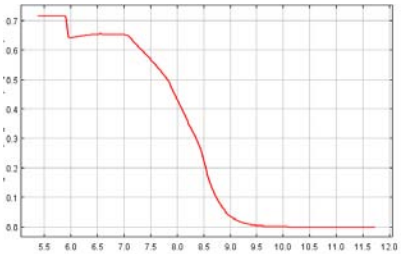
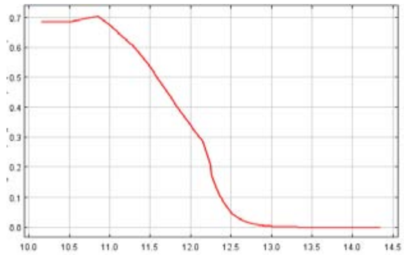


Figure 13: Red Spruce Response to Elevation
This graph displays the change in probability of red spruce presence, as measured by the logistic output values of the model along the y-axis, to changes in elevation along the x-axis.

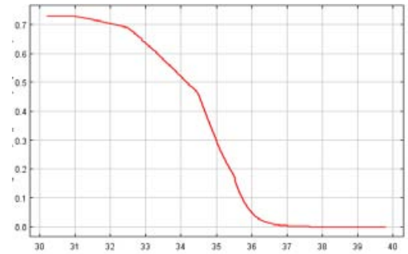
Figure 14: Red Spruce Response to Temperature Bioclimatic Variables
These graphs display the change in probability of red spruce presence, as measured by the logistic output values of the model along the y-axis, to changes in the temperature factors along the x-axis.



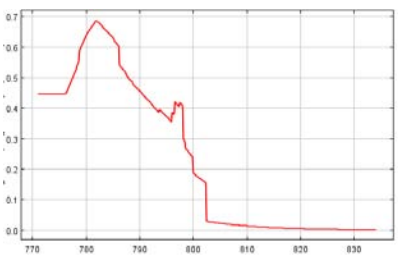
Annual Mean Temperature (°C)
BIO01



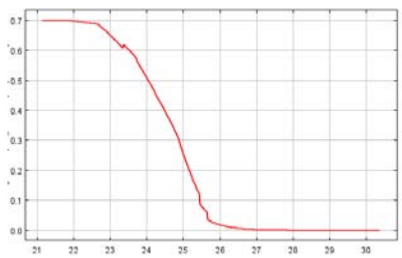
Mean Diurnal Range (°C)
BIO02



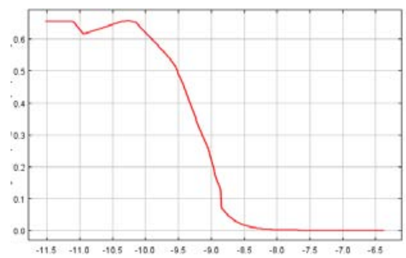
Isothermality
BIO03



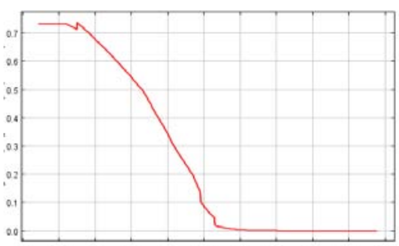
Temp. Seasonality (Coeff. of Variation)
BIO04



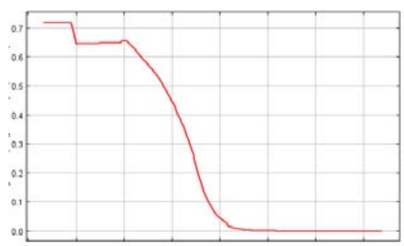
Max. Temp. of Warmest Month (°C)
BIO05



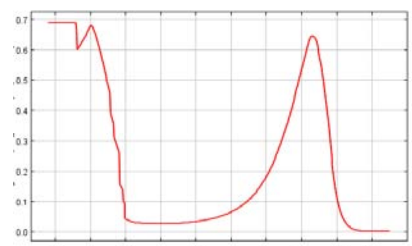
Min. Temp. of Coldest Month (°C)
BIO06



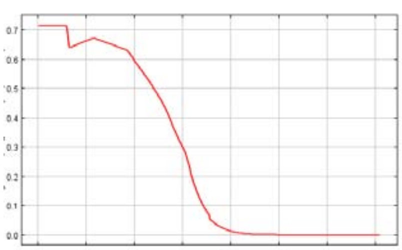
Temperature Annual Range (°C)
BIO07



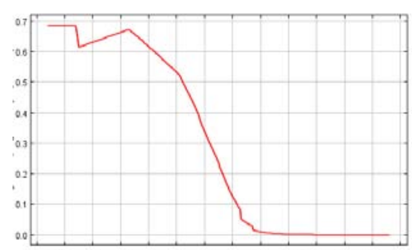
Mean Temp. of Wettest Quarter (°C)
BIO08



Mean Temp. of Dryest Quarter (°C)
BIO09

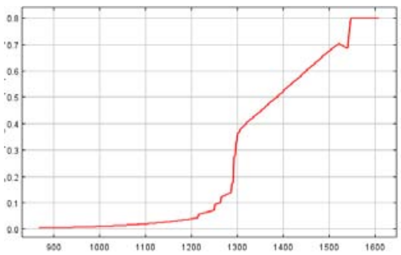


Mean Temp. of Warmest Quarter (°C)
BIO10

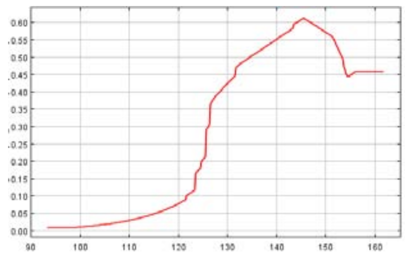


Mean Temp. of Coldest Quarter (°C)
BIO11

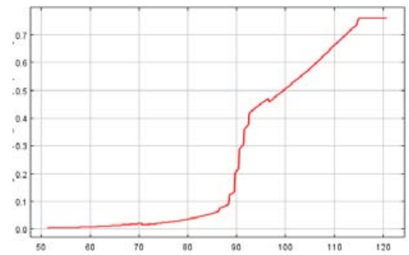
Figure 15: Red Spruce Response to Precipitation Bioclimatic Variables
These graphs display the change in probability of red spruce presence, as measured by the logistic output values of the model along the y-axis, to changes in the precipitation factors along the x-axis.



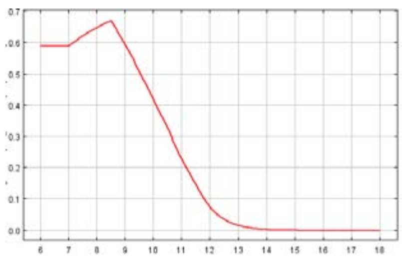
Annual Precipitation (mm)
BIO12



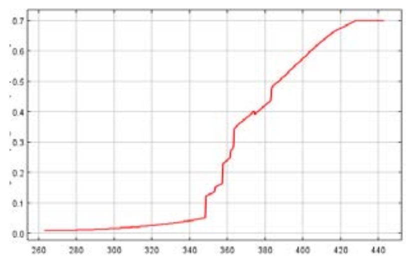
Prec. of Wettest Month (mm)
BIO13



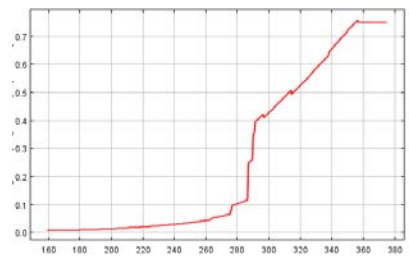
Prec. of Driest Month (mm)
BIO14



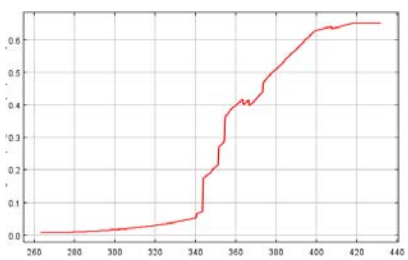
Prec. Seasonality (Coeff. of Variation)
BIO15



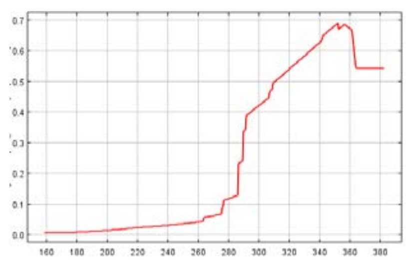
Prec. of Wettest Quarter (mm)
BIO16



Prec. of Driest Quarter (mm)
BIO17



Prec. of Warmest Quarter (mm)
BIO18



Prec. of Coldest Quarter (mm)
BIO19

Chapter Five: Discussion

The outputs generated by the Maxent model, based on the chosen climatological inputs and design of the study, reveal a very noticeable diminishing of red spruce habitat suitability in most areas of the Monongahela National Forest due to climatic change (Figures 11 and 12). Maps for location reference are provided on the following page (Figures 16 and 17).

The diminishing trend begins most strongly in the vicinity of Cranberry Wilderness in the southwestern corner of the Forest. This is the most vulnerable region to red spruce decline at present. The most significant climatic factors that explain red spruce distribution are maximum temperature of the warmest month, mean temperature of the warmest quarter, and annual mean temperature. Regional mean temperature rises and greater temperature extremes at this southern location may put significant stresses on the red spruce community. Enhanced evaporation rates and increasingly uneven annual precipitation rates could create soil water shortages, and the species is particularly sensitive to dry conditions and variable precipitation. Upslope invasion by grasses, shrubs, and trees favoring warmer temperatures could occur the soonest in this area. Given a relatively slow rate of conifer migration, the warming and drying could begin to induce a mass mortality in place by the end of the century.

Effects on habitat suitability are not as pronounced further northeast in 2050, and are unaffected in the ridge and valley area of the central east. Climatic conditions in the regions of Spruce Knob, Seneca Rocks, and Laurel Fork Wilderness remain within the suitability envelope of the species. The Dolly Sods Wilderness maintains its suitability, but the model reveals indications of increasing red spruce stress in Otter Creek Wilderness and Canaan Valley.

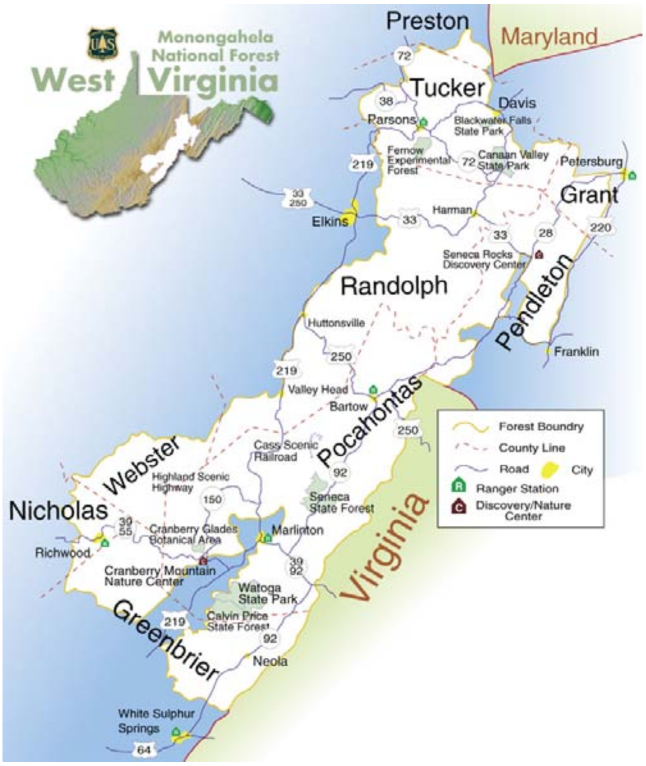


Figure 16: County Map of Monongahela National Forest (United States Forest Service, n.d.)

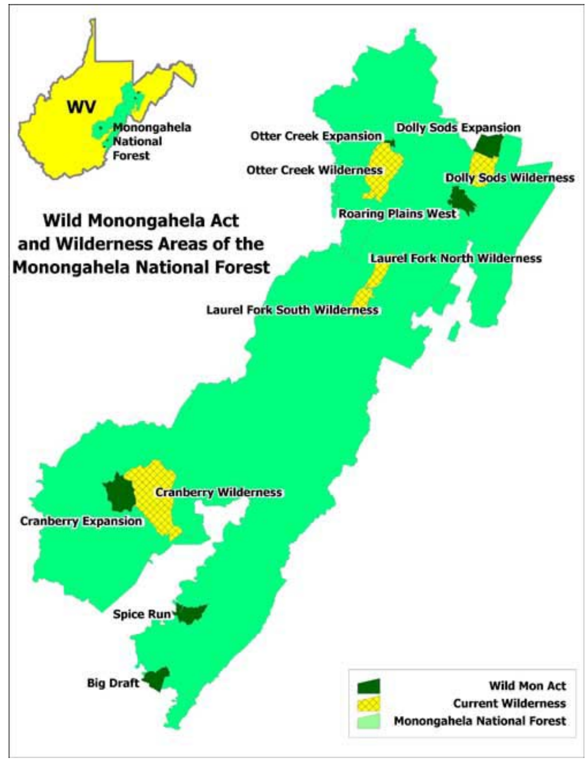


Figure 17: Wilderness Areas of Monongahela National Forest (West Virginia Highlands Voice, 2009)

By the year 2080, nearly all of the red spruce forests are projected to be under significant stress, particularly those in the southwest, central, and northwest parts of the National Forest. The exception is on the top of ridges along the border between Randolph and Pendleton Counties and extending into the far north of Pocahontas County. These are the only areas that are projected to maintain habitat suitability.

Surprisingly, habitat suitability appears to shift eastward across the National Forest area rather than solely northward. The red spruce forest is somewhat constrained to the north by decreasing elevations, and therefore warmer temperatures. It appears that a combination of warming temperature and increasingly variable precipitation factors in the western side of the National Forest greatly reduce suitability while factors are stable or even enhanced in the eastern side. One theory is that precipitation increases in this area, while the high elevations help to serve as a temporary buffer against temperature spikes at the lower elevations. Red spruce in this area could have a longer period of time in which to migrate or otherwise adapt to changing conditions.

Based on the habitat suitability change maps (Figure 12), red spruce conservation efforts will remain critically important in the border region between Randolph and Pendleton Counties and extending north to Dolly Sods Wilderness. As red spruce forests in other regions are projected to be under significant stress and experiencing decline, spruce plantings and efforts to promote animal biodiversity here should be prioritized. At the same time, planting new species of trees in areas of mass spruce mortality may be essential in maintaining forest integrity, offsetting wildfire susceptibility, and avoiding large-scale soil erosion issues. The addition of new federally owned acreage to the National Forest is another potentially important course of action in the effort to sustain regional biodiversity.

The only notable limitation of this study involves a degree of uncertainty in the actual distribution change of red spruce. While the model performs a complex analysis on all environmental inputs, variable migration rates and highly localized ecosystem interactions could affect the distribution in ways the model cannot presently predict. Soil typology and thickness along with microclimates could play small roles. The model is also based on a particular emissions scenario and general circulation model, and their internal structures and outputs may change with time and subsequent IPCC assessment reports. The actual responses of red spruce and its broader ecosystem to climatic change must continue to be monitored for additional data.

The Maxent modeling method and inputs selected for this study are some of the best available for making estimations of future ecological conditions. As modeling methods and our understanding of climatological processes continue to improve, they will be met with an increasing need for biodiversity conservation planning and practices due to global and regional climatic changes. The red spruce forest of Monongahela National Forest is a natural treasure worth preserving.

Bibliography

Elith, J., Graham, C. H., Anderson, R. P., Dudik, M., Ferrier, S., Guisan, A., Hijmans, R. J., Huettmann, F., Leathwick, J. R., Lehmann, A., Li, J., Lohmann, L. G., Loiselle, B. A., Manion, G., Moritz, C., Nakamura, M., Nakazawa, Y., Overton, J. McC., Peterson, A. T., Phillips, S. J., Richardson, K. S., Scachetti-Pereira, R., Schapire, R. E., Soberon, J., Williams, S., Wisz, M. S., & Zimmermann, N. E. (2006). Novel methods improve prediction of species' distributions from occurrence data. *Ecography*, 29, 129-151.

Gomez-Mendoza, L., & Arriaga, L. (2007). Modeling the effect of climate change on the distribution of oak and pine species of Mexico. *Conservation Biology*, 21 (6), 1545-1555.

Hannah, L., Midgley, G. F., & Millar, D. (2002). Climate change-integrated conservation strategies. *Global Ecology and Biogeography*, 11, 485-495.

Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G., & Jarvis, A. (2005). Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology*, 25, 1965-1978.

Holt, R. D. (1990). The microevolutionary consequences of climate change. *Trends in Ecology and Evolution*, 5.

Intergovernmental Panel on Climate Change (IPCC). (2000). *Special report on emissions scenarios: A special report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom.

Intergovernmental Panel on Climate Change (IPCC). (2007). *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom.

Kelly, A. E., & Goulden, M. L. (2008). Rapid shifts in plant distribution with recent climate change. *Proceedings of the National Academy of Sciences of the United States of America*, 105 (33), 11823-11826.

McKenney, D. W., Pedlar, J. H., Lawrence, K., Campbell, K., & Hutchinson, M. F. (2007). Beyond traditional hardiness zones: Using climate envelopes to map plant range limits. *Bioscience*, 57 (11), 929-937.

McLaughlin, S. B., Joslin, J. D., Robarge, W., Stone, A., Wimmer R., & Wullschleger, S. D. (1998). The impacts of acidic deposition and global change on high elevation southern Appalachian spruce-fir forests. *Ecological Studies*, 128, 255-277.

Meadows, M. E., & Hill, T. R. (2002). Issues in biogeography: Diversity in theory and practice. *South African Geographical Journal*, 84 (1), 116.

Mueller, R. F. (1992). The Monongahela National Forest. *Wild Earth*, 2 (3), 56-60.

Musser, K. (2009). *Location of Monongahela National Forest*. [Online Image]. Retrieved October 25, 2009 from http://en.wikipedia.org/wiki/Monongahela_National_Forest

Natural Resources Conservation Service. (2004). *The PLANTS Database: Red Spruce*. Retrieved November 20, 2009 from http://plants.usda.gov/

Parmesan, C. (1996). Climate and species' range. *Nature*, 382, 765-766.

Peterson, A. T., Tian, H., Martinez-Meyer, E., Soberon, J., Sanchez-Cordero, V., & Huntley, B. (2005). Modeling distributional shifts of individual species and biomes. *Climate Change and Biodiversity*, ed. Lovejoy, T. E., & Hannah, L. New Haven: Yale University Press.

Petit, R. J., Hu, F. S., & Dick, C. W. (2008). Forests of the past: A window to future changes. *Science*, 320 (5882), 1450-1452.

Phillips, S. J., Anderson, R. P., & Schapire, R. E. (2006). Maximum entropy modeling of species geographic distributions. *Ecological Modeling*, 190 (3-4), 231-259.

Phillips, S. J., & Dudik, M. (2008). Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. *Ecography*, 31, 161-175.

Rohde, R. A. (2006). *Carbon Dioxide Emissions Scenarios*. [Online Image]. Based on IPCC data. Retrieved October 25, 2009 from http://www.globalwarmingart.com/

Rohde, R. A. (2006). *Global Warming Projections*. [Online Image]. Based on IPCC data. Retrieved October 25, 2009 from http://www.globalwarmingart.com/

Thomas, C. D., & Lennon, J. J. (1999). Birds extend their ranges northwards. *Nature*, 399, 213.

United States Forest Service. (1988). *1988 Red Spruce Habitat*. [GIS Data].

United States Forest Service (2008). *Monongahela National Forest: About The Forest*. Retrieved November 18, 2008 from http://www.fs.fed.us/r9/mnf/

United States Forest Service (n.d.). *Monongahela National Forest Map*. [Online Image]. Retrieved November 18, 2008 from http://www.fs.fed.us/r9/mnf/

United States Forest Service. (2009). *Surface Ownership Distribution of Monongahela National Forest*. [GIS Data].

United States Geological Survey. (1999). *Red Spruce Distribution*. [Online Image]. Retrieved November 12, 2009 from http://www.conifers.org/pi/pic/rubens1.gif

Turner, II, B. L., Lambin, E. F., & Reenberg, A. (2007). The emergence of land change science for global environmental change and sustainability. *Proceedings of the National Academy of Sciences of the United States of America*, 104 (52), 20666-20671.

West Virginia Highlands Voice. (2009). *Wild Monongahela Act and Wilderness Areas of the Monongahela National Forest*. [Online Image]. Retrieved November 20, 2009 from http://wvhighlands.org/wv_voice/?m=200903

White, P. S., & Cogbill, C. V. (1992). Spruce-fir forests of eastern North America. *Ecological Studies*, 96, 3-39.

WorldClim. (2005). *WorldClim Global Climate Data*. [GIS Data]. Museum of Vertebrate Zoology, University of California at Berkeley. Retrieved from http://www.worldclim.org/