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The purpose of this research was to relate the influence of site suitability variables to Eastern monarch butterfly migratory patterns and behavior. Weather, land use, and physical geography layers were input into a site suitability model using geographic information systems (GIS) to compare geocoded butterfly locations with site specific conditions. Elevation, temperature, precipitation, and land use data layers were overlaid to collectively consider how these variables affected the way that butterflies migrated, recolonized, and overwintered during the 2016/2017 migratory cycle. The variables were collected as individual raster layers which were reclassified into layers ranking suitability as either bad, good, or great with respective scores of one, three, or five. Map overlay methods were used to create a model weighting the variables equally, with a second model that individually weighted the variables allowing for variations in influence. The results of this study indicated that site suitability was a large driving factor for migratory monarchs with a heavier emphasis placed on average temperature and land/cropland use. Possible displaced and sink populations were identified for further study, while the effects of agriculture and climate change were considered regarding flyway connectivity and behavior.

THE DIRECT AND INDIRECT EFFECTS OF SITE SUITABILITY

ON EASTERN MONARCH BUTTERFLY

MIGRATORY POPULATIONS

by

Karen Keller Kesler

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TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER I

INTRODUCTION

In the words of Nathaniel Hawthorne, "Happiness is like a butterfly which, when pursued is always beyond your grasp, but which, if you sit down quietly, it may alight upon you" (Edwards, 1891, p. 215). For centuries artists, poets, writers, and scientists have admired butterflies for their beauty and fragility; however, no species has captured their imagination quite like the monarch butterfly. With their distinct orange and black coloration, monarch butterflies (*Danaus plexippus*) are one of the most recognizable members of the butterfly order Lepidoptera, which also includes members of the moth family. While there are several species of butterflies that have migratory patterns, monarch butterflies migrate over 3000 miles from their overwinter sites in the mountains of Mexico to their summer breeding grounds in the northern United States and southern Canada. As temperatures begin to fall and daylight hours yield to longer nights, the butterflies repeat the 3000-mile journey home to the Sierra Madre Oriental Mountains in Mexico (Journey North, n.d.).

Their migration has been observed for centuries and has great cultural and regional importance for the local people along the migration route and at the overwinter sites. Native Americans believe that the butterflies returning to Mexico are the souls of their deceased loved ones returning to Earth to walk among the living during the Día de los Muertos, or Day of the Dead, celebration. This spiritual holiday has ancient roots that link the festival to the indigenous people that inhabited the area in 1800 B.C, which hint at the longevity of the Eastern monarch migration (Baumle, 2017). In the past, other groups have nicknamed monarchs “harvester butterflies” as their arrival signaled that the time had arrived to harvest several crops and to prepare for winter (Goldman, 2008).

With critical years becoming more frequent, scientists and conservationists are working diligently to identify and remediate some of the challenges encountered by migrating and overwintering monarchs. However, this has proven to be a complicated matter. Two of the difficulties encountered while studying migratory flyways are the facts that insects have short life spans and can have erratic flight paths (Max-Planck-Gesellschaft, 2009). There is also concern for physical harm that could occur when attaching sensors or identifiers to the butterflies. This is further challenged by the small size of the butterflies who weigh roughly 0.5 g, or 1/5 the weight of a penny (Baumle, 2017). Due to their small mass, radio tracking is not possible at this point in time, and it is unknown what effects the signal and added weight could have on the butterfly’s internal navigation system and flight ability (Cant et al., 2005)

Despite the aforementioned challenges, there have been some advances that have significantly aided and changed how scientists study monarchs. With the advent of Citizen Scientist data collection, butterfly sightings have been tracked and given coordinates and attributes that make their general movement and numbers easier to visualize (Prysby & Oberhauser, 2015; Davis & Howard, 2005). Now that a large scale dataset is available with temporal and geographic attributes attached, scientists can easily identify where the butterflies are, as well as consider where they have been, and make predictions as to where they are going. Furthermore, if scientists know where the butterflies are at a certain temporal intersection, then it is also possible to study the conditions that exist around them. However, as with most biological phenomenon, individual factors do not work in isolation. The ecological factors are intertwined with the physical factors, and the anthropogenic factors affect both the ecological and physical outcomes. Isolating these factors is impossible, but there is value in understanding their interconnectedness as well as how they affect the butterflies.

This study investigated the relationship between monarch butterfly migratory patterns as they related both directly and indirectly to physical, land use, and environmental factors. While butterfly behavior is rooted in biology and animal behavior studies, migratory behavior has a distinct geographical element. With the availability of historic temperature and precipitation readings, land use and crop data, soil profiles, and elevation measurements, it was possible to develop a geographic model using these variables that could begin to delineate optimal site conditions. With monarch populations declining at a rapid and unstable rate, conservation efforts will need to be targeted. This research has merit not only in locating the optimal areas for the Eastern monarch butterflies, but there is also value in locating the uninhabitable areas. Focusing on fractured flyways will better serve the efforts to improve recolonization rates as well as improve population numbers that reach the summer breeding grounds and overwinter sites. Inversely, having the knowledge of areas that are not suitable could save funding and manpower that would be better utilized elsewhere. Another wildcard factor to consider is that climate change and anthropogenic activities could be of further detriment to monarchs and other pollinators.

With all of the obstacles that migratory species face in a changing environment, there is still reasonable hope that the negative effects can be curbed. Unlike some conservation efforts where the only way that citizens can become involved is to donate money used solely for litigation and lobbying for governmental protections, monarch butterfly conservation has a more tangible means of involvement. Planting indigenous milkweed, avoiding herbicides and pesticides in lawncare and landscaping, and planting nectar producing plants can greatly aid in the healing of fractured flyways. Grassroots organizations such as local garden clubs, educational groups, and wildlife conservation associations can inexpensively improve areas where conservation is needed (Baumle, 2017). However, time is of the essence. Despite a recent surge in overwinter population numbers, monarch butterflies and other pollinators are still struggling to maintain healthy numbers. The goal of this research was to further investigate factors that are known contributors to monarch site suitability in an effort to better understand how specific factors are driving migrations. With this understanding, scientists, conservationists, and citizens alike can educate themselves and focus efforts that could ultimately result in a resurgence of the once plentiful Eastern monarch butterfly.

CHAPTER II

BUTTERFLY BIOLOGY, ECOLOGY, AND LITERATURE REVIEW

2.1 Butterfly Biology and Life Cycle

Most students receive their introduction to butterfly biology in their primary school years. Topics such as metamorphosis and mimicry are frequently discussed when we try to understand some of nature's anomalies. However, monarch butterflies have even more peculiarities than just metamorphosis and mimicry. To better understand the migration, we must first consider the butterfly life cycle and biological factors that shape it.

Butterfly life cycles are unique in that they transition from larva to pupa and emerge as fully mature adult butterflies (Figure 2.1). The four stages of the life cycle are divided based on their physical form: egg, larva, pupa, and butterfly. During the first stage, the butterfly larva exists inside a small egg that is similar in size to a grain of salt (Baumle, 2017). Eggs are usually attached directly to the undersides of the leaves of a milkweed plant so that the newly hatched larva will have an immediate food source. Monarchs spend an average of four days developing inside the egg before emerging as a small white, translucent larva with a black head (Journey North, n.d; .Oberhauser, 2004).

Figure 2.1. Four Stages of the Butterfly Life Cycle. (Retrieved from monarchs-and-milkweed.com)

As soon as the larva emerges, it will consume the remains of the egg and embark on a two-week stage that will increase its size and prepare for the final metamorphosis. The larva, or caterpillar, will spend the next 9-14 days ingesting milkweed, growing, and molting four times until it has grown to approximately 2000-3000 times its initial larval body mass (Baumle, 2017; Oberhauser, 2004; North Carolina Wildlife Federation [NCWF], n.d.). Once the larva is ready to transform into a chrysalis, it will cease milkweed consumption and prepare for the fifth and final molt. When the larva finds a suitable location, it will create a sticky, silk adhesive that will attach the larva to its surface so that it can hang inverted beneath it. Prior to molting, larva will hang in a “J” shaped formation aptly referred to as “J-ing”, which can last for up to 24-hours. While J-ing, the larva prepares its internal organs for the next stage in the life cycle. When the larva finally pupates, the outer layer of skin molts revealing the chrysalis (Baumle, 2017; Oberhauser, 2004). The pupa will develop inside the chrysalis for 9-15 days until it emerges as a fully developed adult butterfly. Adult butterflies can live for two to five weeks in the only stage of the butterfly life cycle that has true mobility (Journey North, n.d.). As adult butterflies, monarchs rely on nectar for energy and resources while remaining close to milkweed to deposit the eggs for the next generation (United States Department of Agriculture [USDA], n.d.).

While most life cycles have some variability, butterflies in particular seem to vary the amount of time spent at each developmental stage as an extension of temperature. Warmer temperatures tend to speed the process up at every stage, while cooler temperatures can substantially slow it down (Harvey et al., 2015; Solensky 2004). Years that have unusual temperatures can encourage fast monarch maturity sometimes resulting in a "bonus" fifth generation (Trezza, 2018), or it could theoretically slow it down and truncate the number of generations that monarchs have to migrate and breed, which could have a negative impact on recolonization numbers (Davis & Howard, 2005).

2.2 Migration Biology and Ecology

While only 1/3 of the monarch's life is spent as a butterfly, it is in this stage that all migratory activities occur. The migration and summer breeding season typically lasts from early March to late October with the number of butterflies proliferating through an average of four-generations (Journey North, n.d.). While many insects have migrations and predictable movement patterns, monarchs travel approximately 3000 miles north from the Sierra Madre Oriental Mountains to the Great Lakes and Midwest regions of the United States and southern Canada. They spend their summer months completing breeding and recolonization activities until they receive an internal, biological trigger signaling that it is time to return to the overwinter sites in Mexico (Harvey et al., 2015).

The biological trigger is not yet fully understood; however, scientists believe that it prompts the butterflies to cease all breeding activity as a means to conserve resources and energy for the southern migration and subsequent overwintering (Solensky, 2004). In a sometimes-large mass exodus (Journey North, n.d.), the butterflies leave the northern breeding grounds and begin a race against falling temperatures back to the overwinter sites where they will remain until temperatures begin to rise the following spring signaling the beginning of the next journey north.

The southern migration is different than the northern migration in several aspects. The first difference is that while it can take more than four consecutive generations of monarchs to reach the summer breeding grounds, a single butterfly makes the entire journey south, overwinters, and emerges laying the first eggs for the next migration (Davis & Howard, 2005). This generation of butterflies has a longer life expectancy which has earned it the nickname “The Methuselah Generation” (Baumle, 2017; United States Fisheries and Wildlife Service [USFWS], n.d.). The average monarch butterfly life expectancy is generally 40-60 days including all stages (or six-weeks on average); however, the last generation of each migration can live for up to seven months (Solensky, 2004).

A second difference between the migrations is that the butterflies migrating south tend to take a more easterly route back to Mexico. Northward migrating butterflies fly north out of Mexico and take a north to slightly northeastern route to the summer breeding grounds. The migration north is more concise, but it can be complicated by the generations entering and departing the migratory population. The southern migration occurs swiftly and somewhat incoherently with some individuals being left behind (Journey North, n.d.). The eastern route helps the butterflies conserve as much energy as possible by taking advantage of Atlantic Ocean breezes and ridge lift winds off of the Appalachian Mountains to preserve lipid stores that will be essential to their overwinter survival (Xerces Society, 2015). Another possible advantage is that temperatures can often be slightly warmer improving their energy efficiency as well as optimizing their ectothermic metabolism (Figure 2.2).

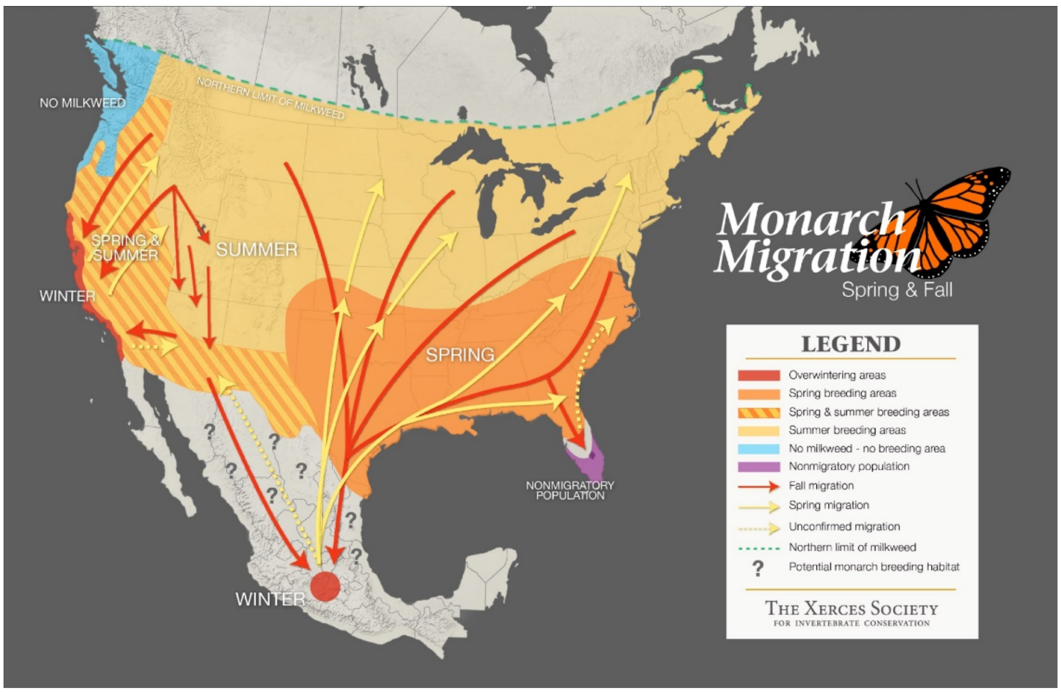


Figure 2.2. Northern and Southern Migration Routes. (Retrieved from xerces.org)

2.3 Milkweed and Monarch Butterflies

During the breeding and northern migratory generations, a female monarch will deposit an estimated 500-700 eggs to the undersides of milkweed leaves as the population slowly travels to the summer breeding grounds in the northern United States and southern Canada (Figure 2.3) (Wells, 2010). Depositing the eggs directly to the milkweed leaves is important because it provides the resulting larva with an immediate food supply (Oberhauser, 2004). Since the larvae will spend nearly 100% of their time-consuming milkweed, a plentiful supply is necessary to support the recolonization efforts of the annual northern migrations (Davis & Howard, 2005).

Figure 2.3. Tropical Milkweed. (Retrieved from www.dallasnews.com)

Milkweed plants (family Asclepias) are available in several species that are suitable for a variety of tropical and arid climates (United States Department of Agriculture [USDA], n.d.). One of the interesting aspects of all milkweed species is that the plant itself is toxic. While having no negative effect on the larva or adult butterflies, these toxins will later serve as a defense mechanism against natural predators during the larval and butterfly life stages (Journey North, n.d.). Predators are deterred from consuming monarchs and larva due to the bitter taste from the toxins passed on from the milkweed plants (Hoevenaar & Malcolm, 2004); however, the potency of the toxin fades over time making the older butterflies of the Methuselah Generation more vulnerable to predators in the latter life stages (Journey North, n.d.).

While once plentiful, recent anthropogenic activities have decreased the amount of milkweed available along the migration route. Genetically modified (GM) corn and soy crop practices have largely eradicated wild milkweed in the Midwest and Great Lakes Regions over large sections of agricultural land (Pleasants, 2015; Pleasants & Oberhauser, 2012). This loss has resulted in broken flyways from Mexico to the northern summer breeding grounds (Brower et al., 2012). Pesticides and lawn treatments further decrease residential milkweed populations creating more gaps in flyways with concerns that climate change will only exacerbate the issue (Lemoine, 2015). However, concerned citizens and conservationists are planting indigenous milkweed to improve flyway connectivity, while state and local agencies are promoting programs that designate personal, commercial, and community gardens as members of butterfly and pollinator highways. These programs work to educate their members on natural pesticides and proper pollinator garden care and design to encourage migrations and recolonization (North Carolina Wildlife Federation, n.d.).

2.4 Overwintering Sites and Challenges

While Eastern monarch migrations have been observed and recorded for hundreds of years, it was not until 1976 that scientists positively identified where the butterflies were overwintering. According to the US Forest Service, overwintering butterflies preferred the higher elevations of 2400-3600-meters where temperatures fall to between 32- 59º F. These moderately cool temperatures aid the butterflies in the state of diapause which allows them to decrease their metabolism and preserve bodily resources so that they may emerge in early March to begin the next year's journey north. Thousands of butterflies attach to oyamel fir (*Oyamel mexicano*), holm oak (*Quercus ilex*), and pine trees in clusters so dense that the branches typically bend under their weight (Figure 2.4) (Urquhart & Urquhart, 1976). A micro-habitat acts as an insulating shield further protecting the fragile butterflies during their overwinter stage (Solensky, 2014). In January of 1975, an expedition of scientists finally discovered the exact location of one of the eight main overwinter sites. Urquhart and Urquhart (1976) were part of an expedition the following year that revisited the site in the Mexican state of Michoacan. They (1976) noted that the monarchs covered every inch of the oyamel trees except for the highest part of the crown where winds would dislodge the inactive butterflies (Figure 2.5). They also noted that the butterflies were up to 10-cm thick in density in some places creating an impossible feat to actually count the number of butterflies present. (Urquhart & Urquhart, 1976).

Figure 2.4. Overwintering Monarchs. (Retrieved from goodnaure.nathab.com)

Figure 2.5. Aerial Image of Overwintering Monarchs. (Retrieved from jounreynorth.org)

Sadly, the sites today are very different than they were in 1975. Deforestation and general habitat destruction has destroyed much of the overwintering land cover leaving the butterflies with limited space and vegetation (Journey North, n.d.). In 2008 the United Nations Educational, Scientific, and Cultural Organization (UNESCO) extended support and protection for three known monarch overwinter sites. The Cerro Altamirano site, Chincua-Campanario-Chivati-Huacal site, and the Cerro Pe´lon site are currently under the protection and management of UNESCO agencies to ensure that the sanctuaries are secure and have limited access to protect the overwintering butterflies (United Nations Educational, Scientific, and Cultural Organization [UNESCO], n.d.).

2.5 Climate Change and Other Concerns

Concern over the effects that climate change could bring are far reaching and uncertain. Endemic populations of plants and animals are already disappearing in areas where their environment has changed more rapidly than they could adapt (WallisDeVries, 2007). Naturally, migration biologists are already asking questions regarding the impacts of changing temperatures, unpredictable weather, and extreme atmospheric events. With a new era of weather and climate, some scientists question if the entire migration phenomenon may be at risk of disappearing (Thogmartin et al., 2017; Brower et al., 2012).

Scientists are concerned that migratory monarchs may find themselves too far north without ample time to return to Mexico (Trezza, 2018). Delayed migrations have been reported as recently as November 2017 by Bud Ward with the *Yale Climate*

Connection. Ward's team sighted southbound monarchs in Cape May, New Jersey, as much as two weeks late (Ward, 2017). If the butterflies do not depart the summer breeding grounds soon enough due to warmer temperatures at higher latitudes, what would the effect be on overwinter populations (Vidal & Rendón-Salinas, 2014)? With butterfly populations already showing significant signs of distress (Zipkin et al., 2012), research and resources need to be focused to understand these outcomes as quickly as possible.

Another concern regarding temperature is that warmer temperatures could alter general weather patterns as well as butterfly life cycles. As mentioned previously, warmer temperatures can shorten life stages, while cooler temperatures can extend them. Whether there are bonus generations due to faster butterfly development or fewer generations due to slowed development, the effects could have serious implications to recolonization numbers. Severe atmospheric events could also be problematic despite high population numbers. In 2002 an unprecedented winter storm struck the overwinter sites at Sierra Chincua and El Rosario. Brower et al. (2004) believed that that single event was responsible for the loss of 74% of the butterflies at Sierra Chincua Sanctuary and 80% of the butterflies at the El Rosario Sanctuary. These two sanctuaries are two of the largest known monarch overwinter sites and are believed to house 2/3 of the overwintering Eastern monarch butterfly population (Journey North, n.d.). With severe storms possibly becoming stronger and more destructive due to climate change, events such as the 2002 storm could have devastating effects on butterfly colonies that may already be suffering from lower numbers (Knutson, 2010).

Other concerns from climate change range from milkweed distribution changes, too much precipitation, drought, and the loss of the biological trigger signaling for the monarchs to return to Mexico. Monarch sink populations are becoming a concern in South Florida (Harvey et al., 2015) and along the South Carolina coast (Peterson, 2019) where it is believed that the populations have lost the desire to migrate and are remaining in the same location and breeding year-round.

2.6 Non-Migratory Populations

When considering why butterflies migrate the way that they do, it is important to consider the inverse. If a monarch's natural behavior is to migrate, what does it mean when they stop migrating? Florida has presented itself as an anomaly with regard to the migrating population with new reports of similar populations on the South Carolina coast. Some scientists believe that monarchs are possibly migrating to southern Florida as opposed to Mexico (Satterfield, Maerz, & Altizer, 2015); however, the population in Florida does not appear to leave. Due to tropical temperatures, plenty of moisture, and milkweed that grows year round, the Florida monarch population has ceased migratory behavior and been designated a "sink" population (Harvey et. al., 2015).

Another important question regarding climate change is that if higher latitudes were to experience warmer temperatures, would this create more sink populations? Scientists are in the early stages of investigating the Florida population and are questioning whether or not these butterflies may eventually become a new sub-species of monarchs (McClung, 2007). With an ample supply of year round milkweed coupled with favorable temperatures, the Florida population is exhibiting signs that they are also breeding year round (Harvey et al., 2015). Aside from the concern that non-migratory behavior is not natural, the problems are more complex than a group of butterflies who never leave. Some studies have identified a protozoan parasite that has infested the Florida milkweed which is ingested by the monarch during the larval stage (Wells 2010; Altizer, Oberhauser, & Brower, 2000). Milkweed is a cyclical plant that experiences a dieback when the number of daylight hours decreases and temperatures decline. The dieback acts as a reset for the plant with new stands growing at the advent of the new growing season. Since milkweed grows year-round in Florida, the dieback never occurs meaning that all parasitic infestations and genetic abnormalities continue uninterrupted. There is concern that any parasitic infestation could lead to an unhealthy adult monarch population, which could have a yet undefined effect on the larger population should an infected monarch rejoin the migration (Satterfield, Maerz, & Altizer, 2015).

2.7 Citizen Science Movement and The Journey North Database

With all of the complexity of an everchanging environment coupled with the difficulty associated with tracking insect populations, it could be a near impossible feat for trained scientists to complete any large-scale study of monarchs and their migratory whereabouts and activities. Since traditional transmitters and tracking devices are not yet in use for large numbers of butterflies, other methods of data collection have had to be developed (Cant et al. 2005; Prysby & Oberhauser, 2004). Citizen scientist databases have been an excellent source of data for projects that require monarch butterfly sightings at a large spatial level (Davis & Howard, 2005). Anyone with access to the internet can log a sighting as well as upload an image. Each record contains information regarding location, number of butterflies sighted, date, time of day, latitude, and longitude.

While there are some concerns regarding citizen scientist data, it would be impossible for scientists to collect and manage large scale comprehensive datasets by themselves (Prysby & Oberhauser, 2004). Despite the knowledge that these types of databases will always contain some element of unchecked error, the data appears to be generally accurate when compared to what scientists already know about monarch butterfly behavior and migration. When considering the geographic scale as well as the need for real-time data, citizen scientist data collection has revolutionized how scientists conduct research and will continue to improve with proper education and increasing citizen involvement (Gura, 2012; Wells, 2010).

While the *Journey North* database has improved the ability to track monarch butterfly sightings throughout the year, this data is not immune to accuracy issues (Figure 2.6). Since there is no training required to report sightings, the most serious concern is the likelihood that the citizen scientist may erroneously identify a different butterfly species (Gura, 2013; Prysby & Oberhauser, 2004). Viceroy butterflies are known mimics using similar orange and black coloration to deter predators who decline consuming monarchs due to the bitter milkweed toxins accumulated in their bodies. Other butterflies frequently confused with monarchs are queen butterflies, painted ladies, and red admirals (Baumle, 2017). Another issue with the sightings database is that the data can lead to erroneous conclusions if interpreted incorrectly. For example, the presence of sightings is helpful for studying migratory patterns; however, the lack of sightings does not automatically indicate that monarchs were not present. There is also the possibility that the sighting was entered incorrectly with regard to number of butterflies present as well as the exact location of the sighting. But despite the inherent error that cannot be removed from these datasets, the data is still more helpful than any other dataset currently offered at such a broad scale.

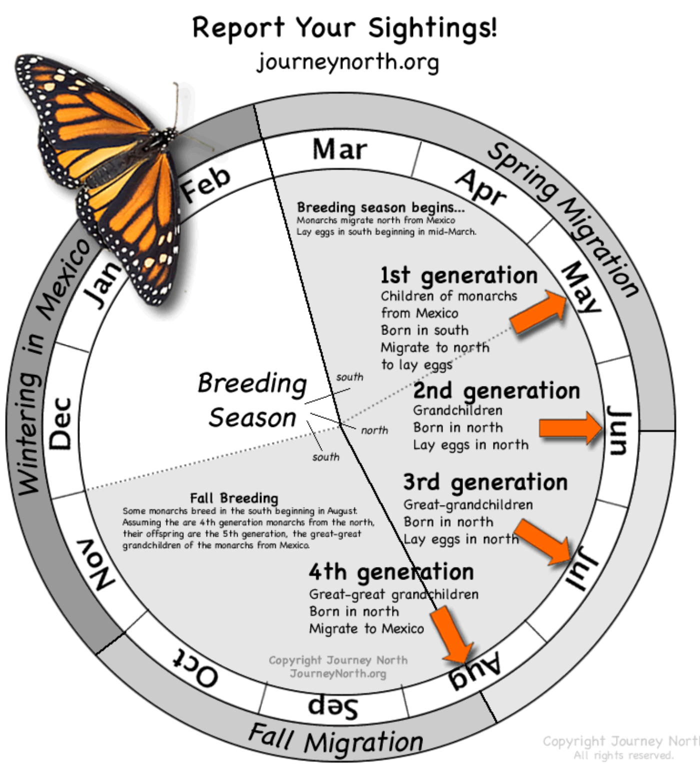


Figure 2.6. The Journey North Maintains a Citizen Scientist Database that Tracks Monarch Egg, Larva, and Butterfly Sightings. (Retrieved from journeynorth.com)

CHAPTER III

STUDY AREA AND DATA

3.1 Study Area

While monarch butterflies exist on both the east and west coasts of the United States, their migratory patterns provide a well-defined separation between the two populations. Western monarchs have a smaller migratory distance with a few butterflies in the southwestern United States migrating into Mexico and mixing with the Eastern monarchs (Journey North, n.d.; Oberhauser, 2004). However, this occurs in very small numbers, and populations remain largely separated with neither population able to traverse the elevation of the Rocky Mountains (Gallou et al., 2107). Western monarchs migrate from overwinter sites in southern California to summer breeding grounds in Oregon, Washington, and southern Canada, while Eastern monarchs migrate from overwinter sites in Mexico to the Midwest and Great Lakes Region of the United States and southern Canada (Journey North, n.d.; Oberhauser, 2004). This study only evaluated the Eastern monarch population bound by the Atlantic Ocean to the east, the Gulf of Mexico and Mexican border to the south, the Canadian border to the north, and the Rocky Mountains to the west. The study extent included the entire United States portion of the eastern migration which enters the United States at the Texas and Mexico border and travels to the summer breeding grounds in the northern United States and southern Canadian border (Figure 3.1).

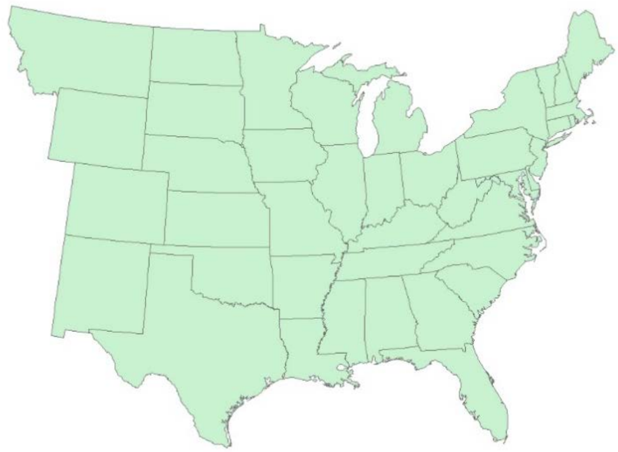


Figure 3.1. Study Extent

3.2 Weather Data

The weather data used for this study was retrieved from the National Centers for Environmental Information (NCEI), formerly the National Climatic Data Center (NCDC). Using land-based stations, temperature and precipitation records were selected and mapped using their corresponding latitude and longitude coordinates. To supplement missing or unrecorded data, datasets were completed using entries from the *Daily Weather Sheets* produced by the National Oceanic and Atmospheric Administration (NOAA). The data downloaded was coincident with monthly data for the extent of this study with files collected from November 2016 through November 2017.

While weather may appear to be a singular variable, the ectothermic nature of insects complicates how butterflies interact with the temperatures that surround them. While temperatures in excess of 55°F are required for butterflies to become warm enough to fly (Baumle, 2017), they can survive short periods of freezing temperatures. Monarch butterflies have an optimal zone of 80-96° F, but they can experience heat stress at temperatures which exceed 100.4° F (Baumle, 2017; Nail et al., 2015). Freezing temperatures are more forgiving as butterflies are less likely to experience hypothermia and instead take advantage of their ectothermic metabolism and cool with their surroundings (Nail et al., 2015; Brower & Oberhauser, n.d.; Journey North, n.d.).

To complete this study, three separate temperature datasets were constructed. Average temperature was used to understand the daily functionality of butterflies as well as optimal temperature ranges. A high temperature dataset was used to outline the optimal cutoffs and the temperature where heat stress and mortality rates would affect populations. And a low temperature dataset was used to outline where monarchs would begin to experience difficulty flying and hypothermia leading to stress and death.

The final weather variable to consider when attempting to rank site suitability was precipitation. Brower and Oberhauser (n.d.) noted that while butterflies can survive surprisingly low temperatures for a short amount of time, moisture can complicate their ability to survive freezing temperatures (Journey North, n.d.). While a butterfly has 50% odds of surviving a temporary temperature drop, a cold and wet butterfly's odds of succumbing are as high as 80-90% (Brower & Oberhauser, n.d.). Precipitation also has implications with regard to adverse weather that can be damaging to butterflies. While high winds and heavy rain create an obvious impediment to butterfly flight, butterflies cannot fly in mild to moderate rain either. Normal precipitation is considered necessary for healthy milkweed and nectar producing plant growth, as well as being tied to healthy butterfly populations. Some studies even link normal amounts of precipitation to the acquisition of lipid stores that monarchs must have to survive the overwintering and diapause process (Brower et al., 2015; Nail et al., 2015) as well as to provide adequate moisture to encourage egg and larval development (Oberhauser, 2004). However, areas that experience abnormal rain or frequent storms can become problematic for site suitability (WallisDeVries et al., 2007).

3.3 Elevation Data

The elevation data was retrieved from the United States Geological Survey (USGS). This study used 30-meter, or 1-arc second, resolution Digital Elevation Models (DEMs) from the National Elevation Dataset (NED). The data for these files were collected between 2006-2016 and were published in February 2018. This dataset had a dual purpose as a site suitability variable as well as a method to delineate the study area extent. As previously noted, areas of higher elevation are not passable due to low temperatures that fall below conditions suitable for butterfly flight which created a natural barrier between Eastern and Western monarchs. However, elevation does create multiple niches that often support biodiversity richness making it a reasonable suitability factor across the study area (Gallou et al., 2017).

3.4 Land Use, Land Cover, and Cropland Use Data

The land use dataset was retrieved from the United States Department of Agriculture (USDA) data download site and was created by the Multi-Resolution Land Characteristics (MRLC) Consortium. It was published in 2014 using 2011 Landsat data and a 16-class classification decision tree. This dataset identified various land uses such as low, medium, and high intensity development as well as agriculture and open spaces. An interesting component of this dataset was that unlike average temperature, elevation, or precipitation, there is some element of control that can be exerted over land use. Development and intensity could be factors in flyway continuity due to habitat destruction as well as the use of herbicides and pesticides in residential and commercial areas (Pleasants & Oberhauser, 2012).

Land cover refers to the various types of physical landforms and environmental categories at a given location. This dataset identified land covers such as open water, forests, wetlands, permanent ice fields, and shrublands. Butterflies favor open areas with full sun and adequate amounts of milkweed and nectar producing plants (Baum & Mueller, 2015; Thogmartin et al., 2017). Since butterflies do not fly at night, they also prefer protected areas where they can be shielded from the elements and predators such as forests and woodlands (Bergman et al., 2018; Baumle, 2017).

The cropland dataset identified most of the crop varieties commercially planted in the United States. This dataset was created by the United States Department of Agriculture and National Agricultural Statistics Service (USDA-NASS). The Cropland Data Layer (CDL) was collected between March 1997 and September 2006 at 30-meter resolution. Cropland is optimal for butterflies due to the fact that it usually contains large, open areas with plenty of sun, ample moisture, and optimal soil properties (United States Forest Service [USFS], n.d.). Generally, most cropland would be favorable for butterflies and milkweed; however, there are two crops that present a challenge (Pleasants, 2015).

Soy and corn plots are plentiful in the Midwest and Great Lakes Regions where Eastern monarchs recolonize at their summer breeding grounds. Genetically modified (GM) varieties have been largely used to decrease costs and produce larger corn and soy yields. These varieties are herbicide resistant allowing the farmer to apply herbicides that kill all plants except for the GM specific crop. As a result, large swaths of land used for corn and soy have become uninhabitable for milkweed, nectar producing plants, and by extension, butterflies (Pleasants, 2015).

3.5 Soil Composition Data

Soil type has a profound effect on which plants can germinate and grow, as well as how healthy and abundant that plant will become. Milkweed is a naturally occurring plant and until its link to monarch butterflies and other pollinator species was regarded largely as a flowering weed (Xerces Society, 2015). With efforts to stabilize and encourage monarch recolonization, milkweed is now being planted as residential and community projects (North Carolina Wildlife Federation [NCWF], n.d.). While there are multiple milkweed species, monarch butterflies have displayed an affinity to certain types. According to the National Wildlife Federation, there are nine milkweed species that monarchs prefer that grow naturally within the study area: common milkweed (*Asclepias syriaca*), butterflyweed (*Asclepias tuberosa*), swamp milkweed (*Asclepias incarnata*), antelope-horns milkweed (*Asclepias asperula*), purple milkweed (*Asclepias purpurascens*), showy milkweed (*Asclepias speciosa*), white milkweed (*Asclepias variegate*), whorled milkweed (*Asclepias verticillata*), and green milkweed (*Asclepias *viridis*) (United States Forest Service [USFS], n.d.; North Carolina Wildlife Federation [NCWF], n.d.). The soil data used in this study was retrieved from the USDA Gridded Soil Survey Geographic (gSSURGO) Database and was collected from the Web Soil Survey in January 2014, published in 2018. Using plant and soil profiles available through the United States Forest Service, the soil layers were used to estimate areas of milkweed viability.

3.6 Monarch Butterfly Population Data

Monarch butterfly sighting data was retrieved from an open database through The *Journey North* project. These sightings were downloaded and sorted into eastern and western populations before selecting only the eastern population for this study. While the database has been accepting sightings data since 1997, records had substantial gaps when organized into seasonal counts. However, with increasing awareness of the program, sightings for 2016 and 2017 were substantial enough to reflect known trends regarding the migrations (Journey North, n.d., Monarch Watch, n.d.). Monarch butterfly sightings were retrieved from the *Journey North* database for all study months beginning in November 2016 through November 2017. This dataset was used to validate the scores established by the site suitability model and to further enhance analysis using sightings and migration patterns. If successful, sightings would be aligned with suitable sites or would be able to be explained otherwise. In the event that there were sightings that were not in a suitable location and their presence could not be reasonably explained, it would become necessary to reassess the variables used and consider that there may be more factors involved in monarch site suitability that would need to be partisan to future research.

CHAPTER IV

METHODOLOGY

This study investigated the relationship between Eastern monarch butterfly (*Danaus plexippus*) migratory patterns as they related both directly and indirectly to physical, land use, and environmental factors. Acceptable ranges of temperature not only affect butterfly survival rates, they also affect the viability and availability of multiple species of milkweed plants (family Asclepias) which are the sole food source for monarch butterfly larvae (Baumle, 2017; Nail et al., 2015; United States Department of Agriculture [USDA], n.d.). Anthropogenic factors, such as land use and agriculture, further complicate milkweed abundance which is already tempered by physical factors such as elevation and soil type (Gallou et al., 2017; Baum & Mueller, 2015; Pleasants 2015). While the basis for most migration research is rooted firmly in biological and ecological science, this study used a multidisciplinary approach by utilizing biological and ecological knowledge as well as geography and geographical information systems (GIS) to map, model, analyze, explain, and predict monarch butterfly spatial patterns as they related to eight geographic variables.

While eastern monarch butterflies have a lengthy seasonal migration from the overwinter sites in Mexico to the breeding grounds in the northern United States and southern Canada, populations that have ceased to migrate and lower total numbers are perhaps indicators of the delicate balance that exists between butterflies and their environment. Southern Florida has witnessed a population that is present during the overwintering months (late-November to late-March) when the larger population is in a state of suspended animation (or diapause) at reserves in Mexico (Baumle, 2017; Journey North, n.d.). This loss of an ability that has been inherent for centuries has led many scientists to question if the entire migratory phenomenon may be at risk (Thogmartin et al., 2017; Brower et al., 2012). This study: 1) mapped eight physical variables and compared monarch butterfly sightings to create a model that may be used to analyze and understand site suitability; 2) established migratory flyways and possible areas of focus to improve connectivity; and, 3) compared the South Florida non-migrating zone to the preferred zones of the migrating population to try to understand why sink populations have initiated.

This project utilized GIS to visualize the link between weather variables such as temperature and precipitation; land use; elevation; and soil type as factors that drive and manipulate Eastern monarch butterfly migratory behavior. This research used cartographic principles and remote sensing imagery to provide spatial and temporal visualizations of a model that identified areas of interest where limited resources may be focused to improve declining monarch recolonization rates. While GIS has been used to understand the annual recolonization of monarch butterflies (Davis & Howard, 2005) and to understand the degradation of the overwinter habitat (Brower et al., 2002), there are no geographically based studies that have analyzed the relationship between monarch butterflies and site suitability as a comparison method between the migratory and non-migratory populations. Proven methods could be used in subsequent years to compare historic populations with current populations and possibly to estimate future monarch populations and migratory patterns. The modeling process accepted variable input layers which were reclassified into scored categories representing the various cutoffs utilized to score monarch butterfly site suitability. The reclassified layers were overlaid using map algebra principles and techniques to output a composite suitability feature layer. The first iteration of this process was completed using equally weighted variable inputs (Figure 4.1), with the second iteration weighting the variables independently (Figure 4.2).

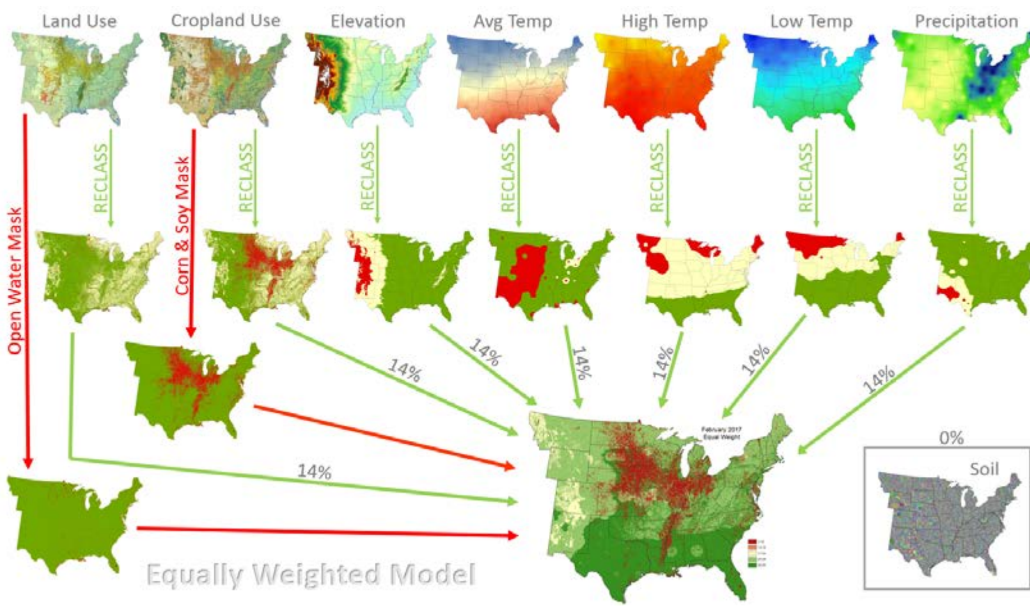


Figure 4.1. Workflow of the Site Suitability Model Using Equal Weighting

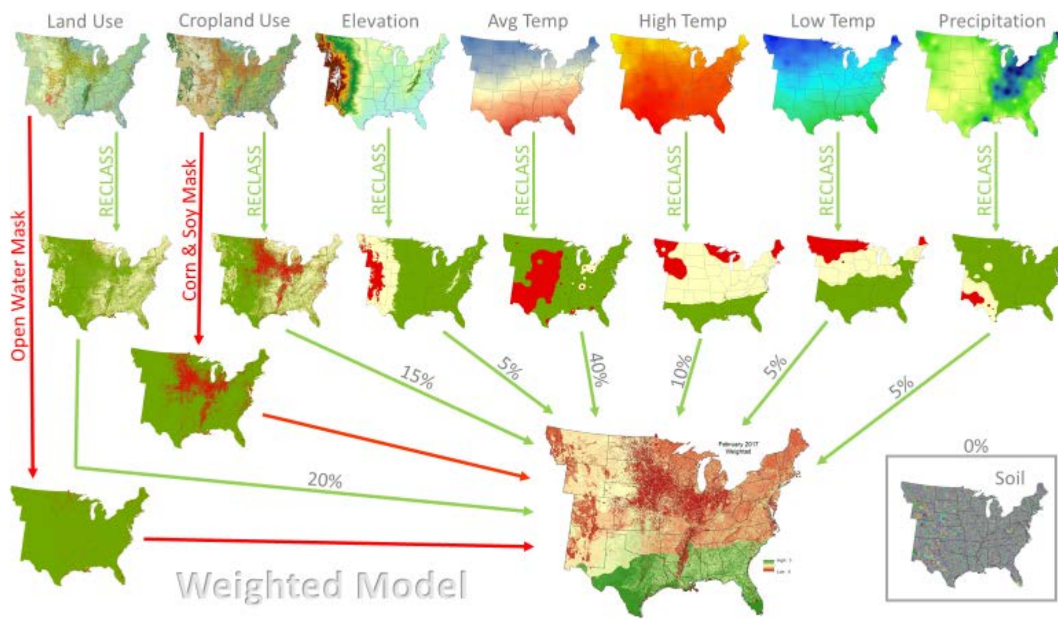


Figure 4.2. Workflow of the Site Suitability Model Using Independent Weighting

4.1 Data Collection and Preparation

The data used for this study was outlined in Chapter III; however, given the large file format and detail involved in this study, the data needed to be prepared for analysis. The Land Use (Figure 4.3), Cropland Use (Figure 4.4), and Soil (Figure 4.5) datasets were retrieved from the USDA data server and were downloaded as statewide files. After the states required by the study extent were imported into GIS, the individual files were mosaicked to create a singular, seamless feature layer.

Figure 4.3. Land Use Layer. (Retrieved from www.usda.gov)

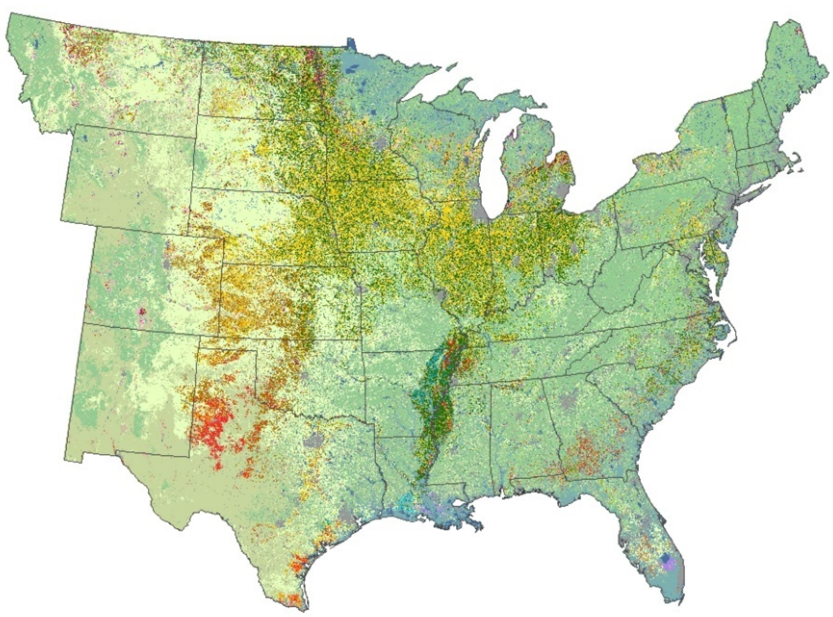


Figure 4.4. Cropland Use Layer. (Retrieved from www.usda.gov)

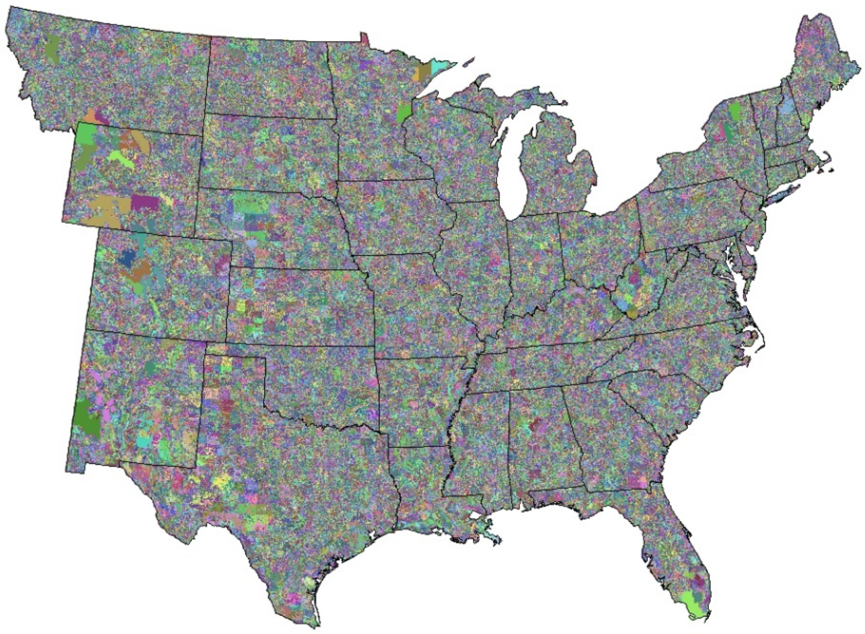


Figure 4.5. Soil Layer. (Retrieved from www.usda.gov)

The elevation layer adhered to the same process as the Land Use, Cropland Use, and Soil layers, except that elevation files were much smaller due to the 30-meter resolution and detail available in each file. However, once all files were retrieved from the USGS download database, the files were mosaicked to produce a single, seamless elevation data layer (Figure 4.6).

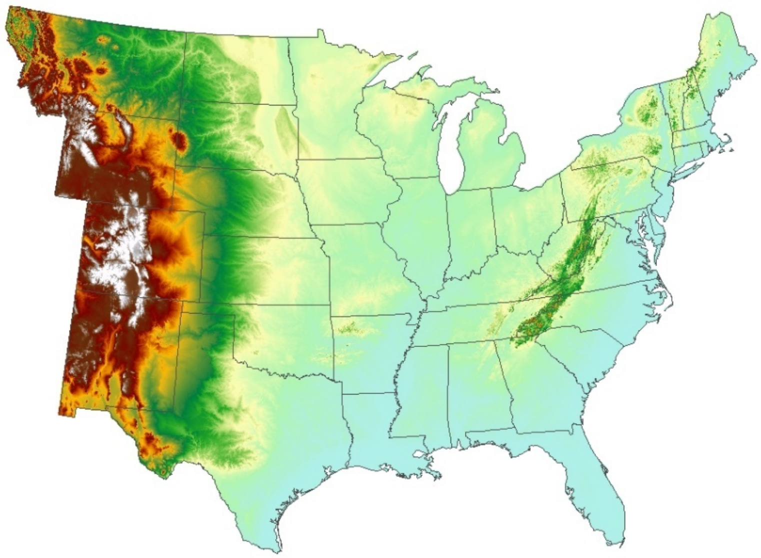


Figure 4.6. Elevation Layer. (Retrieved from www.usgs.gov)

The weather data files required more preliminary work to output a usable GIS data layer. Spreadsheet data files were retrieved from the NCEI data request site with weather attributes available by individual weather station. Each station contained all weather data collected by the NCEI on an hourly basis. This study retrieved the dry bulb hourly temperature in degrees Fahrenheit and the hourly precipitation data. A separate spreadsheet was created to calculate the average monthly temperature, the highest monthly temperature, and the lowest monthly temperature. Precipitation recordings had to be addressed before totals could be calculated as some readings were recorded as “T”. Trace precipitation is generally any amount less than 0.01 inches, which is the lowest recorded measurable amount at the individual weather stations (National Centers for Environmental Information [NCEI], n.d.). For the purpose of this study, all trace records were replaced with a value of 0.01 inches. While the actual amount of trace precipitation could have been lower, this amount had a small overall effect on the precipitation totals in the data that was resampled to analyze the cumulative effect of the 0.01 substitution. Given the minimal effect, the substitution seemed reasonable when considering the precipitation analysis cutoffs for this study.

Once the average temperature (Figure 4.7), high temperature (Figure 4.8), low temperature (Figure 4.9), and precipitation total (Figure 4.10) were calculated for each month, each station was geocoded using the latitude and longitude provided as a station attribute. Temperatures were assigned to all cells in between the surveyed weather stations using the Inverse Distance Weighted (IDW) interpolation method.

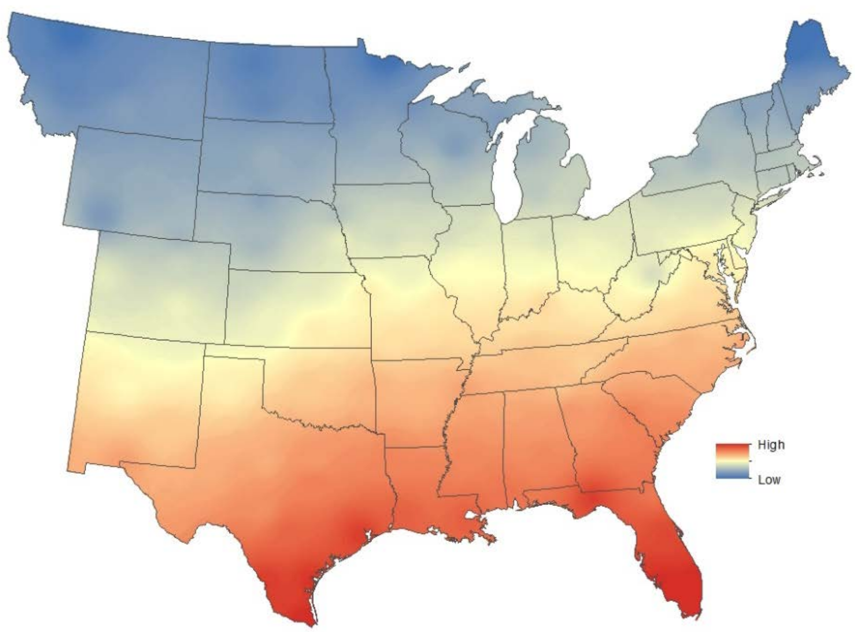


Figure 4.7. Average Temperature Layer. (Data retrieved from www.ncei.gov)

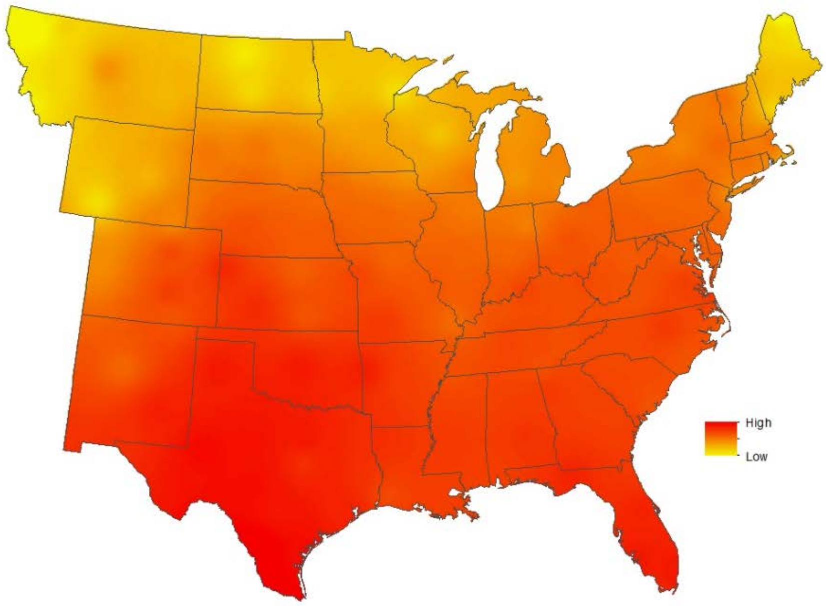


Figure 4.8. High Temperature Layer. (Data retrieved from www.ncei.gov)

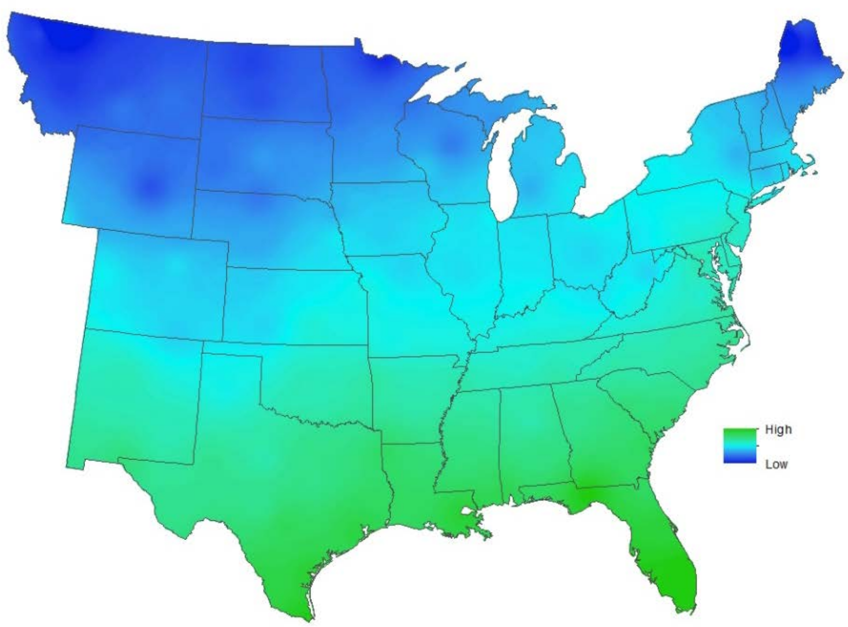


Figure 4.9. Low Temperature Layer. (Data retrieved from www.ncei.gov)

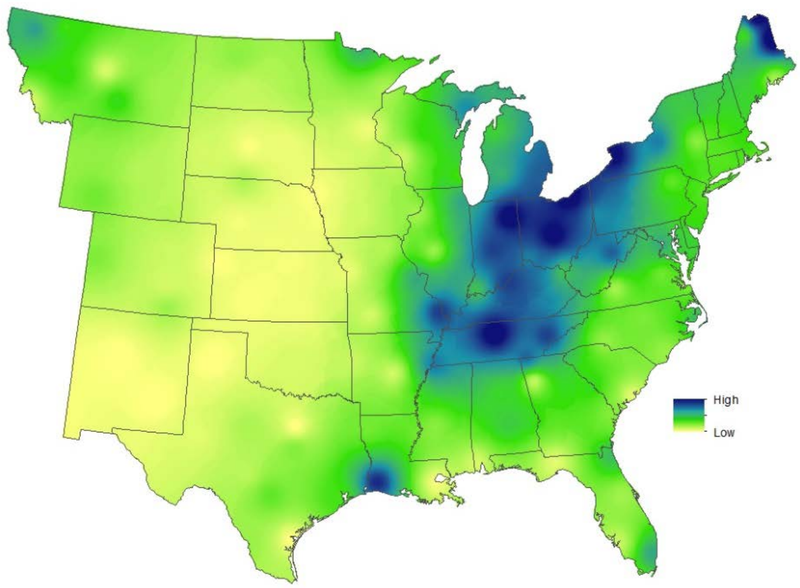


Figure 4.10. Precipitation Layer. (Data retrieved from www.ncei.gov)

4.2 Site Suitability

Once the raster layers were created, each variable was analyzed to apply cutoffs to determine whether a particular cell was *bad, good, or great* for Eastern monarch optimal suitability. Once the cutoffs were implemented, a score was attached to each rank that could be totaled with other coincident variable scores to create an overall site suitability score.

Before a rubric could be assigned to suitability, it was necessary to define exactly what “suitable” meant for this study as well as to understand the assumptions about Eastern monarch butterflies that would need to be taken. This study defined suitability at its most basic level. Was the site viable for Eastern monarch butterflies to maintain normal activities such as: 1) sustaining life through the availability of water and nectar, 2) milkweed availability to promote recolonization, 3) temperatures and atmospheric conditions conducive for survival, and 4) a habitat that fundamentally supported butterfly populations. However, the assumption that was taken with this model was that there were no other events that would affect monarch butterflies outside of the selected variables. This was not realistic as multiple factors account for site outcomes, but it was necessary to hold all other factors not listed as isolated from the model. In short, the general assumption taken holds all other factors irrelevant to the model outcome.

After suitability was defined and assumptions acknowledged, the cutoffs for each raster layer needed to be defined. Each raster layer was addressed and reclassified according to three classifications: *bad*, *good*, and *great*. A rating of *bad* indicated that the cell was generally not suitable for monarch butterflies. A rating of *good* indicated that conditions were suitable for monarch butterflies, and a rating of *great* indicated that conditions exceeded basic suitability and were likely optimal. For conditions that received a *bad* rating, the cell received a numeric score of one. For conditions that received a *good* rating, the cell received a numeric score of three. And for conditions that received a *great* rating, the cell received a numeric score of five.

To begin the reclassification process, cutoff limits were established for the variables in each separate raster layer. The suitability model was designed to track the suitability on a monthly basis across a single 13-month migratory cycle. The study began with data collected from November 2016 and closed with data from November 2017. November as a start month was important because it aligned with the return of the migratory monarchs to the overwinter sanctuaries in Mexico effectively closing the 2015-2016 migration. The monarchs remained in Mexico until they began the 2016-2017 northern migration in late February. March through mid-October encompassed the northern migration and summer recolonization at the summer breeding grounds, while October and November 2017 represented the southern migration and return to the overwinter sanctuaries. In order to represent the dynamic variables across the months, average temperature, high temperature, low temperature, and total precipitation layers were created for each of the 13 study months. Elevation, land use, cropland use, and soil type were static variables which were created once and reused each month in conjunction with that month's weather layers to gain a complete site suitability analysis for that month. To implement the *bad/good/great* classifications, the reclassify method was used to output raster layers that sorted the cells into their assigned classifications. The reclassification cutoffs were established for each variable using a literature review and logical analysis defined in the following sections.

4.2.1 Weather Layer Reclassification

Butterflies are insects with ectothermic metabolism and rely on direct sunlight and warm temperatures for energy (Baumle, 2017; Journey North, n.d.). They require a minimum of 55°F to have the energy to fly and function normally (Brower & Oberhauser, n.d; Journey North, n.d.; Baumle, 2017), but they can survive temperatures as low as -4°F (Nail et al., 2015). Despite the fact that low temperatures do not necessarily indicate mortality, temperatures in excess of 107.6°F can lead to death from heat stress (Nail et al., 2015). It is also important to understood that butterfly life cycles can be slowed and accelerated due to the temperatures surrounding them which can altogether create a complex relationship between butterflies and their environment. To create a site suitability model, it became clear that a single weather layer could not encapsulate this complex relationship.

With low temperatures being more forgiving with regard to butterfly mortality, high temperatures were more dangerous. To capture these two variables, map layers were created for both low and high temperatures for each of the study months. Nail, Batalden, and Oberhauser (2015) completed a study that tested the limits that extreme temperatures had on monarch butterflies and their larva by exposing test subjects to pulses of extreme temperatures with mortality rates calculated following each exposure. According to their research, monarchs could survive temperatures up to 107.6°F at one extreme and survive as low as -4°F at the other extreme. For high temperatures, monarchs functioned optimally up to 100.4°F before exhibiting signs of fatigue and heat stress. When exposed to higher temperatures the butterflies and larva indicated that they needed to rest, hydrate, and shelter before they began to succumb due to heat exposure (Nail et al., 2015).

However, monarchs had a more forgiving relationship with cold temperatures. Since their metabolism relies on heat, butterflies' body temperatures cool with their surroundings. With their metabolism slowing with the cooling temperatures, they were not at threat for immediate hypothermia. In fact, lower temperature aids overwintering butterflies by lowering their metabolism and thus preserving their lipid stores that allow them to survive diapause (Oberhauser, Journey North, n.d.). This ability to not expend unnecessary energy to stay warm has allowed butterflies to survive subfreezing temperatures and to survive the lower temperatures at the overwinter sites. According to

Nail et al. (2015), monarchs were relatively safe from death at temperatures as low as 14°F. Larva were the most sensitive to extreme cold and had increased mortality rates below 14°F with increasing rates at -4°F and below.

Once the temperatures were established for high and low extremities, average temperature was used to consider the general temperature range that monarch butterflies function in daily. These temperature ranges were less concerned with mortality, and more concerned with optimal recolonization and functionality. Butterflies cannot fly below 55°F, requiring the lower acceptable limit for average temperature to be set at a minimum of 55°F (Baumle, 2017; Brower & Oberhauser, n.d.; Journey North, n.d.). According to Nail et al. (2015), data from the Monarch Larva Monitoring Project (MLMP) showed no presence of monarchs above a mean temperature of 86°F. As a result, this temperature was ultimately used to set the high temperature cutoff for acceptable average temperatures. With the high average temperature set at 86°F, and the low average temperature set at 55°F, the lower limit for a *great* classification was set at 70°F. This cutoff was logical when considering that the optimal temperature range for butterfly activity is 82-102°F (Journey North, n.d.). Mean calculations absorb extreme values making 70°F as a monthly average reasonable as the lower optimal limit.

Precipitation data was collected hourly and were input into each layer as a monthly total. Precipitation cutoffs were more difficult to define numerically due to the fact that high amounts of rain as well as drought conditions are usually an extension localized averages. For example, drought conditions in Florida would be different than drought conditions in New Mexico.

Creating a reasonable cutoff that defined high and low conditions for an area as large as the study extent was difficult. Since literature provided no general numeric value, a comprehensive evaluation was conducted to determine which precipitation totals were average, versus which totals were at the extremes. After reviewing normal precipitation totals for each of the weather center locations, it became clear that the precipitation totals gathered for this study were elevated. After three major hurricanes (Harvey, Irma, and Maria) coupled with possible La Niña effects, it was confirmed that general totals would be elevated which further complicated defining precipitation cutoffs (National Weather Service, National Oceanic and Atmospheric Administration [NOAA], n.d.).

After reviewing the precipitation totals gathered for this study, it was evident that multiple areas received an excess of 10 inches of precipitation during some monthly periods. When considering the normal precipitation totals for weather stations across the study area, locations in Florida routinely received 10 inches of rainfall during normal years making this total a reasonable high-end cutoff. Similarly, months that received less than 1 inch per month were likely arid, making 1 inch the low-end cutoff. The high and low cutoffs are important due to basic butterfly biology and mobility. According to Nail et al. (2015), drought and arid conditions have negative effects on butterflies who require moisture at all stages of development (Baumle, 2017). Of further detriment, monarchs who spend too much time in arid places tend to have lower lipid stores which can compromise their ability to survive diapause while overwintering (Brower et al., 2015; Nail et al., 2015). Aside from the harm that could be inflicted on butterflies due to wind and severe rain, butterflies will not fly during any amount of rain, or at least not for long.

To remain dry and unharmed, butterflies seek protection from all precipitation by either sheltering under a structure such as a bench or tree branch or crawling between tall blades of grass (Brower & Oberhauser, n.d.; Journey North, n.d.). While average amounts of rainfall are a part of daily butterfly life, elevated amounts of rain could be problematic for breeding and transit.

The final precipitation cutoff delineated the break between *good* and *great* conditions. This cutoff was also subjective and required a "best informed" selection. Most stations experienced an average of 3-8 inches of precipitation; therefore, the last cutoff set the *great* range for butterfly suitability from 1-8 inches. While setting cutoffs for precipitation was imperfect with regard to the variety of locations, landscapes, and atmospheric exposure, the defined cutoffs were reasonable for the study's purpose of delineating instances of moderate to extreme precipitation totals (Figure 4.11).

	Average Temp	High Temp	Low Temp	Precipitation
Great 5	70 - 86° F	≤ 100.4° F	> 14° F	1 - 8 in
Good 3	55 - 70° F	100.4 - 107.6° F	(4) - 14°	8 - 10 in
Bad 1	> 86° F < 55° F	> 107.6° F	≤ -4°	0 - 1 in 10+ in

Figure 4.11. Temperature Layer Cutoffs

4.2.2 Land Use Reclassification

Land cover and land use can be sorted into categories based on how optimal the use or cover is for supporting butterflies. Butterflies require sunlight for warmth, moisture, milkweed, shelter, and nectar (Baumlee, 2017; Oberhauser, 2004; Journey North, n.d.). As long as these necessities were present, the likelihood of supporting monarchs was high. In order to classify the various land covers and land uses, it had to be determined if the type was conducive to providing the necessities that monarchs required.

The land use and land cover layer obtained from the United States Department of Agriculture and the National Agricultural Statistics Service (USDA-NASS) categorized land according to either its physical characteristics or its anthropogenic uses. Physical land cover included forests, wetlands, permanent snow and ice fields, open water, and barren land. Examples of anthropogenic land uses were developed land, agriculture, and pasture land. Utilizing knowledge of the nature of the various land uses and covers, each category was sorted into a *bad/ good/ great* classification garnering a respective score of one, three, or five.

The easiest classification to sort was the *bad* classification. Open water and perennial snow and ice were not conducive to milkweed or nectar plants. Barren land was also generally not optimal due to the fact that the soil was typically thin and unsuitable for vegetation (National Aeronautics and Space Administration [NASA], n.d.). The final unsuitable land use was highly developed areas. These areas had a large footprint and tended to remove most natural land cover including milkweed (Nilsson et al., 2008). While some nectar producing plants could be present, the likelihood of having necessary quantities to support migrating butterflies was not high. These categories were all classified as *bad* conditions for monarchs and given a score of one.

With the unacceptable uses culled out, the remaining uses were deemed habitable for monarchs; however, some land covers and uses were better than others. Examples of land uses and covers that would be classified as *great* were: shrub/scrub, hay/pasture, herbaceous, cultivated crops, open space, low density developed, and deciduous and mixed forests. The shrub/scrub, hay/pasture, herbaceous, and open space categories had all of the characteristics required for monarch butterfly suitability. These types of sites generally had plenty of sunshine, and the land was usually conducive to milkweed and nectar plants (Journey North, n.d.). Cultivated cropland was also suitable for milkweed and nectar plants for the same reasons that they were suitable for crops. Fertilized soil and plenty of moisture made this category a great location for wild milkweed and flowering plants (Thogmartin et al., 2017). Low intensity development does create a footprint with structure construction and herbicide and pesticide use for lawns and gardens; however, low intensity could still foster a healthy environment for monarch support and recolonization (Blair, 1999). Initiatives such as the Butterfly Highway have encouraged residential and commercial properties to eliminate the use of pesticides and herbicides and to plant indigenous milkweed and nectar plant varieties (North Carolina Wildlife Federation [NCWF], n.d.). With a growing interest in the declining number of pollinators, monarch butterflies have been on the receiving end of grassroots initiatives in low and medium density developed areas to improve flyways and recolonization numbers (Journey North, n.d.; Monarch Watch, n.d.; North Carolina Wildlife Federation [NCWF], n.d.). Mixed forests and deciduous forests were both considered *great* for butterflies as forest areas can have adequate light, plant biodiversity, shelter, and clearings. Forest clearings can capitalize on the open sunlight as well as the nearby shelter of trees. Forested areas cleared for utilities such as power lines can also provide protected open areas for butterflies as well as the necessary plant life (Bergman et al., 2018).

With the *bad* and *great* categories defined and populated, all remaining uses in the acceptable range were deemed *good* receiving a score of three. Medium intensity development was viewed as acceptable due to it not being as damaging as high intensity, but also not as acceptable as low intensity. According to Forest & Range (n.d.), wetland plants are considered hydrophytes. Tropical milkweed and swamp milkweed grow well in wetland areas; however, tropical milkweed is not indigenous to the study area. Recent research has attached the year round growth of tropical milkweed to negative impacts on migrating monarchs, especially when coupled with warmer temperatures (Harvey et al., 2015; Xerces Society, 2015). Stands of tropical milkweed that do not experience an annual dieback have been associated with parasites as well as decreased motivation for monarchs to migrate to the overwinter sites in Mexico (Satterfield et al., 2015; Altizer et al., 2000). While all wetlands are not subject to this negative outcome, they are possible locations making them less than optimal by default.

4.2.3 Cropland Use Reclassification

As described in the land use section, croplands are usually ideal for fostering milkweed and nectar producing plants. There is also plenty of sunshine and moisture available for butterflies, eggs, and larva; however, despite these otherwise optimal conditions, three crops were not considered suitable for monarch butterflies. Commercial farmers have begun planting GM varieties of corn and soy which are herbicide resistant (Thogmartin et al., 2017; Pleasants, 2015; Pleasants & Oberhauser, 2012). This resistance allows farmers to spray herbicides with no concern for harming the corn or soy; unfortunately, all other vegetation is eradicated in the process including wild milkweed and nectar plants.

The reclassification sorted crops into *bad*, *good*, and *great* categories with the respective scores of one, three, and five. The *bad* category contained soy and corn as well as sod, which received a score of one. Sod was included due to the herbicides used in cultivating commercial and residential plots. All remaining crops were categorized as *great* for monarchs due to the probability of milkweed and nectar producing plant growth and received a score of five.

4.2.4 Soil Reclassification

It is generally accepted that most plant growth has a direct relationship with the soil within which it grows. Nutrients, density, permeability, physical make-up, and oxygen are some of the factors that make soil suitable for growth according to the USDA (United States Forest Service [USFS], n.d.). Milkweed has varieties that can survive and thrive in most climates and soil types. After reviewing the profiles of nine varieties of milkweed that were favored by monarch butterflies on the USDA Forest Service website, at least one or more species grew in all areas of the study extent. Given that so many soil types were acceptable, this layer was removed from the model due to the fact that it would not add value or weight to the final score. As a result, a reclassification layer was not created, and soil was not a calculable layer in the site suitability analysis.

4.2.5 Elevation Reclassification

Elevation had a dual purpose in this study. Monarch butterflies are rare in higher elevations, and it is currently believed that they will not cross the higher altitudes of the Rocky Mountains (Gallou et al., 2017). The National Park Service website for Rocky Mountain National Park even listed monarch butterfly sightings as very rare due to the altitude and temperatures despite the availability of meadows, natural ground cover, and species richness and abundance of wildflowers (National Park Service [NPS], n.d.). Gallou et al. completed a study which investigated the effects of elevation and butterfly species richness in the French Alps. The study revealed that butterfly species richness increased in number up to 700 meters in elevation. After 700 meters, richness remained constant without increases, until it dropped sharply at 1900 meters (Gallou et al., 2017). Using the three-tiered classification system of *bad*, *good*, and *great* with scores of one, three, and five, elevations up to 700 meters were deemed *great*, with elevations between 700 – 1900 meters as *good*, and elevations above 1900 meters as *bad*. (Figure 4.12)

	Land Use		Cropland Use	Elevation
Great **5**	Mixed Forest Shrub/Scrub Herbaceuous Hay/Pasture	Open Space Developed, Low Intensity Cultivated Crops Deciduous Forest Evergreen Forest	All other crops	< 700 m
Good **3**	Developed, Medium Intensity Woody Wetlands Emergent Herbaceuous Wetlands		Developed, Mid Intensity	700 - 1900 m
Bad **1**	Open water Perennial snow/ice Dev High Intensity Barren Land		Soy Corn Sod	>1900 m

Figure 4.12. Land Use, Cropland Use, and Elevation Layer Cutoffs

4.3 Composite Analysis with Variables Weighted Equally

After all layers were reclassified using a universal scoring system, the scores for each cell could be calculated using map algebra. The final result was a composite feature layer that provided a total score for each cell that illustrated the site suitability of all variables combined. However, before final site suitability could be calculated, there were three conditions that were uninhabitable despite the suitability of the other layers.

A rating of uninhabitable received a score of zero that would supersede any other variable's individual or composite score. If a cell received a score of zero, all other variable scores would be nullified to create a composite site score of zero. For example, optimal temperatures may be negated if the cell was over open water. Butterflies could not survive long-term in this location, and they would be forced to continue past or avoid that cell. There were only three attributes in the study extent that were deemed uninhabitable: open water, soy cropland use, and corn cropland use. As discussed in the example, open water would not be a viable location for butterflies due to the lack of milkweed, nectar plants, and shelter (Baumle, 2017; Journey North, n.d.). Corn and soy received the uninhabitable rating due the herbicide resistant GM varieties currently used that allowed farmers to spray herbicides that killed all vegetation other than the corn and soy (Thogmartin et al., 2017; Pleasants, 2015; Pleasants & Oberhauser, 2012).

Two mask layers were used to create the three uninhabitable conditions. To create the corn and soy mask, the cropland layer was replicated and reclassified using binary scores of zero and one. Corn and soy were assigned a score of zero with all other categories assigned a score of one. The process was duplicated using the land use layer with open water assigned a score of zero while all other categories received a score of one. Using the masks and reclassified layers, the following formula was input into the raster calculator:

$$(\textit{Average Temperature}_1 + \textit{High Temperature}_1 + \textit{Low Temperature}_1 + \textit{Precipitation}_1 + \textit{Land Use} + \textit{Cropland Use} + \textit{Elevation}) * \textit{Cropland Mask} * \textit{Land Use Mask}$$

The formula was repeated 12 times substituting the specific month's weather layers while reusing the Land Use, Cropland Use, Elevation, Cropland Mask, and Land Use Mask layers. The resulting layers represented a composite map layer scored on a scale from 0-35. A score of 0-12 indicated that monarch butterfly suitability was not acceptable and possibly uninhabitable. For a cell to receive a score of 12, the average score of the seven input layers was 1.28, indicating poor site suitability. Scores of 13-16 were marginally better, but still poor with an average score of 2.07. Butterflies in areas that had poor scores would need to move out of those areas quickly to avoid the unfavorable effects of a poor environment. Scores of 17-24 were habitable but not optimal for monarchs. The average site suitability score in this range was 3.00 which fell squarely in the *good* classification. Scores of 25-29 were trending toward optimal suitability conditions with an average score of 4.00. These conditions were good for monarchs and indicated areas where multiple variables were at the *good* or *great* level. Optimal areas were scored from 30-35 and required a minimum of five out of the seven variables at the *great* level. The average score in this range was 4.71 with some scores at the 5.00 level for optimal site suitability (Figure 4.13).

Uninhabitable	Bad	Poor	Habitable	Good	Great
0	7-12	13-16	17-24	25-29	30-35

Figure 4.13. Scoring for Equally Weighted Variable Model

4.4 Composite Analysis Using Weighted Variables

While the default is generally to treat variables equally, this type of actual equality is often only theoretical. The interrelationships between variables and their environment are complex, and the reality is that some variables have a larger or smaller effect on the outcome. At the completion of the first model for site suitability analysis, weighting the variables equally created an image that seemed more optimistic than most data and studies were reporting. A reasonable adjustment was to consider weighting the variables allowing some to have more or less of an effect on the final layer. Using literature, logic, and reason, weights were applied to the formula in the raster calculator to output a different image of monarch suitability.

There was a rich supply of biological research surrounding the effects of temperature on all butterfly species. Given that butterflies are ectothermic, they will forever be irrevocably linked to temperatures and the weather surrounding them. While studies and lab results revealed temperature cutoffs for stress and viability, no numbers existed for exactly what proportion of a butterfly's existence relied upon temperature. Reasonably, scientists knew that temperature affected the time spent during each stage of the life cycle (Oberhauser, 2004). Temperatures in the 90°F range were optimal leading to faster recolonization rates by speeding up the time spent at each life stage, while lower temperatures could possibly slow it down leading to fewer generations (Nail et al., 2015; Oberhauser, 2004; Solensky, 2004). They also knew that temperatures below 55°F were not suitable for flight, leaving the monarchs immobile and vulnerable to harm and predation (Baumle, 2017). While scientists are not certain what initiates the trigger for northern monarchs to begin the southern migration, it is widely accepted that temperature also plays a sizeable part in those conditions as well (Guerra & Reppert, 2013). High temperatures could lead to heat stress and death, while low temperatures were less likely to result in immediate mortality (Nail et al., 2015).

However, despite the lack of a studies providing a clear-cut percentage of the weight that temperature carries for butterfly vitality and population sustainability, it was clear throughout this research that it should be a large portion of the weight applied to the site suitability model. Since average temperature was used to measure the day to day heat requirement that butterflies need for mobility, life stage progression, and basic life functions, the weight applied was 40%.

High temperatures are of importance because heat stress can harm butterflies between 100.4-107.6°F with temperatures in excess of 107.6°F causing death in test populations (Nail et al., 2015). Since this variable only affected the model at the extreme, it was weighted at 10% due to the fact that it could result in harm or death more swiftly than cold temperatures. This weight was considered reasonable at 10% to negatively affect the model if there were conditions present that could harm the butterflies, but the high temperature weighting would also work in conjunction with the already weighted average temperature layer. It would be reasonable to believe that if a high temperature was achieved that could cause heat stress or death, the average temperature would also be elevated as well. High temperature, as a single measure of viability, and average temperature, as a cumulative measure of sustainability, would therefore work together at a total of 50% weight to explain the effects of warmer temperatures on monarch site suitability.

Similar in construct, low temperatures worked with average temperature in the same way. Low temperature was used as a measure of viability and mortality; however, its effects proved more forgiving than high temperatures (Nail et al., 2015; Brower & Oberhauser, n.d.; Journey North, n.d.). When lab tests were completed on the effects of extreme cold temperature pulses on larva, survival was sustained for low temperatures due to their ectothermic metabolism. This allowed the larva to slow their metabolism and lower their body temperature without experiencing hypothermia (Nail et al., 2015;

Journey North, n.d.). It took temperatures of -4°F before larva experienced a higher probability of mortality, which was nearly 60° lower than the temperature where butterflies could no longer fly. Since flight is a major indicator of sustainability, this large differential illustrated that low temperatures had less of a singular effect on butterflies than high temperatures where stress could lead to death sooner. With this information in mind, the low temperature weight was set at 5%, which when coupled with average temperature had a combined weight of 45%. With all temperature weights assigned, the total model weighted temperature factors at 55% which reasonably represented the effect that low, high, and average temperatures had on butterfly wellbeing and site suitability.

Precipitation was a difficult variable to account for from the study onset. Given that moisture is required by butterflies at all life stages including the egg and chrysalis stages (Baumle, 2017; Nail et al., 2015; Oberhauser, 2004), it was not reasonable to negate it from the study. Further compounding the importance of precipitation, past studies have indicated that monarchs who spend too much of their life span in arid climates had lower lipid stores making them less fit than their wetter climate counterparts at surviving diapause during the overwintering months in Mexico (Brower et al., 2015; Nail et al., 2015). The question was: exactly how much precipitation was necessary, and what were the cutoffs for too little or too much? The issues encountered with answering these two questions were complicated by the fact that drought and wet conditions are typically recorded at a local level (National Weather Service, National Oceanic and Atmospheric Administration [NOAA], n.d.). What may be drought conditions in an arid location could have different measurements than drought conditions in a tropical location

While considering that the precipitation totals varied widely across the study area, it became clear that it would only be possible to extract extreme instances of drought and rainfall using a numeric cutoff across a large, diverse area. Ultimately, this proved acceptable for the site suitability model when considering that there were only a few questions that required answers regarding monarchs and precipitation. Was there precipitation in excess of extreme drought or aridness, and if so, was there an unusually large amount of rainfall during any month-long period? Although it is not optimal for butterflies to experience rain since their flight abilities are compromised, they sustain populations in tropical climates such as Florida where rainfall and storm activity are common.

With all of these factors considered, while precipitation was a necessity, it was only extreme sustained amounts that would affect the site suitability (WallisDeVries et al., 2007). Furthermore, precipitation had localized effects which were not easily captured with a generalized cutoff. As a result, the weight applied to precipitation was 5%. This allowed for extreme circumstances to negatively impact the model; however, the impact would be limited since the classification cutoffs were so broad.

Elevation cutoffs were straightforward and were tied to falling temperatures as altitude increased. According to Gallou et al., biodiversity and species richness of butterflies increased in number up to 700 meters. There was no increase between 700-1900 meters, and a sharp decrease was observed beyond 1900 meters (Gallou et al., 2017). This study corroborated the butterfly sightings from the *Journey North* database in visualizing a cutoff where butterflies were less likely to find suitable habitats. This weight was set at 5%, as elevation also interacts with the average temperature variable for sustainability as well as the low temperature variable for suitability, stress, and mortality (Nail et al., 2015). Weighting elevation heavier could have swayed the model when elevation had a strong link to temperature which had already been weighted heavily.

The final set of variables that would take the remaining 35% were the two land use layers. While temperature, elevation, precipitation, and soil type are generally out of anthropogenic control, how humans utilize the land is not. Land cover is in some respects what is left after land use has already been designated. After development and agriculture were removed, the land that was left was categorized into its natural state of forest, water, shrub/scrub, barren, or wetland. For centuries monarchs have been observed in high numbers with their continuous decline a product of the past 20 years (Monarch Watch, n.d.), so it would seem reasonable that something has happened recently to affect their decline. It is often reflexive to blame anthropogenic activities for the loss of the environment and biodiversity within it, but in the case of monarch butterflies, it is a definite cause of concern.

Land use and land cover have a direct effect on butterfly site suitability. Average temperature carried a heavy weight due to the fact that it had a substantial effect on butterfly sustainability as a factor of both biological vitality and viability. Land use and land cover affect the environmental and ecological side of butterfly viability, so it was reasonable that it should also carry a substantial weight. However, certain land uses were more detrimental to migrating butterflies. High intensity development was not suitable for monarchs due to its building and landscaping footprint as well as general destruction of the natural land cover that existed there previously (Blair, 1999). Perennial snow and ice fields, barren land, and open water were also not suitable; while forests, shrub/scrub, pasture, open spaces, low intensity development, and cultivated croplands were good to optimal locations for butterflies (Baum & Mueller, 2015; Pin Koh, 2007). Land use and land cover were assigned a weight of 20% due to the substantial importance that they have to butterfly site suitability.

However, there are two parts to the land use weight. The land use and land cover layer only referenced cultivated crops, hay, and pasture, all of which are generally great land uses for butterflies. But cropland use presented a substantial problem. While most crops were beneficial to butterflies as a prime location for milkweed and nectar producing plants, GM herbicide resistant varieties of corn and soy have made large stands of farmland uninhabitable for all plants except for the planted crop (Pleasants, 2015; Pleasants & Oberhauser, 2012; Hoevenaar & Malcom, 2004). The cropland layer was assigned a weight of 15% to account for the differences in *good* and *bad* crops as they relate to monarch site suitability. Having a separate crop layer provided an extra increase overall for cultivated crops that were beneficial to monarchs with a negative impact to those that were not. This made the overall land use and landcover element of this model valued at 35% when both general and cropland use were combined. This weight was reasonable when compared to temperature weight due to the fact that temperature has a slightly higher effect on day to day butterfly activity with regard to viability, vitality, and mortality. If land use were unsuitable, the butterflies could theoretically leave, especially if the use was not widespread; however, escaping adverse temperatures could be more complicated, especially if the temperature was at the low or high extreme. But it is important to note that land use and land cover are major factors in determining site suitability with that importance appropriately reflected in the model.

Once the weights were assigned, the layers were once again entered into the raster calculator to output a composite layer reflecting the individual scores of the underlying layers. Both the open water mask and the corn/soy mask were used again due to the fact that they were both still uninhabitable areas despite the scores accumulated by the other variables. The raster calculator formula was as follows:

$$((.40 * \textit{Average Temperature}_1) + (.10 * \textit{High Temperature}_1) + (.05 * \textit{Low Temperature}_1) + (.05 * \textit{Precipitation}_1) + (.05 * \textit{Elevation}) + (.20 * \textit{Land Use}) + (.15 * \textit{Cropland Use})) * \textit{Land Use Mask} * \textit{Cropland Use Mask}$$

The formula was repeated 12 times substituting the specific month's weather layers while reusing the Land Use, Cropland Use, Elevation, Cropland Mask, and Land Use Mask layers. The resulting layers represented a composite feature layer scored on a scale from 0-5. A score of zero indicated that the cell was uninhabitable due to the application of one of the two mask layers. Inversely, a score of five indicated that conditions were optimal for monarch butterflies. A score of three was assigned to moderately suitable conditions, while scores of two and four trended respectively towards poor and optimal site conditions. (Figure 4.14)

Uninhabitable	Bad	Poor	Habitable	Good	Great
0	1.00-1.99	2.00-2.99	3.00-3.99	4.00-4.99	5.00

Figure 4.14. Scoring for Individually Weighted Variable Model

The layers created with this method aligned more with previous research as well as the numbers and conditions that lepidopterists had observed on the ground. As a test of validity, geolocated monarch butterfly sightings that were obtained from the *Journey North* database were overlaid on the weighted layers to analyze the locations versus the model outputs. If a site was optimal, butterflies should be located at or near these sites in general, and inversely, they should not be located where suitability was poor.

CHAPTER V

RESULTS

The maps that resulted from the study were successful in creating a visual representation of the Eastern monarch butterfly migration regarding the variables that were selected. The equally weighted layers provided an image of migration flyways that appeared generally optimal for butterflies with some areas that were uninhabitable. Treating each variable equally presented a more optimistic image of the migration trail than had been reported by other studies and scientists on the ground (Trezza, 2018; Thogmartin et al. 2017; Lemoine, 2015; Satterfield et al., 2015; Pleasants, 2015; Pleasants & Oberhauser, 2012; Altizer et al., 2000). The question surrounding the validity of these layers prompted a second analysis in which each variable was weighted differently with average temperature and land use having a larger impact on the outputs. The weighted layers provided a contrasted view of the previous model and seemed to corroborate the conditions that have been reported for the past decade. However, to better understand the weighted layers and how they were developed, it was first necessary to consider the results and conclusions that were drawn from the equally weighted analysis and resulting maps.

5.1 Equally Weighted Variables Site Suitability Analysis and Results

The first model of site suitability weighted all variables equally at a weight of approximately 14% each. While this method of weighting is frequently the default, it was merely a place to start since no site would naturally have variables that equally affected the outcome. However, there was still important information that could be extracted from the first series of maps.

The first observation was that there was a large number of red cells in the Midwest and Great Lakes Regions indicating that the areas were either bad for monarchs, or possibly uninhabitable (Figure 5.1). The most alarming revelation was that the highest concentration of red cells was centered over the summer breeding grounds. This corroborated research that GM varieties of corn and soy were having negative effects on milkweed and nectar plant populations in the Midwest, which by extension was negatively affecting monarch recolonization numbers (Thogmartin et al., 2017; Pleasants, 2012). This observation was disappointing due to the fact land use and agricultural practices are largely anthropogenic factors. With temperature, precipitation, and elevation out of human control, land use is directly affected by anthropogenic decisions and management. If other iterations displayed the same area of interest, this would be alarming due to the realization that whatever factor was causing the red cells was present despite the weighting of the variables, or it was one of the masks that automatically led to uninhabitable site suitability.

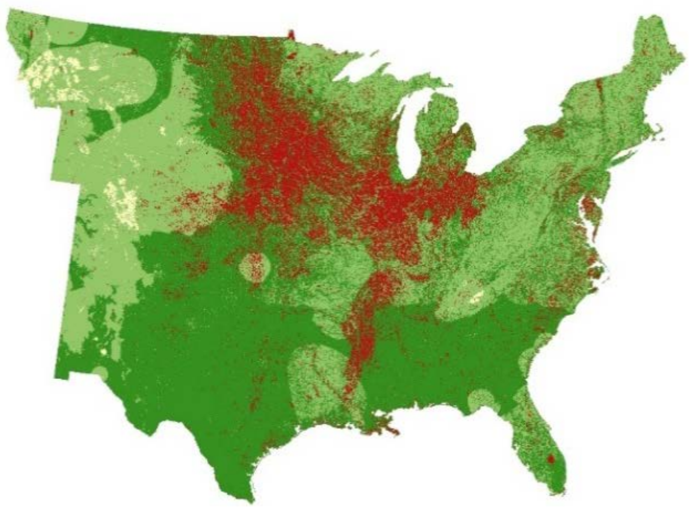


Figure 5.1. Equally Weighted Model

5.2 Weighted Variables Site Suitability Analysis and Results

With the validity of variable weighting being questioned, the first model was repeated using adjusted weights that allowed for certain variables to carry a higher or lower influence on the output layers (Figure 5.2). Average temperature carried a heavier weight with other variables such as high and low temperature working in collaboration. Land use and cropland use were also weighted differently so that they could work in unison to affect the model at a heavier weight when combined. Ultimately, elevation and precipitation were given lower weights due to their individual importance as well as any interactions that they may have had with other variables.

The individually weighted analysis presented a less optimistic interpretation of the overall site suitability, yet it appeared to be more reasonable. With average temperature and land use having a larger weight, the new model reflected a more moderate outcome with more cells falling into the habitable range (yellow) as opposed to the optimal range (green). The new model also appeared to capture the changing temperature that would affect the leading edge of the northern migration as it entered the United States and made its way to the summer breeding grounds. Subsequently during the fall and early winter, the layers were more indicative of the southern migration and the weather conditions that would usher in the close to the migration year.

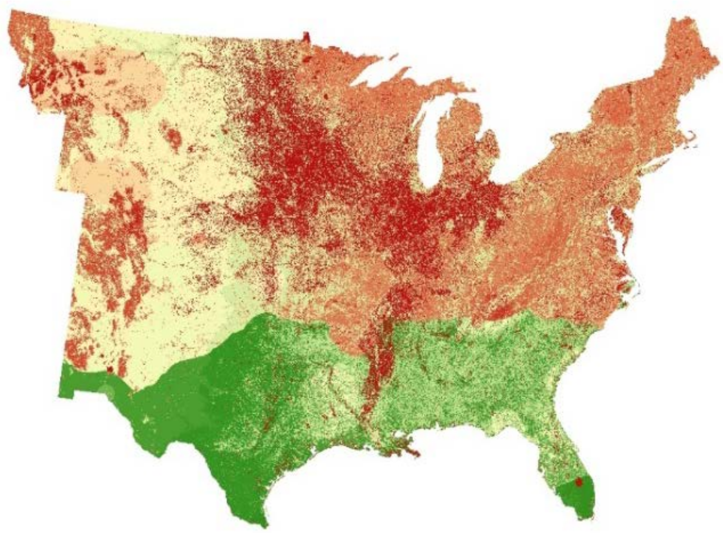


Figure 5.2. Individually Weighted Model

The best way to draw conclusions from the two models was to view each month side by side to compare what observations appeared in both iterations, as well as to visualize the differences between the two. With the cutoffs defined identically for both models, the weighting was the only factor that changed proving how powerful an effect that each variable could possibly have on migratory species (Figures 5.3 – 5.15).

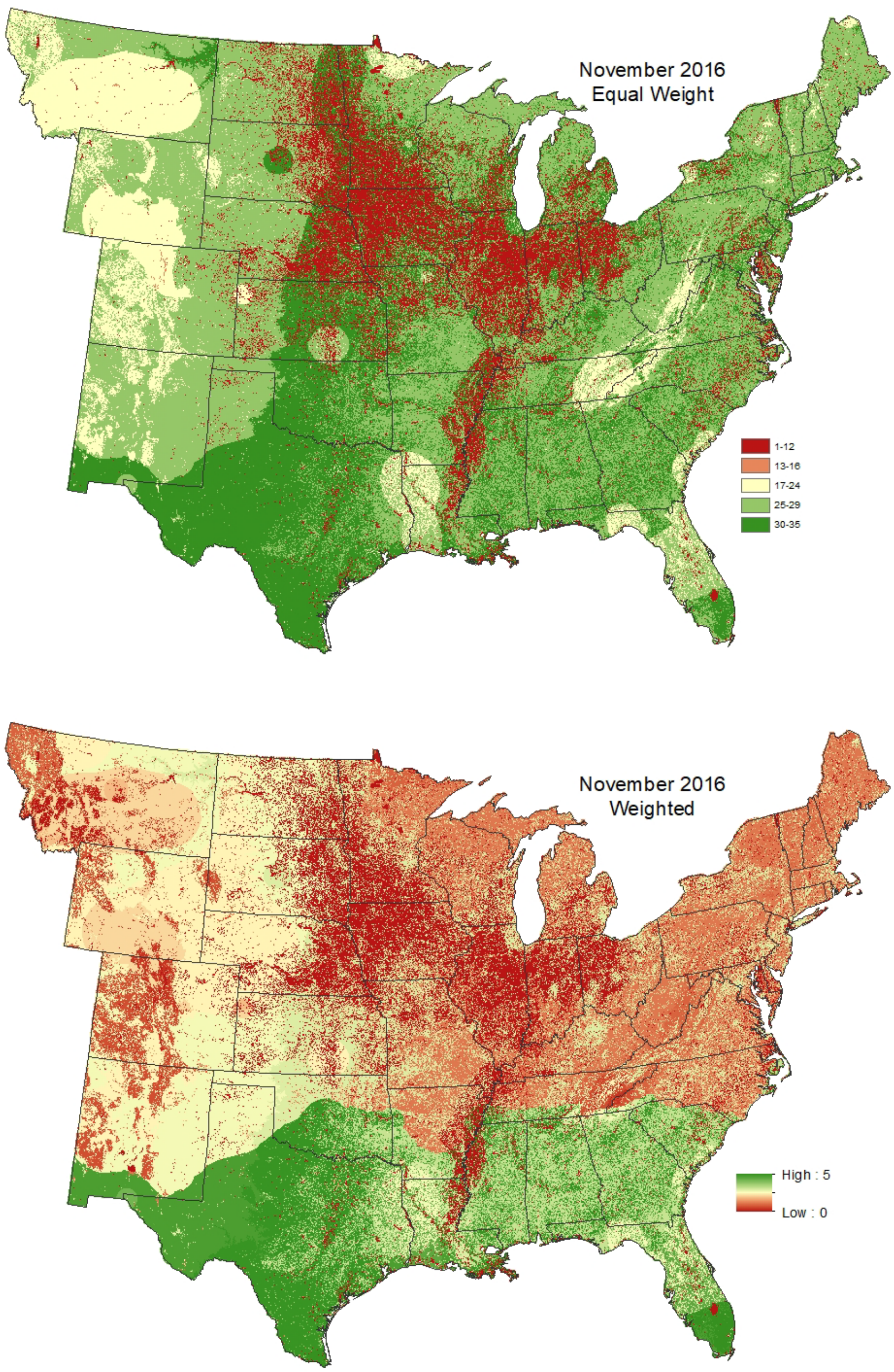
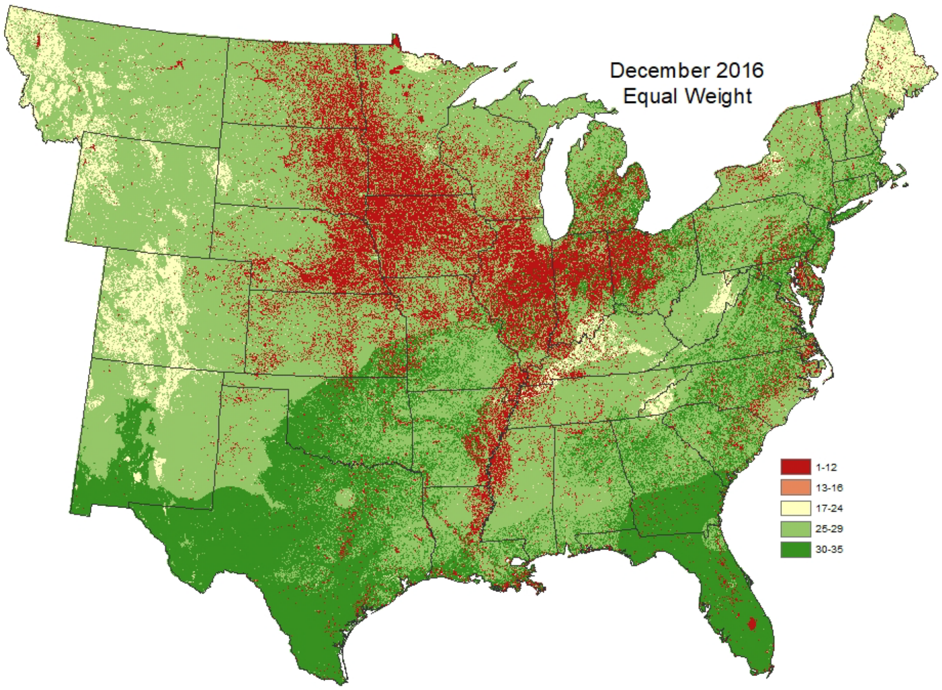


Figure 5.3. November 2016 Equally Weighted and Individually Weighted Models



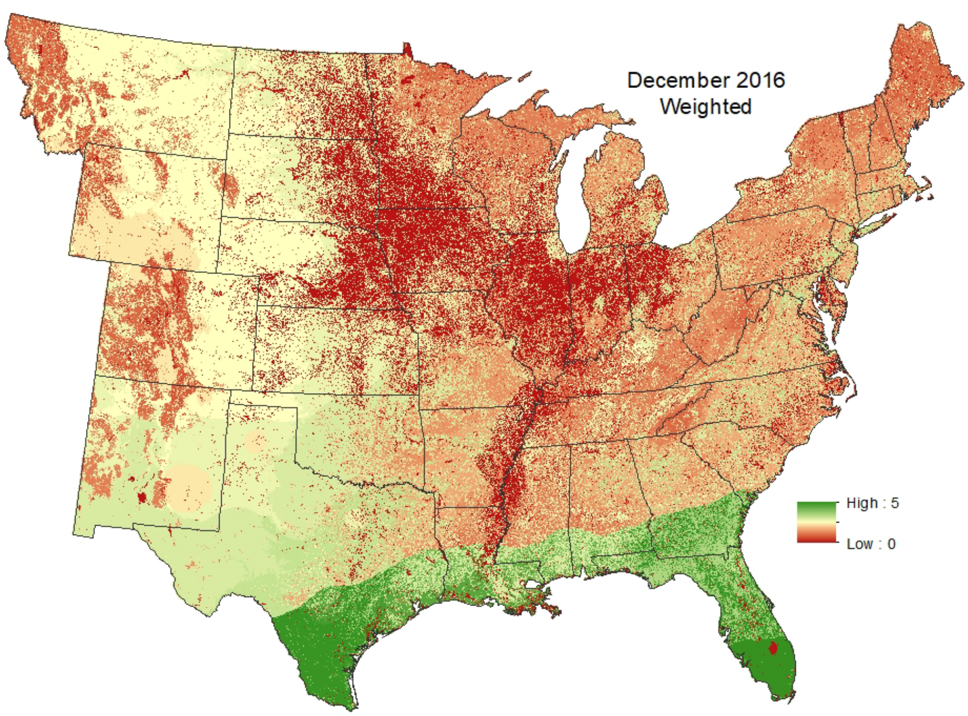


Figure 5.4. December 2016 Equally Weighted and Individually Weighted Models

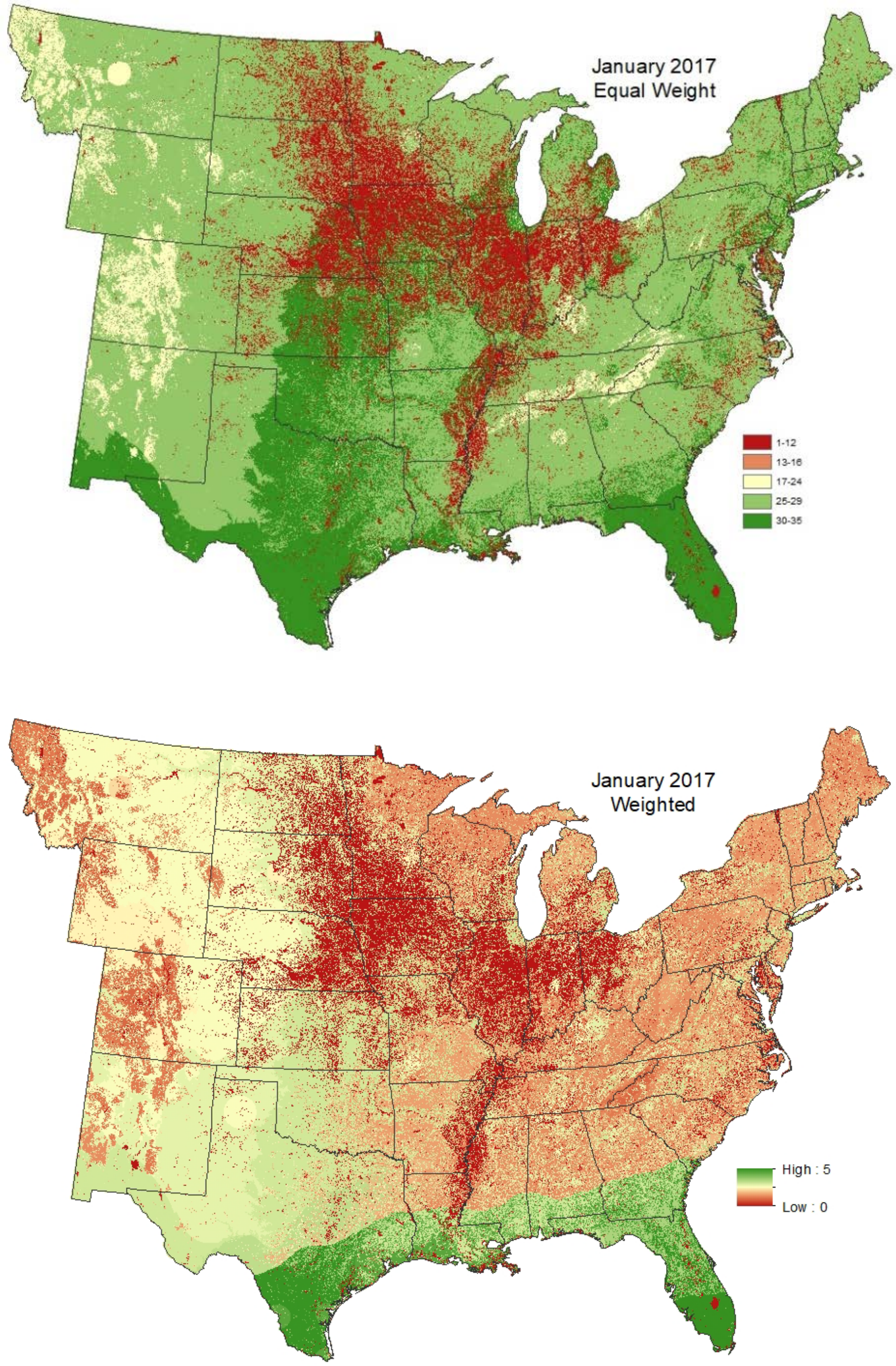


Figure 5.5. January 2017 Equally Weighted and Individually Weighted Models

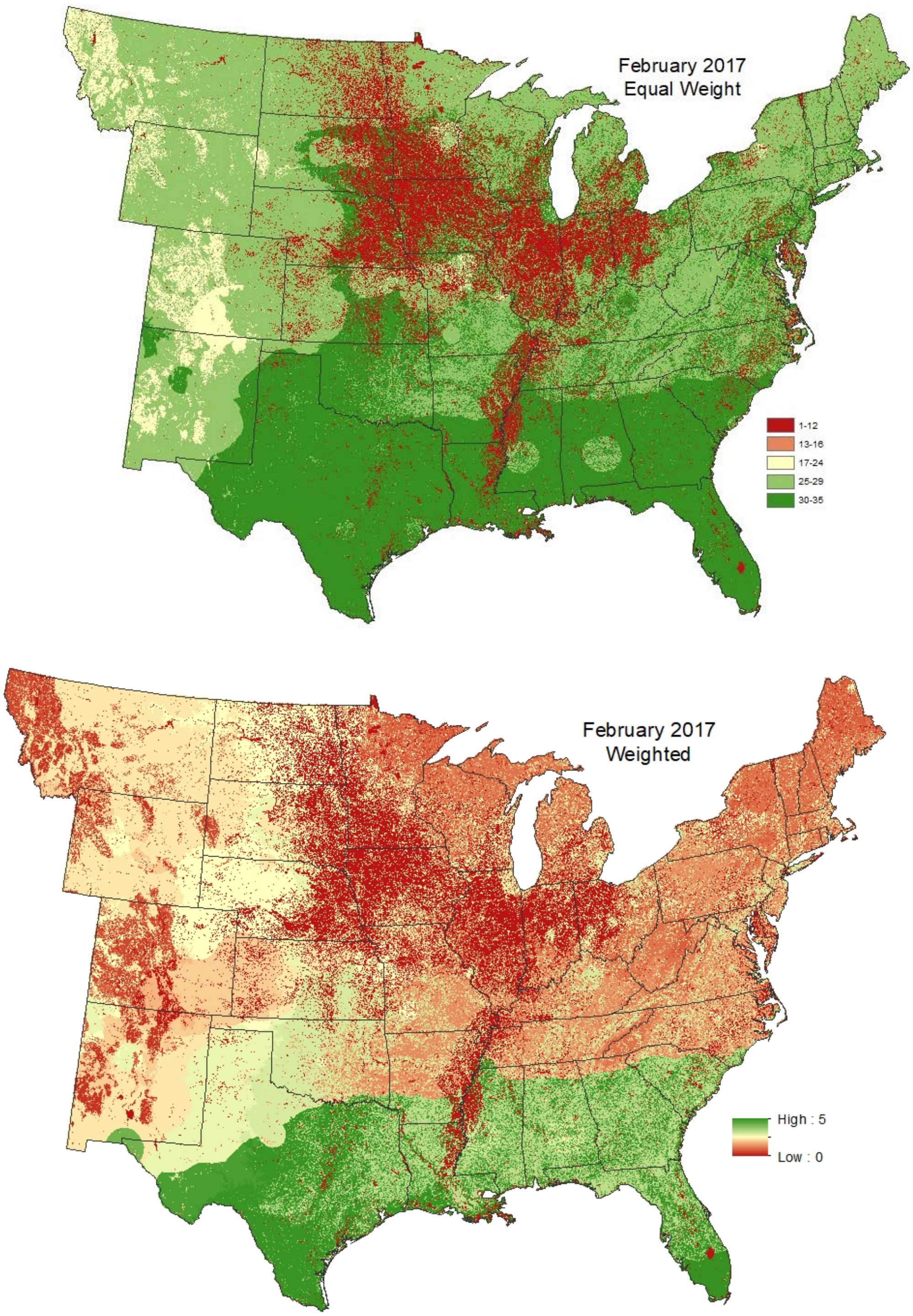
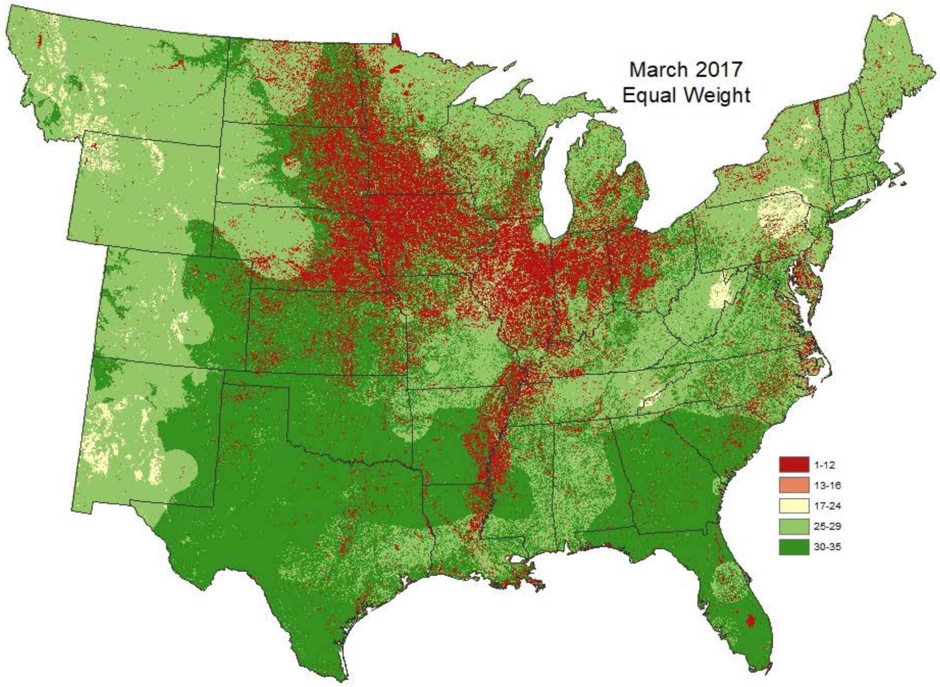


Figure 5.6. February 2017 Equally Weighted and Individually Weighted Models



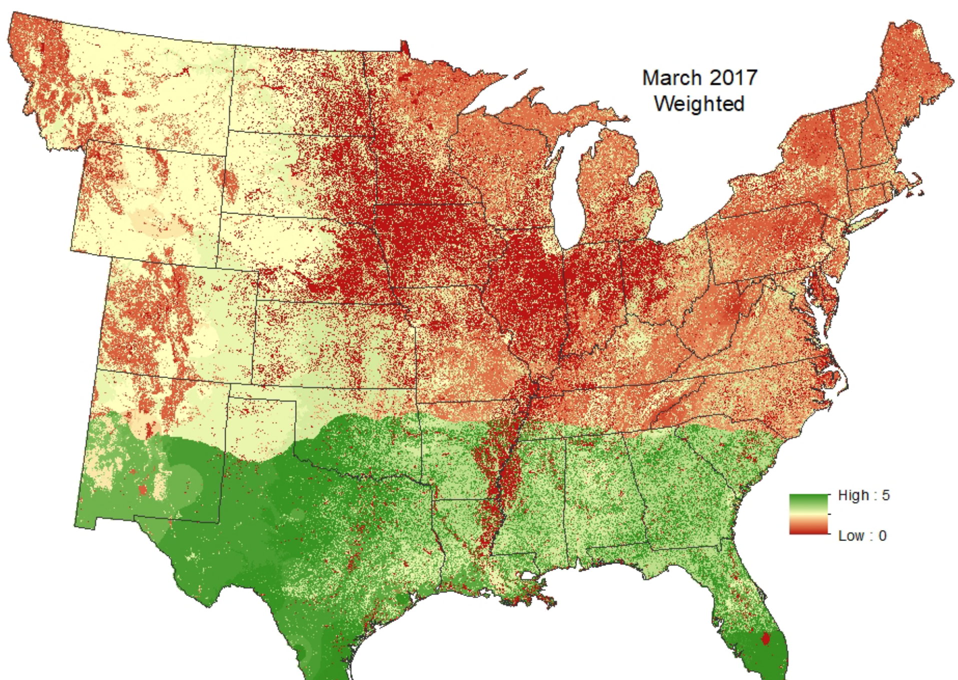
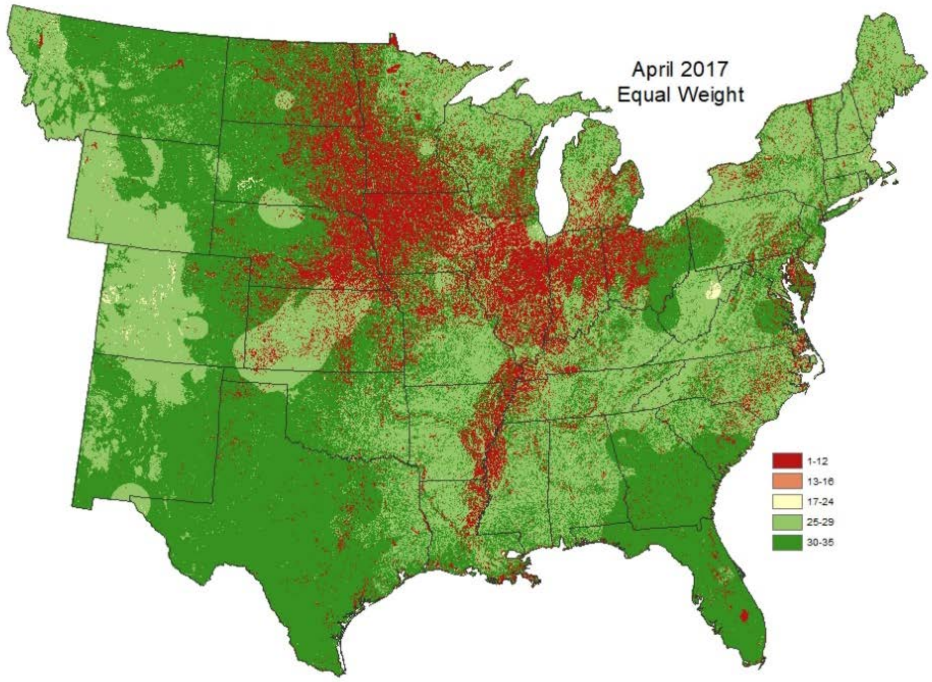


Figure 5.7. March 2017 Equally Weighted and Individually Weighted Models



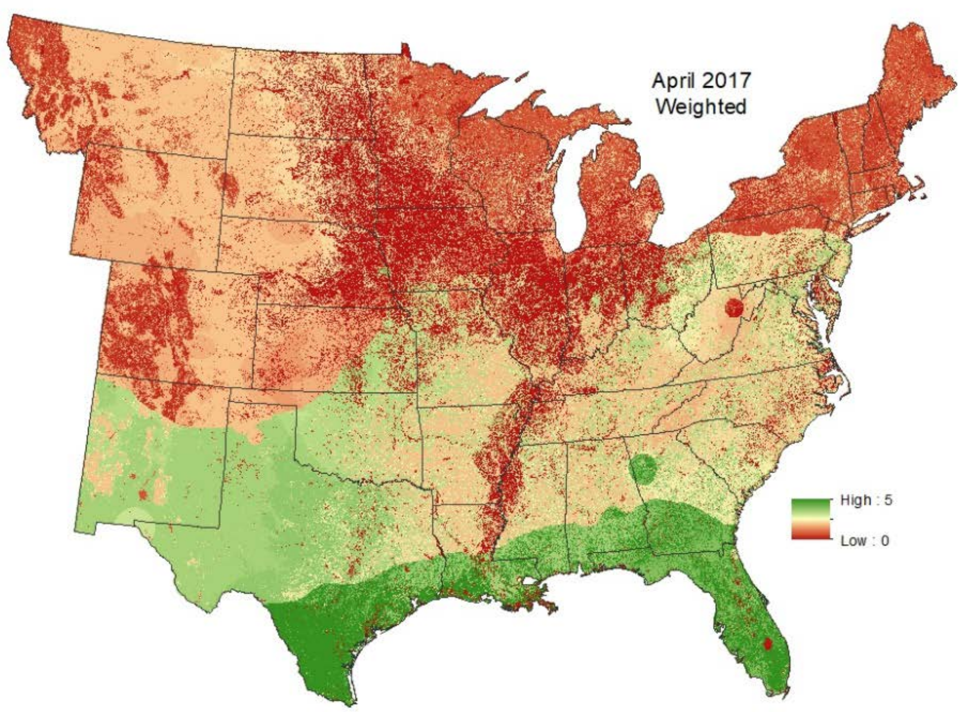


Figure 5.8. April 2017 Equally Weighted and Individually Weighted Models

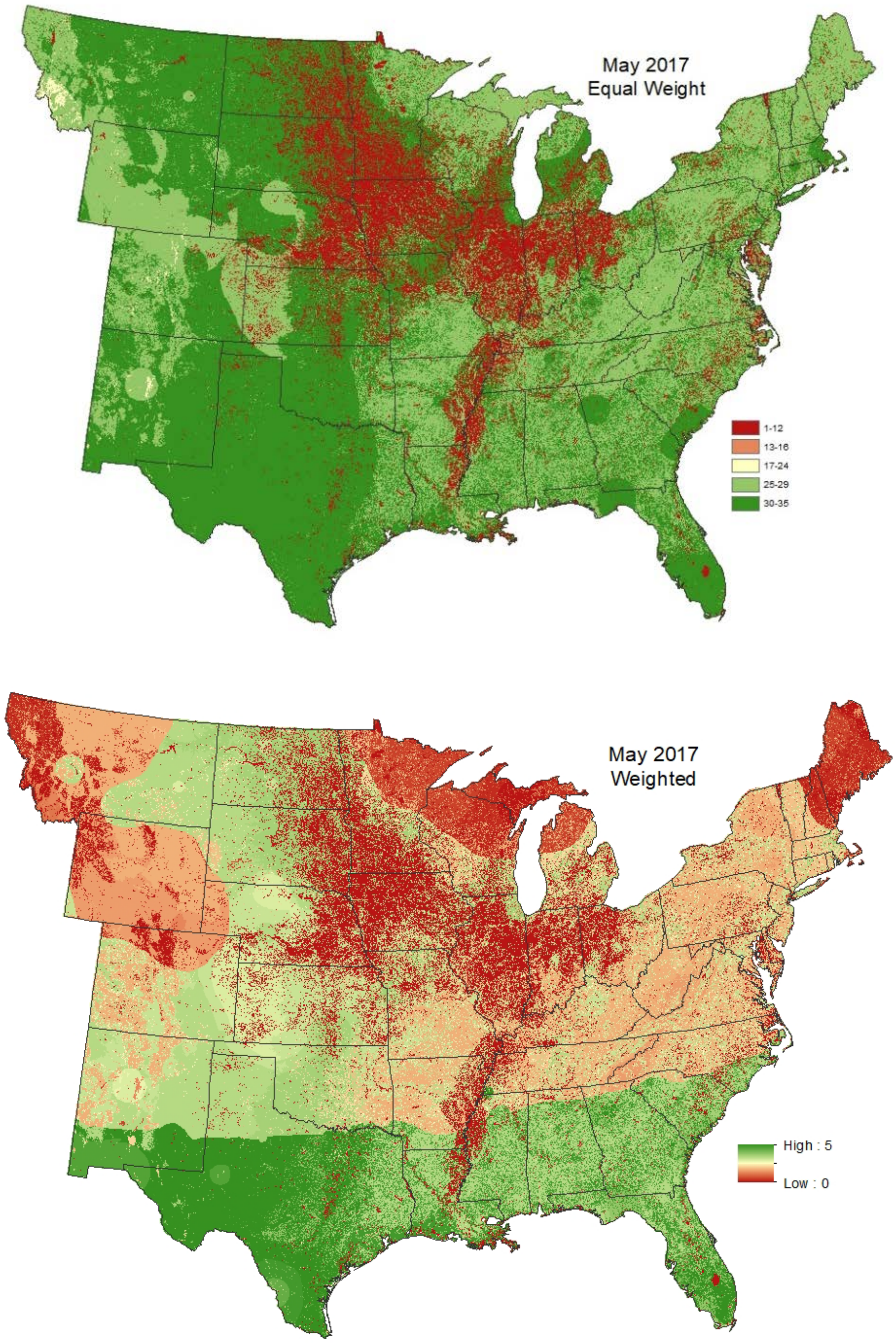


Figure 5.9. May 2017 Equally Weighted and Individually Weighted Models

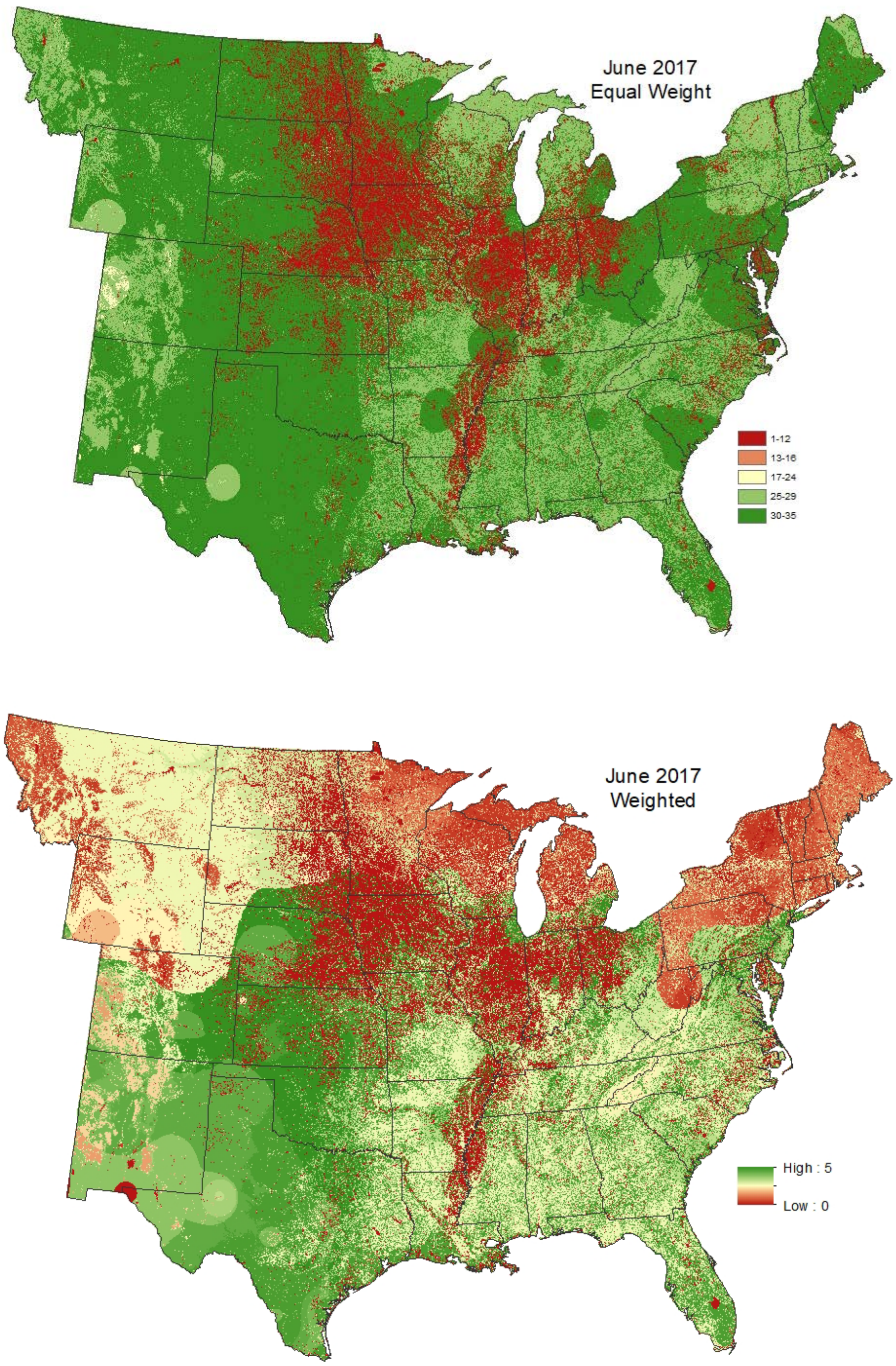


Figure 5.10. June 2017 Equally Weighted and Individually Weighted Models

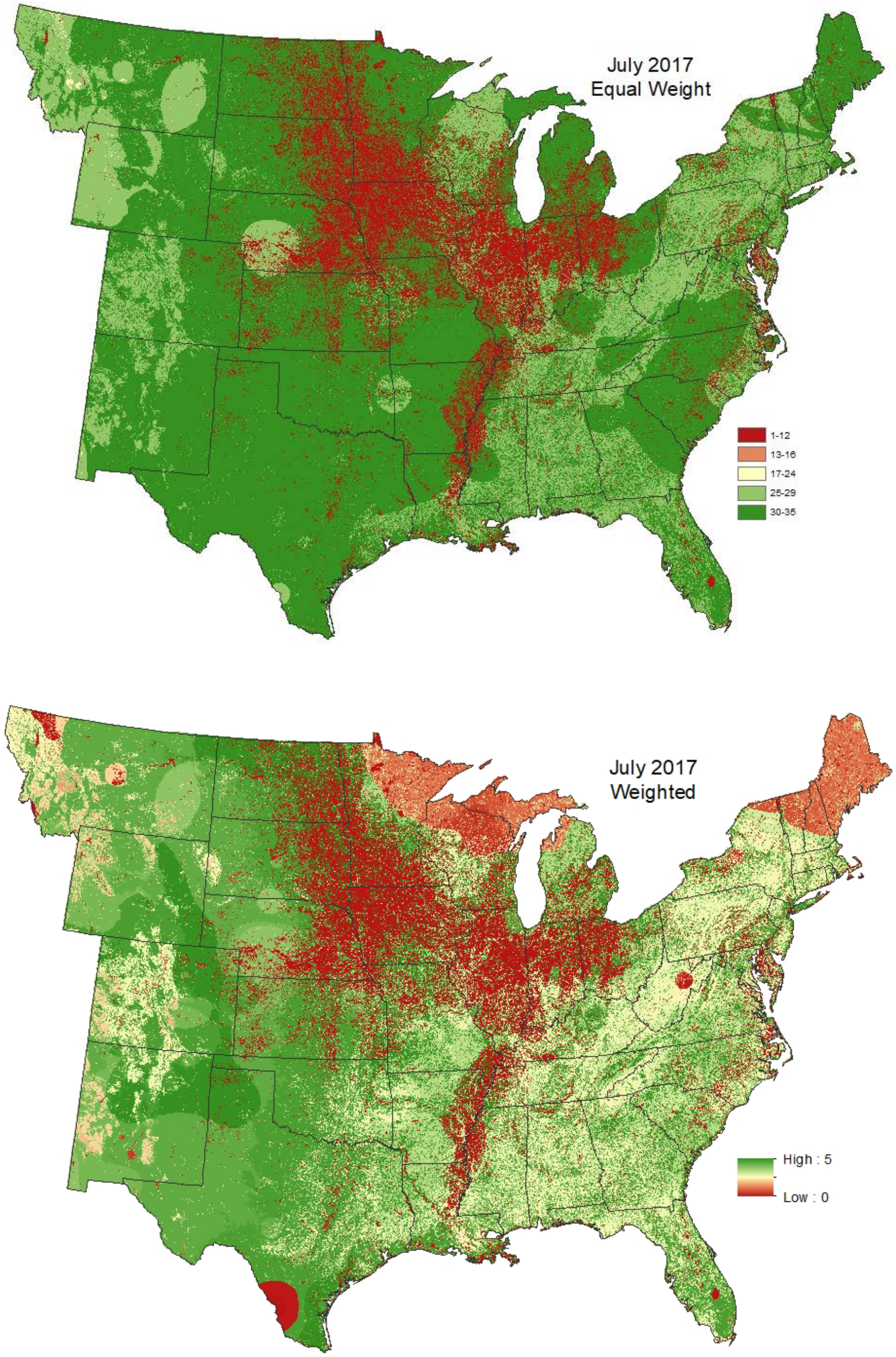


Figure 5.11. July 2017 Equally Weighted and Individually Weighted Models

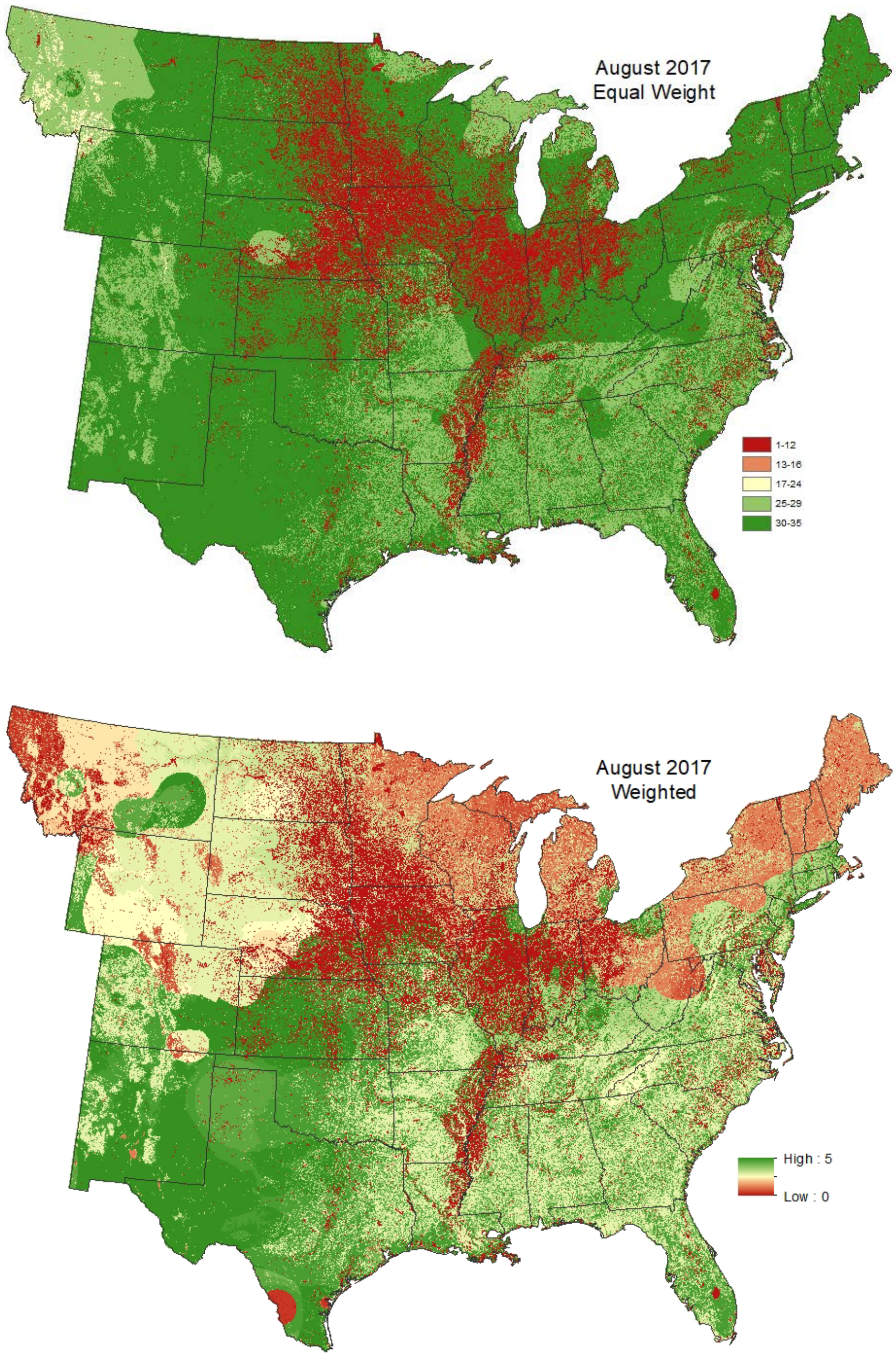


Figure 5.12. August 2017 Equally Weighted and Individually Weighted Models

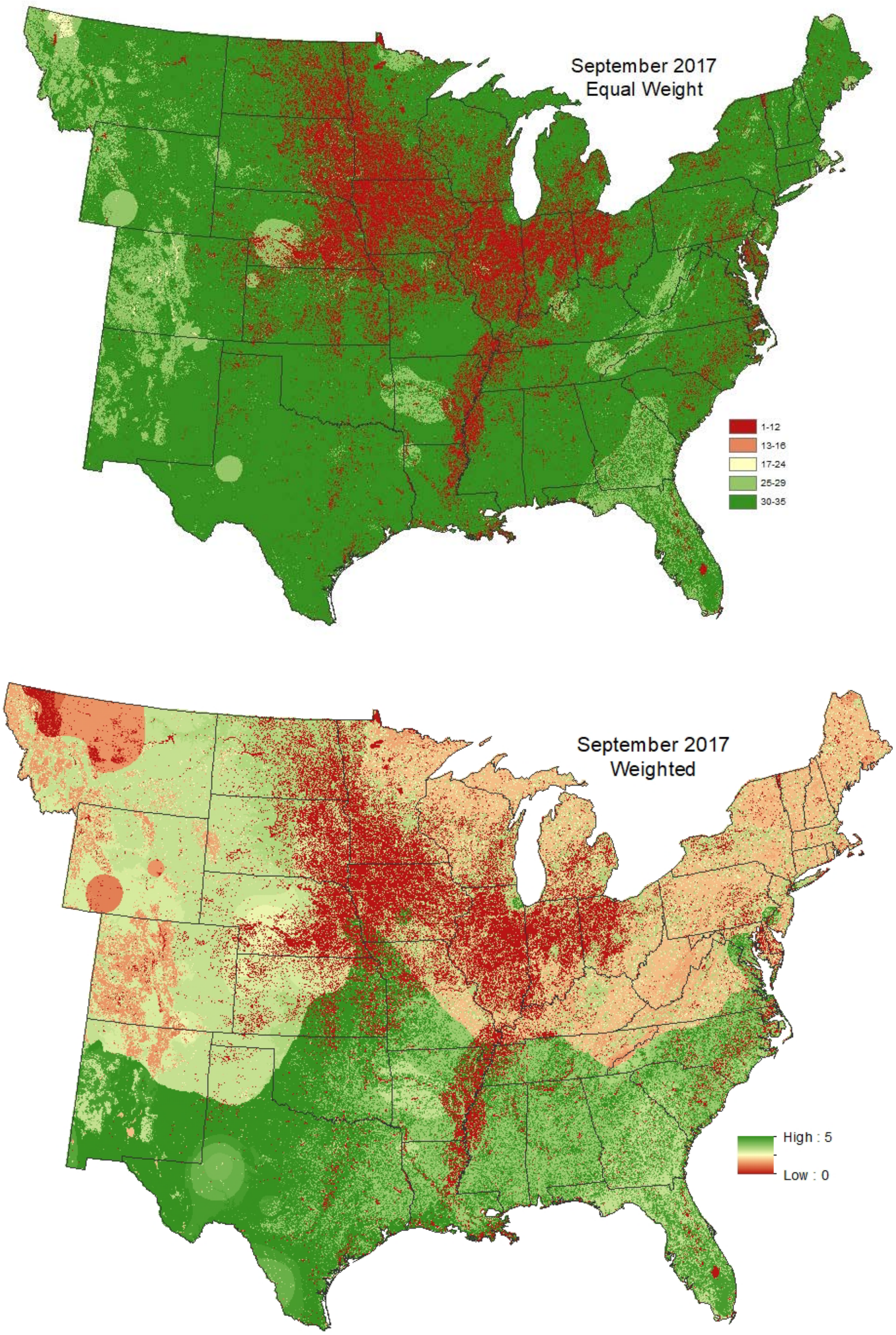


Figure 5.13. September 2017 Equally Weighted and Individually Weighted Models

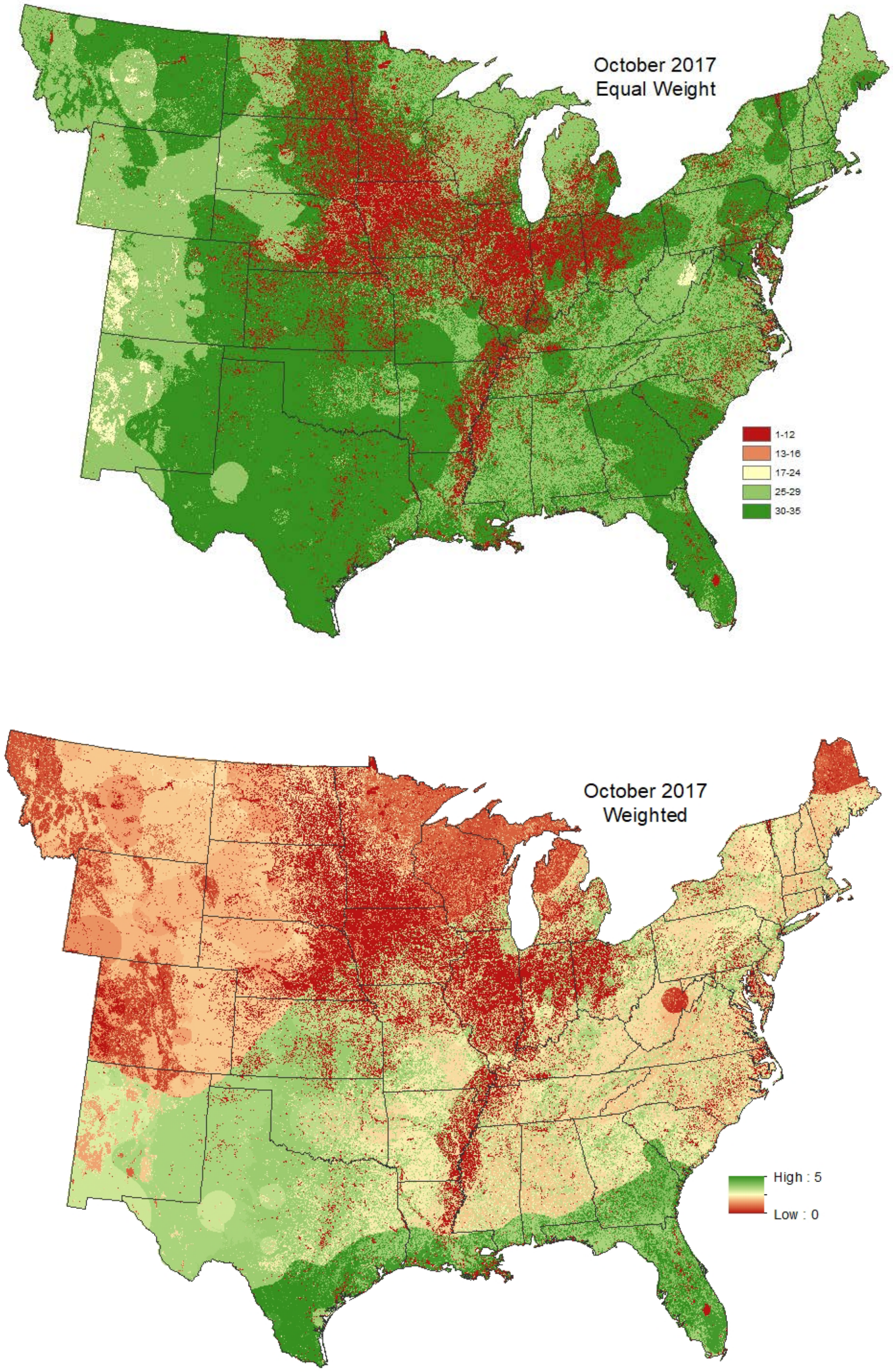
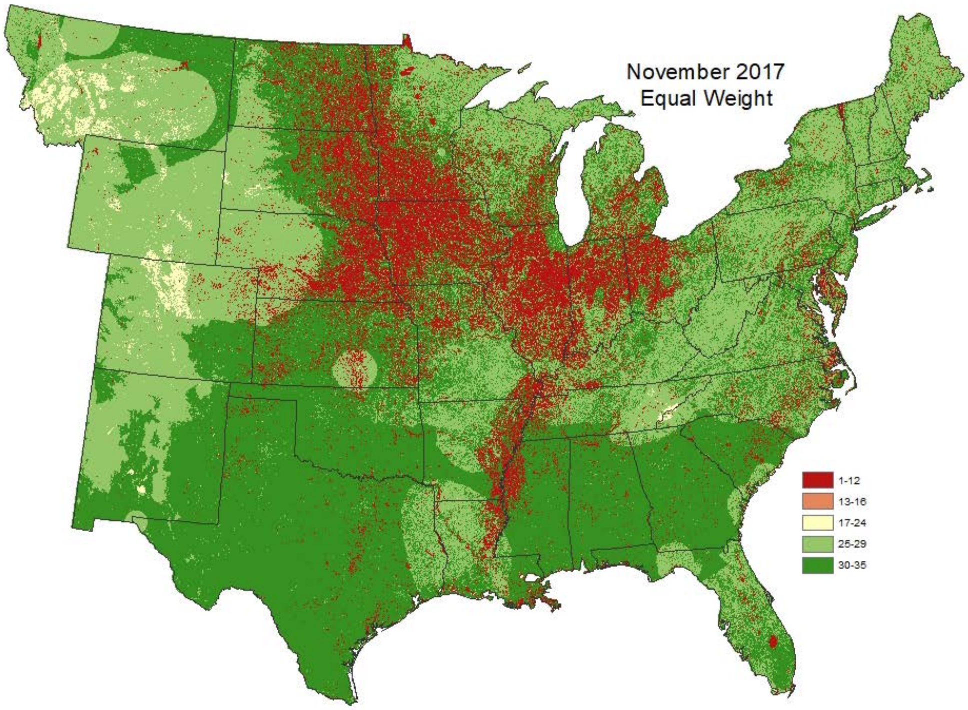


Figure 5.14. October 2017 Equally Weighted and Individually Weighted Models



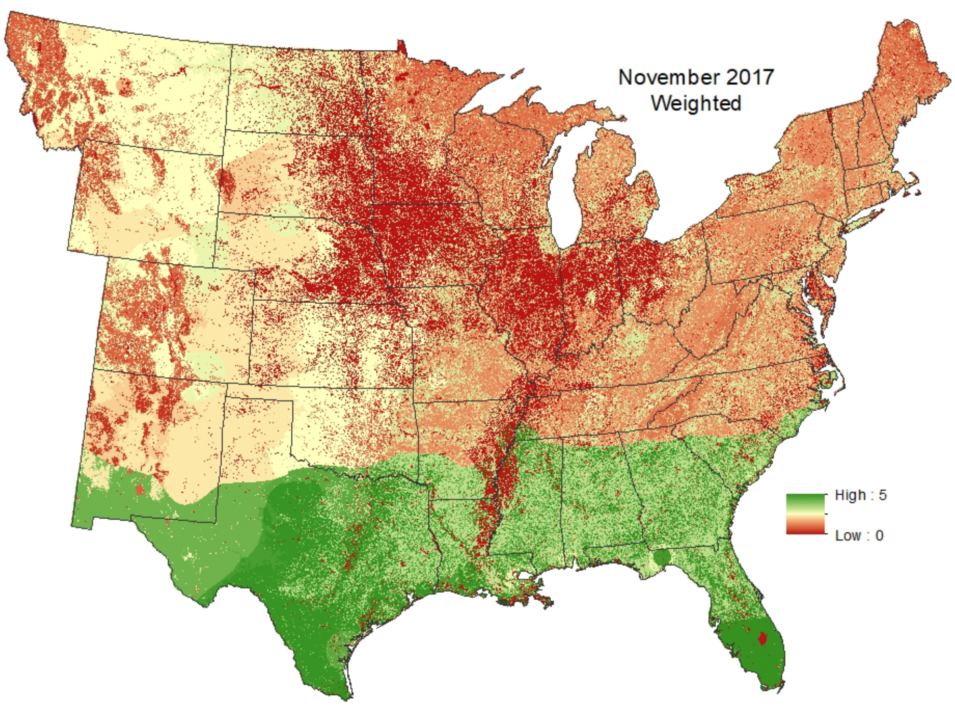


Figure 5.15. November 2017 Equally Weighted and Individually Weighted Models

5.3 Corn and Soy Mask

The red cells in the Midwest and Great Lakes Regions were a definite cause for concern. The majority of the cells were dark red with a score of zero making them a result of one of the mask layers. In an effort to determine the causation of the uninhabitable areas, as well as the potential effect, the model was run again using the weighted layers; however, the corn and soy mask was omitted from the raster equation. When compared side by side with the summer breeding grounds highlighted, the reality of the red cells became unequivocally clear.

With the corn and soy mask removed, the site suitability beneath the mask revealed a different picture. The layers and cutoffs were unaltered with corn and soy scoring a one for poor site suitability within the cropland use layer. However, the other variables were favorable enough for most cells to still score in the habitable range for site suitability. The mask was employed to supersede all other variables due to the fact that the impact of the GM resistant varieties eliminated all milkweed and nectar producing plants from that cell. While using the GM varieties likely has cost implications, returning to original practices where herbicides were not sprayed as heavily could have a large and immediate positive impact on monarch site suitability. (Figure 5.16)

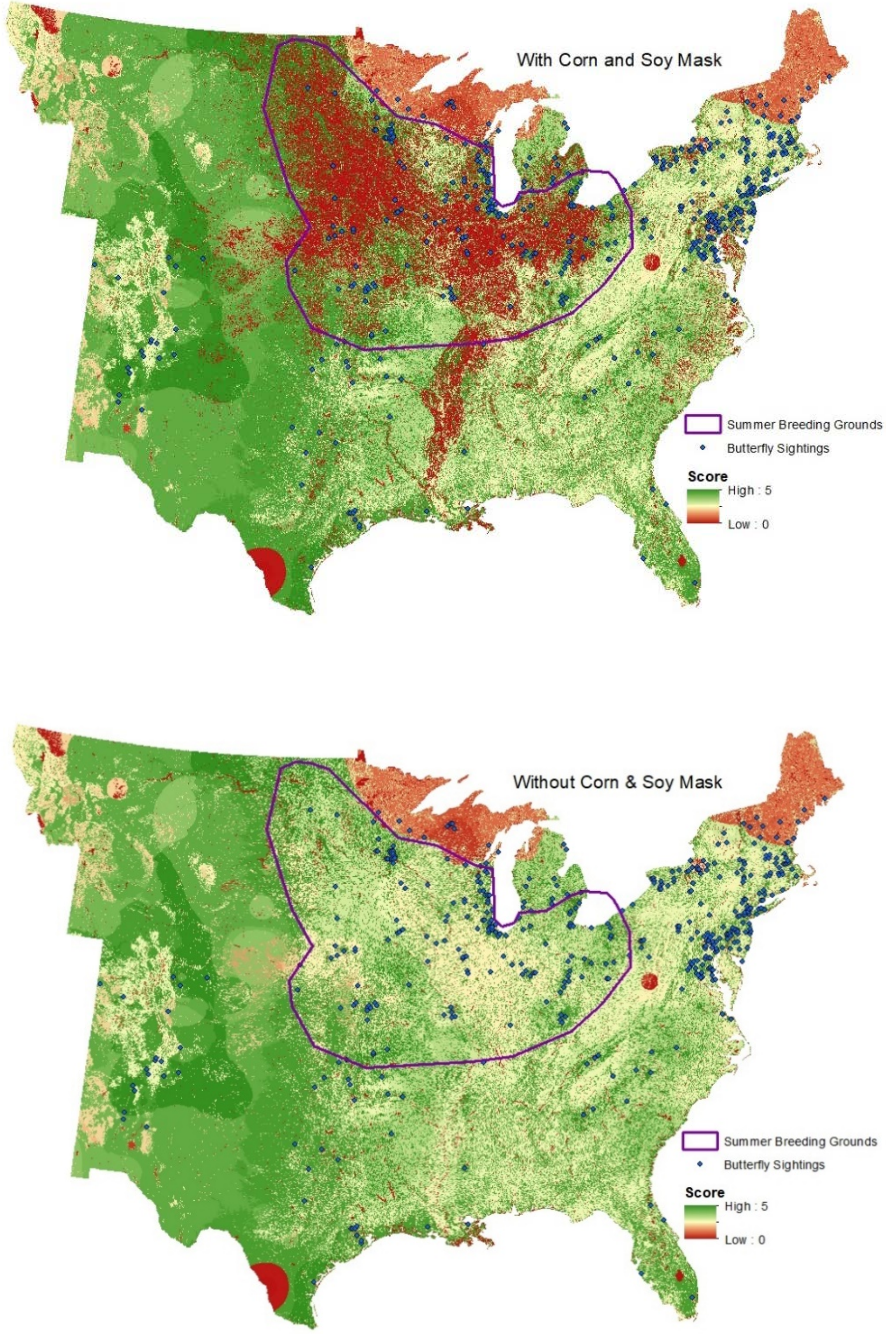


Figure 5.16. Site Suitability with and without the Soy and Corn Mask

5.4 Butterfly Sightings

As a test of validity and accuracy for the weighted layers, the butterfly sightings from the *Journey North* database were added. Theoretically, the sightings should be where cells were habitable (yellow) to optimal (green). If butterflies were located in cells with poor suitability (red), then it would be necessary to explain why they were in an unsuitable location or consider how the model could be changed to better understand the discrepancies. While the leading edge of the northern migration sightings validated the weighted model, once butterflies began the southern migration, it was less clear. While this may seem to invalidate the model initially, there was a reasonable explanation.

After the model was analyzed using equal weight for all variables, the suitability was too optimistic. With studies that had reported that Eastern monarchs were encountering issues, the equally weighted model did account for variations in the influence of factors. Since the model did not corroborate research that was already available, it was reasonable to make adjustments in an effort to account for factors that had more or less influence on the model outcome. The second iteration utilized individualized weights for each variable based on the findings from other studies. To test the validity of this model, butterfly sightings were used for each month to track the migration as it coincided with site suitability conditions.

November 2016 (Figure 5.17) marked the return of the southern migration bringing a close to the 2015-2016 migratory year. While sightings were in areas that clearly lacked suitability, there was a valid reason. The biological trigger that butterflies receive is not fully understood; however, it is believed to be related to temperature

(Harvey et al., 2015; Oberhauser, 2004; Solensky, 2004). Until the butterflies received the trigger, they would have continued with breeding and recolonization resource expenditures. The last eggs that were laid would not have become butterflies for approximately 30 days or longer, dependent upon if cooler temperatures slowed the life stages. If temperatures fell below 55°F, the newly emerged butterflies would not have been able to fly, and mobility would have further decreased as temperatures continued to fall. The reality in this case was that while a sunny day with temperatures above 55°F would have allowed these butterflies to fly and be observed, they would likely not complete the journey to the overwinter sites before succumbing to low temperatures. In short, the last generation of eggs and larva would have been left behind to survive for as long as possible until all sightings in the northern United States disappeared.

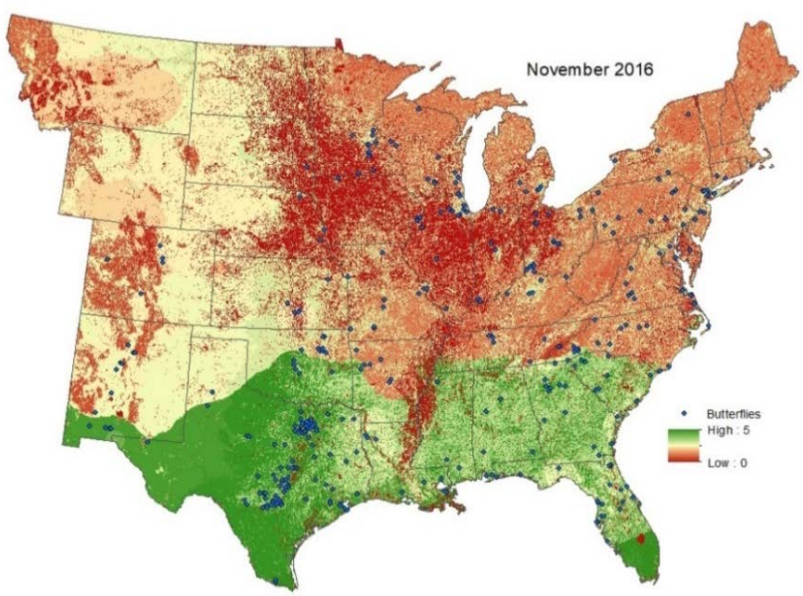


Figure 5.17. November 2016 Weighted Layer with Corresponding Butterfly Sightings

As the first full month of the overwinter season, December 2016 (Figure 5.18) provided the stark reality that some monarchs would not complete the journey south. The model suggested that the butterflies had largely retreated to Mexico or the last remaining optimal sites in the southeastern United States. There were sightings in Texas that suggested that those may be the last monarchs making the trip to the overwinter sites, as well as sightings that were in possible sink locations. As the most probable sink population, Florida had the most sightings outside of the migratory flyways with 37% of the total sightings for the month. December validated the model, as well as the hypothesis that the November sightings were the last generation of newly emerged butterflies that would not complete the journey.

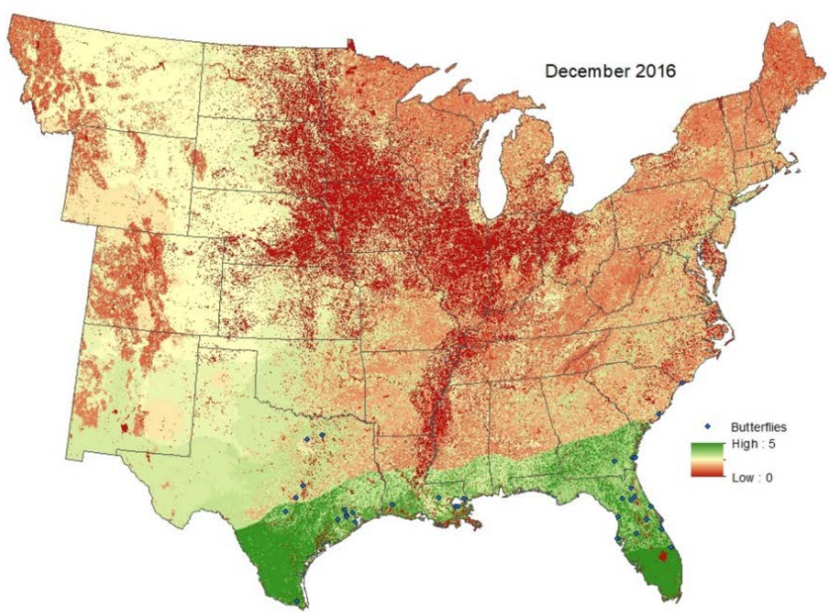


Figure 5.18. December 2016 Weighted Layer with Corresponding Butterfly Sightings

January 2017 (Figure 5.19) was reasonable for overwinter numbers and provided more validation for the model and its respective weights. The butterflies were sighted only within the remaining optimal sites with a large presence in the possible sink locations. Hilton Head, South Carolina, has recently been identified as having a permanent population of monarchs that do not leave during the overwinter months, which would make that location worth observing in future migratory seasons (Journey North, n.d.). Florida held strong with a steady number of sightings while Texas sightings decreased overall. It was also verified that the northern Texas sightings from December were likely the last individuals in transit to Mexico.

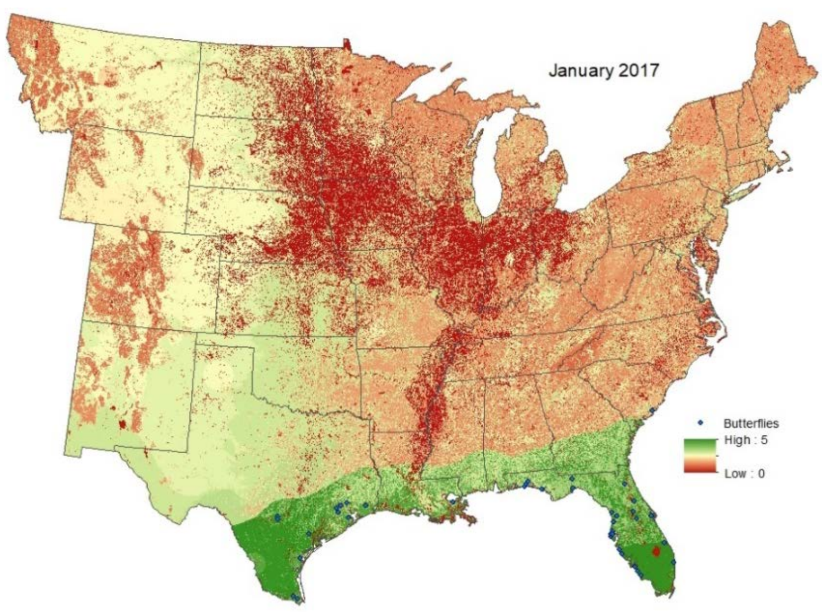


Figure 5.19. January 2017 Weighted Layer with Corresponding Butterfly Sightings

February 2017 (Figure 5.20) was similar to January with consistent sightings in Florida, Hilton Head, and the Gulf Coastline. This month showed strong correlations between the results of the weighted model and the sightings data. While some butterflies do exit the overwinter reserves in late February, March is typically when the formal migration north begins. As expected, March 2017 (Figure 5.21) displayed the leaders of the northern edge of the 2016-2017 migratory season. The butterflies sighted migrating north were likely the Methuselah Generation from the previous year. While their life expectancy is longer than most generations, their time on this migration was short. After laying the first eggs, this generation exited the population yielding to subsequent generations to complete the journey to the summer breeding grounds. Also as expected, the butterflies moved directly north out of Mexico with the leaders still within the optimal ranges. Since sightings remained within the suitable areas, March provided more validation to the accuracy of the weighted model.

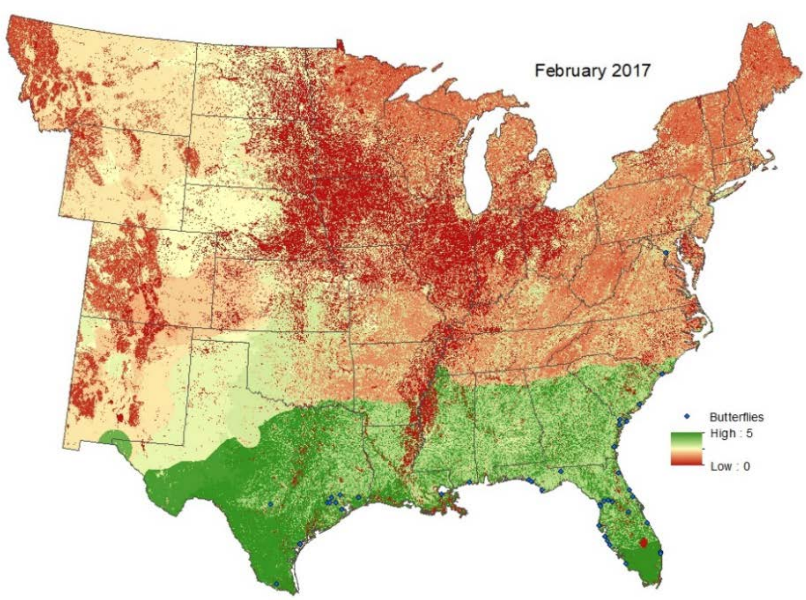


Figure 5.20. February 2017 Weighted Layer with Corresponding Butterfly Sightings

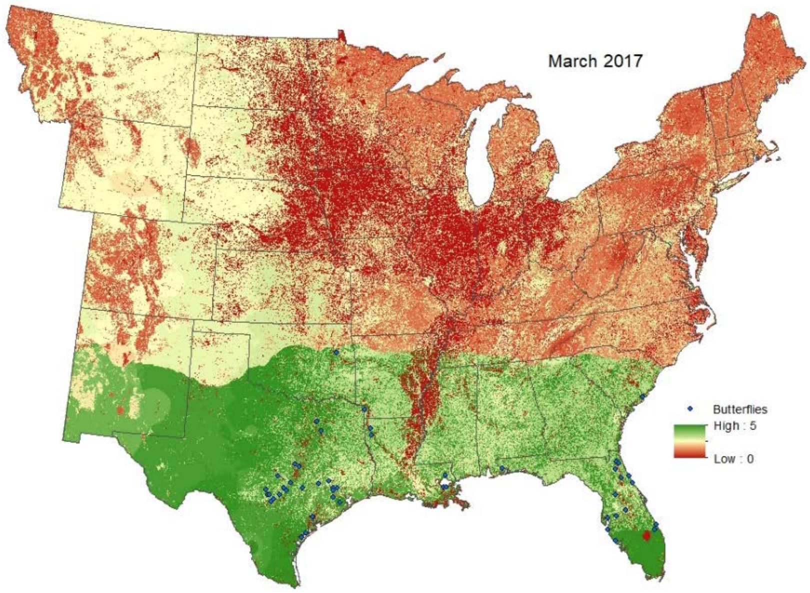


Figure 5.21. March 2017 Weighted Layer with Corresponding Butterfly Sightings

April 2017 (Figure 5.22) continued the journey north with the members of the first generation beginning to enter the migratory flyways. The sightings revealed the first arrivals at the summer breeding grounds with butterflies located largely in optimal to acceptable locations with the exception of the corn and soy cells which would just be entering the planting months. A few butterflies were sighted in Kansas and Nebraska in areas that scored poorly in the model; however, these outliers were very close to optimal locations making their sightings less of a concern.

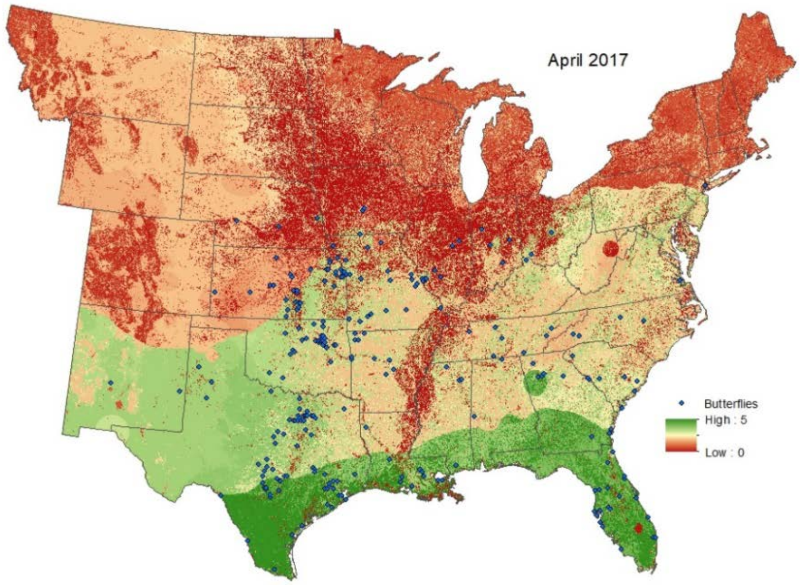


Figure 5.22. April 2017 Weighted Layer with Corresponding Butterfly Sightings

May through October 2017 represented the recolonization of the 2016-2017 monarch season. These sightings contained the second, third, and fourth generations with population numbers proliferating through each month. May 2017 (Figure 5.23) still revealed the northern migratory flyway out of eastern Texas with still consistent sightings numbers in Florida and Hilton Head. Individual sightings typically were located at habitable and optimal site locations with many sightings still located over the soy and corn dark red cells in the summer breeding areas. As the temperatures warmed, suitability improved consistently further north facilitating the migration and validating the sightings data with the weighted suitability model. Areas with temperatures still too low to support butterflies were highlighted with the model, and sightings were not observed in those locations.

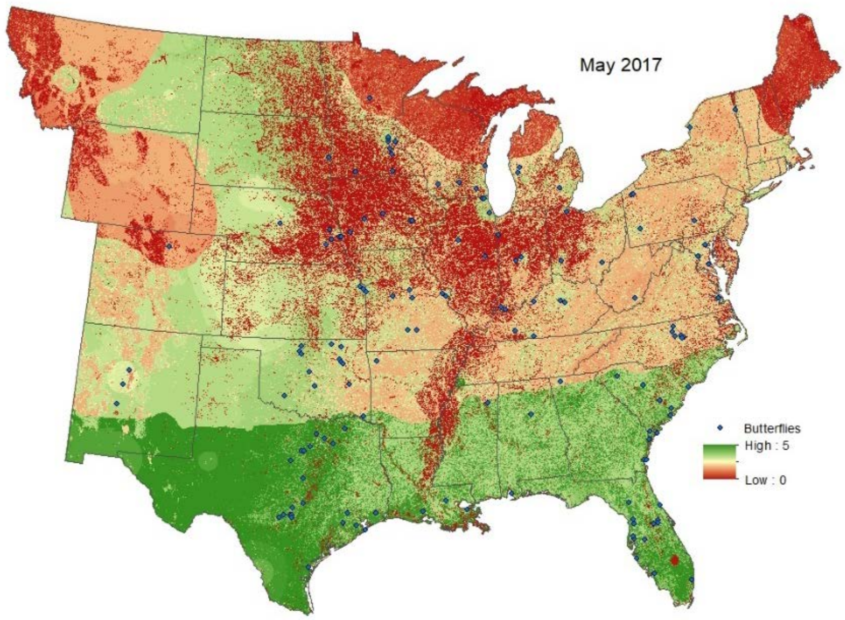


Figure 5.23. May 2017 Weighted Layer with Corresponding Butterfly Sightings

June 2017 (Figure 5.24) revealed the rapid improvement of warmer temperatures that butterflies prefer which continued through July (Figure 5.25). As population numbers and sightings increased, sightings began to concentrate more heavily to the east of the breeding grounds. With corn and soy planting season from April to June, these sites would have reached full levels of poor suitability (United States Department of Agriculture [USDA], n.d.). As suitable locations within the breeding grounds decreased, this would have influenced the possible exodus east. The model and sightings together visualized the increase in eastern sightings in areas of reasonable suitability with some sightings further north into areas that were less habitable. It appeared that while the areas in New Hampshire, Vermont, and Maine were generally not suitable, there were pockets of suitability that the butterflies could tolerate if more habitable areas were overpopulated with butterflies and larvae putting strain on the milkweed and nectar producing plants.

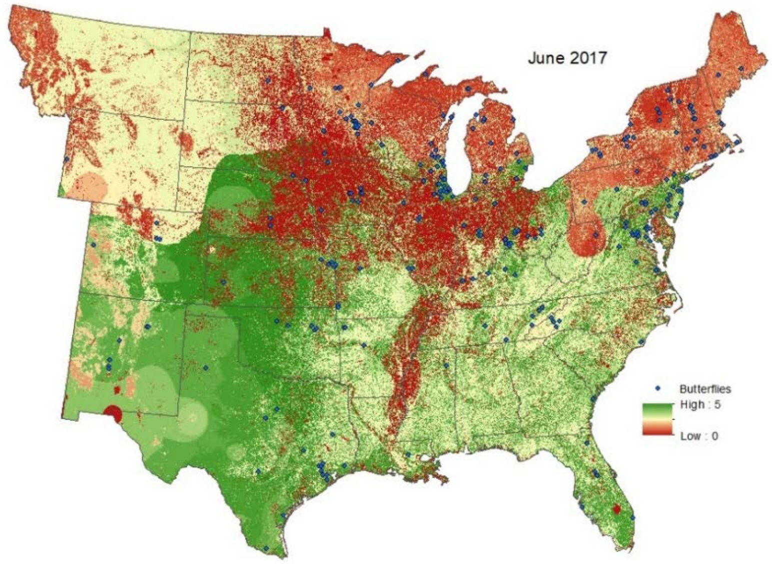


Figure 5.24. June 2017 Weighted Layer with Corresponding Butterfly Sightings

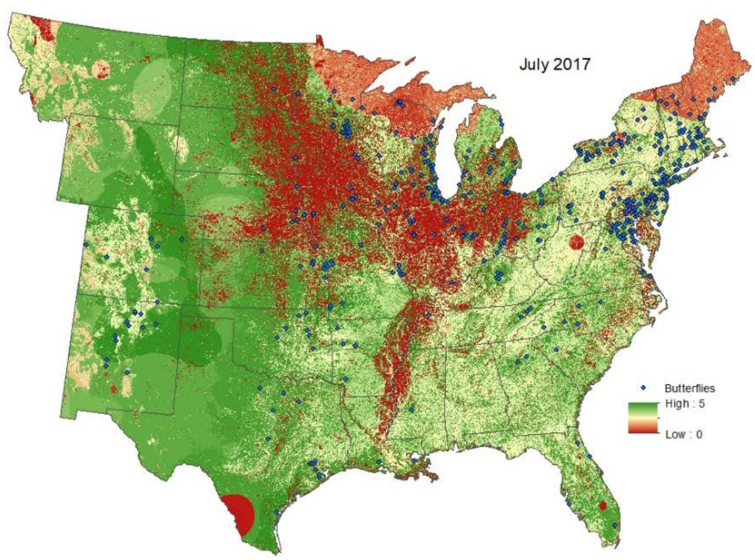


Figure 5.25. July 2017 Weighted Layer with Corresponding Butterfly Sightings

August (Figure 5.26) and September 2017 (Figure 5.27) provided more of the same butterfly activity witnessed in June and July; however, some site suitability decreased. During these months, temperatures began to fall in the northernmost states with low temperatures dipping below 55°F. While these temperatures would reasonably lower suitability, the butterflies were still in breeding mode and had not received the trigger to move south. With average temperatures still in a suitable range, the butterflies would likely have experienced periods of poor temperatures which decreased their mobility; however, once temperatures warmed, they would have become mobile again and continued as normal. Despite the suitability not being good in some areas, the conditions were survivable which would not necessarily provide immediate concern for the model. The model merely identified areas that were less hospitable; how the butterflies adapted for bursts of cooler temperatures could have maintained their presence there despite the lack of optimal suitability.

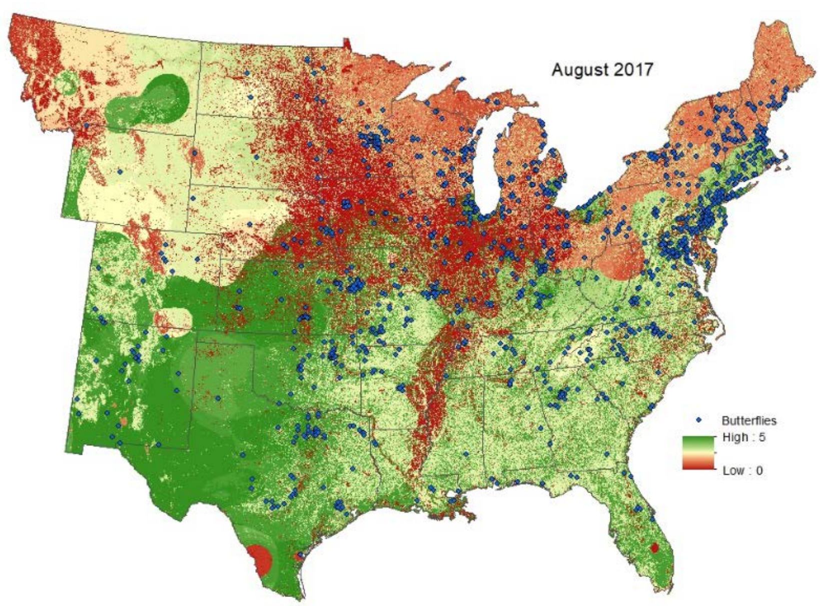


Figure 5.26. August 2017 Weighted Layer with Corresponding Butterfly Sightings

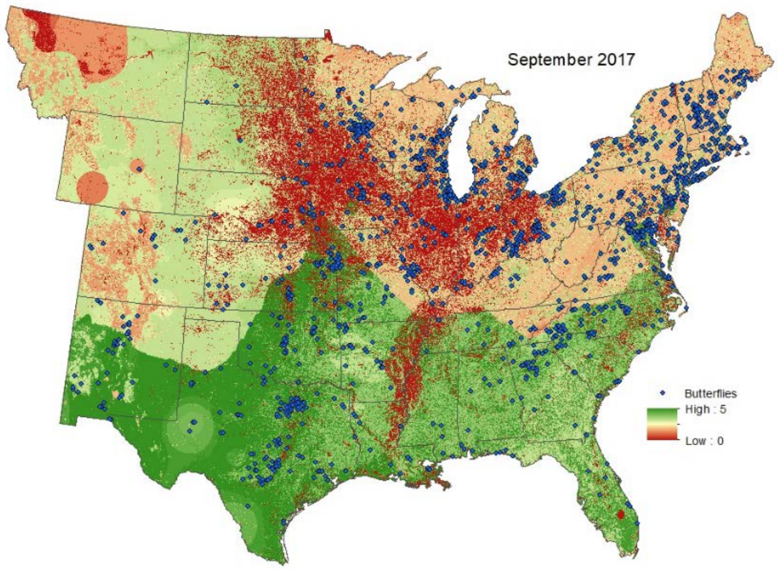


Figure 5.27. September 2017 Weighted Layer with Corresponding Butterfly Sightings

October 2017 (Figure 5.28) represented an important junction in the migration year. Populations were at the highest, yet suitability conditions were falling. During this month, conditions would likely converge to induce the trigger for the monarchs to return to Mexico; however, with individuals departing and entering the population, it was difficult to decipher which butterflies were already migrating, and which ones were newly emerging. It is important to realize that even though a monarch has received the trigger to stop breeding, eggs and larvae would still be present at the northernmost points. With the confusion created with southbound butterflies and newly emerged butterflies, sightings would be reasonably incoherent until the last viable generation (the Methuselah Generation) had moved south, and the individuals left behind had died out. The model successfully represented the falling temperatures and site conditions, as well as the monarch population at large being in a state of flux.

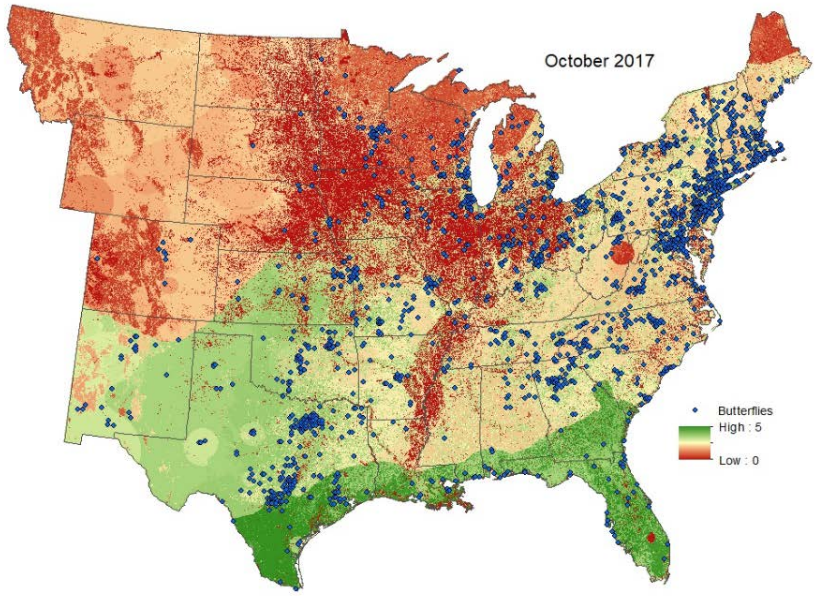


Figure 5.28. October 2017 Weighted Layer with Corresponding Butterfly Sightings

November 2017 (Figure 5.29) was similar to November 2016 in the fact that suitability and sighting locations were generally the same. With the Methuselah Generation entering Mexico and the last individuals left in the northern United States, the migration was coming to an end. However, 2017 had some interesting anomalies regarding sightings. Ward (2017) with the *Yale Climate Connection* observed that the more eastern population was migrating late. These butterflies were observed in Cape May, New Jersey, two weeks behind schedule. The sightings data corroborated this finding as the monarchs were visually moving down the Atlantic Coast. As with most of the November northern monarchs, most of this population probably would not complete their journey; therefore, the suitability and locations were commensurate with general trends observed in November 2016.

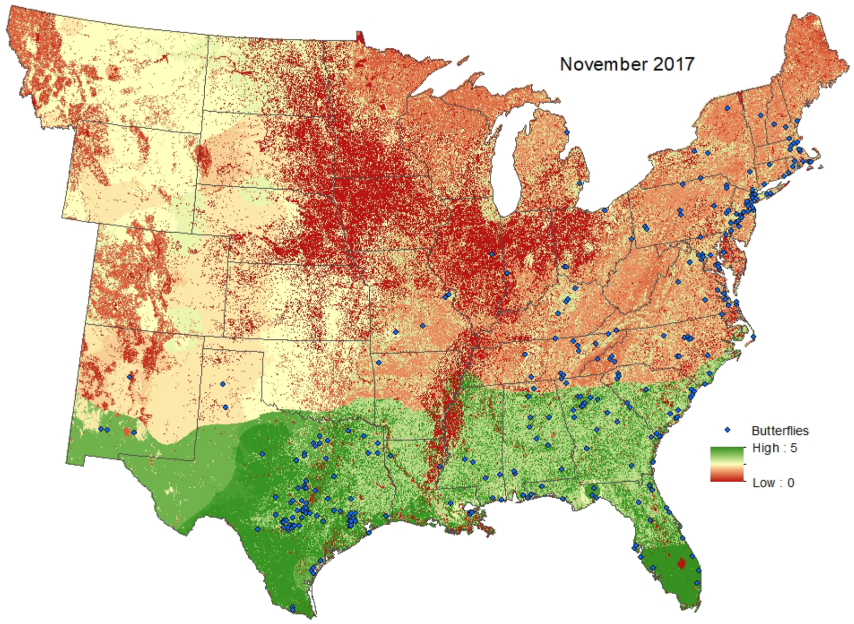


Figure 5.29. November 2017 Weighted Layer with Corresponding Butterfly Sightings

The monarchs located east of the summer breeding grounds were a possible cause for concern. Some scientists have noted that monarchs have been using more easterly routes back to Mexico (Journey North, n.d.); however, this study may indicate that the failing suitability of the summer breeding grounds has pushed the butterflies east seeking more suitable areas to recolonize. When a species is pushed out of its intended habitat, conditions may not be optimal; however, the suitability may be more favorable than the sites that they had vacated. This hypothesis would be worth following in future research to understand the negative impacts that GM crops may be having both directly and indirectly on local wildlife and ecology.

5.5 Sink Populations

Sink populations were first reported in southern Florida where monarchs were reported active year round (Harvey et al., 2015; Williams, 2015; Duhaime-Ross, 2014). With available milkweed and tropical temperatures, monarchs never appeared to receive the trigger to migrate to Mexico. Scientists and researchers began to question what made these butterflies different. According to McClung (2007), the Florida monarchs may even be a new sub-species of their migrating counterparts, while other scientists suggested that these monarchs may be migrating to Florida as opposed to Mexico (Williams, 2015). While the topic is still being debated, the reality appears to be that these butterflies are monarchs who are stuck in a perpetual recolonization mode.

Sink populations are generally recognized as an anomaly, but what if they are an indication of changes that may be coming? With the concern that climate change could bring warmer temperatures to higher latitudes, these colonies of non-migrating monarchs may be how this species is adapting. Scientists and researchers are asking serious questions regarding migratory monarchs, such as if conditions were to change, would more butterflies begin to lose their ability to migrate (Duhaime-Ross, 2014)?

When analyzing the output layers from the weighted model with the butterfly sightings, the overwinter and early northern migration months always had a presence of butterflies in Florida when the migratory population should reasonably be located elsewhere. While sightings were not great in number, they were consistent. Adding more validity to the argument that the number of sink populations is increasing, there was at least one sighting reported on the South Carolina Coast during the same months.

According to the Journey North (n.d.), residents of Hilton Head Island have reported that monarchs are no longer vacating the area during the winter months. The database entries added further credence to the claim that another sink population may be developing there (Howard & Davis, 2010). However, sightings are currently too low to deem the South Carolina colony a sink population, but the area should be investigated over the coming years in an attempt to understand why these pockets of butterflies never leave. If loss of their migration trigger were established as the causation of their static location, it would be reasonable to consider sites with similar suitability conditions for other possible sink population locations.

While one year is not statistically enough data to prove any new trend, it is enough to begin to identify areas that may be of interest. After analyzing the maps, especially the overwintering and early migration months, the following areas may be areas of interest for developing sink populations: Hilton Head Island, South Carolina; Pensacola, Florida; Mobile, Alabama; and New Orleans, Louisiana (Figure 5.30). These areas not only recorded butterfly sightings during overwintering months, they reported steady sightings year round indicating that a stable breeding population was present during all months. These locations were generally habitable to optimal site locations which was consistent with conditions in South Florida. As citizen scientists are encouraged to accurately record more sightings, it may be possible to gain a better understanding of these areas of interest and to identify new areas where sightings were not yet consistently reported.

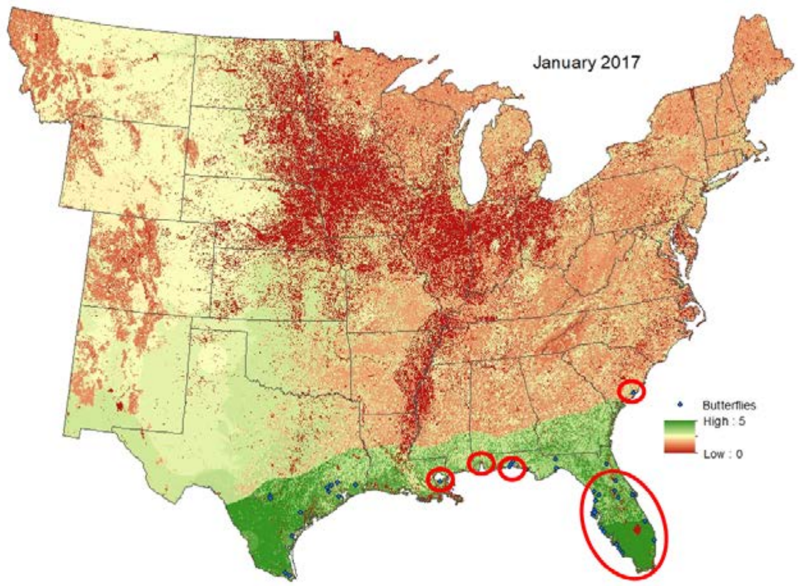


Figure 5.30. Locations of Possible Sink Populations

5.6 Fractured Flyways

One of the goals of this research was to identify gaps in the northern and southern migration flyways. The large amount of soy and corn that were likely genetically modified (GM) varieties provided an alarming negative impact at the summer breeding grounds where monarchs completed most of their recolonization activities. The breeding grounds were generally habitable to optimal except for the mask that was applied eliminating all corn and soy cropland uses from the habitable ranges. Another notable observation was that corn and soy had numerous uses along the Mississippi River Basin (Figure 5.31). This line of red cells created a divide between the east and west sides of the study area. It is uncertain, however possible, if the butterflies may not be crossing the uninhabitable zone. While some sightings do appear on each side, it is inconclusive if the monarchs to the east may have ventured north from some of the coastal areas, or if they were members of the northern migration out of Mexico. However, once the mask was removed, site suitability had a visible change from uninhabitable to habitable making this a definite fracture. With land use and agriculture practices clearly anthropogenic, it stands to reason that discontinuing these practices could benefit the recolonizing butterflies as well as other species of insects and pollinators who were negatively impacted.

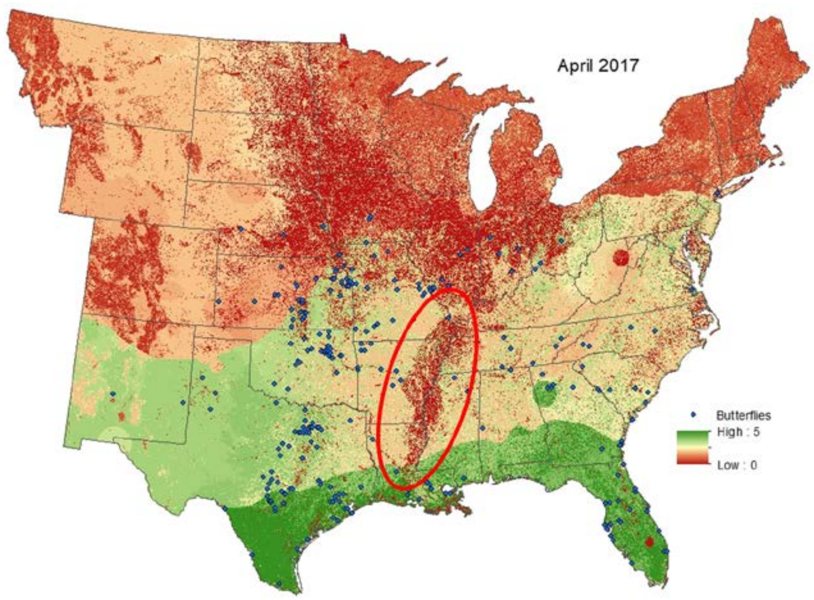


Figure 5.31. GM Corn and Soy Uses along the Mississippi River Basin

Another concern regarding GM corn and soy was the large presence of uninhabitable sites within the summer breeding grounds. With the high quantity of unsuitable cells, monarchs may be being forced to seek more habitable sites to recolonize. The high number of sightings to the Northeast may be displaced monarchs forced to seek more suitable conditions further altering the migration flyways. While there is not enough data or evidence to define this as a trend, monarchs were sighted in numbers that may have exceeded the numbers sighted in the breeding grounds.

Ultimately, this could be an artifact of an area with higher reported sightings, but these sightings continued consistently into the final generations of 2017.

Sink populations also add fracture to flyways by providing an exit from the general migratory populations. It is not certain if these butterflies permanently leave the migration, or if they could possibly re-assimilate at a later date. However, this is cause for concern due to the parasitic infested milkweeds that are frequently consumed by sink population larvae (Satterfield et al., 2015; Altizer et al., 2000). If unhealthy butterflies who have remained separate suddenly rejoined the larger population, the outcome could add further damage to populations by creating generations of less healthy adult butterflies.

5.7 Future Studies

The current concern surrounding Eastern monarchs is ongoing. Conservationists have improved flyways by planting indigenous milkweed and nectar producing plants. They have succeeded in properly identifying some of the major problems that have aided in focusing manpower and funding to efficiently improve the areas in need. However, this study was merely a snapshot in a long series of migrations past, and migrations yet to come. The Eastern monarch's story is not over, and their problems are not solved. Unlike certain conservation causes where the only method of support is to donate money, monarchs can immediately benefit from beneficial use of the land and eliminating detrimental agricultural, commercial, and residential practices.

While the Eastern monarch's story is not complete, neither is the research. As data becomes available through the *Journey North* database, and more years of historic variable data become available, it would be possible to continue using this study's methods to observe how the sites and sightings are evolving. One migration is not enough research to delineate any sustainable trends, but it can set a baseline. Future data will show how site suitability is changing, as well as how the butterflies are adapting. Past data could also be studied with proper caution allotted for any deficiencies that may exist.

By exploring the past and future patterns of the corn and soy crops with the geocoded monarch sightings, we could begin to determine if the butterflies are being displaced from their summer breeding grounds. Developing sink populations could provide insight into how monarchs are adapting to changing conditions, as well as what the future may hold if climate change brings warmer temperatures further north. It would also be beneficial to explore data options for Mexico to unravel some of the conditions and concerns surrounding the overwinter sites including the migration in and out of the United States. It may also be of interest to conduct a study of the Western Monarch population. Their decline and sites could provide input for site suitability for the eastern population, while simultaneously supporting research and conservation for them as well.

Going forward it would be necessary to monitor the variables from this study for any instances of change. If agriculture practices change, how would those changes affect the butterflies? If development increases, what effects would it have on flyways? If weather and temperature conditions change, how would it alter migrations? While this study focused predominantly on 2017, the findings are current and pertinent. Pollinators are in decline, and their loss would have an impact on agriculture, plant life, food webs, and biodiversity. Answers are needed, and the time to achieve them is limited.

CHAPTER VI

CONCLUSION

Eastern monarch butterflies are one of the most recognizable butterflies in North America. They complete a 6000-mile migration every year and have done so without fail for centuries. They have roots that pre-date the Aztec Empire and have a prominent role in the culture and history of the Central American people. They are pollinators who improve our agriculture, and they have an aesthetic value that entices many gardeners to welcome them. They neither bite nor sting, nor do they harm the land that they traverse. However, despite the benefits, Eastern monarch butterflies are experiencing a decline that many scientists fear may eventually lead to their extinction. With the challenges that the butterflies face at their overwinter sites, summer breeding grounds, and along the migration flyways, scientists and conservationists are leading a movement to improve these conditions before monarchs reach terminal numbers.

However, despite years of low recolonization counts and low hectare counts at the overwinter sites, Eastern monarchs had a good year in 2018 (Figure 6.1). According to MonarchWatch (n.d), the number of monarch-occupied-hectares reached the highest number witnessed since 2007. While it is reasonable to have variations in populations from year to year, the past ten years have witnessed a rapid and unstable decline of monarchs assessed at the overwinter sites. The winter assessment is crucial to lepidopterists because at no other time are so many monarchs present in one place. In fact, there are so many present that counting the individual butterflies at each site would be impossible. Counts are collected in hectares based on the assumption that roosting butterfly density is reasonably static (Brower et al., 2004). Illegal logging and deforestation have squeezed the butterflies into even smaller areas due to the fact that they return to the same roosts that their great-great grandparents left the previous year. UNESCO has extended membership and protection to three of the largest preserves to manage and protect the vulnerable butterflies as they await their next journey north.

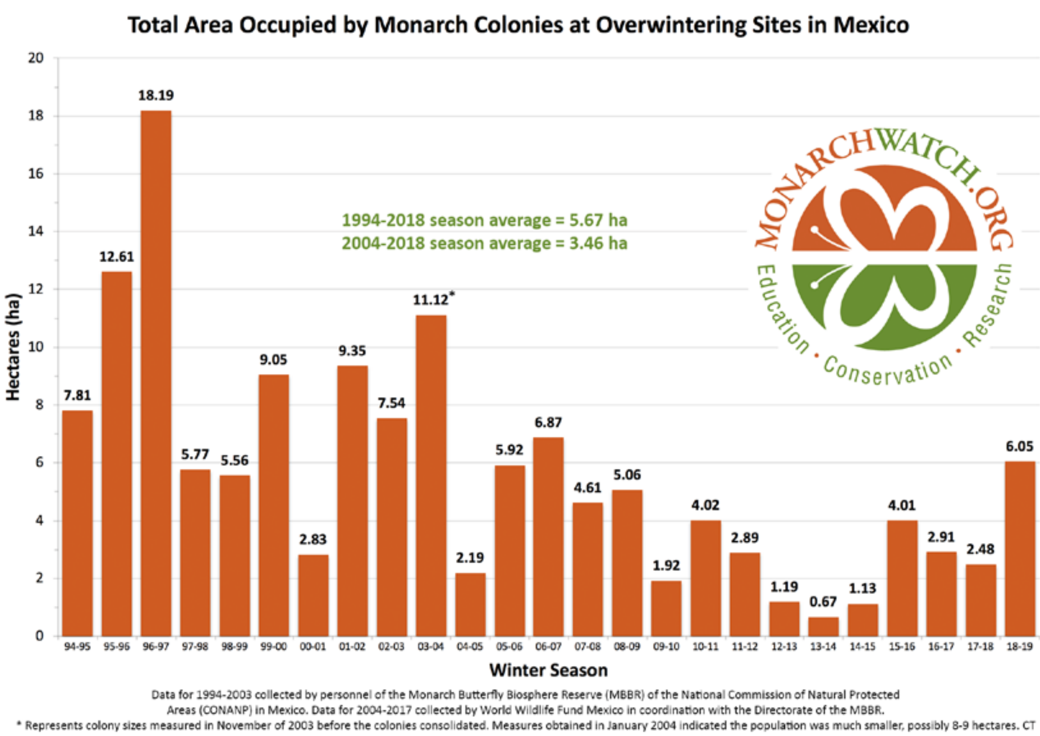


Figure 6.1. Monarch Population Observed at the Overwinter Sites

However, the migration trail has experienced many setbacks and complications of its own. While natural factors such as temperature and atmospheric events have the potential to derail migrations, conservationists are limited in their ability to aid the butterflies based on these conditions alone. For example, the winter storm that eliminated nearly 2/3 of the Eastern monarch overwintering population was not preventable by means of anthropogenic intervention (Brower et al., 2004). Despite the large loss, scientists used the opportunity to count the fallen butterflies for the first real population numbers that had ever been collected. Further defying the odds and as a testament to their resiliency, monarchs had strong numbers the following year despite the overwinter losses (Monarch Watch, n.d.).

Another cause for concern is the effects that climate change may have on monarchs at all life stages. While there is evidence of an anthropogenic effect on climate change, actions and remedies to improve these effects are still highly debated. Scientists have warned that unusual temperatures, severe storms, and jet stream fluctuations could impact monarch butterfly population numbers, but the change to remedy these factors would not be swift and is largely beyond any immediate human control (WallisDeVries, 2011; Knutson, 2010).

This, however, has not been the case with agricultural practices and land use. Land use and cropland use had a collective weight of 35% in the final site suitability model emphasizing the effect that the physical sites have on suitability. GM soy and corn have had a substantial negative impact on monarch recolonization in the Midwest and at the summer breeding grounds. This loss of suitable sites may be pushing migrating monarchs further east and squeezing them against colder temperatures to the north and the Atlantic Ocean.

Sink populations may provide us with an option to total extinction, but it is questionable if non-migrating monarchs could even be considered the same species. With a sustainable population of non-migrating monarchs in southern Florida and several other sites of interest, this anomaly may be providing us with a glimpse of what is to come if site conditions do not improve. Butterflies add value as pollinators and species richness to biodiversity, and their fragility and annual migration have made them good candidates as indicator species for other insect populations. If monarchs stop migrating, what does that mean for other migratory insects?

Despite many setbacks, monarchs have proven resilient when previous populations have reached critical numbers. Grassroots initiatives and concerned citizens have begun to intervene on behalf of all butterflies and pollinators. Individuals planting indigenous milkweed and nectar producing plants have worked diligently to improve flyway connectivity. Eliminating the use of pesticides, herbicides, and fungicides in residential lawncare and increasing the amount of wilderness and protected lands has further improved local conditions. With the recent surge in hectares at the overwinter sites in the 2018-2019 migration year, there is hope. However, time is of the essence. The Western monarch numbers are still declining, but the Eastern population had a great year.

The use of GIS, geospatial data, and modeling lends itself to migratory data without negating the importance of species biology and habitat ecology. Monarch butterflies are still trying to journey the same paths that their ancestors did before them, but site degradation is a growing concern. Research methods that could identify areas that were negatively impacted could improve response time and resource allocation making site suitability analyses integral to any streamlined conservation effort. The second model created in this study utilized physical and land use variables to understand, analyze, and predict how monarch butterflies were existing within their environment. While they are attempting to follow the same patterns that they have for centuries, many conditions existed at the summer breeding grounds and along the flyways that were causing the butterflies to deviate from their normal behavior. The lack of suitability has created conditions that if left unchanged could lead to the loss of this once rich species. Targeted initiatives to improve the suitability at the summer breeding grounds and along flyways are the best way to aid these colorful travelers who will traverse more miles in their short lifetime than many people. Conservation efforts need to continue with the hope that Eastern monarchs will continue to enchant, inspire, and teach generations to come, and GIS will be available to help them do it.

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