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Modeling Migratory Patterns of the Eastern Monarch Butterfly

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ABSTRACT

The purpose of this research was to relate the influence of specific site suitability variables to eastern monarch butterfly migratory patterns and behavior. Elevation, temperature, precipitation, and land use data layers were overlaid to collectively consider how these variables affected the way that butterflies migrated and recolonized during the 2016/2017 migratory cycle. The variables were reclassified into layers ranking suitability as either unsuitable, suitable, or optimal with respective scores of one, three, and five. Three uninhabitable variables were identified that deemed a site unsuitable despite the influence and possible optimal suitability of the other variables. 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, development, and climate change were considered regarding flyway connectivity and behavior.

KEYWORDS

Eastern Monarch Butterfly, Geographic Analysis, Geographic Information Science, Geographic Information Systems, GIS, Migration, Modeling, Site Suitability

INTRODUCTION

Migratory species are known to traverse a wide variety of physical conditions and landscapes over an infinite combination of spatial and temporal ranges. Given the fluctuations that can occur on these journeys, migratory species must be able to quickly adapt to their surroundings and remain sensitive to triggers that indicate that it is time to vacate a certain area. However, with recent fears of climate change that have already affected several endemic species, scientists are questioning what the future may hold for migratory species, and if the entire migratory phenomenon may be at risk (Thogmartin et al., 2017a). Eastern monarch butterflies (*Danaus plexippus*) have received attention due to the challenges that they face while completing their 3000-mile annual migration and recolonization. Destruction of overwinter sites, herbicide and pesticide use, agriculture practices, and changing climate have all been listed as threats to a species of insect that has migratory roots that date to 1800 B.C. (Baumle, 2017). With unstable and erratic population counts becoming more frequent, understanding the conditions experienced along the migratory flyways has become necessary to streamline conservation efforts and to target the locations that need intervention and remediation.

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This study investigated the relationship between Eastern monarch butterfly migratory patterns as they relate 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. Previous studies have previously modeled monarch butterfly migrations; however, most models have relied heavily on statistical analyses across multiple migratory flight years. These studies have examined specific circumstances such as the effects of climate change on migratory behaviors (Lemoine, 2015), as well as multivariate analyses that explored the effects of specific herbicides, temperature, precipitation, and survival statistics (Thogmartin et al., 2017a). Dingle et al. (2005) utilized GIS and cartographic modeling to investigate the perceived distribution shift of Western monarch butterflies utilizing local collection and tag/recovery data as well as elevation and temperature as driving factors. With the availability of historic temperature and precipitation readings, land use and crop data, and elevation measurements, this study developed a geographic model that could begin to delineate optimal site conditions as well as sites that may require mitigation. 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.

Butterfly Biology and Ecology

As members of the Lepidoptera Order, monarchs undergo a physical metamorphosis resulting in a fully mature adult butterfly that is physically and functionally different from any of its previous life stages. Monarchs spend roughly four days in the egg stage before spending an additional 9-14 days in the larval stage. After molting multiple times and growing to approximately 2000-3000 times their initial body mass, the larva will spend 9-15 days developing inside the chrysalis before emerging as a fully mature adult butterfly that will live for an additional two to four weeks (Baumle, 2017; Oberhauser, 2004; North Carolina Wildlife Federation [NCWF], 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 processes up at every stage, while cooler temperatures can substantially slow them down (Harvey et al., 2015; Solensky 2004). Years that have unusual temperatures can encourage fast monarch maturity sometimes resulting in “bonus” generations (Nail et al., 2015), or it could theoretically slow it down and truncate the number of generations that monarchs have to migrate and recolonize (Davis & Howard, 2005). Despite the fact that 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 spans from late February until November with the number of butterflies proliferating through an average of four-generations (Journey North, n.d.).

Migration

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 northeastern 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 and enter a reproductive diapause as a means of conserving resources and energy for the southern migration and subsequent overwintering (Solensky, 2004). While monarchs migrate north over four successive generations, a single butterfly makes the entire journey south to Mexico, overwinters, and lays the first eggs for the next year’s northern migration.

During the breeding and northern migratory generations, a female monarch will deposit an estimated 300-400 eggs to the undersides of milkweed leaves as the population slowly travels north to the summer breeding grounds (Oberhauser, 2004). Depositing the eggs directly to the milkweed leaves is necessary as it provides the resulting larva with an immediate food supply (Oberhauser, 2004). Milkweed plants (*Asclepias* spp.) are available in several species that are suitable for a variety of tropical, neutral, and arid climates and are the sole food source for developing larva (United States Department of Agriculture [USDA], n.d.). While once plentiful, recent anthropogenic activities have decreased the amount of wild 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) resulting in broken flyways (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).

Overwinter Sites

While Eastern monarch migrations have been observed and recorded for hundreds of years, it was not until 1975 that scientists positively identified where the butterflies were overwintering in the Sierra Madre Mountains of Mexico. According to the US Forest Service, overwintering butterflies preferred the higher elevations of 2400-3600-meters where temperatures fall to between 32- 59° F. These moderately cool temperatures aid the butterflies in the overwintering months by allowing them to decrease their metabolism and preserve bodily resources so that they may vacate the overwinter sites in late February/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 (Urquhart & Urquhart, 1976). Unfortunately, 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.).

Climate Change and Other Threats

Climate change has recently become a major concern for many species, and butterflies are no exception. Endemic populations of plants and animals are already disappearing in areas where their environment has changed more rapidly than they could adapt (WallisDeVries, 2011). Naturally, migration biologists are already investigating what impact changing temperatures, unpredictable weather, and extreme atmospheric events could have on migrating monarchs with some scientists questioning if the entire migratory phenomenon may be at risk of disappearing altogether (Thogmartin et al., 2017a; Brower et al., 2012).

One of the major concerns is that migratory monarchs may find themselves too far north without ample time to return to Mexico (Nail et al., 2015; Zalucki, 1982). 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, the effect on overwinter populations could be substantial (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.

Non-Migratory Populations

When considering why butterflies migrate the way that they do, it is also 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 and overwintering population with new reports of a similar population developing on the South Carolina coast (Peterson, 2019). 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 are breeding year round leading to their designation as a “sink” population (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 that never leaves. Some studies have identified a protozoan parasite that has infested the Florida milkweed which is ingested by the monarchs during the larval stage (Altizer, Oberhauser, & Brower, 2000). Since milkweed grows year-round in Florida, an annual dieback never occurs allowing all parasitic infestations and genetic abnormalities to 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).

Pending Threatened Species Status

With critical population numbers becoming more frequent, it has become necessary to consider what the future implications would be if the butterflies continued on their current trajectory. Following a decade of rapidly decreasing population counts, the U.S Fish and Wildlife Service (FWS) began its petition in 2014 to protect Eastern monarch butterflies with threatened species status under the Endangered Species Act (ESA). According to their petition, monarchs are threatened with becoming endangered in the near future due to loss of habitat and curtailment of range (Brower et al., 2014). As the petition is being evaluated, a thorough investigation is currently underway utilizing the Species Status Assessment framework with a listing decision due by December 15, 2020.

METHODOLOGY

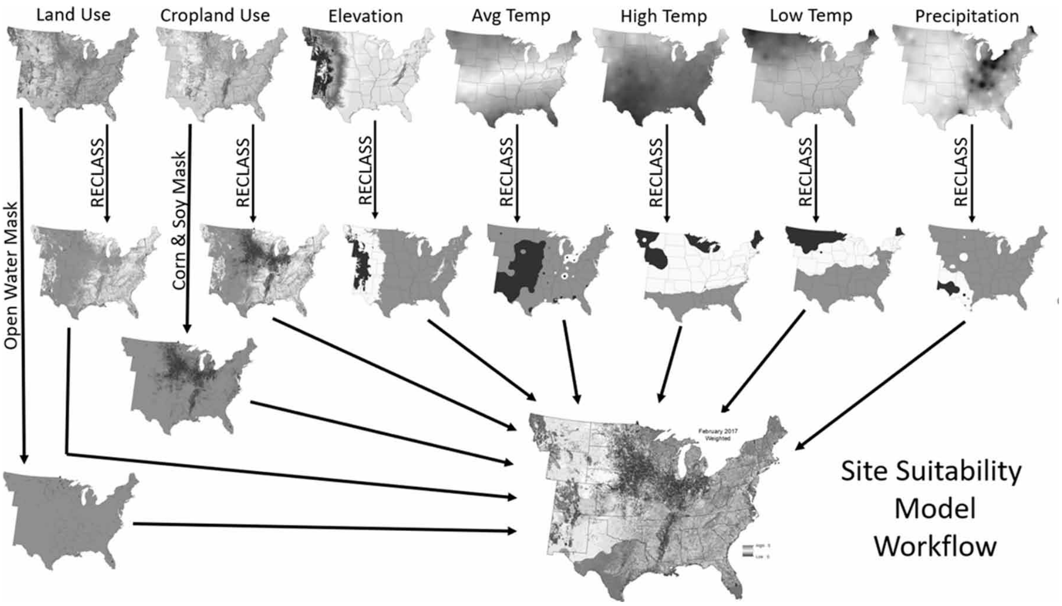
After a review of recent studies and literature, average temperature, high temperature, low temperature, precipitation, land use/land cover, cropland use, and elevation were selected as major conditions that contributed to monarch butterfly sustainability. Each dataset was retrieved and reclassified to score each variable according to its suitability to support and sustain migrating and recolonizing populations. Optimal, suitable, and unsuitable locations were identified, as well as conditions that were considered uninhabitable. All seven reclassified layers along with the two uninhabitable mask layers were input into the site suitability model to create a composite suitability score (Figure 1) which was ultimately analyzed in conjunction with geocoded butterfly sightings.

Study Area and Datasets

This study utilized four datasets to provide suitability variables over a 13-month Eastern monarch migratory cycle. November 2016 was the first study month as it encompassed the close of the 2016 migration. December 2016, January 2017, and February 2017 represented the overwinter months where the migratory population should have been absent from the study area. March, April, May, June, July, August, and September of 2017 represented the northern migration, breeding, and recolonization segment of the migratory year. The biological trigger that signals for reproductive diapause typically occurs in October marking October 2017 as the beginning of the southern migration with November 2017 closing the migratory flight year. Given the wide range in which Eastern monarch butterflies migrate, the study area had to be large enough to include all individuals in the butterfly dataset for the full migratory cycle. Since monarch butterflies are not typically present in higher elevations, the study area was bounded by the Rocky Mountains in the West to the Atlantic Ocean in the East with the northern and southern United States borders defining the north and south extents.

The weather dataset was retrieved from the National Centers for Environmental Information (NCEI) and used to create the average temperature, high temperature, low temperature, and precipitation variables for the site suitability model. While weather may appear to be a singular variable, the ectothermic nature of insects complicates how butterflies interact with the temperatures that surround them. Weather data was collected for each of the 13-months and incorporated into the

Figure 1. Site suitability model workflow



model as a monthly average temperature, monthly highest and lowest temperature, and the monthly sum of all precipitation.

The second dataset, elevation, was retrieved from the United States Geological Survey (USGS) as 30-meter Digital Elevation Models (DEMs) from the National Elevation Dataset (NED) published in 2018. The third dataset employed in this study was the land use and land cover dataset which was retrieved from the United States Department of Agriculture (USDA) using 2011 Landsat data. Cropland data was the fourth dataset retrieved to compliment the previously acquired land use and land cover dataset. The cropland dataset was created by the United States Department of Agriculture and National Agricultural Statistics Service (USDA-NASS). It was collected between 1997 and 2006 and identified most of the crop varieties commercially planted in the United States.

While not used specifically for the suitability model, a butterfly sightings dataset was also retrieved in order to geocode and analyze butterfly locations as well as general migratory patterns and movement. The *Journey North* database contained monarch butterfly sightings as reported by citizen scientists through their web interface with sightings records updated daily. Each sighting contained latitude and longitude data as well as butterfly counts and the date of each sighting. This study incorporated over 11,000 separate sightings which were applied by date sighted to each corresponding month's model output. This layer was useful in that it provided larger migratory patterns as well as tested the effectiveness of the model outcomes. For example, if an area was classified as unsuitable and had multiple sightings, it would be necessary to make sure that there was a valid reason for the butterfly locations, or it could indicate that the model or weights needed adjustment.

Reclassification

Before any model could be utilized, the datasets had to be reclassified to reflect *optimal, suitable*, and *unsuitable* site locations. To begin the reclassification process, cutoff limits were established for each of the variables. The end result provided seven distinct raster layers that were scored to reflect the site's suitability with regard to the variable being measured. If a site was assessed to be *unsuitable*, it received a score of one; if the site was assessed to be *suitable*, it received a score of three; and if a site was assessed to be *optimal*, it received a score of five.

The first variables to be reclassified were the four temperature layers. Butterflies are insects with ectothermic metabolism and rely on direct sunlight and warm temperatures for energy (Baumle, 2017). They require a minimum of 55°F to have the energy to fly and function normally (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). For high temperatures, monarchs functioned optimally up to 100.4°F before exhibiting signs of fatigue and heat stress. However, monarchs had a more forgiving relationship with cold temperatures. With their metabolism slowing with the cooling temperatures, they were not at threat for immediate hypothermia. This ability to not expend unnecessary energy to stay warm allowed butterflies to survive subfreezing temperatures as well as 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 temperatures were established for high and low extremities, the average temperature was reclassified to consider the general temperature range in which monarchs function optimally. 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). 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 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 an *optimal* classification was set at 70°F. Mean calculations tend to absorb extreme values making 70°F as a monthly average reasonable as the lower optimal limit.

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 of localized averages. When considering the normal precipitation totals for weather stations across the study area, locations in Florida routinely received 10-inches of rainfall per month 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 locations tend to have lower lipid stores which can compromise their ability to survive diapause while overwintering (Brower et al., 2015; Nail et al., 2015). However, despite the fact that butterflies will not fly in the rain, average amounts of rainfall are a part of daily butterfly life with only elevated amounts of rain becoming problematic for breeding and transit (Table 1).

The next set of reclassifications delineated the suitability regarding land use and land cover. Butterflies require sunlight for warmth, moisture, milkweed, shelter, and nectar (Baumlee, 2017; Oberhauser, 2004). As long as these necessities were present, the likelihood of a location supporting monarchs was high. The easiest classification to sort was the *unsuitable* classification. Open water and perennial snow/ice fields 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 locations had a large footprint and tended to remove most natural land cover including milkweed (Nilsson et al., 2008).

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 *optimal* were: shrub/scrub, hay/pasture, herbaceous, cultivated crops, open space, low density developed, and deciduous and mixed forests. Medium intensity development was viewed as *suitable* due to it not being as damaging as high intensity, but also not as acceptable as low intensity. According to the United States Forest Service (USFS), 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) leading to only a *suitable* rating.

A separate variable layer was reclassified to delineate the suitability of cropland use. Land used for cultivated crops typically had plenty of sunshine and moisture; however, despite these otherwise optimal conditions, three crops were not considered suitable for monarch butterflies. Commercial farmers have begun planting genetically modified (GM) varieties of corn and soy which are herbicide resistant (Thogmartin et al., 2017a; Thogmartin et al., 2017b; 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. Sod was also included due to the herbicides used in cultivating commercial and residential plots. As a result of these detrimental agricultural practices, corn, soy, and sod were classified as *unsuitable*. All remaining crops were categorized as *optimal* for monarchs due to the probable occurrence of milkweed and nectar producing plant growth as well as abundant sunshine and moisture.

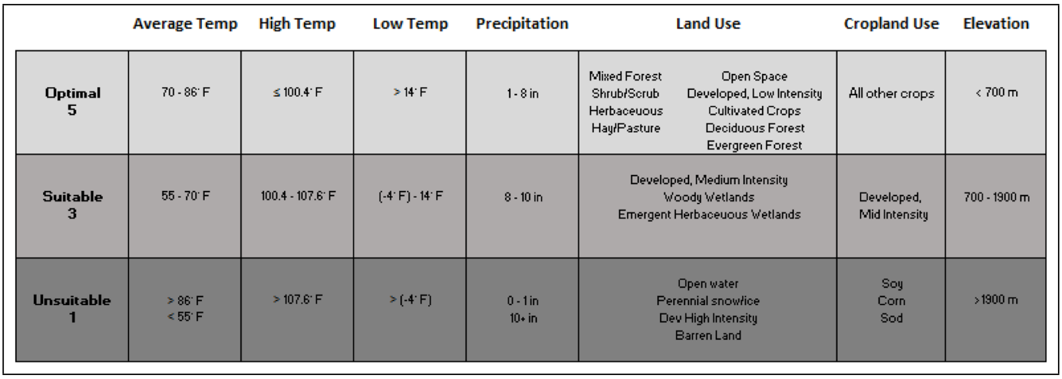
The last layer requiring reclassification was elevation. Monarch butterflies are rare in higher elevations, and it is currently believed that they will not cross the higher altitudes of the Rocky Mountains due to lower temperatures that disrupt their flight ability. However, species richness does have a link to elevation as evidenced by Gallou et al. (2017) who completed a study which investigated the effects of elevation and butterfly species richness in the French Alps. This 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 *optimal, suitable,* and *unsuitable*, elevations up to 700-meters were deemed *optimal*, with elevations between 700 – 1900-meters as *suitable*, and elevations above 1900-meters as *unsuitable* (Table 1).

Site Suitability Model

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 identified as uninhabitable despite the suitability of the other layers.

A rating of *uninhabitable* received a score of zero that superseded any other variable's individual or composite score. 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:

Table 1. Reclassification cutoffs



	Average Temp	High Temp	Low Temp	Precipitation	Land Use	Cropland Use	Elevation
Optimal **5**	70 - 86° F	≤ 100.4° F	> 14° F	1 - 8 in	Mixed Forest Shrub/Scrub Herbaceuous Hay/Pasture Open Space Developed, Low Intensity Cultivated Crops Deciduous Forest Evergreen Forest	All other crops	< 700 m
Suitable **3**	55 - 70° F	100.4 - 107.6° F	(-4° F) - 14° F	8 - 10 in	Developed, Medium Intensity Woody Wetlands Emergent Herbaceuous Wetlands	Developed, Mid Intensity	700 - 1900 m
Unsuitable **1**	> 86° F < 55° F	> 107.6° F	> (-4° F)	0 - 1 in 10+ in	Open water Perennial snow/ice Dev High Intensity Barren Land	Soy Corn Sod	>1900 m

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). Corn and soy received the uninhabitable rating due to the herbicide resistant GM varieties currently used that allows farmers to spray herbicides that eliminates all other vegetation (Thogmartin et al., 2017b; Pleasants, 2015; Pleasants & Oberhauser, 2012).

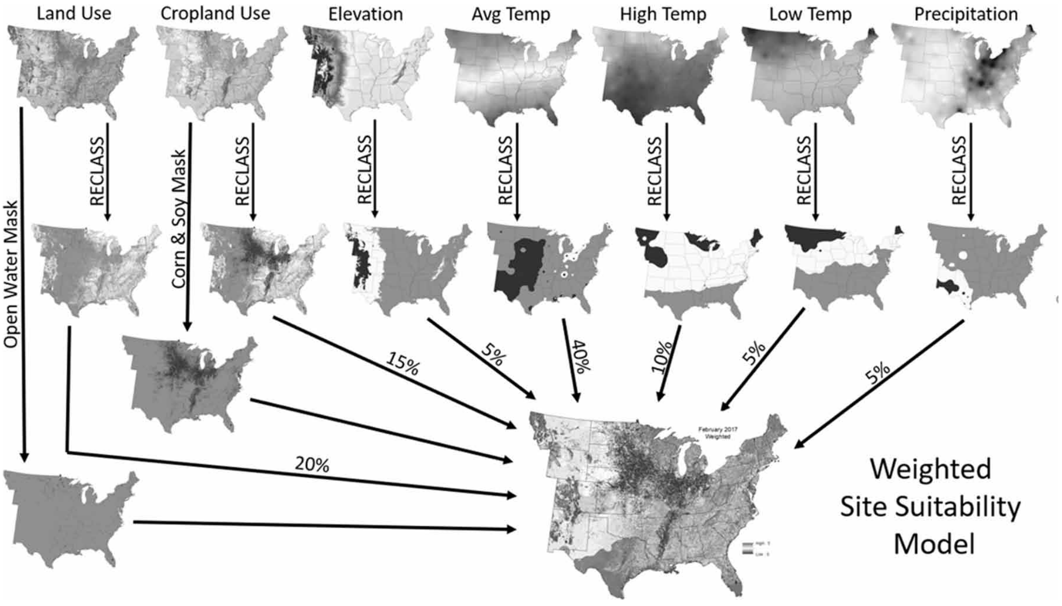
Two mask layers were used to create the three *uninhabitable* conditions. To create the corn and soy mask, the cropland layer was replicated and reclassified using binary scores of zero and one. Corn and soy were assigned a score of zero with all other categories assigned a score of one. The process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

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. After a preliminary model output was not consistent with past research and known trends, it seemed a reasonable adjustment to consider weighting the variables to allow for some to have more or less of an effect on the final composite layer (Figure 2).

To begin the weighting process, temperature was considered for its individual variable layers as well as a conglomerate. 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. However, despite the lack of a studies providing a clear-cut percentage of the weight that temperature carried 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 needed for mobility, life stage progression, and basic life functions, the weight applied was 40%.

High temperatures were 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%. This weight was

Figure 2. Workflow for the site suitability model using individual weights



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 heavily 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 in unison to form a 50% weight.

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). 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, mortality, and site suitability.

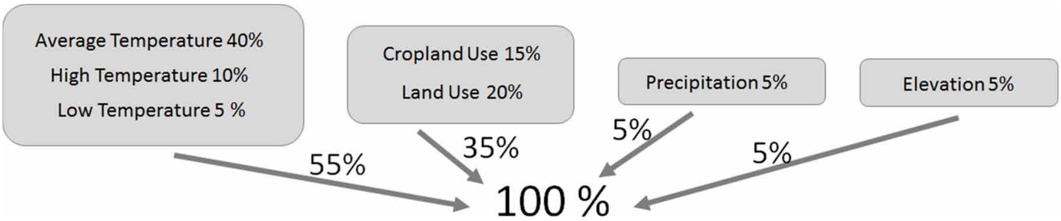
Precipitation was a difficult variable to account for from the study onset. Given that moisture is required by butterflies at all life stages (Baumle, 2017; Nail et al., 2015; Oberhauser, 2004), prolonged periods of extreme precipitation or drought had a negative effect on both butterfly functionality and mortality. With all 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 had to be so broad.

Elevation cutoffs were straightforward and were tied to falling temperatures as altitude increased. According to Gallou et al. (2017), 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. 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. 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 than others. 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 collectively assigned a weight of 20% due to the substantial importance that they have to butterfly functionality and viability.

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 optimal 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

Figure 3. Collective weights applied to suitability model



was assigned a weight of 15% to account for the differences in *optimal, suitable* and *unsuitable* crops as they relate to monarch site suitability. Having a separate crop layer provided an extra increase in overall score 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 (Figure 3). 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 exit the area, especially if the use was not widespread; however, escaping adverse temperatures could be more complicated.

Once the weights were assigned, the layers were entered into the raster calculator to output a composite layer reflecting the individual scores of the underlying layers. The raster calculator formula was as follows:

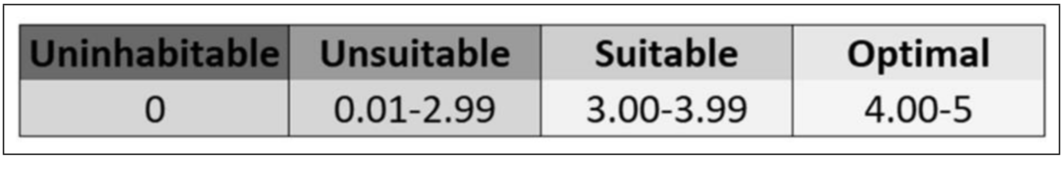
((.40 * Average Temperature$_1$) + (.10 * High Temperature$_1$) + (.05 * Low Temperature$_1$) + (.05 * Precipitation$_1$) + (.05 * Elevation) + (.20 * Land Use) + (.15 * Cropland Use)) * Land Use Mask * Cropland Use Mask

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 0.00 – 5.00. A score of 0.00 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 ˃ 0.00 - 2.99 indicated that the site was *unsuitable*, while scores between 3.00 - 3.99 indicated reasonable *suitability*. Scores of 4.00 and higher indicated that most variables were favorable and led to a composite *optimal* classification (Table 2).

RESULTS

When considering monarch butterfly recolonization, milkweed abundance held a pivotal role as the sole food source for developing larva as well as providing a nectar supply for the adult butterflies. However, as with most plant occurrences, it was difficult to capture comprehensive and continuous

Table 2. Scoring for individually weighted variables



Uninhabitable	Unsuitable	Suitable	Optimal
0	0.01-2.99	3.00-3.99	4.00-5

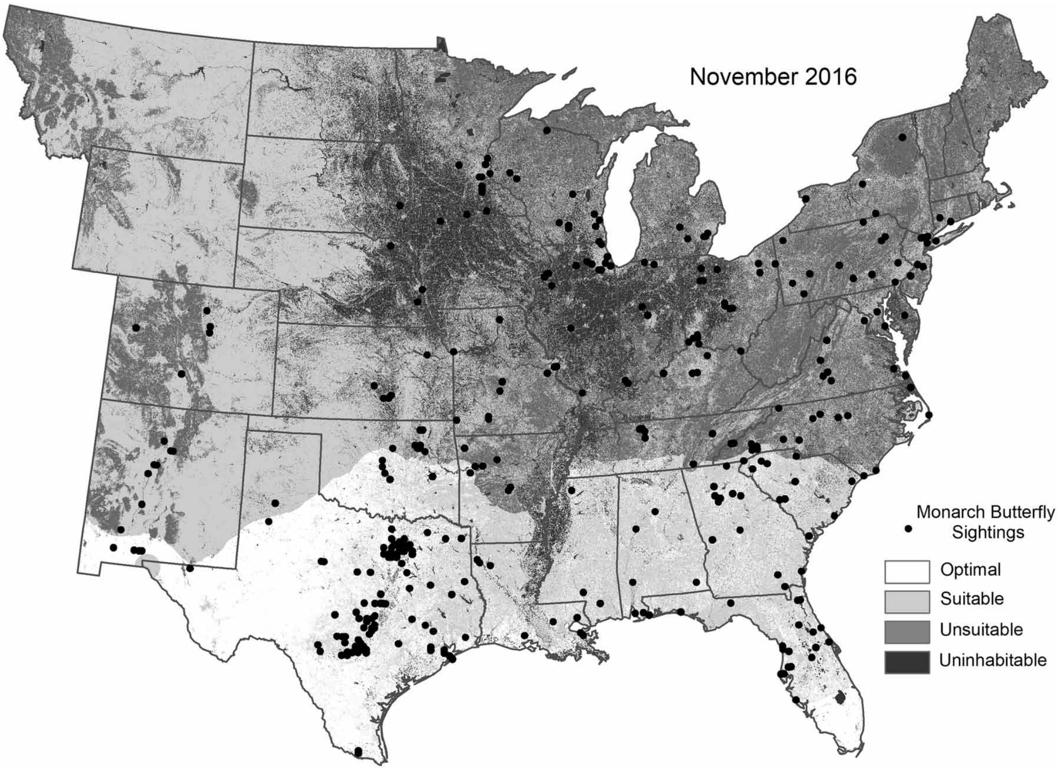
milkweed occurrence as an isolated factor across the entire study area. In a review of milkweed species distribution, it became clear that there were several species of milkweed that had ranges that collectively covered the entire study area. Since this study was only looking for a “yes /or/ no” milkweed presence potential, there was no added value in attempting to distinguish which milkweed species could be present at a specific location. As a result, macro variables were useful in indicating where general plant life, including milkweed and nectar producing plants, could optimally exist. With this objective in mind, temperature, precipitation, and land use layers were scored and weighted with milkweed and nectar producing plant potential considered as major factors within the larger variable. Land use, land cover, and cropland use proved to be the most effective layers at representing areas where milkweed had a high or low occurrence probability when considering the effects of urban construction, density, residential lawn care, and the use of genetically modified corn and soy. In addition to the reclassified land cover, land use, and cropland use layers, both mask layers specifically addressed the milkweed habitat question, while the temperature and precipitation layers provided more input regarding the probability that milkweed could be present within a site location based on weather and climatological factors. The mask layers theoretically carried the heaviest weight in this study as the application of uninhabitable sites removed all other variable scores from the composite layer leaving a final score of zero at that location.

After incorporating all weighted variables and mask layers, the maps that resulted from this study were successful in creating a visual representation of the Eastern monarch butterfly migration regarding the variables that were selected both directly and indirectly. Past seasonal trends and patterns coupled with geolocated butterfly sightings were used to compare the results of the model outputs to check for validity as well as effectiveness of the overall weighting logic. One of the benefits of using a weighted model was that having a higher weight for temperature effectively captured how the changing temperatures affected the leading edge of the northern migration as well as the dramatic disappearance of sightings in December and January when most of the study area became unsuitable.

After validating the model and taking note of some of the more noticeable overall factors, model outputs were analyzed individually with that month’s corresponding butterfly sightings. November 2016 was established as the first month for this study because it marked the return of the butterflies to Mexico to overwinter effectively ending the previous year’s migration. This month should reflect less suitability in the northern United States and have most butterflies nearing their final destination and exiting the study area. 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 completely (Figure 4).

As the first full month of the overwinter season, December 2016 (Figure 5) 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 or were perhaps located in possible sink populations. Other probable non-migratory sink populations were identified along the Gulf Coastline in Louisiana, Alabama, Mississippi, and Florida. Florida had the most sightings outside of the migratory flyways accounting for 37% of the total sightings for the month.

Figure 4. November 2017 site suitability with corresponding butterfly sightings



January 2017 (Figure 6) was reasonable for overwinter numbers, and butterflies were sighted only within the remaining optimal sites with a large presence in the possible sink locations. February 2017 (Figure 6) was similar to January with consistent sightings in Florida, Hilton Head, and the Gulf Coastline. 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 7) displayed the leading edge of the northern migration of the 2016-2017 flight year. Also as expected, the butterflies moved directly north out of Mexico with the leaders still within the optimal ranges. April 2017 (Figure 7) continued the journey north with the members of the first generation beginning to enter the migratory flyways. April also marked the first arrivals at the summer breeding grounds with butterflies located largely in suitable to optimal 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 as suitable pockets could likely be found.

May through October 2017 represented the recolonization of the 2017 monarch season. These sightings contained the second, third, and fourth generations with population numbers proliferating through each month. May 2017 (Figure 8) still revealed the northern migratory flyway out of eastern Texas with still consistent sighting numbers in Florida and Hilton Head. Individual sightings typically were located at suitable and optimal site locations with many sightings still occupying small pockets of suitability among the soy and corn uninhabitable cells in the summer breeding areas.

June 2017 (Figure 9) revealed the rapid improvement of warmer temperatures that butterflies prefer which continued through July (Figure 9). As population numbers and sightings increased, sightings

Figure 5. December 2016 site suitability with corresponding butterfly sightings

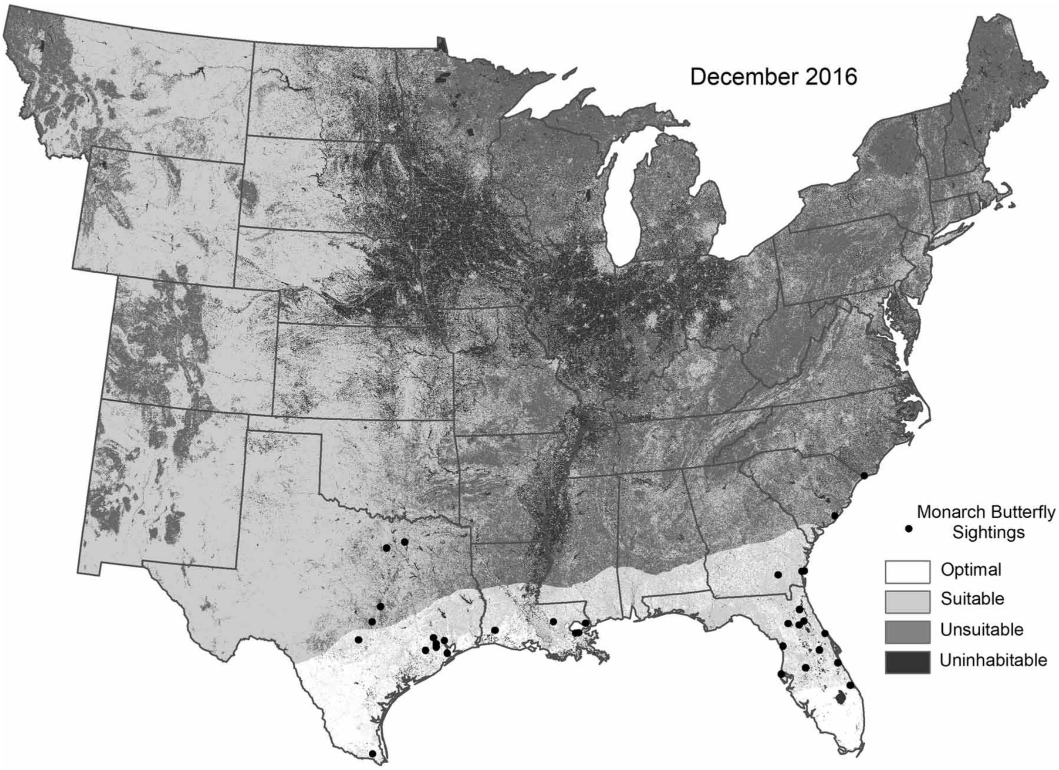
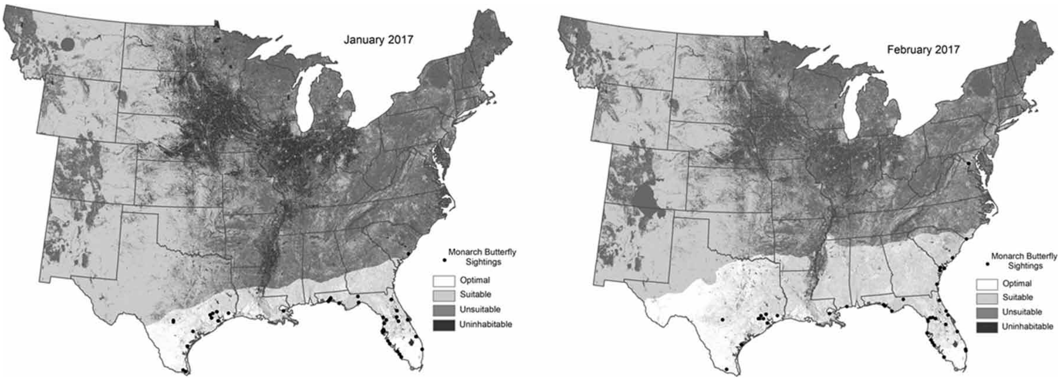


Figure 6. January and February 2017 site suitability with corresponding butterfly sightings



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.). The model and sightings together visualized the increase in eastern sightings in areas of reasonable suitability with some sightings further north relying on areas that were less than optimal. 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

Figure 7. March and April 2017 site suitability with corresponding butterfly sightings

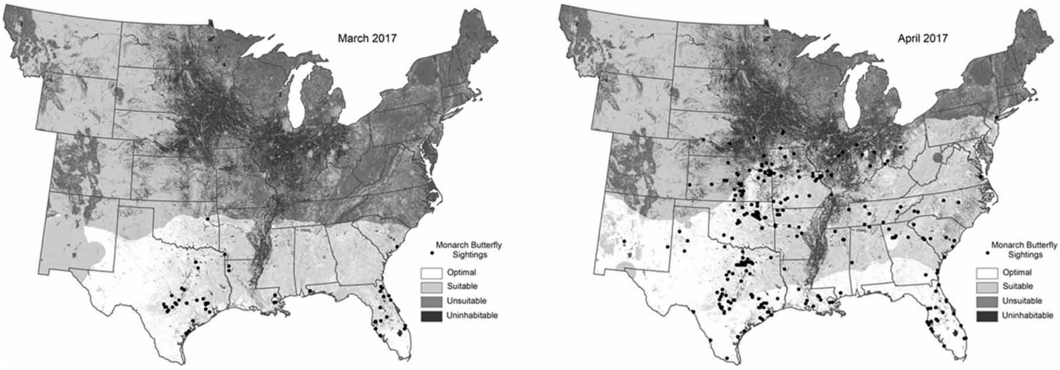
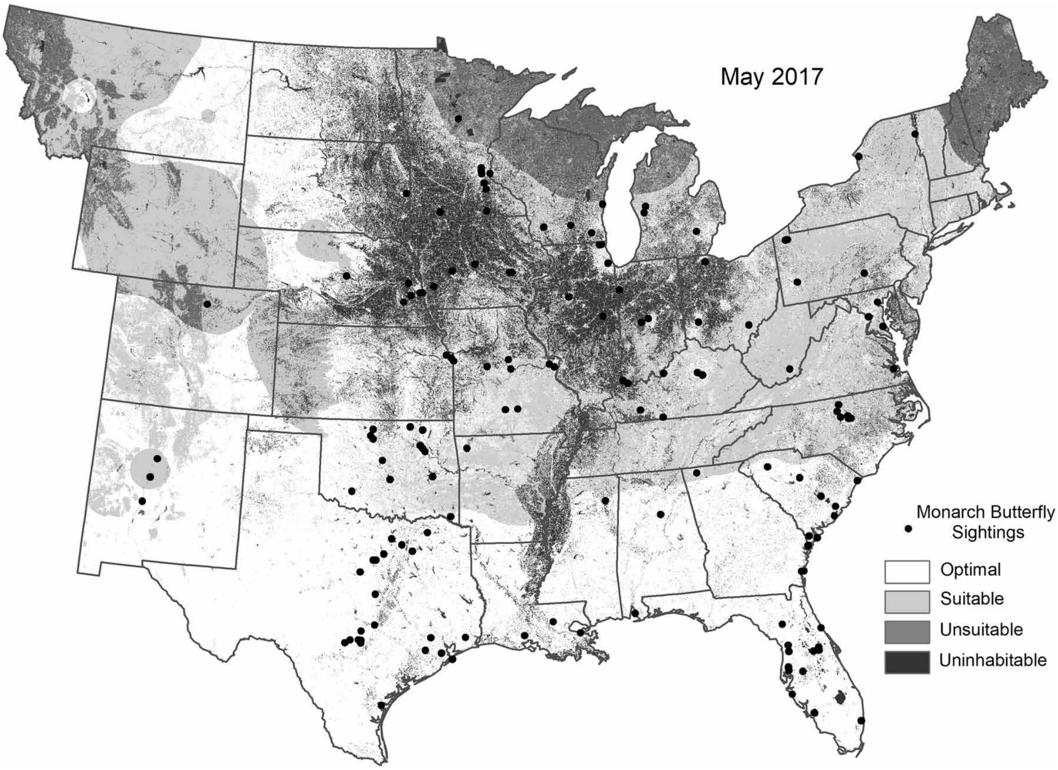


Figure 8. May 2017 site suitability with corresponding butterfly sightings



in the event that more habitable areas were overpopulated with adult butterflies and larvae putting strain on the milkweed and nectar producing plants.

August (Figure 10) and September 2017 (Figure 10) provided more of the same butterfly activity witnessed in June and July; however, site suitability began to decrease. 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

Figure 9. June and July site suitability with corresponding butterfly sightings

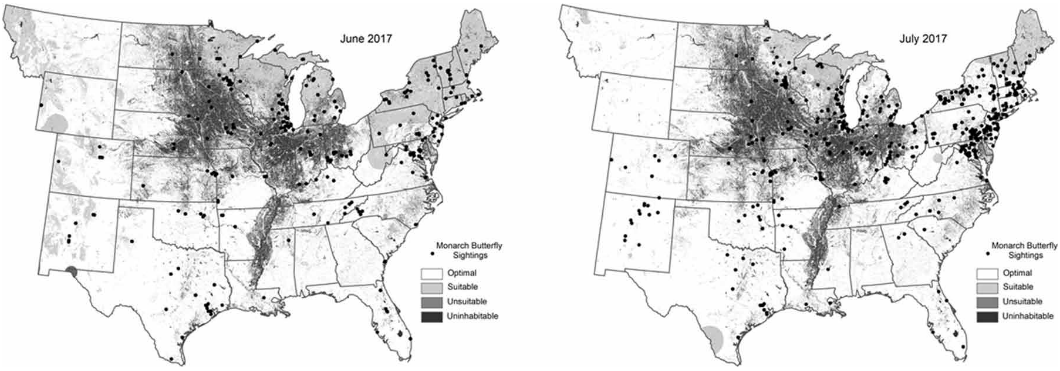
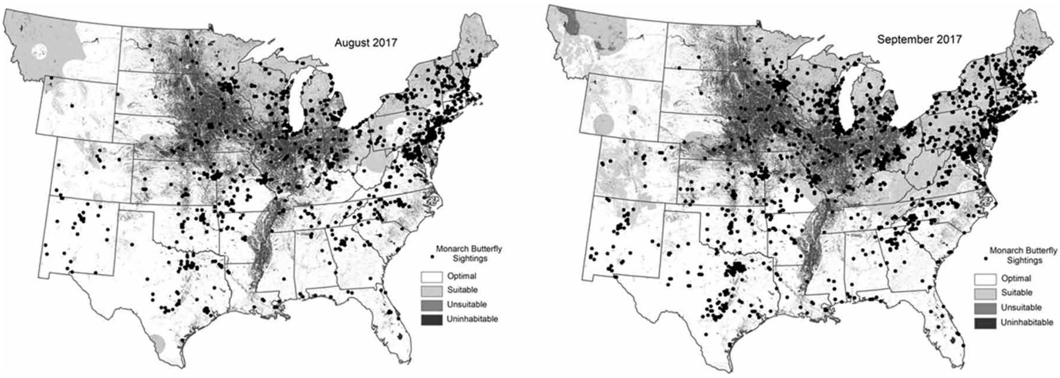


Figure 10. August and September 2017 site suitability with corresponding butterfly sightings

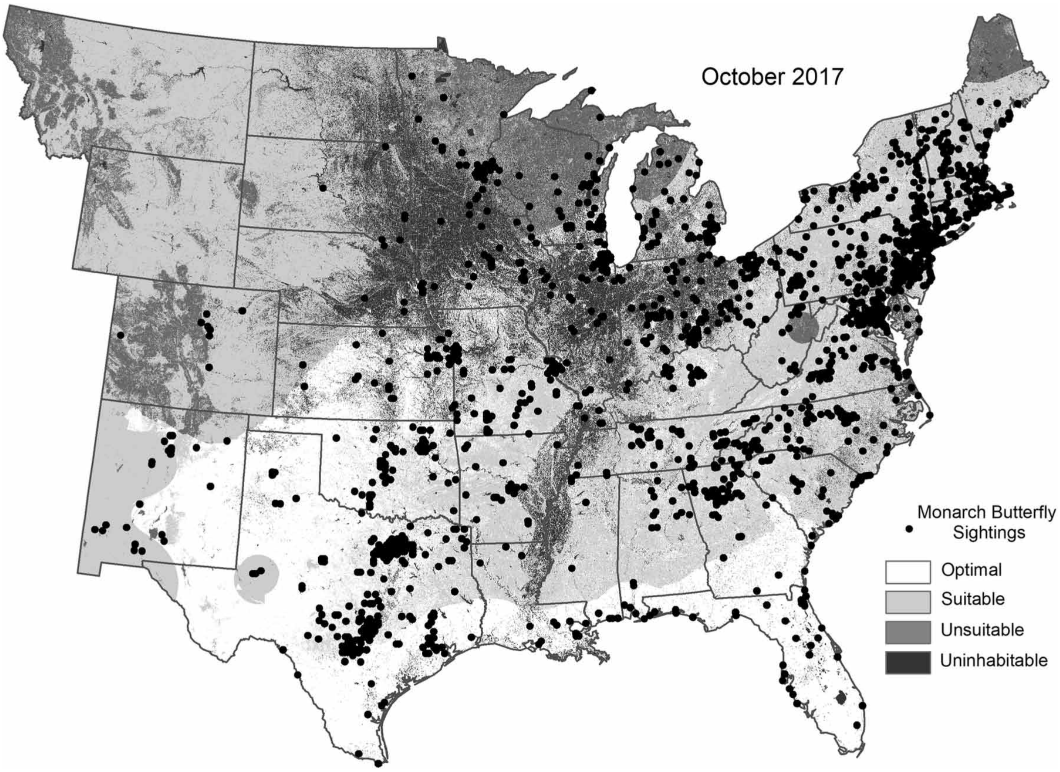


their mobility; however, once temperatures warmed, they would have become mobile again and continued as normal.

October 2017 (Figure 11) represented an important junction in the migration year. Populations were at the highest, yet suitability conditions were declining. During this month, conditions would likely converge to induce the trigger for the monarchs to return to Mexico; however, with individuals departing and simultaneously 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 had 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 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.

November 2017 (Figure 12) was similar to November 2016 in that suitability and sighting locations were generally the same. With the last viable generation entering Mexico and the individuals left behind in the northern United States beginning to die out, the migration was coming to an end. However, 2017 had some interesting anomalies regarding sightings. Ward (2017) with the *Yale Climate Connection* observed that a portion of the eastern population was migrating late. These butterflies were observed in Cape May, New Jersey, two weeks behind schedule and were identified as a possible "bonus generation." The sightings data corroborated this finding as the geocoded sightings were

Figure 11. October 2017 site suitability with corresponding butterfly sightings



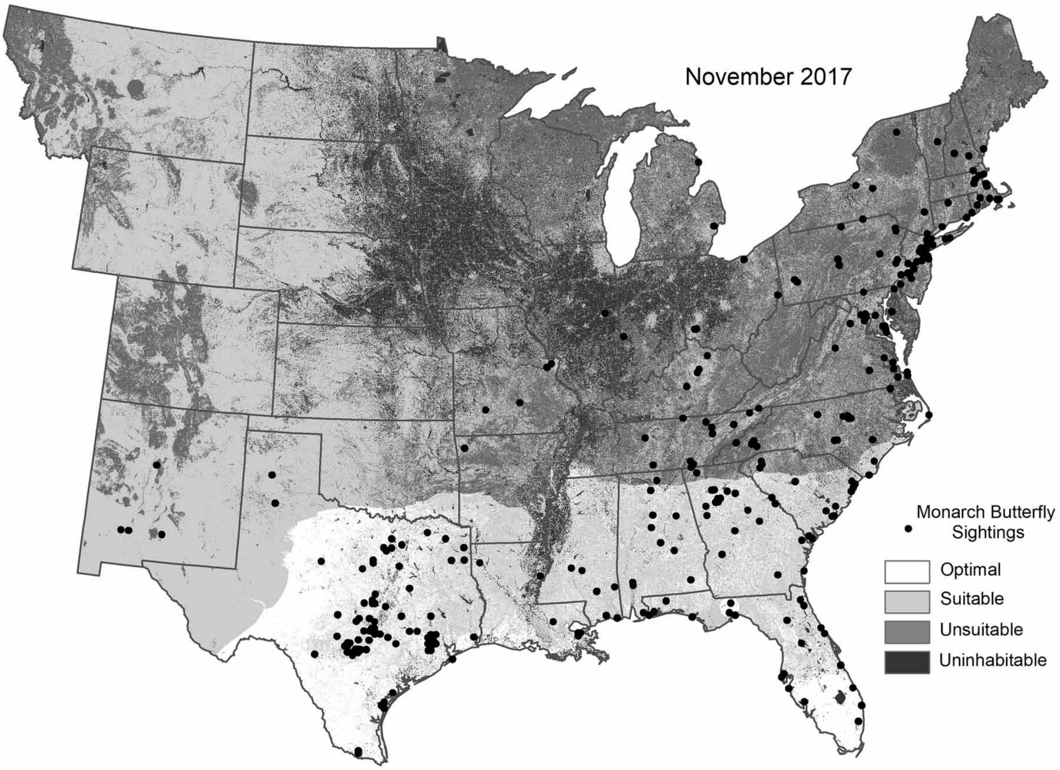
visibly located in New Jersey and along the Atlantic Coast. As with most of the November northern monarchs, most of this population probably would not complete their journey; therefore, the suitability and locations were commensurate with general trends observed in November 2016.

Sink Populations

Sink populations were first observed in southern Florida where monarchs were reported active year round (Williams, 2015; Duhaime-Ross, 2014). With available milkweed and tropical temperatures, some scientists believe that the monarchs never receive the trigger to migrate to Mexico and are stuck in a perpetual recolonization mode (Harvey et al., 2015). With the concern that climate change could bring warmer temperatures to higher latitudes, these colonies of non-migrating monarchs could be how this species is beginning to adapt. 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 and whether or not they may ultimately become a new subspecies (Duhaime-Ross, 2014)?

When analyzing the model output layers, 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.) and Peterson (2017), residents of Hilton Head Island have reported that monarchs are no longer vacating the area during the winter months. However, sightings are currently too low to deem the South Carolina colony a sink population, but the area should be investigated over the

Figure 12. November 2017 site suitability with corresponding butterfly sightings

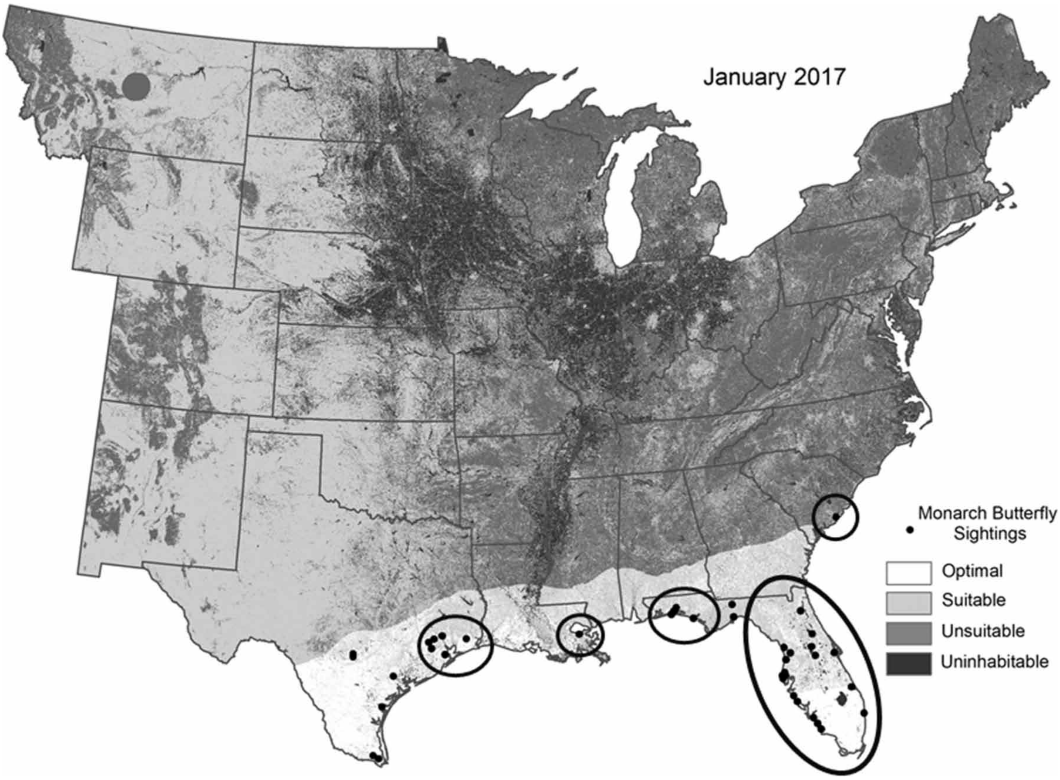


coming years in an attempt to understand why these pockets of butterflies never leave. If loss of their migration trigger were established as the causation of their static location, it would be reasonable to consider sites with similar suitability conditions for other possible sink population locations. 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; the Florida panhandle; the Alabama coastline; the Louisiana coastline and Mississippi delta; and Houston and Beaumont, Texas (Figure 13).

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. With the presence of GM corn and soy, it was reasonable to question how the same area would have appeared without the *uninhabitable* mask. To test this theory, the model was repeated for the month of July without the corn and soy mask (Figure 14). Observance of the area typically known as the "corn belt" confirmed that without corn and soy identified as *uninhabitable* as an extension of the mask layer (yet still using the unsuitable weight in the reclassified layer), the entire region was rated as suitable to optimal. This alone indicated that GM varieties could be having a very large effect on recolonization as the area with the most corn and soy was also the location of a large segment of the summer breeding grounds. Another notable observation was that corn and soy had numerous uses along the Mississippi River Basin (Figure 14). This line of uninhabitable cells

Figure 13. Monarch butterfly possible sink populations



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.

Another notable observation was the high number of sightings to the Northeast which may possibly be displaced monarchs forced to seek more suitable conditions. 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

Figure 14. Site suitability with and without soy and corn mask

higher human population numbers and therefore higher reported sightings; however, these sightings were consistently reported into the final generations of 2017 and should not be disregarded.

Sink populations fracture flyways in a different way 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.

While the results from this research reiterate the current concerns surrounding Eastern monarchs, the information from this study and others like it have the ability to transform and sharpen conservation efforts. However, this study was merely a snapshot in a long series of migrations past, migrations present, and migrations yet to come. As data becomes 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 to delineate any substantial trend, but it could be very useful as a baseline for future studies to build upon. Future data will show how site suitability is changing, as well as how the butterflies are adapting. Past data and parallel studies focusing on Western monarchs or other migratory butterfly species could also prove beneficial in an effort to improve site suitability models and variable weighting methods. However, as with most species in decline, time is of the essence.

CONCLUSION

This study was able to successfully visualize the 2017 Eastern monarch butterfly flight year while simultaneously modeling some of the physical factors that affect migratory behavior. After a review of current studies and literature revealed that temperature, precipitation, elevation, and land use had varying effects on general flight patterns, weights were formulated to replicate their effects over a thirteen-month migratory period. Average temperature and land use were found to have the most influential effect while high temperature, low temperature, and crop land use had synergistic roles when combined with average temperature and land use. Elevation and precipitation had smaller contributory roles; however, they could not be entirely negated from the study as extreme occurrences could still affect migrations. Open water and genetically modified corn and soy were identified as absolute uninhabitable zones which superseded all other conditions despite otherwise possible optimal suitability. Once results were displayed geographically, impediments such as incomplete flyways, displaced and sink populations, and other anomalies were analyzed with regard to their influence on migratory patterns and behavior.

While it is impossible to completely understand all aspects of Eastern monarch butterfly migrations from a singular flight year, future research could aid in the development of conservation policies and programs that support butterflies along migratory flyways as well as improve the rate of recolonization at the summer breeding grounds. With the possibility of national protection through the Endangered Species Act (ESA) on the horizon, it will become even more important to target areas where support is needed. Like many large-scale problems, the causation can be complex and have many factors that require remediation; however, studies such as this can put local conditions into perspective across large spatial and temporal ranges. Addressing unfavorable agriculture and development practices coupled with planting indigenous milkweed and nectar producing plants could have a positive effect on butterfly sustainability as well as provide benefit to other pollinators. While monarchs have recovered from critical numbers in past years, their resilience has its limits. If their plight continues unchanged, it is probable that monarchs will become endangered in the near future; however, with proper protection, education, favorable agriculture and development practices as well as improved flyway connectivity, it is possible to curtail some of the damage that has already been done.

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