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North American monarch butterfly populations have been declining at an alarming rate. While animal studies tend to favor biological methods, migratory phenomenon has a distinct geographical element. This body of research uses geographic information science, cartography, spatial analysis, and remote sensing to assess threats to monarch butterflies that occur along the migratory flyways and at the summer breeding grounds and overwinter sites. A site suitability model was created to assess the suitability of temperature, land cover, agriculture, elevation, and precipitation as it applies to butterfly viability and functionality. Cartographic techniques were used to visualize the impacts of herbicide resistant crops on milkweed availability in the summer breeding grounds as well as to substantiate the presence of reported non-migratory populations in Florida and along the Southern Atlantic and Gulf Coasts. Remote sensing technology was used to ascertain the loss and level of land degradation that has occurred at the overwinter sites in Mexico and to isolate naturally occurring milkweed using spectral signatures with the goal to protect present stands and to monitor locations for future migrations. Results indicated that the monarch butterflies are encountering substantial threats at every stage of their migration with the two most substantial factors being loss of naturally occurring milkweed and loss of viable habitat.

GIS APPLICATIONS TO MODEL AND INTERPRET MONARCH BUTTERFLY MIGRATORY BEHAVIOR AND POPULATION DECLINE

by

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CHAPTER I: INTRODUCTION

Monarch butterflies have been a flagship species for animal conservation for several years. Their striking orange coloration and their substantial 3000-mile migration has made them the most recognizable butterfly in North America. However, despite their appeal and migratory significance, monarch butterfly populations have been decreasing at an alarming rate over the past several decades (Preston et al., 2021). Anthropogenic impacts such as development and agricultural practices have led to substantial decreases in naturally occurring landcover, including the loss of milkweeds and nectar-producing plants. Adult monarchs require nectar for energy, but it is the loss of their host plant, milkweed, that has become the overarching threat to recolonizing butterfly populations (Pleasants & Oberhauser, 2013). As climate change challenges all migratory species who occupy large spatial areas at various times during their migratory cycle, North American monarch butterflies are at risk of becoming a threatened species in the very near future (Brower et al., 2012).

However, not all monarchs migrate. The unusually large migration of the North American monarch, which is more akin to avian migrations than traditional insect migrations (Flockhart et al., 2015), is unique and has been steeped with cultural, religious, and scientific significance. In Mexico, the annual arrival of the monarchs returning to the overwinter sites typically aligns with the Día de los Muertos [Day of the Dead] celebrations where native people believe that the butterflies contain the souls of their ancestors and loved ones returning to walk the Earth (Baumle, 2017). As such, orange monarch wings and butterfly art in this region are prominently on display indicating how deeply important monarchs are to the cultural and religious heritage of the local people. Butterflies are biologically and ecologically important as pollinators who are associated with improved crop yields (Bandyopadhyay et al. 2014) and increased plant biodiversity and resilience (Hillebrand et al., 2018). Monarchs are welcomed visitors to many gardens and, unlike milkweed, are not on any pest species lists. As insects, they are middle level members of traditional food webs and are typically situated just above plant producer levels and serve as a food source to other animal species that can tolerate their bitter taste from sequestered cardenolides (Adams et al., 2021).

Despite their cultural and biological significance, Eastern and Western monarchs have encountered multiple challenges during their annual migratory cycles. After years of extremely low population counts, monarchs have always managed to rebound with improved numbers the following year; however, there is always the concern that these types of borderline, quasi-extinction rebounds will not continue forever. While some challenges affect both populations, there are some impediments that are specific to each population due to various geographical factors. Eastern monarchs are plagued with development and agriculture practices in their summer breeding grounds (Pleasants & Oberhauser, 2013), as well as degradation a their overwinter sites in Mexico, while Western monarchs have had to navigate dense development around their overwinter sites (Xerces Society, n.d.), wildfires and drought (Baum & Sharber, 2012; Vogel et al, 2010), and high elevations that curtail flyway habitat (Gallou et al., 2017). All issues were collectively acknowledged when the United States Department of the Interior [DOI] heard the case to protect monarch butterflies under the *Endangered Species Act* following a preset research framework and reporting period (Brower et al, 2014). On December 15, 2020, the commission agreed that the petitioners had established the need for monarch butterflies to be protected; however, they were listed as “warranted, but precluded” as there were already more critically endangered species that had still not received protection and resources (FWS, 2021).

As monarchs await protected status, conservationists, scientists, and citizens alike have worked diligently to incorporate new technologies and research to better understand the complex interactions that migratory monarchs have with each other and within their ever-changing environment. This body of research was designed to forward monarch butterfly conservation using a Geographic Information Science approach. While biology, ecology, entomology, and climatology can explain many of the conditions that are negatively impacting migratory monarchs, the migration aspect adds a distinctly geographical element. Three separate studies were conducted following a previous site suitability model that investigated conditions relevant to the Eastern monarch flyways and summer breeding grounds (Kesler & Bunch, 2020). Chapter three continues this line of research by creating a site suitability model to investigate similar conditions along the Western migratory flyways as well as conditions that were specific to the study area. Average temperature, maximum temperature, minimum temperature, precipitation, land use, cropland use, elevation, wildfire boundaries, and solar farms were scored, weighted, and modeled as a composite indicator of the probability that a specific 30-m^2 cell could support and sustain monarch butterflies and their larvae (Kesler & Bunch, 2023). Results were visualized by creating monthly maps and comparing geolocated monarch butterfly sightings to the underlying suitability conditions.

Chapter four included a series of three smaller studies that were designed to substantiate and address notable threats that had been reported in previous literature and were prevalent in the Eastern and Western monarch site suitability models. The effects of genetically modified crops designed to be herbicide resistant, degradation and loss of natural landcover at the Eastern monarch overwinter sites in Mexico, and the possibility of non-migratory monarch populations were identified as substantial threats to the overall monarch migration and official overwinter population counts. While each of these threats could have severe negative impacts individually, the effects of all three combined could be largely responsible for the recent population declines.

Chapter five contained a theoretical study using remote sensing techniques to provide a pilot methodology that could be used to locate, monitor, and preserve naturally occurring milkweed. While conservationists have encouraged the planting of indigenous species of milkweed to help repair flyway connectivity, little has been done to locate, monitor, and protect the remaining naturally occurring milkweed. Citizen scientist sightings databases, such as the *Journey North* and the *Western Milkweed Mapper*, have provided a way to gain spatial information regarding the location and counts of butterflies, larvae, and milkweed; however, there will always be a level of inaccuracy associated with these types of datasets (Howard et al., 2010). Despite the inaccuracy and lack of confidence in this data, it remains the best data available due to the widespread migratory footprint that prevents scientists from recording sightings in all locations at the same time. Using drones with onboard hyperspectral sensors could provide a middle ground that allows geographers to be directed to areas with recent milkweed sightings while conducting a remote sensing field analysis to locate milkweed, monitor its health and density, and protect it for future flight years. With precision agriculture [PA] studies occurring concurrently with this study, the possibility of research and methods that could be shared, transferred, or adapted could lead to faster solutions for both conservation and agriculture, as well as support the development of application specific sensors that could make this type of technology more economical and accessible.

Generally, Geographic Information Science and GIS have been underutilized in migratory species studies that instead tend to focus on biology, physiology, and local ecology. GIS introduces the ability to view problems across time and space, which can provide information that may be less apparent in traditional laboratory studies alone. Complex issues require complex methods and solutions, and few topics are more complex than the migration of the North American monarch butterfly.

CHAPTER II: BUTTERFLY BIOLOGY, ECOLOGY, AND GEOGRAPHY

1.0. Butterfly Biology

As members of the *Insecta* class, butterflies must function within the realm of their ectothermic limits while navigating a multitude of landscapes and atmospheric conditions. Temperature is particularly relevant since insects metabolize using heat energy, which is crucial during the migration and overwinter processes (Nail et al., 2015). Ecologically, butterflies are confined to specific temperature ranges for optimal functionality and require moisture at all life stages. They tend to prefer environments that have open sunlight to fuel their ectothermic metabolism with an adequate amount of shelter and availability of milkweed and nectar producing plants (Fisher et al., 2020).

1.1. The Butterfly Life Cycle

Several species undergo a full metamorphosis; however, few are as widely recognized as members of the Lepidoptera order which includes all moths and butterflies (Oberhauser, 2004). The monarch butterfly life cycle progresses through four separate stages before ultimately emerging as a fully formed adult butterfly that is distinctly different from any of its previous life stages. While the time at each stage varies depending primarily on site-specific temperatures, monarchs will generally spend approximately three to five days in the egg before hatching (Journey North, n.d.). Since butterflies are arthropods, they have an exoskeleton that must be shed to sustain changes in body mass. This is prevalent during the larval stage when monarchs will molt five separate times after consuming milkweed non-stop for 11-18 days and increasing their body mass by 2000-3000 times its original size (Baumle, 2017). After molting four times, the larva will cease milkweed consumption and hang upside down in a “J-shaped” formation before molting one final time to reveal the monarch chrysalis with the developing pupa inside

(Baumle, 2017). After pupating for an additional 8-14 days, the pupa emerges as a fully grown adult butterfly that is physically and biologically different than any of its previous life stages (Oberhauser, 2004; Journey North, n.d.; North Carolina Wildlife Federation [NCWF], n.d.). Butterflies will continue to live for an additional 2-4 weeks (Journey North, n.d.), and it is relevant to note that all migratory, recolonization, and overwintering activities occur in this fourth and final stage of development (Figure 1).

Figure 1. Butterfly Life Cycle

Note. (Retrieved https://dnr.maryland.gov/wildlife/Pages/plants_wildlife/monarch.aspx)

1.2. Milkweed

Milkweed (*Asclepias spp.*) (Figure 2) is vital to the survival of monarch butterfly populations and is available in multiple species that are adapted to survive in nearly all climates including wet, arid, and tropical locations (United States Department of Agriculture [USDA], n.d.; United States Forest Service [USFS], n.d.). As the sole food source for developing larva and as a nectar source for migrating adult butterflies, milkweed is frequently utilized to delineate monarch butterfly habitat ranges (Waterbury et al., 2019; Xerces Society, n.d.). Female butterflies will typically oviposit between 500-700 eggs to the undersides of milkweed leaves which ultimately provides an immediate food supply for the newly hatched and developing larvae (Wells, 2010; Oberhauser, 2004). While there are over 100 species of milkweed in the United States and Southern Canada, less than half have been designated as monarch host plants (Borders & Lee-Mäder, 2014). The number of host plants is further reduced as studies have shown that female monarchs prefer certain species over others (Greenstein et al., 2022; Fisher et al., 2020). *Common Milkweed (Asclepias syriaca),* butterfly weed *(Asclepias tuberosa),* and swamp milkweed *(Asclepias incarnata)* have proven more highly attractive to female monarchs, while tropical milkweed (*Asclepias curassavica*) has been deemed an invasive species (Wheeler, 2018). Tropical milkweed has been listed as one of the milkweeds that does not experience an annual winter die back, which often leads to parasitic and protozoan infested milkweeds that could result in less healthy butterflies (Geest et al., 2019; Majewska et al., 2019; Altizer et al., 2015). This type of year-round milkweed could also be a root cause for non-migratory populations (Freedman et al., 2018).

Figure 2. Milkweed

Note. [*(Left to Right)* Common Milkweed *(Asclepias syriaca)* (Photo Credit: David Taylor); Butterfly Weed *(Asclepias tuberosa)* (Photo Credit: Larry Stritch); Swamp Milkweed *(Asclepias incarnata)* (Photo Credit: Jennifer Anderson) (USFS, n.d.)]

Milkweed is typically classified as a flowering herb and only has a few species that are considered weeds; however, milkweed has been considered a pest plant in both plant and animal agriculture (Borders & Lee-Mäder, 2014). Milkweed contains various toxins including cardenolides that are toxic to humans and other animals. Monarchs are able to sequester the toxins that are consumed during the larval stage which transfers the defense system to the adult butterflies. Predators have learned to avoid the orange butterflies due to the unpalatable, bitter taste from the sequestered cardenolides (Adams et al., 2021) which has led to cases of mimicry where other species develop to look like monarchs (Journey North, n.d.).

2.0. Ecology

2.1. Temperature and Climate Change

As insects, butterflies are irrevocably linked to the environment around them. Temperatures directly affect their ability to function since they metabolize heat for energy. To fly and function normally, butterflies require temperatures at or above 55°F; however, temperatures below 55°F do not necessarily lead to hypothermia or death (Nail et al., 2015). Monarch larvae are capable of surviving freezing temperatures up to -4°F for short amounts of time as their ectothermic bodies cool with the surrounding air and do not require the expenditure of heat to stay warm (Nail et al., 2015). In fact, this ability to cool and use less energy to survive has proven beneficial during the overwinter months in the San Madre Mountains where temperatures frequently drop below 55°F (Vidal et al., 2014; Aridjis, 2008). High temperatures are less forgiving as temperatures above 107.6°F can lead to heat stroke and death. This leaves a range of 55 °F to 107°F as the functional range where butterflies can suitably fly, recolonize, and migrate (Kesler & Bunch, 2023; Kesler & Bunch, 2020). Temperature also affects the amount of time that monarchs spend at each life stage. Warmer temperatures reduce the amount of time required for development, while cooler temperatures may require more time at various life stages (Zipkin et al., 2012; Zalucki, 1982).

Climate change is concerning for all migratory species that travel across large distances and environments (Espeset et al., 2016). Ill-timed migratory responses can lead to death, while unusually optimal temperatures can defer migration behaviors causing butterflies to become sedentary (Tenger-Trolander et al., 2019). As warmer temperatures are experienced further north, areas in the Southern United States have reported sightings of monarch butterflies nectaring and breeding when they should be reasonably located at the overwinter sites in Mexico in a state of reproductive diapause (Brower et al., 2012). This shift in migratory behavior is troubling due to parasitic and protozoan infestations that occur in milkweeds that do not experience a seasonal die back (Geest et al., 2019; Majewska et al., 2019; Wells, 2010). Other concerns include changes in wing and body morphology in sedentary butterflies that could make them unsuitable for long migrations (Altizer et al., 2015).

2.2. Anthropogenic Impacts

While some changes are natural due to the dynamic nature of changing cycles and systems, much of the loss of critical butterfly habitat has been directly linked to anthropogenic development and agricultural practices (Majewska et al., 2019; Blair, 1999). As urban landscapes and residential communities have developed, natural landcover has been removed and replaced with structures, aggressively managed landscaping, and impervious surfaces. To offset some of the development that has already occurred, conservation groups have advocated for residents to plant pollinator gardens containing indigenous milkweeds and nectar plants in developed areas; however, while efforts have helped, they are not a lateral replacement for naturally occurring milkweed and critical landcover (Knight et al., 2019; Aguirre-Gutiérrez et al., 2015).

Agricultural practices have had one of the largest impacts on the Eastern summer breeding grounds and migratory flyways (Thogmartin et al., 2017; Pleasants, 2015; Pleasants & Oberhauser, 2013). The Annual recolonization typically occurs in the Northern United States in the Midwest and Great Lakes Regions and in Southern Canada (USDA, n.d.; USFS, n.d.; Xerces Society, n.d.). Nicknamed "*The Corn Belt*", this area is known for its large commercial farms that primarily specialize in the production of corn and soy (Pleasants & Oberhauser, 2012). To boost production and to reduce costs, most commercially available corn and soy varieties have been genetically modified to be herbicide resistant which allows for the sweeping and widespread application of herbicides without harming the planted crop (Pleasants, 2015). These types of practices have been responsible for the mass removal of naturally occurring milkweed that had previously grown around the crop perimeters and in between rows (Boyle et al., 2019). Further compounding the loss of milkweeds occurs when herbicides drift beyond the area of application. Herbicide drift has been documented to affect vegetation at distances ranging from 30-feet to over a mile from the point of application depending on the type of herbicide, environmental conditions, and the application method (Brain et al., 2017). To a lesser extent, cotton and canola have been identified as varieties that employ the same type of genetic modification which has created similar issues along the Mississippi River Basin effectively creating a barrier to migratory butterflies (Kesler & Bunch, 2020; Richards et al., 2005).

Commercial and landscaped lawns further reduce the presence of milkweed through the use of herbicides, while pesticides administered to eradicate "pest" insects have negatively impacted migrating and recolonizing butterflies (Thogmartin et al., 2017; Pleasants, 2015; Pleasants & Oberhauser, 2012). Loss of milkweed combined with other negative impacts such as climate change (Lemoine, 2015) and aggressive mowing along roads and right-of-ways (ROWs)

(Ozcan et al., 2020; Knight et al., 2019) has created gaps in flyways (Brower et al., 2012); however, concerned citizens and conservationist groups have supported the planting of indigenous milkweed varieties as well as discouraged the use of herbicides and pesticides through programs such as *The Butterfly Highway* (NCWF, n.d.), the *Journey Nor*th (n.d.), the *Western Milkweed Mapper* (n.d.), the Xerces Society (n.d.), and *Monarchwatch.org* (n.d.).

2.3. Non-Migratory Sink Populations

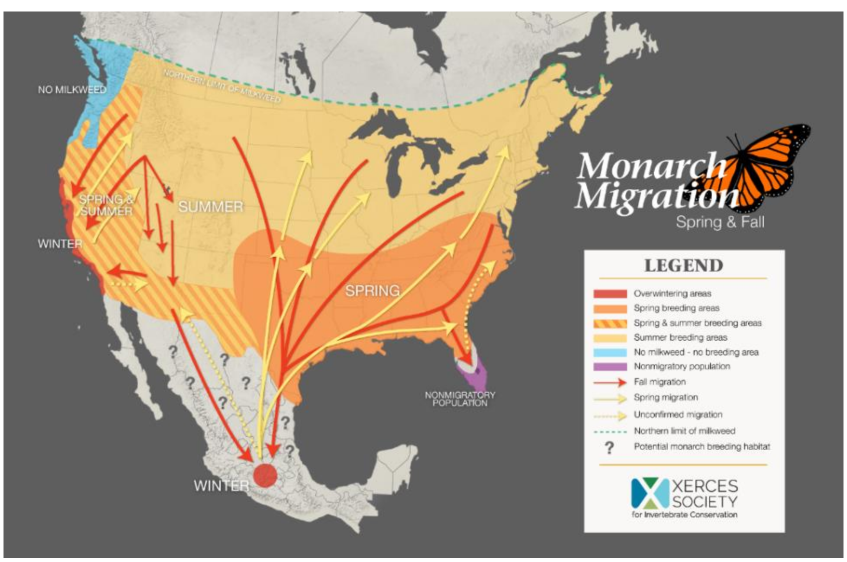
While North American monarch butterflies undertake an avian-like annual migration, populations throughout the Caribbean, Central and South America, and Australia appear to be more sedentary or only migrate short distances (Altizer & Davis, 2010; Clarke & Zalucki, 2004). It is unclear if the migratory tendency is the norm or the exception, but several factors may be creating pockets of non-migratory monarchs. With optimal temperatures in Southern Florida and along the South Atlantic and Gulf Coastlines, monarchs may not be receiving the biological trigger that signals for the newly emerged butterflies to remain in reproductive diapause and return to the overwinter sites in Mexico (Williams, 2015). While the impacts that these populations could have on the larger migratory population is not fully understood, there has been concern regarding the health of the non-migratory butterflies. Altizer & Davis (2010) documented that sedentary monarchs had developed smaller bodies and rounded wings that made them less suitable for long-distance flight, while parasitic infested milkweeds that grew year-to-year without the traditional perennial die back could lead to less healthy butterflies (Geest et al., 2019; Majewska et al., 2019).

3.0. Geography

3.1. Migration and Recolonization

The Eastern population is the most recognizable due to the scale of the migration that begins in the overwinter sites in the Sierra Madre Mountains of Mexico and travels to the summer breeding grounds in the Northern United States and Southern Canada (Figure 3). The migration north is roughly 3000-miles and occurs over three to four successive generations (Baumle, 2017; Xerces Society, n.d.). Once in the summer breeding grounds of the Midwest and Great Lake Regions, the butterflies recolonize with peak proliferation occurring in early fall. Once it is time for the butterflies to return to the overwinter sites, an onboard biological trigger signals for the newly emerged butterflies to remain in reproductive diapause, cease recolonizing, and begin the migration south (Harvey et al., 2015). While the northern migration occurs across multiple generations, the southern migration is made by a single butterfly. This butterfly makes the entire journey south, overwinters until late February/early March, exits the overwinter site, and lays the first eggs for the next migration north (Solensky, 2004).

Figure 3. Monarch Butterfly Migratory Flyways



Note. Retrieved from xercessociety.org

3.2. Overwinter Sites

The migration begins and ends at the overwinter sites in California and Mexico. In late February and early March, Eastern monarchs emerge from overwinter sites in the San Madre Mountains of Mexico (Journey North, n.d.), while Western monarchs vacate overwinter sites along the Central and Southern California Coast during April and May (Journey North, n.d.; Western Milkweed Mapper, n.d.). After the migration and recolonization segments of the migratory cycle come to a close, monarchs receive a biological trigger that signals the return migration that ends in September for the Western population and in November for the Eastern population (Howard et al., 2010; Solensky, 2004).

3.2.1. Eastern Population

While monarch butterfly migrations have been described for multiple centuries, it was not until 1975 that a group of scientists located the overwinter roost sites in the San Madre Mountains east of Mexico City. When Urquhart & Urquhart (1976) located the colonies, the butterflies were roosted so densely that the branches of the oyamel fir (*Oyamel mexicano*), holm oak (*Quercus ilex*), and pine (*Pinus spp.*) trees bent under their weight (Figure 4). Following this discovery, the Mexican government protected several known overwinter sites until the United Nations Educational, Scientific, and Cultural Organization [UNESCO] extended coverage to the Monarch Butterfly Biosphere Reserve [MBBR] as a world cultural heritage site in 2008 (Aridjis, 2008).

Figure 4. Densely Roosted Overwintering Butterflies

Note. Retrieved from Goodnature.nathub.com

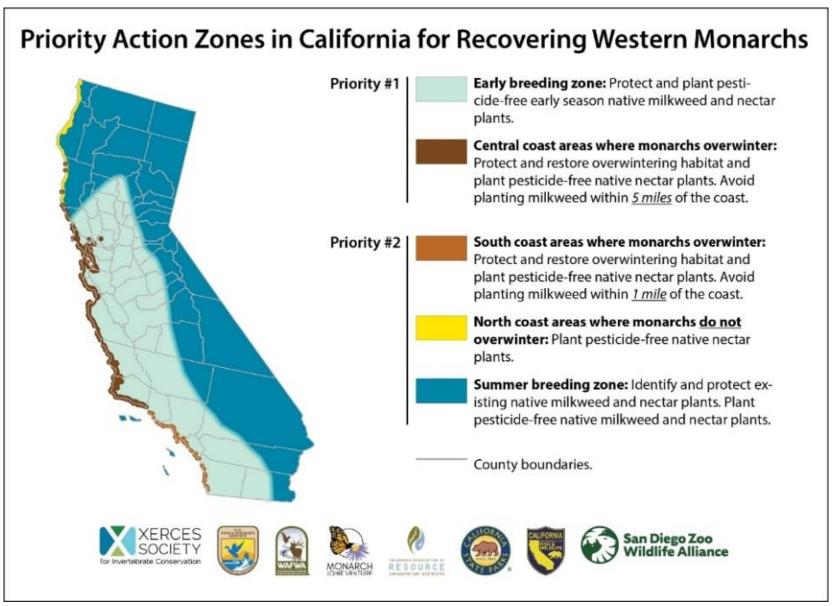
The MBBR currently contains 56,259-ha of forested land and protects 12 of the 14 known overwinter monarch butterfly sites; however, residential, agricultural, and commercial development has encroached on the MBBR which has negatively impacted all unprotected land outside of the reserve (Brower et al., 2002). With the population in Mexico City continuing to increase, it is unlikely that the need for land and natural resources will diminish, which has led to illegal logging inside the MBBR protected zone (Flores-Martínez et al., 2019; Vidal et al., 2014). These local conflicts turned violent in 2020 when two butterfly conservationists were murdered for publicly denouncing illegal resource extraction (López-García & Navarro-Cerrillo, 2020). With unprotected land outside of the MBBR experiencing severe degradation, and the protected land inside the MBBR being logged illegally, critical vegetation and roost habitat have been substantially reduced with remaining vegetation becoming less dense and less healthy (López-García & Navarro-Cerrillo, 2020; Aridjis, 2008).

3.2.2. Western Population

Western monarchs overwinter in sites along the California Coastline with some sites adjacent to densely populated and developed areas including San Francisco, Los Angeles, and

San Diego (Dingle et al., 2005; Xerces Society, n.d.) (Figure 5). While it is possible that Western monarchs could migrate to Mexico and join the Eastern migration, it is believed that the Eastern and Western populations do not intermix due to the unfavorable altitude and temperatures in the Rocky Mountains which serves as a boundary between the two populations (USFS, n.d.). Currently there is no evidence that Eastern and Western monarchs are a subspecies of one another; however, sightings data indicates that Western monarchs could be exhibiting behaviors similar to their non-migratory counterparts (Journey North, n.d.; Western Milkweed Mapper, n.d.). These monarchs roost in groves of coastal eucalyptus (*Eucalyptus spp*.), Monterey pine (*Pinus radiata*), and Monterey cypress (*Cupressus macrocarpa*) before exiting the overwinter sites for a similar, yet smaller-scale migration (Malcolm, 2018).

Figure 5. Western Monarch Overwinter Sites



4.0. Future of Monarch Butterfly Conservation

4.1. Pending Threatened Species Status

As monarch populations continue to experience a general decline, it has become necessary to consider what protections and conservation resources could be provided to prevent future extinction. In 2014, following decades of increasing losses, the U.S Fish and Wildlife Service (FWS), The Xerces Society, The Center for Biological Diversity, and The Center for Food Safety, and Lincoln Brower petitioned the United States Department of the Interior (DOI) to protect Eastern monarch butterflies with threatened species status under the Endangered Species Act (ESA). Their petition listed monarch butterflies in danger of becoming extinct in the near future due to loss of habitat and general curtailment of range (Brower et al., 2014).

Following a formal petition filing and research period, the DOI heard the petition and its supporting evidence on December 15, 2020. While the petitioners were successful in substantiating that monarchs did meet the criteria for protection under the ESA, protection was deemed "warranted, but precluded". Following the decision, monarchs were placed on a waitlist behind other candidate species that were considered more critically threatened (FWS, 2021). Their status would be monitored for any substantial changes that could alter their standing or ranking on the waitlist, and as of this publication, monarchs have not received any formal protection, funding, or resources (Pocius et al., 2018)

4.2. Citizen Science Data

Citizen Scientist or Community Science data has become more widely used in research as a method of capturing widespread phenomenon that occurs simultaneously across multiple spatial and temporal scales. In migration studies, these datasets have opened new paths for visualizing and analyzing datasets that were previously unavailable in regard to the size (number of data points), time (ability to collect data points continuously), and space (the ability to collect data at any location.

This body of research utilized two citizen reporting datasets: *Journey North* and the *Western Milkweed Mapper*. Despite the large datasets that are available through these two platforms, citizen scientist data is not without its problems (Howard et al., 2010; Kountoupes & Oberhauser, 2008). The largest obstacle when using citizen scientist data for research and funding purposes lies with the inherent error that exists in a system where anyone can make a data entry and entries may or may not go through any verification process. This opens the data to errors in butterfly identification and in sighting time, location, and counts that can lead to reduced confidence in the overall dataset. While there will always be a level of inherent inaccuracy associated with these types of datasets, they are currently the most robust repository for near real-time butterfly and milkweed sightings data.

4.3. Significance of Monarch Butterflies

Monarch butterflies have long been recognized as the face of conservation and insect migration (Preston et al., 2021). Biologically, butterflies are arthropods that must shed their exoskeleton to gain body mass before completing a metamorphosis into an adult butterfly that is biologically and physically different than any of the other life stages (Baumle, 2017). While several butterflies and insects migrate, monarchs are unique in that they complete a 3000-mile migration from overwinter sites in Mexico to the summer breeding grounds in the Northern United States and Southern Canada over three to four consecutive generations, while a single butterfly makes the entire 3000-mile journey south, overwinters, exits the overwinter sites, and lays the first eggs for the next year's migration (Solensky, 2004). While monarch butterflies typically live for an additional two to four weeks post metamorphosis, the generation that makes the southern migration can live for an additional four to seven months. This generation has been nicknamed "The Methuselah Generation" or "The Super Generation" due to its abnormally long lifespan and the ability to make the 3000-mile journey to Mexico. It is in this return to Mexico that aligns with the Día de Los Muertos, or Day of the Dead, celebration on November 1-2. The butterflies hold cultural, social, and religious significance for the local people as many natives believe that the monarchs are the souls of their ancestors and loved ones returning to walk the Earth for the duration of the celebration (Baumle, 2017).

Adult monarchs are classified as pollinators which has received much attention due to their association with increased plant biodiversity due to cross pollination which increases plant yields (Bandyopadhyay et al. 2014), resiliency, and disease resistance (Traveset et al., 2017). Pollinator gardens have become a popular method of conservation to help rebuild monarch flyways as well as to support native bees and birds; yet, while monarchs are known for their cultural, historical, aesthetic, and migratory significance, they are ultimately valued for their environmental services and as a base-level animal species in local food webs (Bull et al., 2013; USDA, n.d.).

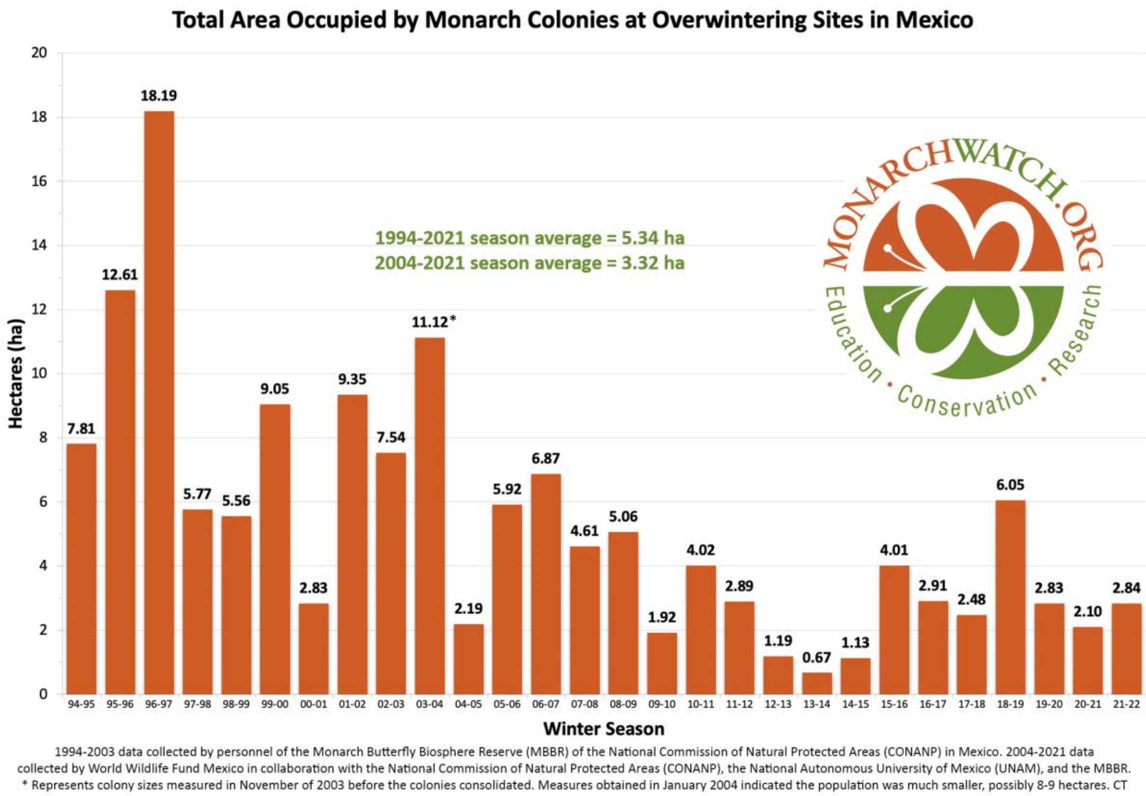
4.4. Population Declines

While insect populations often experience “boom or bust” recolonization years, isolated years of lower or larger than average counts have little bearing on the overall health of the population (Gherlenda et al., 2016). However, butterfly counts have been trending downward at a rapid rate that does not appear to be slowing. Western populations were reported below quasi-extinction benchmarks during the 2020/2021 flight year where the population was feared to be unrecoverable (Engen & Sæther, 2000). Eastern populations continue to decline at such a rapid rate that conservationists fear that it is a matter of time before their populations could also become unrecoverable.

4.4.1. Eastern Population

Monarchs in Mexico typically roost in dense clusters that cause the trees to droop under their weight, which makes counting individual butterflies impossible (Urquhart & Urquhart, 1975). As such, Eastern monarchs are reported as hectares occupied (Figure 6). “Boom or Bust” populations are clearly visible; however, the downward trend is indisputable.

Figure 6. Eastern Monarch Counts

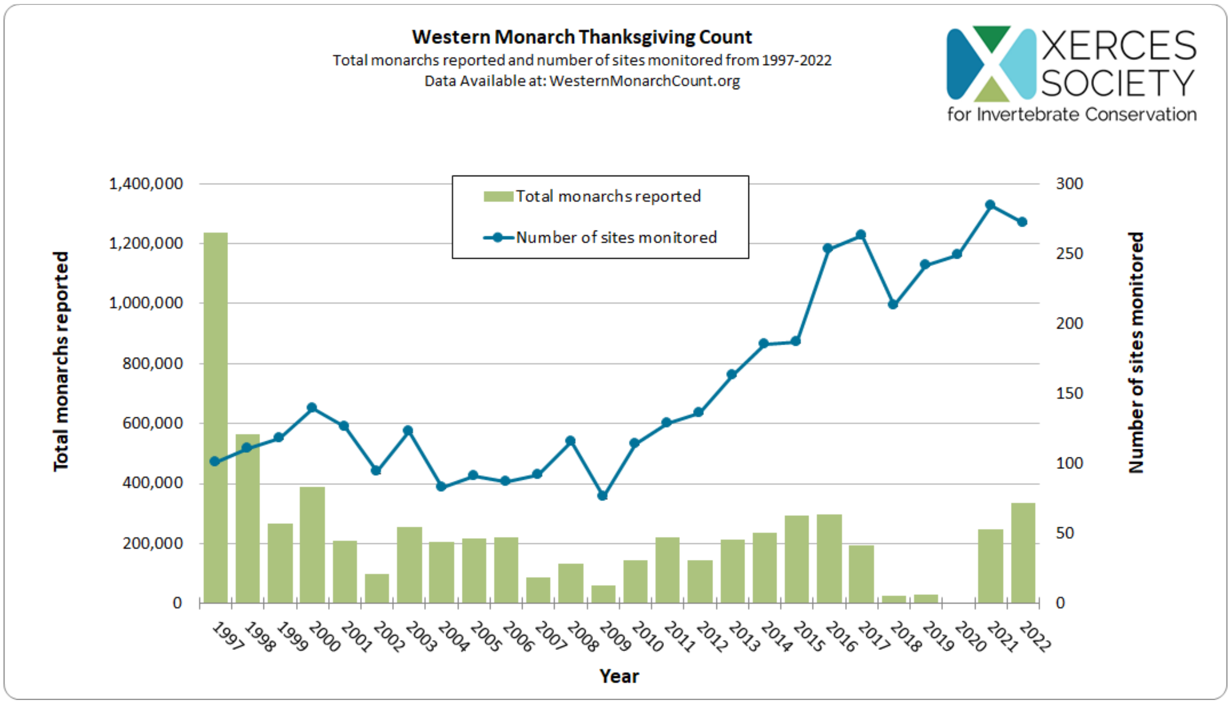


Note. Retrieved from MonarchWatch.Org

4.4.2. Western Population

The Western population has always been smaller than its Eastern counterpart and recorded as butterfly counts. The Xerces Society (n.d.) conducts annual Thanksgiving Counts during the month of November as well as New Year’s Counts in January. Figure 7 visualizes the Western Thanksgiving Counts from the past 25 years illuminating the alarming decline that occurred in the late 1990s. Another concerning factor was that while the number of surveyed sites increased dramatically over the past 10 years, monarch counts did not substantially improve. The lowest count was recorded in 2020 when volunteers for the Xerces Society only tallied 1914 Western monarchs at 261 surveyed locations; however, the monarchs rebounded in 2021 with a total count of 335,479 at 268 surveyed locations (Xerces Society, n.d.). While this rebound is indicative of monarch butterflies' resiliency, the struggle for conservation is far from over.

Figure 7. Western Monarch Thanksgiving Counts



Note. Retrieved from Xerces Society, n.d.

CHAPTER III: MAPPING THE MIGRATION: A WESTERN MONARCH BUTTERFLY SITE SUITABILITY STUDY

Kesler, K., and Bunch, R. (2023). Mapping the migration: A Western monarch butterfly site suitability study. *International Journal of Applied Geospatial Research*, *14*(1): 1–22. https://doi.org/10.4018/IJAGR.316769.

1.0. Introduction

Species population declines have become commonplace as climate change and anthropogenic encroachment have amplified over recent decades. With concerns of extinctions and fear that the entire migratory phenomenon may be at risk (Thogmartin et al., 2017), monarch butterflies have become another candidate on a long list of threatened and endangered species. While Eastern populations have received much attention for their large-scale annual migration and population decline, Western monarchs are rapidly approaching quasi-extinction benchmarks where populations may become unrecoverable (Engen & Saether, 2000).

This study examined physical, environmental, climatological, and anthropogenic factors that affect monarch butterfly migratory, recolonization, and overwintering behaviors. These factors were input into a geographic information system (GIS) and mapped to visualize collective migratory conditions in conjunction with geolocated butterfly sightings. The goal of this study was to identify locations where site suitability and normal butterfly behavior has been compromised and to inform Western monarch conservation agendas.

2.0. Monarch Butterfly Ecology

Butterflies progress through four distinct developmental stages which carry varying implications to the viability of the overall population. While the time at each stage varies, the general rule is that monarchs will spend approximately four days in the egg stage before spending the next 9-14 days as a developing larva. The larva will consume milkweed continually until their body mass has increased by 2000-3000 times (Baumle, 2017). A final molt will transform the larva into a chrysalis in the pupal stage. After developing inside the chrysalis for an additional 9-15 days, the pupa emerges as a fully formed adult butterfly (Oberhauser, 2004). Butterflies will continue to live for an additional 2-4 weeks to complete the fourth and final stage of development where all migratory, recolonization, and overwintering activities occur.

Temperature bears a particular importance as insects metabolize using heat energy, which is a crucial element during the migration and overwinter processes. As such, monarchs must be able to function within the realm of their ectothermic limits while navigating a multitude of landscapes and atmospheric conditions.

2.1. Migration & Overwinter Sites

While Eastern and Western monarchs are genetically the same butterfly, the populations rarely intermingle due to the natural barrier provided by the Rocky Mountains (Gallou et al., 2017). Historically, the Eastern population has garnered the most awareness due to their large-scale migration which spans roughly 3000-miles from overwinter sites in Central Mexico to the summer breeding grounds in the Northern United States and Southern Canada (Solensky, 2004). However, despite the less impressive spatial scale, the Western migration encounters more flyway heterogeneity in the approximately 700-mile migration from overwinter sites along the coast of Southern California (Figure 8) to the recolonization grounds in the Pacific Northwest (Malcolm, 2018). During the overwinter months, Western monarchs roost in coastal eucalyptus (Eucalyptus spp.), Monterey pine (Pinus radiata), and Monterey cypress (Cupressus macrocarpa) in a state of reproductive diapause (Malcolm, 2018). The butterflies exit the overwinter sites during the spring months and migrate north while recolonizing throughout the journey (Baumle, 2017; Solensky, 2004).

Figure 8. Prominent Western Monarch Overwinter Sites

2.2. Milkweed

Milkweed (*Asclepias spp*.) is vital to the survival of monarch butterfly populations and is available in multiple species that are adapted to survive in nearly all climates (United States Department of Agriculture [USDA], n.d.). As the sole food source for developing larvae, female monarchs will deposit between 500-700 eggs to the underside of milkweed leaves which provides an immediate food supply for the newly hatched larvae (Wells, 2010; Oberhauser, 2004).

While milkweed has been plentiful in the past, recent anthropogenic impacts have decreased the amount of natural milkweed occurring along migratory flyways. This issue has been complicated by the use of genetically modified crops (Pleasants & Oberhauser, 2012) as well as herbicide and pesticide use in commercial and landscaped lawns (Thogmartin et al., 2017; Pleasants & Oberhauser, 2012). To repair flyway connectivity, concerned citizens and conservationists have supported the planting of indigenous milkweed varieties as well as discouraged the use of herbicides and pesticides through programs such as The Butterfly Highway sponsored by the North Carolina Wildlife Federation (NCWF) and Monarchwatch.org.

2.3. Climate Change and Other Threats

Like many species, monarch butterflies have experienced challenges presented by climate change at overwinter sites and along migratory flyways. With endemic populations already disappearing in locations where the surrounding environment changed more rapidly than the species could adapt (WallisDeVries, 2007), experts are questioning if the entire migratory phenomenon may be at risk (Thogmartin et al., 2017). Impacts such as changing temperatures, extreme atmospheric events, and unpredictable weather coupled with a multitude of indirect effects has left researchers wondering if monarchs will be able to adapt, or if their populations will eventually decline below recoverable benchmark levels (Brower et al., 2012).

While weather is perhaps the largest concern across insect populations, Western monarchs also experience other anthropogenic, land use, and environmental obstacles. The Western United States frequently experiences periods of extensive drought and excessive precipitation which can impact annual recolonization rates. Monarch butterflies who occupy arid or drought exposed areas tend to develop lower lipid stores which can decrease their viability during the overwinter season, while excessive precipitation is problematic for flight (Nail et al.2015). Wildfires are also common in the Western monarch migratory and overwinter zones, which can damage critical habitat as well as produce widespread smoke, burned debris, and atmospheric ash. However, studies have been conducted to understand the positive effects of fires on milkweed and nectar producing plant growth. With the elimination of dense tree canopies and debris on the forest floor, fires can create better environments for new plant growth which ultimately improves natural habitat (Baum & Sharber, 2012; Vogel et al, 2010).

Development density and its associated residential, agricultural, and commercial footprints tends to reduce habitat and natural landcover, while herbicide use further extends the reach of these footprints (Thogmartin et al., 2017; Pleasants & Oberhauser, 2012). Another concern revolves around the installation of solar farms that may pose specific risks to insects which are drawn to solar panels and towers due to the heat that they emit. Currently, it is uncertain how negatively the farms are impacting monarch populations, but it is believed to create areas of uninhabitable land use (Horvath et al, 2010).

2.4. Threatened Species Status

Given that monarch populations have continued to decline, the U.S. Fish and Wildlife Service (FWS), The Xerces Society, The Center for Biological Diversity, The Center for Food Safety, and Dr. Lincoln Brower filed a petition with the United States Department of the Interior (DOI) to extend threatened species status to monarch butterflies. The original petition was filed in 2014 under the Endangered Species Act (ESA) and listed loss of habitat and curtailment of range as the primary concerns (Brower et al, 2014). The decision was made formal on December 15, 2020, that while protection was warranted, monarchs were precluded from immediate listing. Instead, monarchs were placed on a waitlist behind other candidate species that were considered more critically threatened (FWS, 2021).

2.5. Site Suitability Model

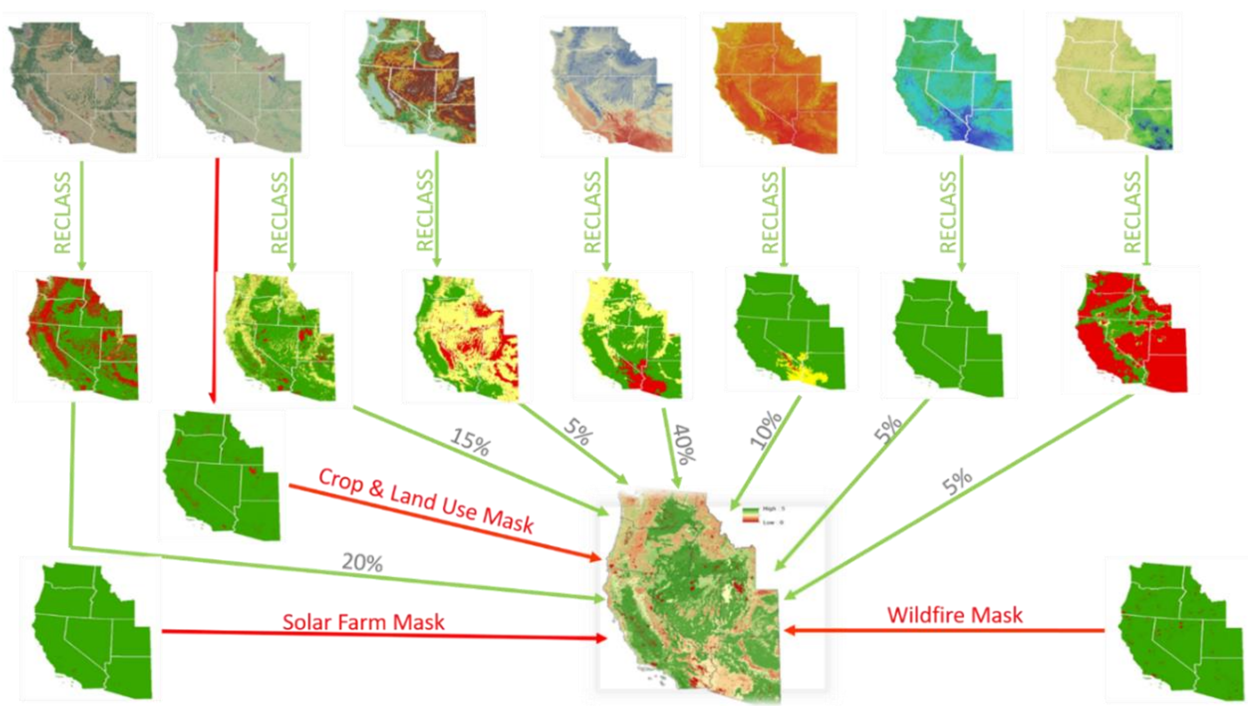
Site suitability studies are appropriate for GIS as they allow for the visualization of multiple factors across spatial and temporal ranges. These studies have utilized GIS for various types of analyses including locating optimal spaces for energy installations (Ali et al., 2019), natural resource management (Qaddah & Abdelwahed, 2015), site impact analyses (Al-Ruzouq et al., 2019), optimal location for crops and agriculture (Young et al., 2017), accessibility and land development (Sarath et al., 2018; Kumar & Shaikh, 2013), and wildlife habitat preservation (Hovick et al., 2015). These studies utilized discrete spatial features such as roads, utility networks, population, neighborhoods, and hydrologic features, as well as continuous features including surface temperature, elevation, soil and substrate type, wind speed, and precipitation to evaluate and rank site conditions to identify optimal locations.

While GIS has been incorporated into other butterfly research models, the use of a site suitability model to locate gaps in migratory flyways has been largely underutilized. Given the ease of obtaining data for multiple physical and anthropogenic factors, a site suitability model that delineates locations with optimal conditions as well as locations in need of mitigation is highly effective and encourages the focused and efficient use of limited conservation resources. This study prioritized factors based on previous research that modeled the Eastern monarch migratory range. Seven factors were identified as major contributors to monarch butterfly viability: mean temperature, maximum temperature, minimum temperature, precipitation, land use/cover, cropland use, and elevation. To construct the model, Kesler and Bunch (2020) reclassified the seven factors to produce suitability rankings. Seven ranked layers plus an uninhabitable layer were input into a model to create a composite site suitability score which was analyzed in conjunction with geolocated butterfly sightings. This model indicated that butterfly migrations were significantly disrupted by the widespread use of genetically modified (GM) corn and soy crops that were herbicide resistant (Pleasants & Oberhauser, 2012), as well as validated reports of non-migratory populations along the Gulf and South Atlantic Coastlines (Satterfield et al., 2015; Howard et al., 2010).

3.0. Methods

This study utilized the seven previously identified factors (Kesler & Bunch, 2020) with the addition of factors more specific to the Western migration such as wildfires, large solar farms, and new genetically modified crop varieties. Each factor layer was reclassified rating conditions as optimal, suitable, or uninhabitable. The factors were weighted and input into the site suitability model to create composite layers that delineated site suitability throughout the migratory flight year (Figure 9). The final layers were analyzed in conjunction with geolocated butterfly sightings and compared to the results from the Eastern monarch model to understand the generalized threats to monarch migrations as well as the unique issues confronted by Western monarchs.

Figure 9. Site Suitability Model Workflow



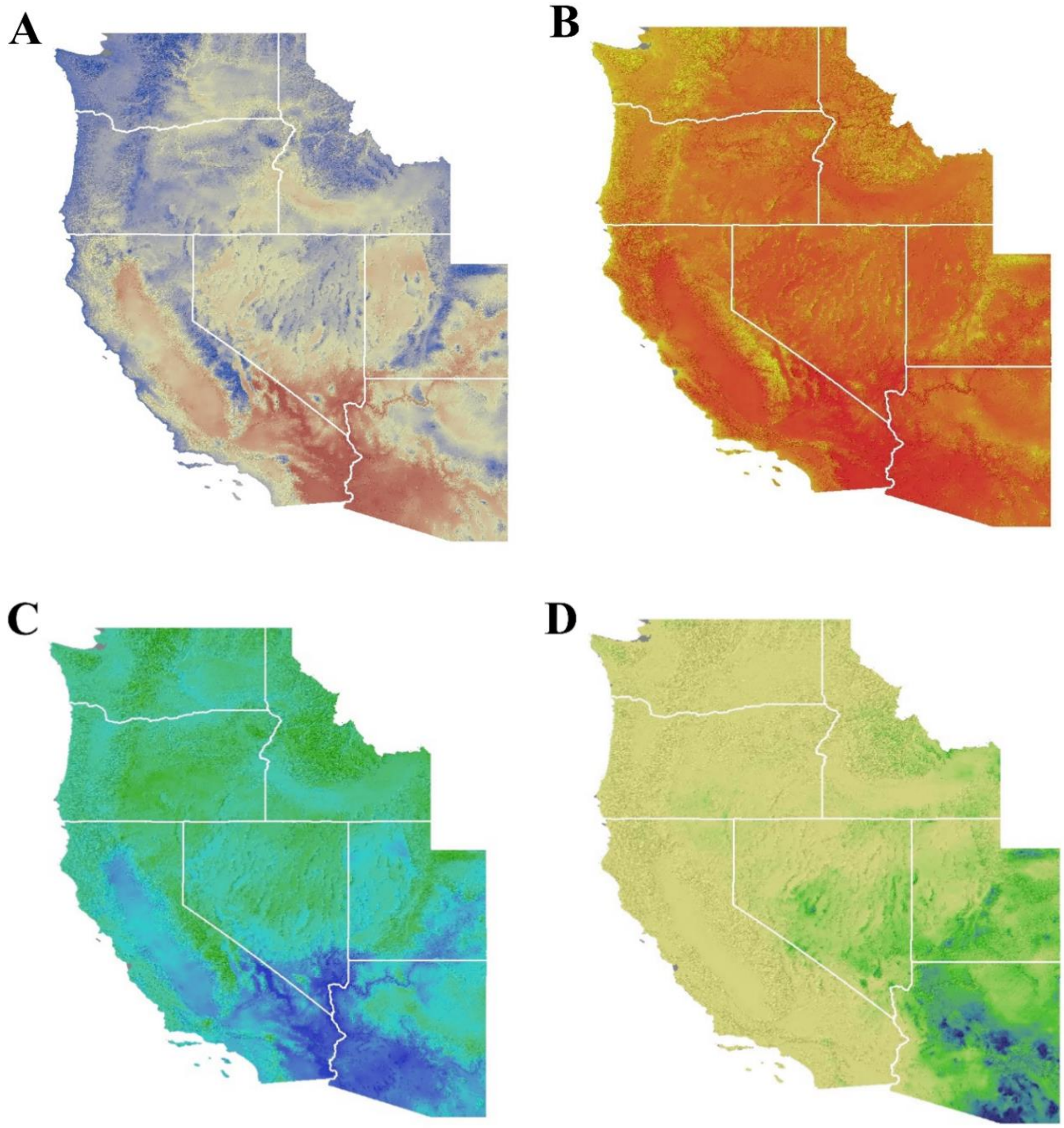
3.1. Study Area and Datasets

This study used nine datasets to provide suitability variables over a 12-month Western monarch migratory flight year. November 2016 was the first study month as it encompassed the close of the 2016 migration. December 2016, January 2017, and February 2017 delineated the overwinter months, while March, April, May, June, July, August, and September of 2017 represented the northern migration and annual recolonization. The biological trigger that signals for the butterflies to enter a state of reproductive diapause and return to the overwinter sites typically occurs in October, which marked October 2017 as the beginning month of the southern migration. Since monarch butterflies are not typically sighted in higher elevations, the study area was identified as the area west of the Rocky Mountains, east of the Pacific Ocean, south of the U.S./Canadian border, and north of the U.S./Mexican border (Figure 10).

Figure 10. Western Monarch Study Area

Weather datasets were retrieved from the Prism Climate Group based at Oregon State University and used to create the mean temperature, high temperature, low temperature, and precipitation variables for the site suitability model. Weather data was retrieved for each of the 12 months and incorporated into the model as a monthly mean temperature (°C) (Figure 11A), monthly maximum temperature (°C) (Figure 11B), monthly minimum temperature (°C) (Figure 11C), and the monthly sum of all precipitation (mm) (Figure 11D).

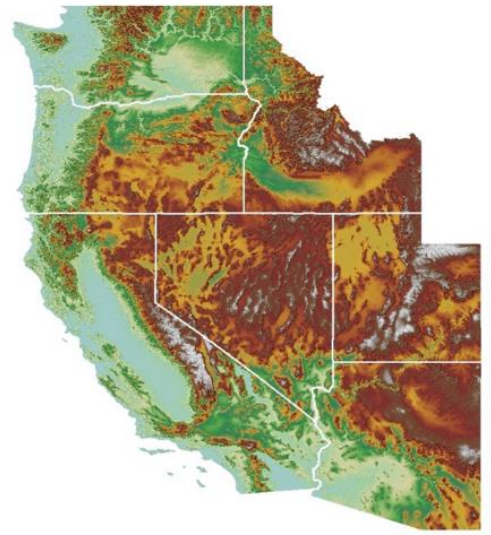
Figure 11. Model Factors



Note. **(A)** Monthly Mean Temperature (°C); **(B)** Monthly Maximum Temperature (°C); **(C)** Monthly Minimum Temperature (°C); **(D)** Monthly Total Precipitation (mm).

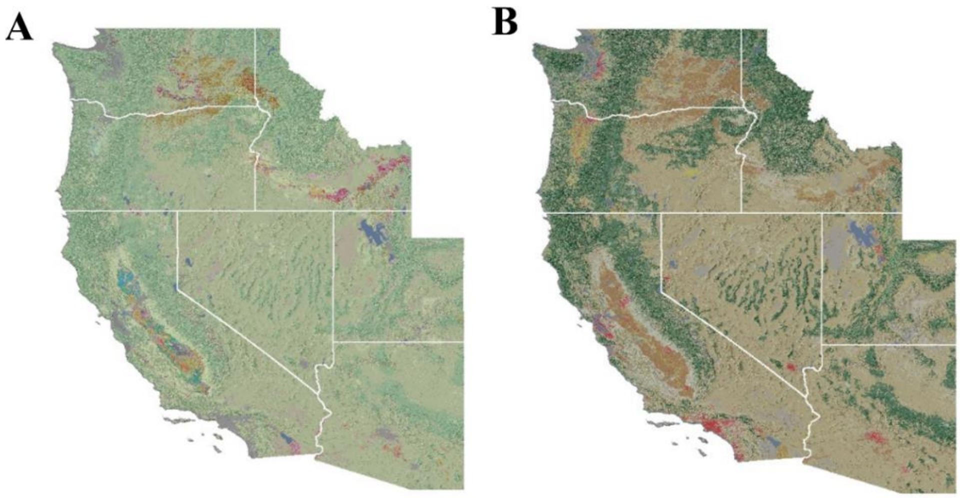
The elevation dataset was retrieved from the United States Geological Survey (USGS) as 30-meter Digital Elevation Models (DEMs) from the National Elevation Dataset (NED) published in 2018 (Figure 12).

Figure 12. Model Factor - Elevation



The land use and land cover dataset was retrieved from the United States Department of Agriculture (USDA) using 2011 Landsat data (Figure 13A). The cropland dataset was retrieved to compliment the land use and land cover dataset by identifying most of the crop varieties commercially planted in the U.S. This dataset was created by the USDA and National Agricultural Statistics Service (USDA-NASS) and was collected between 1997 and 2006 (Figure 13B).

Figure 13. Model Factors



Note. (A) Cropland Use; (B) Land Use

While the seven factors were input as ranked layers, some factors were identified as uninhabitable zones where butterflies could not function despite otherwise optimal conditions. Solar farms were noted for their negative effect on insect mortality (Horvath et al, 2010); therefore, solar farm locations were listed as uninhabitable (Figure 14). This layer was created by identifying large solar installations via aerial and satellite imagery. Wildfires were also classified as uninhabitable and represented by the wildfire area boundary layer obtained via the USGS Wildland Fire dataset (Figure 15). Perennial snow and ice, open water, and genetically modified crops were also used and were subsets of the already obtained land use/cover and cropland use layers.

Figure 14. Solar Farms

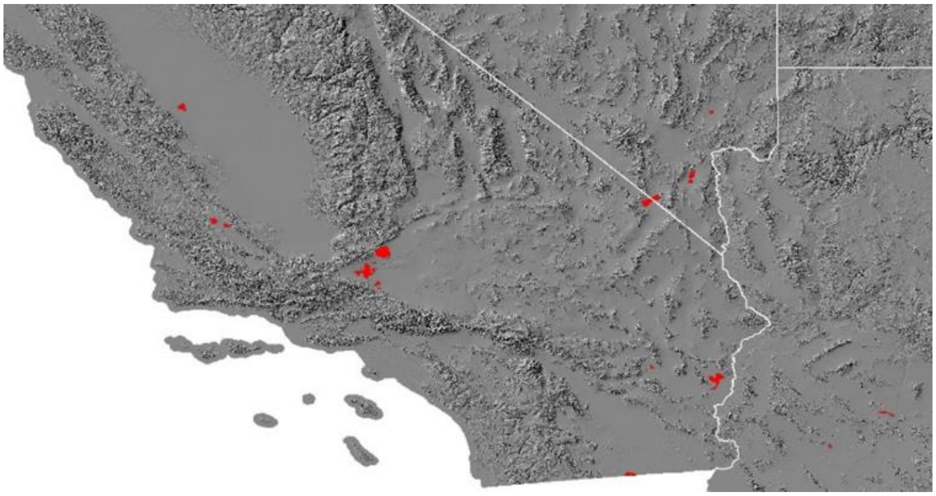
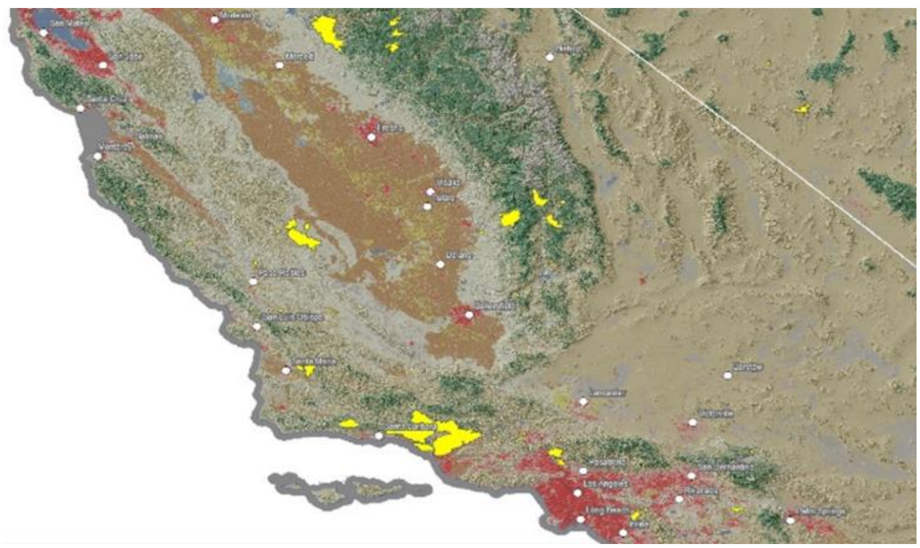


Figure 15. Wildfire Boundaries



The final dataset, a butterfly sightings database, was retrieved to geolocate and analyze butterfly locations in conjunction with the site suitability model results. The Journey North database was populated through a citizen scientist reporting web interface which provided the latitude and longitude, butterfly count, and the date of each sighting.

3.2. Reclassification

Each factor was ranked using thresholds that affect butterfly viability, mortality, sustainability, and/or functionality. Numeric scores were assigned to each cell based on its ranking that would be used to calculate the final output layer. Optimal cells received a score of five, suitable cells received a score of three, and unsuitable cells received a score of one (Kesler & Bunch, 2020).

Maximum and minimum temperatures were assessed to visualize the viable limits for monarch butterflies as they require heat for energy and lose flight capability below 13°C (Baumle, 2017). Despite the inability to fly, monarchs can survive freezing temperatures as low as -20°C by lowering their metabolism as temperatures decrease (Nail et al., 2015). Butterflies tend to avoid hypothermia which has proven useful in the overwintering months when temperatures often fall below the suitable range. The Monarch Larva Monitoring Project (MLMP) noted that larvae were relatively safe up to -10°C; however, mortality rates increased as temperatures approached -20°C (Nail et al., 2015). While freezing temperatures do not necessarily indicate mortality, the same cannot be said for high temperatures. Butterflies tend to function optimally up to 38°C and begin to exhibit signs of heat stress as temperatures approach 42°C leading to increased mortality rates (Nail et al., 2015).

With the high and low temperature extremes established as thresholds for viability and mortality, mean temperature limits needed to be set to define butterfly functional ranges. As noted previously, butterflies can no longer fly as temperatures fall below 13°C, which makes this temperature appropriate as a lower threshold for the suitable range (Baumle, 2017). Data from the MLMP revealed that monarchs were not present at mean temperatures above 30°C, which made this a suitable threshold for acceptable mean temperatures (Nail et al., 2015). The lower limit that divided the suitable and optimal designation was set at 21°C (Table 1).

Land use and land cover had implications to both butterfly viability and sustainability. With certain land covers more conducive to heat, milkweed, nectar, and moisture requirements, the following land uses and covers were ranked as optimal: forest, low density development, shrub scrub, pasture, and croplands (Nilsson et al., 2008). Open water, perennial snow and ice, high intensity development, and barren land were all considered unlikely to properly support butterflies and were thus ranked as unsuitable. All other land uses were considered suitable (Table 1).

The cropland layer provided additional information that was used to delineate crops that had a high likelihood of being genetically modified to be herbicide resistant or typically utilized a high volume of chemical or biological pesticides. Utilizing these parameters, corn, soy, canola, cotton, and commercial sod were identified as unsuitable crops, with all other crops deemed optimal (Pleasants & Oberhauser, 2012). By reclassifying the layer in this manner, it provided a slight increase in score for croplands that did not use GM varieties or high volumes of herbicides and pesticides which provided optimal spaces for insects and host/nectar plants. (Table 1).

Elevation was applied as a suitability factor to capture the number of butterflies and population diversity that occurs as landscapes increase in altitude (Table 1). Gallou et al. (2017) recorded varying populations and species diversity at predictable elevation levels indicating an inverse relationship between butterflies and altitude. Sites located below 700-m tended to be optimal with the most occurrences, while elevations over 1900-m tended to see few occurrences.

Table 1. Reclassification

	Average Temp	High Temp	Low Temp	Precipitation	Land Use	Cropland Use	Elevation
Optimal 5	21 - 30° C	≤ 38° C	> -10° C	25 - 203 mm	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	13 - 21° C	38 - 42° C	-20° F - -10° C	203 - 254 mm	Developed, Medium Intensity Woody Wetlands Emergent Herbaceuous Wetlands	Developed, Mid Intensity	700 - 1900 m
Unsuitable 1	> 30° C < 13° C	> 42° C	> -20° C	0 - 25 mm 254+ mm	Open water Perennial snow/ice Dev High Intensity Barren Land	Soy Corn Cotton Canola Sod	>1900 m

Note. (Kesler & Bunch, 2020)

3.3. Mask Layers

While all study factors informed the overall suitability for a specific site, there were some conditions that could render a cell uninhabitable despite otherwise positive site scores. These factors superseded all other scores and ultimately created a fourth rank of uninhabitable (0). For example, fire damages the natural habitat within the cell. This occurrence renders temperature, elevation, precipitation, and land use irrelevant leading to a final score of zero despite the possibly optimal scores of the other factors.

A previous study listed perennial snow and ice, corn, soy, and open water as uninhabitable conditions (Kesler & Bunch, 2020). Since these factors were relevant to this study, they were incorporated with the addition of four newly identified uninhabitable conditions. Corn and soy were considered uninhabitable due to the widespread usage of GM seed varieties utilized by large commercial farms. These varieties are engineered to be herbicide resistant and allow for the liberal application of chemicals to eliminate all superfluous vegetation including milkweed and nectar plants (Pleasants & Oberhauser, 2012). In addition to corn and soy, this study identified cotton and canola as other uninhabitable crop varieties that had similar traits (Richards et al., 2005). These additions were significant as California was the highest producer of cotton in 2020 as well as a source of winter canola crops in the San Joaquin and San Fernando Valleys (Hmielowski, 2017; USDA, n.d.). Solar farms and solar towers have been investigated for the negative effects that extreme heat sources could have on insect mortality (Horvath et al, 2010), thus their locations in the southern region of the study area made them reasonable uninhabitable land use candidates.

Another newly identified uninhabitable factor, wildfire, has been noted for both the positive and negative effects on local wildlife and plant life, particularly in the Western study area (Baum & Sharber, 2012; Vogel et al, 2010). For this study, wildfires were only assessed for their immediate negative impacts such as habitat loss and localized air quality; however, future studies could include the positive results that are often seen with prescribed burns that encourage new plant understory growth including milkweed and nectar plants.

Using a replicated copy of the cropland use layer, corn, soy, cotton, canola, open water, and perineal snow and ice were reclassified as uninhabitable using a binary scoring system to create the first of three uninhabitable mask layers. These negative land uses/covers received a score of zero (uninhabitable) with all other uses receiving a score of one (habitable). The second uninhabitable layer, the wildfire mask layer, assigned a score of zero to areas contained within the wildfire burn boundaries, while all other cells received a score of one; and the final uninhabitable layer, the solar farm mask layer, scored all cells contained within large solar installations as zero with all remaining cells receiving a score of one.

3.4. Model Weighting

As a default, many studies treat factors equally in terms of cause and effect; however, this type of behavior rarely occurs in the natural world. To reflect realistic conditions more accurately, the factors were weighted to provide a more reasonable accounting of each site's suitability. Previous studies and literature were used to translate the applied effects of temperature, precipitation, elevation, and land use/cover to reflect their individual roles in butterfly viability and functionality as well as their collective contributions. The weights used for this model were developed during previous research (Kesler & Bunch, 2020), which were still applicable for the Western monarch population.

From ectothermic metabolism to the length of time spent at each life stage, temperature is irrevocably linked to all aspects of butterfly life (Solensky 2004). While there was no clear source that stated the percentage that temperature impacts butterfly vitality and functionality, it was clear that temperature should be highly valued in the model output. To properly weight mean temperature as a depiction of daily heat requirements, flight ability, and energy for recolonization, mean temperature was weighted to account for 40% of the model output.

Thresholds that dictate viable temperatures in term of biophysical limits were assessed separately and then considered in conjunction with mean temperatures to assess the overall effect of temperature on site suitability. Butterflies suffered from heat stress between 38-42°C with temperatures more than 42°C resulting in death in MLMP test populations (Nail et al., 2015). This variable affected the upper temperature extreme and had some overlap with mean temperature scores leading to a 10% overall model weight.

In similar form, minimum temperature affected the viable extremity where butterflies would experience hypothermia and death. However, since butterflies are not required to expend energy to remain warm to survive, their relationship with low temperatures was more forgiving. During the MLMP it took temperatures as low as -20°C before mortality occurred in high numbers with larva proving more vulnerable than adult butterflies (Nail et al., 2015). Given this relationship with low temperatures, the weight applied was 5%. With the mean temperature weight set at 40%, the maximum temperature set at 10%, and the minimum temperature set at 5%, the total temperature weight was calculated at 55% for the overall model which was reasonable and supported by the biophysical requirements to function, mature, fly, recolonize, and sustain life.

Butterflies require moisture at all stages of the butterfly life cycle, while plant life relies on appropriate levels of precipitation to flourish and survive; however, the localized nature of precipitation classifications complicated the application of this factor on the broader model scale (Nail et al., 2015; Oberhauser, 2004). Given the metric limitations, this model only allocated 5% of the total weight to total monthly precipitation. The lower allocation was reasonable as this study was primarily isolating extreme or prolonged precipitation events, as well as the fact that localized variation had diminished the ability to heavily weight precipitation with a singular threshold affecting butterfly viability or projecting the availability of host and nectar plants (WallisDeVries et al., 2007).

Elevation typically provided more niche conditions that promoted biodiversity and species richness. Gallou et al. (2017) noted that there were normalized elevation cutoffs where species richness increased and declined. Elevation also had implications to temperature, which allowed this layer to work in unison with the minimum and mean temperature layers. Thus, the elevation layer was weighted at 5% to allow for species and population richness to be accounted for in the model, but it was set low enough to not sway the model totals since the temperature layers were already weighted heavily.

The remaining 35% weight was divided between the land use/cover layer and the cropland use layer. While temperature affects the biological impacts on butterfly vitality and viability, land use and land cover affect the ecological and environmental components of butterfly sustainability. However, the land use/cover layers were weighted less than their temperature layer counterparts as many localized unfavorable land uses/covers could be vacated or avoided by migratory butterflies, while unfavorable temperatures were typically more difficult to avoid. To reflect the importance of anthropogenic land use and natural land cover, the land use and land cover layer was weighted at 20% due to its link to butterfly and milkweed viability and functionality. The second land use element delineated the different types of commercial crops and was used in conjunction with the general land use/cover layer. Since the cropland use layer provided a scoring boost to non-GMO crops reflecting optimal conditions, the cropland use layer was assigned the remaining 15% of the model weight. With the inclusion of the 15% weight for the cropland layer, total land use and land cover layers carried a 35% total model weight. Given the interactions of the factors used in the model, the final distribution allotted 55% of the sustainability outcome to temperature, 35% to land cover and land use, 5% to generalized precipitation, and 5% to elevation (Kesler & Bunch, 2020).

3.5. Composite Model

With the layers reclassified and scored on a scale of one, three, and five (unsuitable, suitable, and optimal), and the mask layers reclassified and scored as either zero or one (uninhabitable and habitable), all layers were input into the model using the following formula:

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

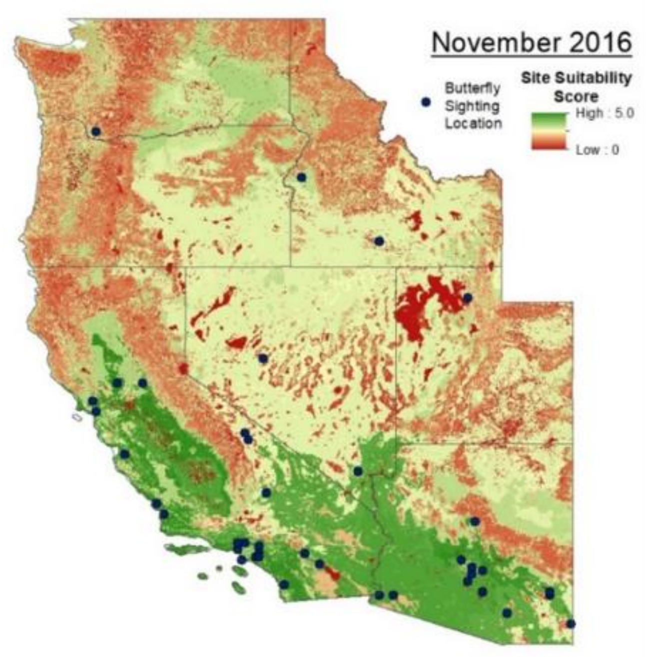
The model was executed for each month during the 2016/2017 study year with results output as monthly maps that delineated the weighted, composite site suitability for Western monarch butterflies. While the land use and land cover layer, cropland use layer, elevation layer, land use and land cover mask, solar mask, and cropland mask were used for each month's output; the mean temperature, maximum temperature, minimum temperature, precipitation and wildfire mask were month specific to reflect the seasonal variability of each factor. Ultimately, the composite score for each cell was calculated on a scale of 0.00-5.00. A score of zero indicated that conditions in that cell were uninhabitable due to the application of one or more of the uninhabitable conditions. Inversely, a score of 4.00 - 5.00 indicated optimum site suitability which was achieved by receiving optimal scores across multiple factors. A suitable site scored between 3.00-3.99, and an unsuitable site scored between 0.01-2.99 (Kesler & Bunch, 2020).

4.0. Results

Results were visualized through a series of monthly maps that reflected the composite calculation of the various factors to reveal areas that ranged from uninhabitable to optimal site suitability. As an additional element of accuracy and model verification, monthly geolocated butterfly sightings were viewed in conjunction with the site suitability output layers to illustrate the general mobility of the migration. Theoretically, butterflies should thrive in suitable to optimal conditions with few to no butterflies present in unsuitable and uninhabitable areas. They should also exhibit typical migratory movement and behavior by exiting and returning to the overwinter sites in a reasonably predictable manner. Sightings largely adhered to the site suitability model output; however, the movement of the butterflies within the Western migration did display some abnormal behaviors that could be relevant to population declines.

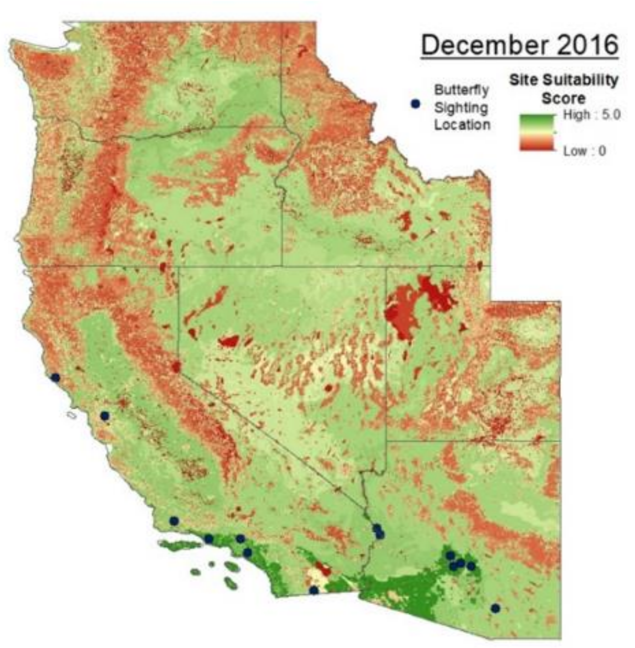
November 2016 was designated as the first month for this study because it marked the end of the previous year's migration where butterflies should be returning to the overwinter sites. This month should reflect the declining suitability in Northern California, Oregon, Washington, Nevada, and Idaho and should have located most butterflies nearing the overwinter sites along the California Coast. While there were some sightings away from the overwinter sites, these sightings were reasonable as the last eggs would have had to complete the first three life stages before a late emergence into unsuitable conditions. As temperatures fell below 13 °C, the newly emerged butterflies would not be able to fly and would likely succumb as conditions continued to decline (Figure 16).

Figure 16. November 2016



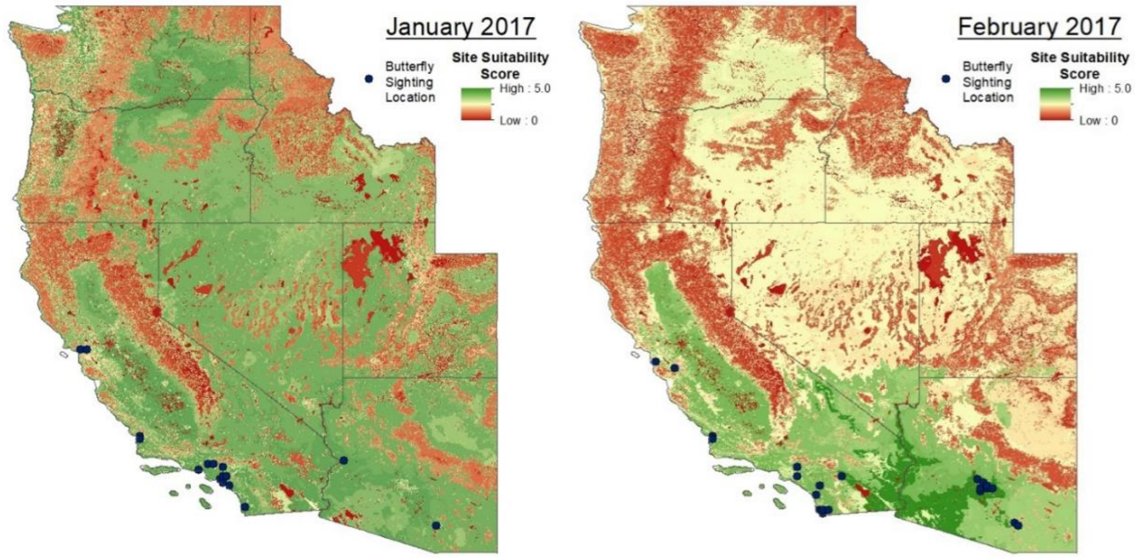
December 2016 (Figure 17) marked the first full overwinter month and generally retained moderate to good site suitability in the lower elevations. While most of the southern range remained good to optimal within the study area, it was noteworthy that several butterfly sightings were logged east of the traditional Western monarch overwinter sites. These butterflies may have been late arrivals at the overwinter sites; however, it is reasonable to question if these butterflies were abandoning the Western sites altogether and migrating to Mexico to overwinter with their Eastern counterparts (Xerces Society, n.d.). Once in Mexico, it is unknown if they would return to the Western migration the following year, or if they would assimilate into the Eastern migration.

Figure 17. December 2016



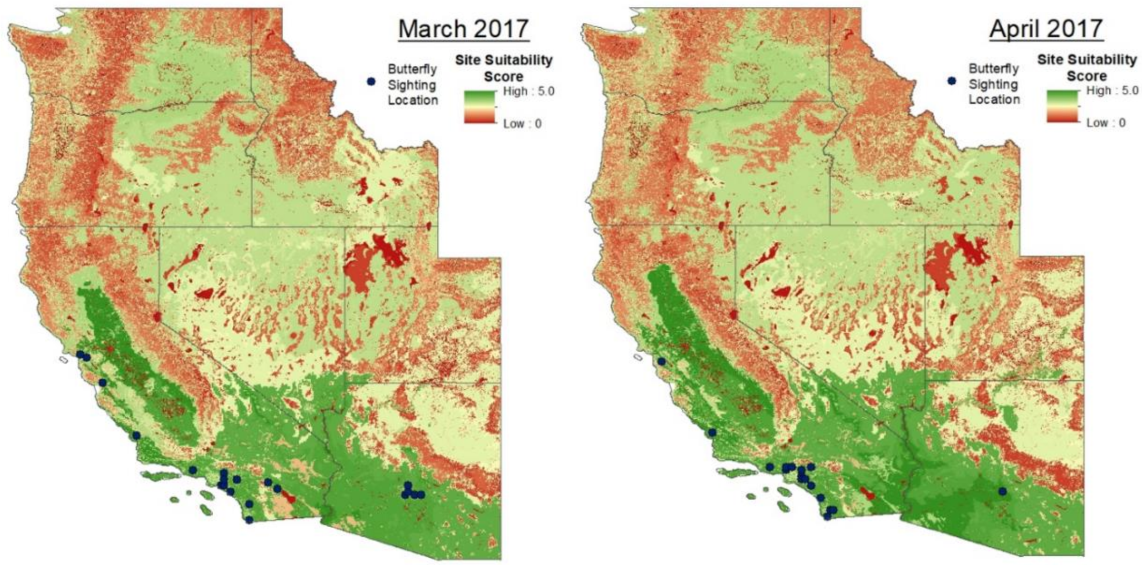
January 2017 (Figure 18) continued on the high end of the suitability spectrum except for locations in higher altitudes and the uninhabitable zones. There were still sightings in Arizona which adds more credence that the butterflies could be overwintering away from the Western sites. February was less suitable across the study area as a result of lower temperatures in Washington, Oregon, Idaho, Nevada, and Utah; however, as expected, overwinter sites remained suitable to optimal and contained most of the sightings (Figure 18).

Figure 18. January and February 2017



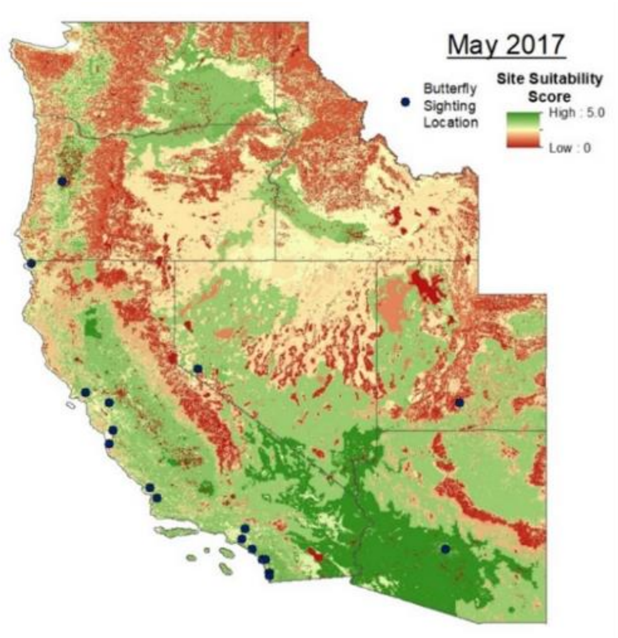
March has historically marked the start of the full-scale northern migration for the Eastern population where the butterflies vacate the overwinter sites; however, the Western population did not appear to exit the overwinter sites in either March or April 2017 (Figure 19). The sightings also persisted in Arizona which could have been butterflies migrating out of Mexico and joining the Western population; or given the frequency of the sightings and the optimal conditions at this location, Arizona could be a new overwinter site or an emerging non-migratory, sink population.

Figure 19. March and April 2017



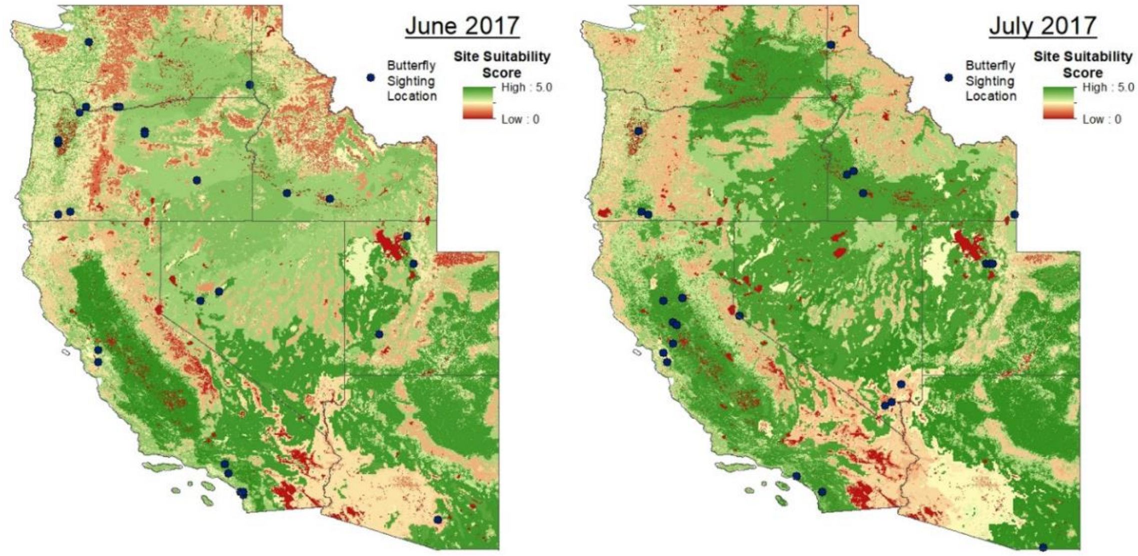
May marked the first migratory activity for the Western monarchs as sightings began to appear north and east of the overwinter sites (Figure 20). While the number of sightings were too low to draw any formal conclusions, it was concerning that the Western population began to vacate the overwinter sites at least two months behind their Eastern counterparts which could indicate a truncation of the Western migratory and recolonization cycle. This delay was also interesting in that site suitability did not improve from March to May, which further confounds the late start if suitable migratory conditions were not the cause. The lack of migratory movement could also indicate the development of behaviors similar to the non-migratory sink populations located along the Atlantic and Gulf Coastlines.

Figure 20. May 2017



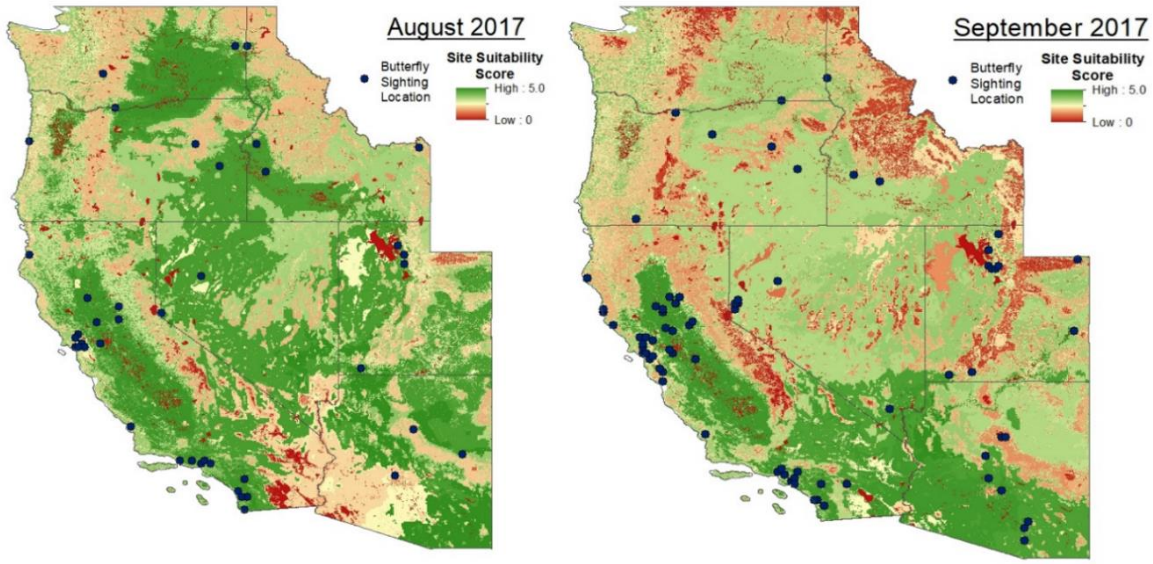
June suitability was much improved from May while the dispersed butterfly sightings indicated that the migration was fully underway (Figure 21). July marked the best conditions with widespread optimal suitability; however, there were several substantial wildfires that could be seen in California and Nevada (Figure 21). While fires can ultimately be beneficial for the environment, active burning and smoke buffer zones indicated hazardous areas that were not suitable for most wildlife. While this model did not factor in an extra buffer area for smoke, ash, and debris dispersal, these factors would have likely affected much larger areas dependent on weather, wind, length of burn, and fire intensity and would merit future studies to understand the full wildfire implications.

Figure 21. June and July 2017



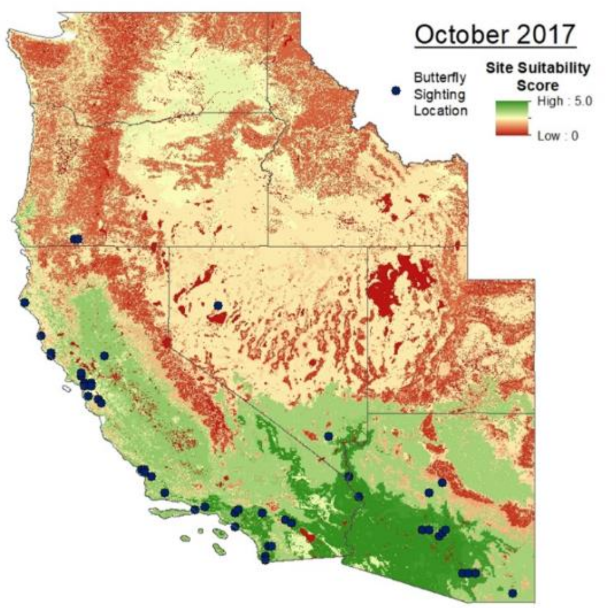
August and September 2017 (Figure 22) displayed similar butterfly activity as witnessed in June and July with a slight proliferation in sightings indicating the end of the summer recolonization. While butterfly sightings were dispersed across the study area, the clustering along the California Coast near Monterey was somewhat unexpected as the clusters were located at some of the most populated overwinter sites. With the wide availability of optimal habitat, it was unusual that the butterflies were already back at the overwinter sites further truncating the Western migratory and recolonization months. More data and sightings would be required as well as a long-range study to indicate if 2017 was perhaps an anomaly year; however, this occurrence is worth further investigation to consider if these populations may have ceased migrating.

Figure 22. August and September 2017



October 2017 (Figure 23) represented an important month in the migratory flight year as it marks the onset of the Eastern return migration. The return migration is initiated with a biological trigger that informs the butterflies to enter a reproductive diapause to conserve resources for the return flight and overwinter process. While Eastern monarchs demonstrate this phenomenon, the Western monarchs' return migration appeared to have already occurred in September with most October sightings already located at known overwinter sites. The cluster of sightings in Arizona appeared again which could be butterflies traveling to Mexico, overwintering in Arizona, or part of a non-migratory colony.

Figure 23. October 2017



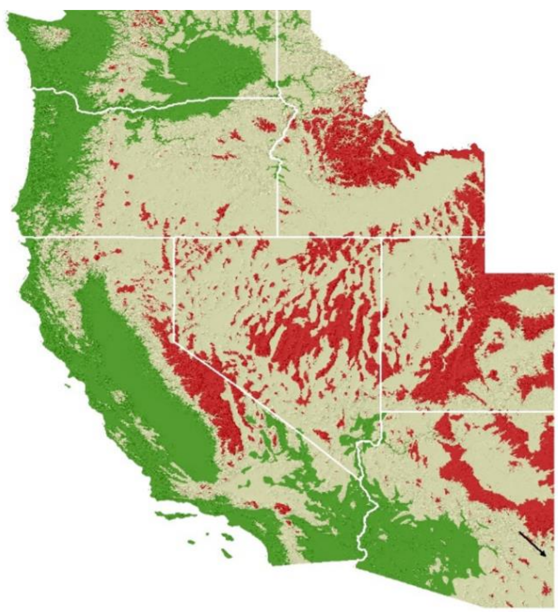
5.0. Discussion

While several findings were outside of the norm, there may be explanations for why some sightings were in unexpected locations. Wildfires and drought have created unfavorable environments for Western monarchs for centuries; however, as climate change effects are becoming more tangible, migratory animals may have difficulty navigating their migratory routes. Solar farms have recorded detrimentally high temperatures which could be attracting migratory butterflies only to trap them within the heat field, or perhaps these solar installations are creating heat pockets that encourage butterflies to cease migration due to favorable isolated conditions. Large anthropogenic footprints including residential, commercial, industrial, and agricultural development will continue to strain resources and degrade critical habitat. However, species can often adapt if conditions do not change more rapidly than they can alter their behaviors.

5.1. Fractured Flyways

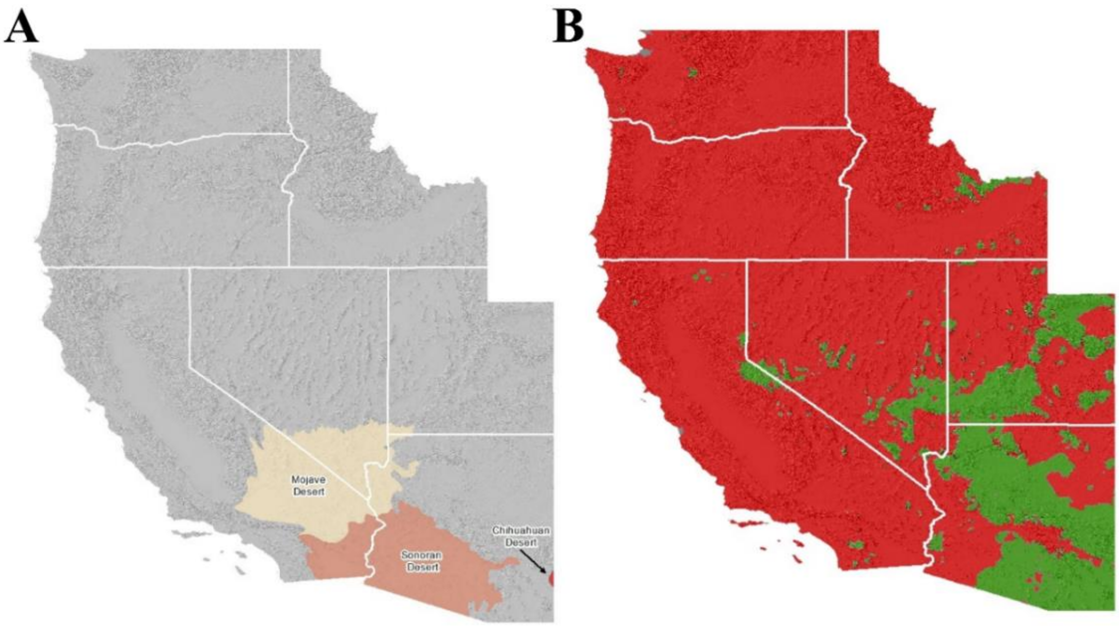
The location and volume of uninhabitable conditions were responsible for many gaps and barriers to migrating butterflies, but the same factors affected the Western population differently than their Eastern counterparts. While elevation was a minor barrier to Eastern monarchs, it was a formidable impediment in the Western study area. High altitudes created multiple barriers as mountain ranges intersected flyways both north and east of the overwinter sites (Figure 24). Future models may want to consider making the highest elevations an uninhabitable layer or increase the factor weight to account for the large number of unsuitable elevations in the Western monarch study area.

Figure 24. Reclassified Elevation



Another factor for Western monarchs was the large amount of area with unsuitable precipitation. The study area contains multiple arid areas including Death Valley, which is recognized as the hottest and driest location in North America, as well as areas within the Great Basin region and Sonoran, Chihuahuan, and Mojave Deserts (Figure 25A). While there are milkweed and nectar species adapted to survive in arid climates, plant and water scarcity coupled with high daytime temperatures could lead to higher rates of butterfly mortality and heat stress (Figure 25B). This model did not weight precipitation heavily due to the overall complexity of local drought and excessive rainfall metrics; however, future Western population studies may need to alter this weight since the arid areas may be more impactful than 5%.

Figure 25. Deserts and Drought



Note. (A) Southwestern deserts; (B) Precipitation American deserts Reclassification – July 2017.

5.2. Abnormal Behavior

While Eastern and Western populations differ in density and areal coverage, scientists must question if it is still reasonable to expect the same basic behaviors from both populations. Eastern and Western monarchs are currently classified as the same species with no evidence that one may be a sub-species of the other; however, they appear to be behaving differently. Perhaps the most prevalent difference between the two populations is the shorter amount of time that Western monarchs spend migrating and recolonizing. Eastern monarchs tend to exit overwinter sites in Mexico at the end of February and early March; however, these locations are substantially further south and may be explained by a simple variation in latitude. Despite this theory, the general site suitability for the entire Western study area had very little variation between the months of March and April and witnessed a slight decline in suitability in May (which was when the Western migration was finally under way). This behavior was unusual and merits future studies to explore why the Western butterflies migrated later.

On the opposing end, Western monarchs also returned to the overwinter sites over a month sooner than the Eastern population. Since Western monarchs only travel approximately 700-miles, it may be less unusual to reach the overwinter sites sooner when compared to Eastern monarchs who travel over 3000-miles. However, if the Eastern monarchs began the return migration in October, the Western population had already returned before the Eastern migration had vacated the summer breeding grounds. With less time spent migrating and recolonizing, population numbers may not be reaching full potential when compared to Eastern populations.

While topographical and environmental effects are largely beyond anthropogenic control, development, habitat destruction, agricultural practices, environmental and ecological policies, and climate change are all artifacts of the current Anthropocene; however, this study may shed light on some alternative explanations to why Western counts are low. One explanation is that Western monarchs may be migrating to Mexico and assimilating into the Eastern population and migration. Another scenario could be that the populations are evolving into sink populations that no longer migrate or have large recolonization seasons. While these are not necessarily positive impacts, both options could have different implications to conservation and population recovery strategies.

5.3. Migrating to Mexico

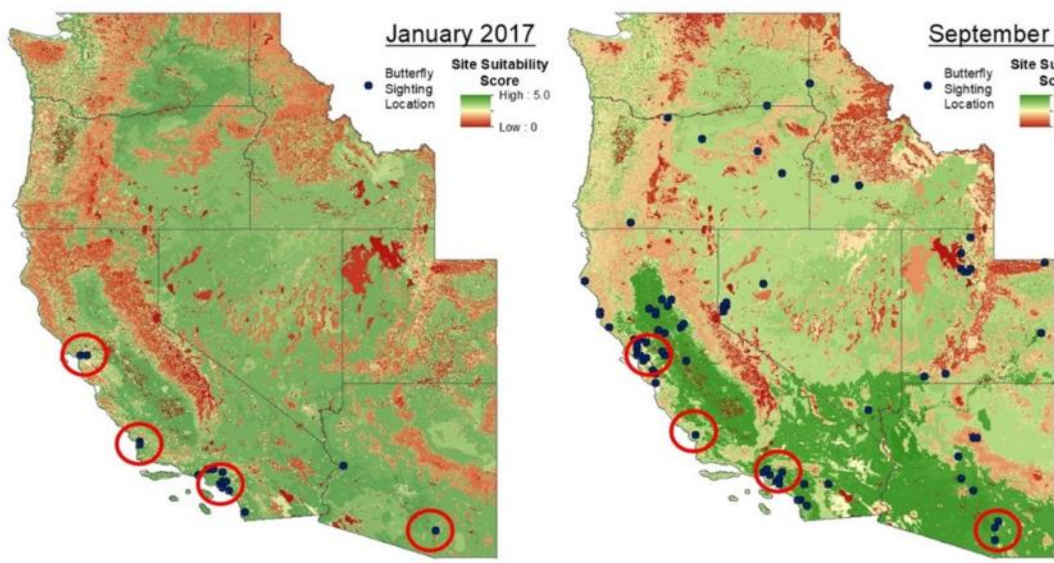
One possibility for the decrease in overwintering populations could be that the Western monarchs have abandoned their typical Western migratory habitat and are migrating to overwinter sites in Mexico. These butterflies may not return to the Western migratory routes the following year which further decreases the already critical population numbers. While large numbers of butterflies have not been reported southeast of the California overwinter sites, there have been sightings reported in smaller numbers. However, it is not unusual to have smaller numbers of sightings in Southern Arizona due to the lack of development and low human populations in this area. This lack of population highlights one weakness in the monarch butterfly sightings dataset in that sightings can only be recorded where people are located. With that in mind, just because a sighting is not recorded, it does not necessarily indicate that butterflies were not present. This weakness in the dataset coupled with some recorded sightings in this area would make this theory worthy of future studies to determine how many butterflies could be breaking away from the Western population and returning to Mexico.

5.4. Sink Populations

Non-migratory monarch butterfly populations have been identified in multiple locations along the Southern Atlantic and Gulf Coastlines (Howard et al., 2010). These populations show no evidence of migratory activity and remain in a static location throughout the flight year. Biologically, these monarchs are believed to never enter reproductive diapause or exhibit overwintering behavior. Given the warmer temperatures where sink populations have been documented, milkweed tends to grow continually with no annual dieback which has led to less healthy plants and a higher occurrence of parasitic infestation. The ingestion of parasites at the larval stage can lead to less healthy adult butterflies who could have an unknown effect should they rejoin the larger migratory populations (Satterfield et al., 2015; Wells, 2010).

During the 2016-2017 flight year, Western monarchs maintained a presence at many overwinter sites throughout the migratory months when the butterflies should reasonably be located at other sites along the migratory flyways (Figure 26). With the truncated migration season, this may indicate that the Western monarchs may in fact be transforming into a few consolidated sink populations. While this does not explain the decrease in population numbers, this could provide insight into how the butterflies are adapting to their changing environment. With favorable temperatures and a constant supply of nectar and milkweed, the butterflies are able to exist in a permanent recolonization resource mode.

Figure 26. Sink Populations



Note. Peak Overwinter (January) and Peak Migration (July).

6.0. Conclusion

Western monarchs have recorded critically low population numbers for the last several decades. With recent counts that may have fallen below the quasi-extinction benchmark, threatened species status may be too late to effectively save this population of migratory butterflies. However, conservation efforts must not stop trying to understand the negative impacts to their migration, recolonization, and overwinter activities.

This study utilized a site suitability model framework that was designed for the Eastern monarch migration and adapted specific features to model Western populations. Wildfire, solar farms, agriculture, drought, GM crops, and large fluctuations in elevation all created a more heterogeneous study area despite the smaller spatial scale. After factor layers were reclassified using unsuitable, suitable, and optimal thresholds, the layers were input into the model using their corresponding weights with several uninhabitable mask layers. The results were assessed through a series of visualizations that conveyed a composite version of site suitability which was analyzed in conjunction with geocoded monarch butterfly sightings. The butterfly sightings provided a layer of model accuracy; however, the Western monarchs did exhibit some abnormal behaviors in several months of the 2016/2017 flight year.

While this population is in immediate need of aggressive conservation, the low number of butterfly sightings and the need for a broader, longitudinal study across migratory cycles did complicate this study’s ability to make formal, hard fast conclusions. However, if the possibility of a migratory exit route to Mexico, a truncated recolonization cycle, or a shift to non-migratory behavior could be positively identified, conservation efforts would need to be modified to better protect the changing populations. With counts for subsequent migrations showing further losses, answers and direction are needed quickly. Since threatened species status was not extended in December 2020, studies must remain vigilant to properly assess populations during their annual audit to determine if their listing timeline should change. While most research currently lies within the biological and ecological sciences, geography and GIS can effectively visualize and analyze anomalies that may be less visible on the ground or in a lab. By using data and maps to analyze migrations with readily available data, it is possible to not only consider where conditions are suitable and unsuitable, but to also consider where the butterflies are in relation to these conditions. With broad spatial studies that assess entire migratory ranges, scientists and conservationists better position themselves to understand the challenges associated with migratory species as well as how to target meaningful and effective conservation strategies.

CHAPTER IV: THREATS TO THE MIGRATION: A GIS ANALYSIS OF HERBICIDE RESISTANT CROPS, DEGRADATION AT THE OVERWINTER SITES, AND NON-MIGRATORY POPULATIONS

1.0. Introduction

Monarch butterflies have been at the forefront of discussions surrounding the impacts that changing environments have had on migratory populations. Annual overwinter counts have continued to decline with the 2022 Western count falling substantially below quasi-extinction benchmarks where populations may become unrecoverable (Semmens et al., 2016). With populations declining at such a rapid rate, scientists, conservationists, and politicians are in a race against time to deliver sustainable measures to insure the future of the two migratory North American monarch populations. With the Eastern population migrating over 3000-miles and Western monarchs migrating approximately 700-miles, the large migratory footprint will require multi-dimensional efforts to protect current flyways, overwinter sites, summer breeding grounds, and to locate gaps that need assistance.

Conservationists recently completed their petition requesting protection for monarch butterflies under the Endangered Species Act (ESA); however, committees for the United States Department of the Interior (DOI) ruled that while protection was warranted under the ESA, monarchs would be precluded and placed on a waitlist behind other more critically endangered species (Pocius et al., 2018; Brower et al., 2014). While on this waitlist, monarchs will be monitored for changes in their current population trajectories as well as any substantial changes in habitat and migratory range that could make them more critically endangered. Monarch butterflies are valued as pollinators that provide an environmental service as well as occupy a base level in many food webs that support both plants and higher order animals. They hold cultural and religious significance to Native Americans as a symbol of family and ancestry as well as biological, ecological, and migratory significance. Thus, the need for studies that seek to isolate specific concerns, as well as possible causes and solutions, are needed to form the basis for the diverse strategies that will be needed. These efforts will require that scientists, researchers, local and national governments, commercial and agricultural businesses, and citizens work together to help monarch populations rebound and flourish once again.

2.0. Literature Review

While many studies have been conducted regarding biological and physical conditions inherent to butterfly populations and environments, migratory species have a very distinct geographical element due to the large habitat that they occupy throughout the course of a migratory year. To understand some of the threats that migratory monarchs encounter during the migration cycle, the authors previously completed two site suitability models designed to visualize specific conditions that were encountered by monarch butterflies during the annual migratory cycle (Kesler & Bunch, 2023; Kesler & Bunch 2020). These studies illuminated specific concerns that merited further study to ascertain the extent of their impact, as well as whether or not the entire migratory phenomenon could be sustained (Espeset et al., 2016; Brower et al., 2012;). The predominance of herbicide resistant agriculture, habitat loss at the overwinter sites, and several locations reporting non-migratory populations became themes throughout both models and have been reported across other studies regarding the decline in population numbers.

2.1. Migratory Legacy

Monarch butterflies are present throughout Central and South America, the Caribbean, Pacific Islands, Europe, and Australia; however, the two main populations in North America have been identified as the only population that undertakes a lengthy, annual migration (Altizer

& Davis, 2010; Clarke & Zalucki, 2004). The Eastern population overwinters in the San Madre Mountains of Mexico and travels north to the summer breeding grounds located in the Northern United States and Southern Canada (Espeset et al., 2016; Vidal & Rendón-Salinas, 2014). This migration occurs over the course of four to five separate generations meaning that the butterflies that exit the overwinter sites are at least two to three generations removed from the butterflies that participate in the breeding and recolonization that occurs from July to October every migratory year (U.S. Fish & Wildlife Service, n.d.). In October, the butterflies receive a yet unidentified biological trigger which directs the butterflies to cease breeding activities and to retain all resources for the return journey to the overwinter sites in Mexico. Unlike the Northern migration which occurs over four to five successive generations, a single butterfly makes the entire migration south, overwinters, and begins the following year's Northern migration (Merlin et al., 2020).

The Western monarch migration occurs in a similar manner; however, it does occur on a smaller spatial scale. Western monarchs overwinter in groves of coastal eucalyptus (*Eucalyptus spp.*), Monterey pine (*Pinus radiata*), and Monterey cypress (*Cupressus macrocarpa*) trees along the California Coast and migrate east and north to summer breeding grounds in Nevada and Idaho (Dingle et al., 2005; Xerces Society, n.d.). Despite the smaller spatial migratory footprint, anthropogenic development, weather conditions, and natural landscapes have created multiple impediments for migratory butterflies (Majewska et al., 2019; Gallou et al., 2017; WallisDeVries et al. 2011; Horváth et al., 2010). Droughts, fires, elevation, agriculture, and residential and commercial development have reduced critical habitat and created large gaps in flyways (Kesler & Bunch, 2023). With recent population counts indicating a dramatic decrease in butterflies, despite surveying more locations each year, Western monarchs may have fallen below quasi-extinction benchmarks and may be unrecoverable despite conservation efforts (Engen & Sæther, 2000).

2.2. Site Suitability Studies

Site suitability studies have been used to locate optimal sites for a variety of subjects from development (Kumar & Shaikh, 2013) and agriculture (Watkins, 1997) to energy (Baseer et al., 2017; Brewer et al., 2015) and habitat protection (Hovick et al., 2015). Given the overarching theory that optimal locations can be located by applying various suitability factors, it also stands to reason that areas with the least habitable site suitability scores could be used to identify the locations that could benefit from actions designated to improve flyway connectivity. As populations continue to decline, monarch butterflies must rely on independent researchers and scientists, conservation initiatives, and concerned citizens to protect their remaining critical habitat. With limited resources, all aid must be carefully targeted and designed to provide optimal impact; therefore, all areas located within the flyways needed to be assessed for suitability to support migratory butterflies. In two previous studies, the migratory range of both the Eastern and Western monarch butterfly populations were visualized across a single migratory flight year by comparing specific site factors to geolocated monarch butterfly sightings (Kesler & Bunch, 2023; Kesler & Bunch 2020).

Temperature, land use, land cover, precipitation, elevation, and agriculture were identified as factors that had specific and collective impacts on butterfly viability, mortality, and functionality for both populations. Locational variations in each factor created zones that were ultimately scored as optimal, suitable, unsuitable, and uninhabitable. To incorporate seasonal variation, maps were created using a composite score of each weighted factor for each month of the 2016/2017 flight year. Once the maps were created, monarch butterfly sightings were geolocated to identify areas that were the most negatively impacted, and if those impacts were candidates for mitigation that could improve flyway connectivity and protect critical habitat (Kesler & Bunch, 2023; Kesler & Bunch 2020).

2.2.1. Results from the Site Suitability Studies

Upon the completion of the site suitability studies, it became clear that some impediments were more widespread and more negatively impacting both the Eastern and Western populations. Use of genetically modified crop varieties, degradation of critical habitat located at the overwinter sites in Mexico, and concerns that some populations are no longer migrating were present in both studies (Kesler & Bunch, 2023; Kesler & Bunch 2020). Substantiating any one of these three threats could have large impacts on migratory butterflies; however, if all three are present, they could be largely responsible for the accelerated population decreases that are being recorded annually. To validate these findings, this study conducted three smaller analyses to investigate these threats and to ascertain if and how they could be driving monarch butterfly population declines.

2.3. Genetically Modified Crops

Genetic modification has allowed scientists to create seed varieties that have been engineered to offset the negative effects of unwanted vegetation, insects, and other animals that feed on crops and produce. However, while these varieties do succeed in subduing their target species, other species that were not targeted are also eradicated (Pleasants & Oberhauser, 2012). While the list of possible genetic modifications is long, varieties that are engineered to have genetic pesticides and be herbicide resistant have become a challenge for several plants and insects (Pleasants; 2015). As the crops themselves are immune to specific herbicides, it allows for widespread, dense application with no harm to the commercial crop. This type of agriculture ultimately removes all undergrowth including milkweed and nectar-producing plants that are required for monarch butterfly recolonization (Pleasants & Oberhauser, 2012).

It is believed that commercial varieties of corn and soy that are herbicide resistant have created large-scale loss of milkweed in the Eastern monarch summer breeding grounds, which may be truncating recolonization numbers. According to the United States Department of Agriculture (USDA) (n.d.) and the National Agricultural Statistics Service (NASS) (n.d.), large areas in the Midwest Corn Belt and the Mississippi River Basin have been utilized for corn and soy cultivation, which when considering the widespread use of genetically modified varieties has created substantial flyway gaps where monarch butterflies are unable to locate milkweed (Vecchia et al., 2009). Similar in form, but at a smaller scale, cotton (Richards et al., 2005) and canola (Hmielowski, 2017) have had similar effects on migratory butterflies as they migrate north into Texas and at the summer breeding grounds in North and South Dakota (United States Department of Agriculture (USDA), n.d.; National Agricultural Statistics Service (NASS), n.d.) .

Historically, milkweed and nectar producing plants have flourished in agricultural areas including the surrounding ditches and road median right-of-ways (ROW) (Ozcan et al., 2020; Baum & Mueller, 2015; Xerces Society, 2015), which has been vital to supporting butterflies while in the summer breeding grounds. With optimal soil, moisture, and nutrients, monarch butterflies benefitted from the abundance of milkweed and fostered a symbiotic relationship with crops by increasing biodiversity through cross pollination (Blair, 1999); however, as engineered crop usage has increased for staple crops such as corn and soy, milkweed abundance has declined substantially (Pleasants, 2015). With the lack of host plants, the summer breeding grounds are not capable of supporting large numbers of larva, which has decreased the number of butterflies reaching adulthood.

2.4. Loss of Critical Habitat at the Overwinter Sites

While Western monarchs overwinter in coastal eucalyptus (*Eucalyptus spp.*), Monterey pine (*Pinus radiata*), and Monterey cypress (*Cupressus macrocarpa*) along the coast of Southern California, Eastern monarchs overwinter in large colonies in the San Madre Mountains in protected groves east of Mexico City (Vidal & Rendón-Salinas, 2014). The two overwinter sites differ in both size and vegetation; however, both suffer from anthropogenic growth, development, and encroachment. The sanctuaries in Mexico have become increasingly squeezed by development from the expanding population of Mexico City as well as the illegal extraction of resources from the seven protected overwinter sites (Aridjis, 2008). Timber and agricultural demands have increased due to the growing population; however, while logging is illegal in the reserves, it has not halted and has frequently led to violence and corruption in the region (Flores-Martínez et al., 2019; Vidal et al., 2014) . In 2020 two outspoken conservationists were murdered for publicly denouncing illegal logging with corrupt law enforcement ultimately being questioned for their actions in both crimes (López-García & Navarro-Cerrillo, 2020). Although it is believed that logging in the area has slowed, it could take decades to recover the loss of critical forest habitat.

Ecotourism has become a lucrative business as tourists and scientists want to observe the roosting butterflies; however, ecotourism has been met with mixed reviews (Ibrahim et al., 2019; Kim et al., 2019). While it does provide income for local residents who value and care for the sites, the number of visitors may need to be limited due to the impacts to the butterflies, plants, and other wildlife (Russel & Wallace, 2004). In 2008 the United Nations Educational, Scientific and Cultural Organization (UNESCO) extended protection to the most prominent overwinter sites as a World Heritage Site with four of the sanctuary reserves in the states of Mexico and Michoacán open to the public (UNESCO, n.d.).

2.5. Non-Migratory Populations

Monarch butterfly populations exist on several continents and islands; however, the North American population is the only group that undertakes a substantial migration (Freedman et al., 2018; Clarke & Zalucki, 2004). With the changes that are currently occurring due to climate (Zipkin et al., 2012; WallisDeVries et al., 2011) and anthropogenic development (Majewska et al., 2019; Aguirre-Gutiérrez et al., 2015; Brower et al., 2012), there have been reports of monarchs that have ceased migratory movement and are remaining in the same location throughout the breeding and overwintering seasons. These butterflies do not appear to enter reproductive diapause but instead breed year-round in a constant recolonization resource mode (Peterson, 2019; Freedman et al., 2018; Altizer et al., 2015; Satterfield et al., 2015). Since the biological trigger to switch from breeding to migrating is not fully understood, scientists are left trying to understand why these butterflies are no longer migrating. With several factors already identified in the previous site suitability studies, it is noteworthy that the locations of the “sink” populations do tend to reside in areas that experience optimal conditions year-round (Kesler & Bunch, 2023; Kesler & Bunch 2020).

While an argument can be made that this type of behavior could serve as a survival technique that ensures that breeding populations avoid extinction, there are other concerns that could negatively impact these individual populations as well as the overall migration. One cause for concern is the identification of parasitic infestations in mature sedentary butterflies (Majewska et al., 2019; Altizer et al., 2015; Satterfield et al., 2015). It is believed that these infestations stem from the ingestion of milkweed that contains common parasites which is exacerbated when plants to not experience a seasonal "die back" (Satterfield et al., 2015; Altizer et al., 2000). Seasonality serves as a reset for plants and eradicates parasites that commonly occur during a growth year (Boczoń et al., 2021); however, when plants exist in locations that have consistently optimal weather and moisture, they can continue to grow uninterrupted year after year.

Another issue in understanding why some monarchs migrate and some do not, there has been research comparing the butterflies in other populations throughout the Caribbean, Pacific Islands, Central and South America, and Australia (Freedman et al., 2018; Clarke & Zalucki, 2004). These butterflies are more sedentary or only undergo short migrations, which introduces the question of what is normal, migratory or non-migratory? Perhaps the large-scale, avian-like migration undertaken by North American monarch butterflies is the exception (Altizer et al., 2015). Another study has identified that wing and body morphology could determine which monarchs migrate, and which do not. Altizer and Davis (2010) identified that some monarchs are genetically and physiologically more suited for long migrations, while others are simply less fit. In this case, localized populations of non-migratory butterflies could be occupying pockets within the larger migration where conditions are suitable for their survival. If this is the case, these monarchs could be developing into a new subspecies that is not abnormal but merely a different kind of monarch butterfly (Altizer & Davis, 2010).

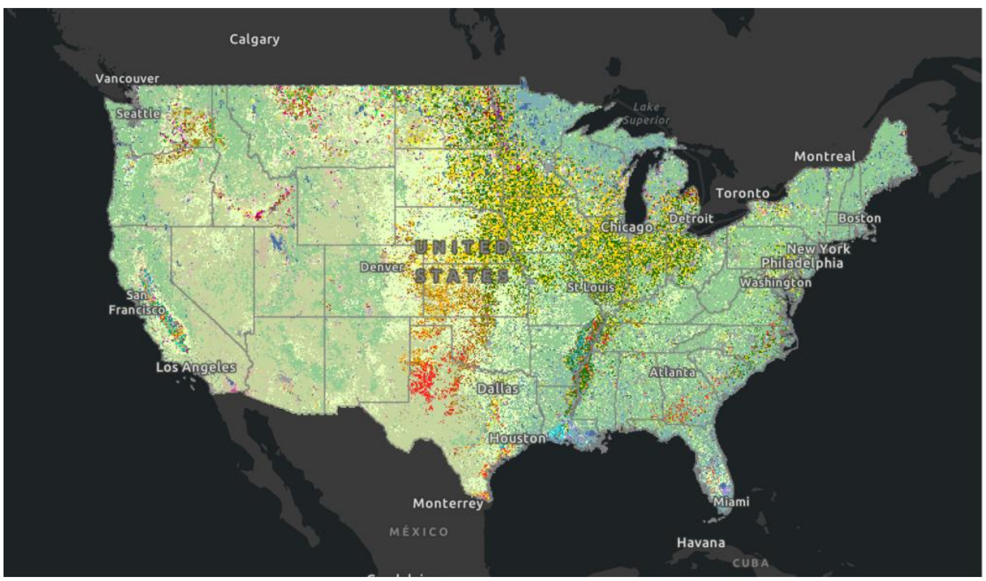
3.0 Methodology

3.1. Genetically Modified Crops

This section of the study was designed to locate areas that had a large number of crops that are typically planted using herbicide resistant variants. Cropland Data Layers (CDL) were retrieved from the United States Department of Agriculture (USDA) and the National

Agricultural Statistics Service (NASS) (Figure 27). Since 2008 was the first year available that contained the complete national dataset, it was used as a base year with subsequent years captured at 2015 and 2022. This allowed analysis over a 14-year period broken into two seven-year intervals. Maps were created to target corn, soy, cotton, and canola to determine the scope and scale that these crops could be negatively impacting milkweed habitat and monarch butterfly recolonization and migration. Statistics were gathered from the individual CDLs to quantify the number of 30-m^2 cells occupied by each target crop, as well as to determine how the crop composition and cell count had changed over the 14-year period.

Figure 27. Cropland Data Layer

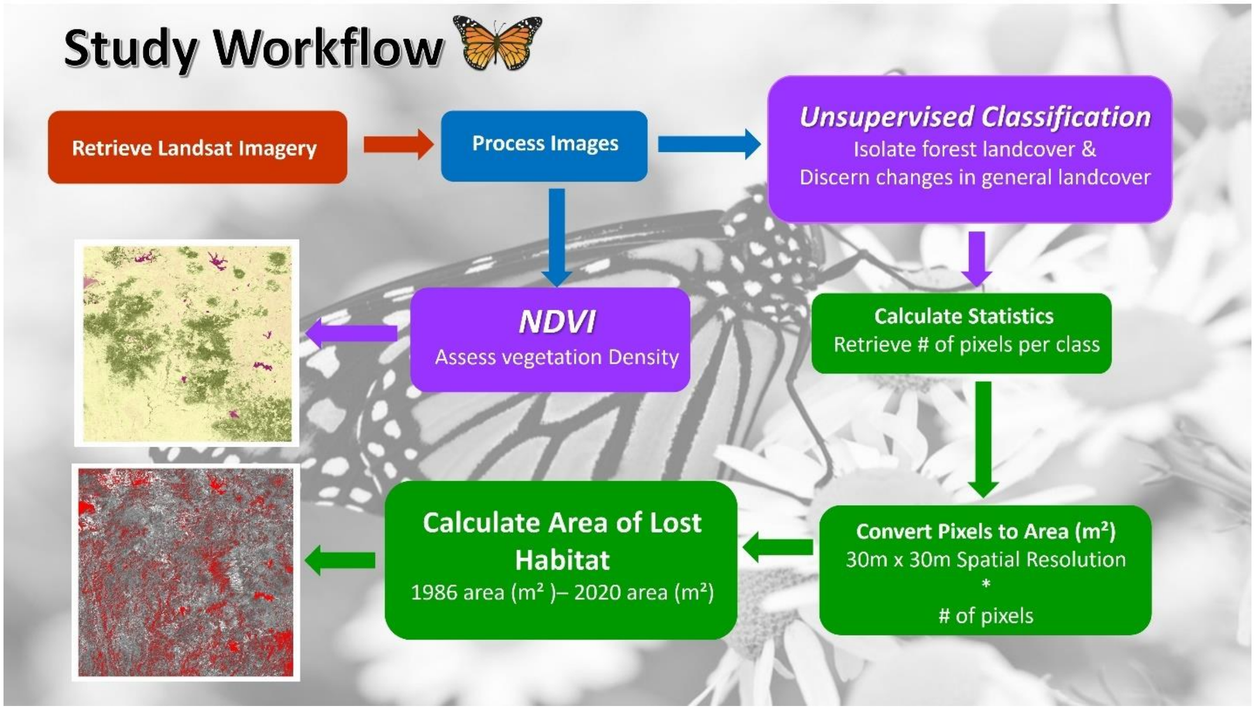


Note. (USDA-NASS).

3.2. Overwinter Sites in Mexico

This section of the study utilized remote sensing techniques and satellite imagery to visualize the land degradation and loss of habitat at the monarch butterfly overwinter sites in Mexico. Once images were retrieved and processed, they were classified and analyzed to detect and quantify changes in butterfly habitat over a 34-year period. The second half of the analysis utilized the Normalized Difference Vegetation Index (NDVI) to assess changes in vegetation density and health over the same 34-year period. Images were created for visual analysis, and statistics and areal calculations were retrieved to understand the magnitude of the loss as well as general trends from 1986 to 2020. Figure 28 illustrated the workflow process as well as the general type of imagery that was output from the classification and NDVI analyses.

Figure 28. Study Workflow

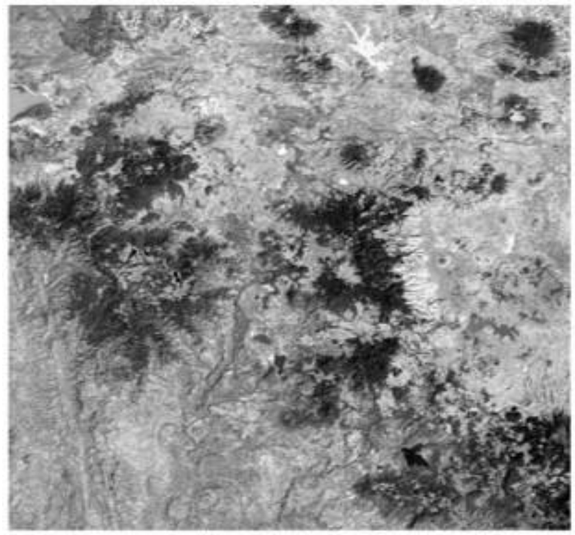


3.2.1. Data and Study Area

The study area encompassed the entire Monarch Butterfly Biosphere Reserve (MBBR) as well as other known overwinter locations to the West and Southeast of the MBBR (Figure 29). Images were collected from the United States Geological Survey (USGS) Earth Explorer data download site and were retrieved in multiple bands from 1986, 2000, and 2020. The first image was dated March 14, 1986, from Landsat-5, which was in service from 1984 to 1997 and used the Thematic Mapper sensor. The second image from May 15, 2000, was retrieved from

Landsat-7 utilizing the Enhanced Thematic Mapper Plus (ETM+) which was in service from 1999-2003. The final image from March 27, 2020, was retrieved from Landsat-8 which was in service from 2013 to the present and utilized the Operational Land Imager (OLI).

Figure 29. Overwinter Area of Interest



3.2.2. Land Use Classification

For this analysis, the Near Infrared (NIR) bands were used to classify the land cover. While both supervised and unsupervised classification techniques were used, the unsupervised ISODATA classification yielded the most reasonable results. The results were compared visually using recent aerial imagery to compare the accuracy of the final classified images. The final classification utilized five iterations and yielded 10-12 classes in each image.

Once the images were fully classified into target land cover groups, ground truthing exercises identified cells that were classified incorrectly due to overlapping spectral signatures and/or reflectance anomalies. The first error located some bodies of water as dense evergreen forests. This error could skew the areal calculation by erroneously counting bodies of water as butterfly habitat and needed to be manually reclassified. The second concern was that some of the target features were sorted into more specific separate classes. For this study, all dense forest was considered acceptable habitat, so the classes were combined, and statistics and areal coverage were recalculated. Once all landcover classes were accepted, the number of cells per class were counted to gain the total number of cells per land cover type. Using the spatial resolution of the Landsat datasets ($30m^2$), it was possible to calculate the total area of butterfly habitat for each image using the following formula:

*Area of Butterfly Habitat per Image = cell length * cell width * # of cells*

After the total area of butterfly habitat was calculated for each image, the quantity of butterfly habitat that had been lost per study period was achieved using basic subtraction. Final results were output as a quantified loss of habitat, and maps were created that identified the remaining butterfly habitat for each image year.

3.2.3. Normalized Difference Vegetation Index (NDVI)

The NDVI calculation was included as a measure of vegetation density and vegetation health. This ratio normalized land cover based on a scale of -1 to 1. A score of -1 indicated zero vegetation present and included cells that were open water, rock, bare soil, and man-made or impervious structures. A score of 1 represented dense, healthy vegetation that could be possible butterfly overwinter habitat. NDVI was calculated using the following formula:

$$NDVI = (NIR - Red) / (NIR + Red)$$

Results were visualized on a scale of -1 to 1.

3.3. Non-Migratory Populations

To create a historic record of migratory movement, monarch butterfly sightings data were retrieved for all twelve months from January 2017 to December 2022. This dataset included both Eastern and Western sightings over a period of six flight years that occurred within the United States boundary. If the butterflies remained in the same location during peak migration and peak overwinter months, they could indicate that a breeding population may not be migrating with the larger group.

3.3.1. Data

Monarch butterfly sightings were retrieved from two citizen science databases: the *Journey North* and the *Western Milkweed Mapper* (Figure 30). The Journey North (n.d.) is an open platform managed by the Arboretum at the University of Madison-Wisconsin and Annenberg Learner that allows individuals to submit a monarch butterfly sighting with fields for the date and location, latitude and longitude, butterfly count, and is able to accept and share uploaded images of the sighting (Figure 30). Given the GIS-friendly format in which the data is recorded, butterfly researchers are able to collect data points for worldwide monarch butterfly sightings that can be geocoded using their X and Y coordinates and sorted by date and location.

Figure 30. The Journey North and Western Milkweed Mapper Data Repositories


Journey North Monarch Fall Roost

	Date	Town	State/Province	Latitude	Longitude	Number	Image
1	09/12/23	Cleveland	OH	41.5	-81.7	30	
2	09/11/23	Ajax	ON	43.8	-79	1450	
3	09/11/23	Cedar Valley	IA	41.7	-91.2	10	
4	09/11/23	Halton Hills	ON	43.6	-79.8	100	
5	09/11/23	Point Pelee National Park	ON	41.9	-82.5	52	
6	09/10/23	Arlington	WI	43.3	-89.4	150	
7	09/10/23	Bement	IL	39.9	-88.6	10	
8	09/10/23	Birkbeck	IL	40.2	-88.9	60	
9	09/10/23	Cambridge	IL	41.3	-90.2	100	
10	09/10/23	Ivesdale	IL	39.9	-88.5	3	
11	09/10/23	London	ON	43	-81.1	30	
12	09/10/23	Pella	IA	41.4	-92.9	25	
13	09/09/23	Angus	IA	41.9	-94.2	75	

While more limited in spatial scope, the Western Milkweed Mapper (n.d.) website operates in a similar manner and is maintained by the United States Fish and Wildlife Service (USFW), Idaho Fish and Game (IDFG), the Xerces Society, the Washington Department of Fish and Wildlife (WDFW), and the National Fish and Wildlife Foundation (NFWF). This database constrains its reporting area to locations specifically associated with the Western monarch population and migration. The database developers also incorporated a milkweed reporting platform and fields for monarch sighting stage of development (egg, larva, pupa, and adult butterfly). These additions allow researchers to not only track monarch butterflies along the migratory flyways, but also to track the various life stages and host plant locations. Some historic sighting records have also been added to this database making it a comprehensive research tool and data collection repository.

4.0. Results of Studies

4.1. Genetically Modified Crops

The use of the Cropland Data Layers (CDLs) confirmed that corn, soy, and cotton were substantial impediments to migratory and recolonizing butterflies (Figures 31, 32, and 33). The overall crop footprint remained largely the same over the 14-year period; however, the crop density increased creating large areas that had fewer pockets of suitable land where milkweed and nectar producing plants could grow. When factoring in that particle and vapor herbicides can travel in the air anywhere from 30-feet to over a mile depending on environmental conditions (Brain et al., 2017), the traditional summer breeding grounds in the Midwest Corn Belt area have experienced major habitat degradation.

Figure 31. 2009 Cropland Data Layer (USDA-NASS)

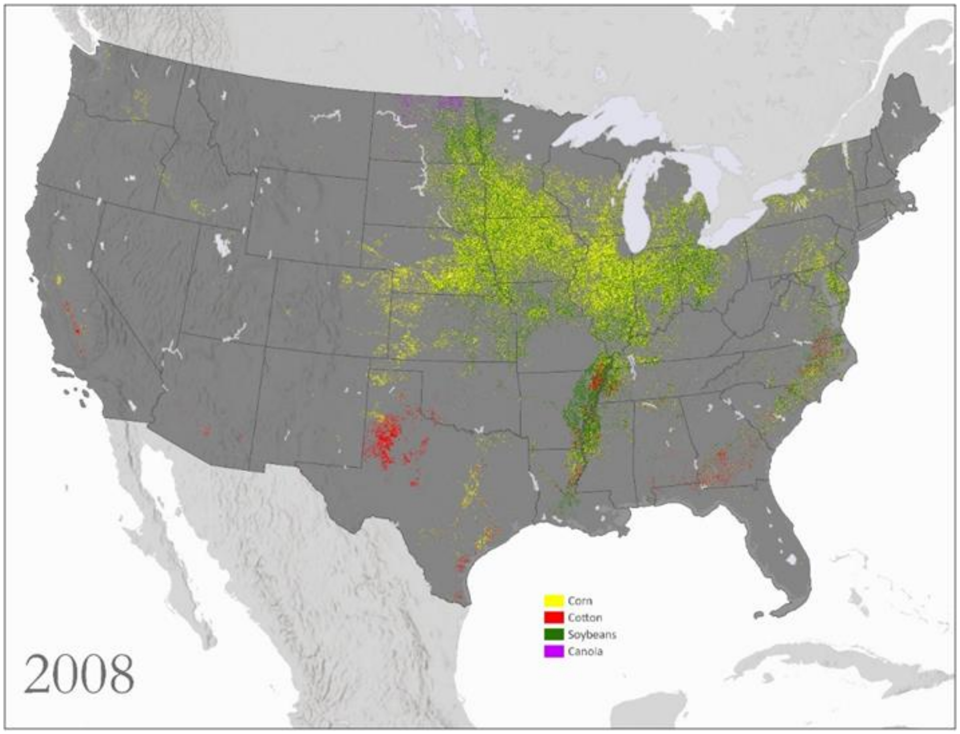


Figure 32. 2015 Cropland Data Layer (USDA-NASS)

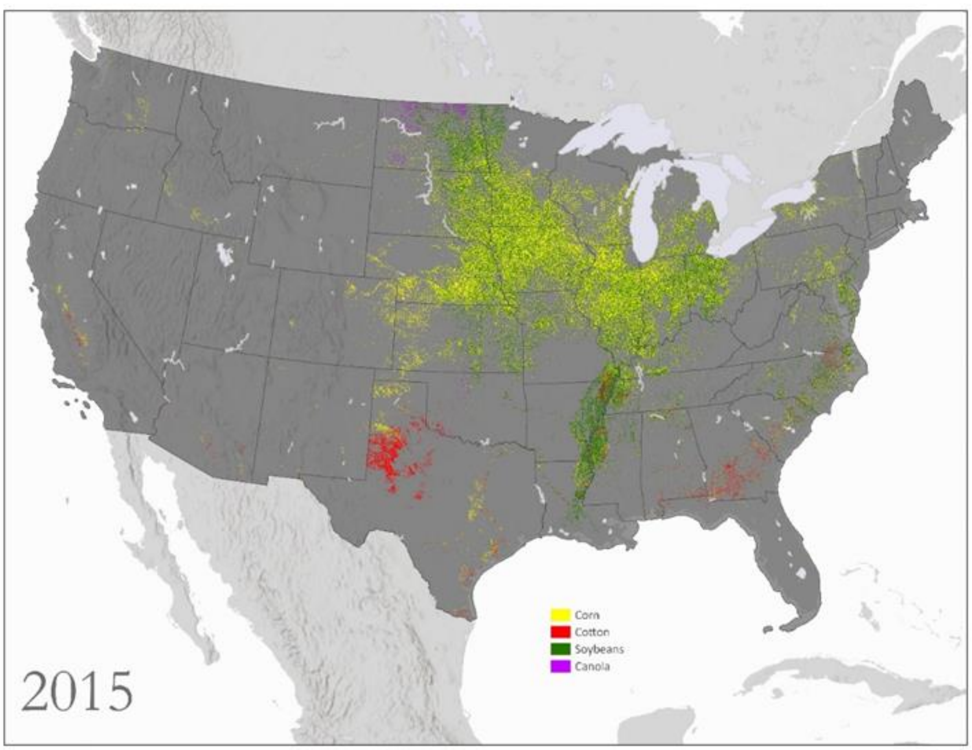
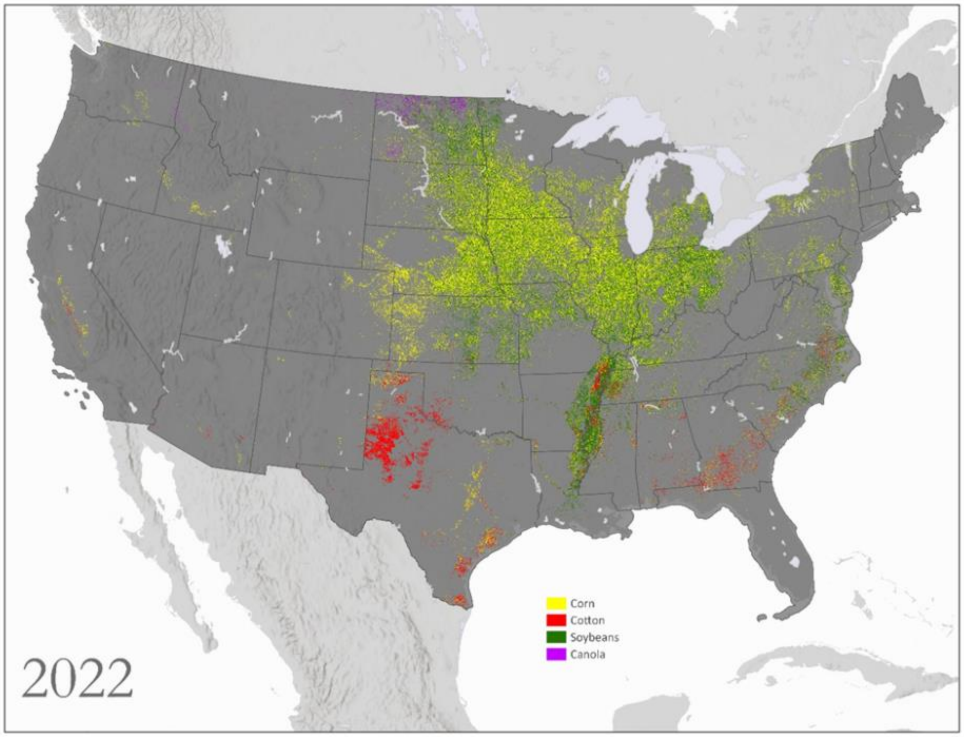


Figure 33. 2022 Cropland Data Layer (USDA-NASS)

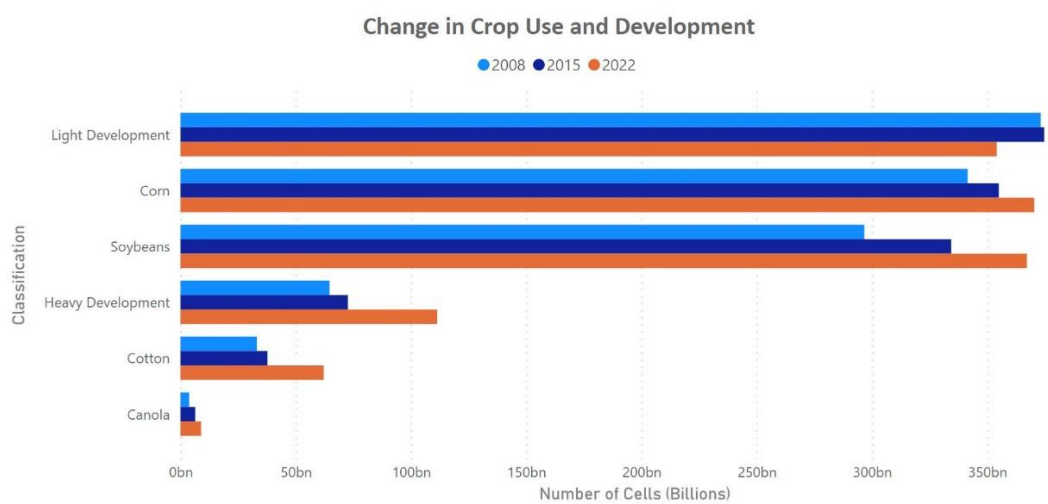


Corn was the most prevalent crop in 2008; however, soy crops grew in density and were comparable to corn in number by 2022. Cotton and canola had substantially smaller use and were largely absent from the Midwest Corn Belt/summer breeding grounds (Table 2). To add perspective to the overarching issue regarding critical habitat and flyway degradation, cells were also counted for light and heavy development. Development has been largely credited with disrupting flyway continuity as well as destroying critical habitat for migratory butterflies (Blair, 1999); however, light development occupied fewer cells than either corn or soy, and heavy development occupied roughly 1/3 of the area occupied by corn or soy. Ultimately, when corn, soy, cotton, and canola were collectively considered for their negative impacts, they covered twice as much area as heavy and light development combined (Figure 34). In the previous site suitability models, light development was considered habitable for butterflies and nectar-producing plants and milkweed (Kesler & Bunch, 2023; Kesler & Bunch 2020). While developed areas are not considered optimal due to lawn chemicals, pesticides, and herbicides, nectar-producing plants were present, while conservation efforts have increased the amount of milkweed in butterfly and pollinator gardens (Baumle, 2017; Kalaman et al., 2020).

Table 2. Change in Corn, Soy, Cotton, and Canola

Crop	2008 Area (ha^2)	2015 Area (ha^2)	2022 Area (ha^2)	Change from 2008-2015 (%)	Change from 2008-2015 (ha^2)	Change from 2015-2022 (%)	Change from 2015-2022 (ha^2)	Total Change 2008-2022 (%)	Total Change 2008-2022 (ha^2)
Corn	7,596,382	7,957,108	8,239,536	↑ 4.75%	360,726	↑ 3.55%	282,428	↑ 8.47%	643,154
Soy	6,598,736	7,437,794	8,167,700	↑ 12.72%	839,058	↑ 9.81%	729,906	↑ 23.78%	1,568,964
Cotton	737,778	840,165	1,382,125	↑ 13.89%	102,388	↑ 64.51%	541,960	↑87.34%	644,348
Canola	83,703	142,645	200,012	↑ 70.42%	58,942	↑ 40.22%	57,367	↑ 138.95%	116,309

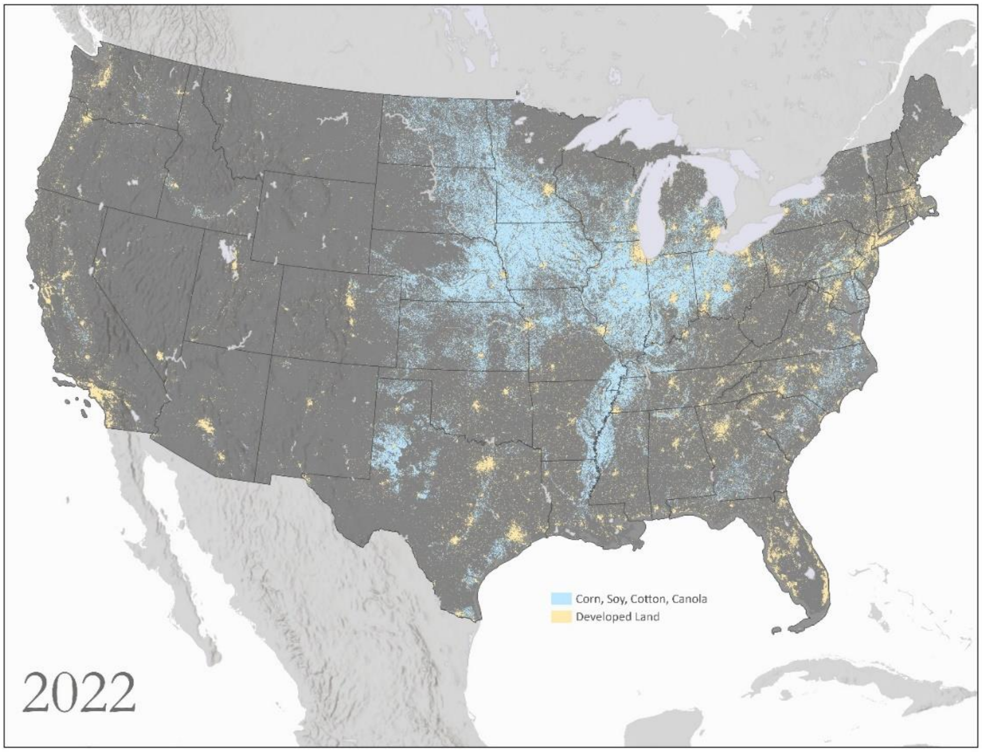
Figure 34. Change in Development and Target Crop Occupied Cells



It was also noteworthy that the national distribution of corn, soy, and cotton crops were concentrated, largely in the Corn Belt Region/summer breeding grounds and along the

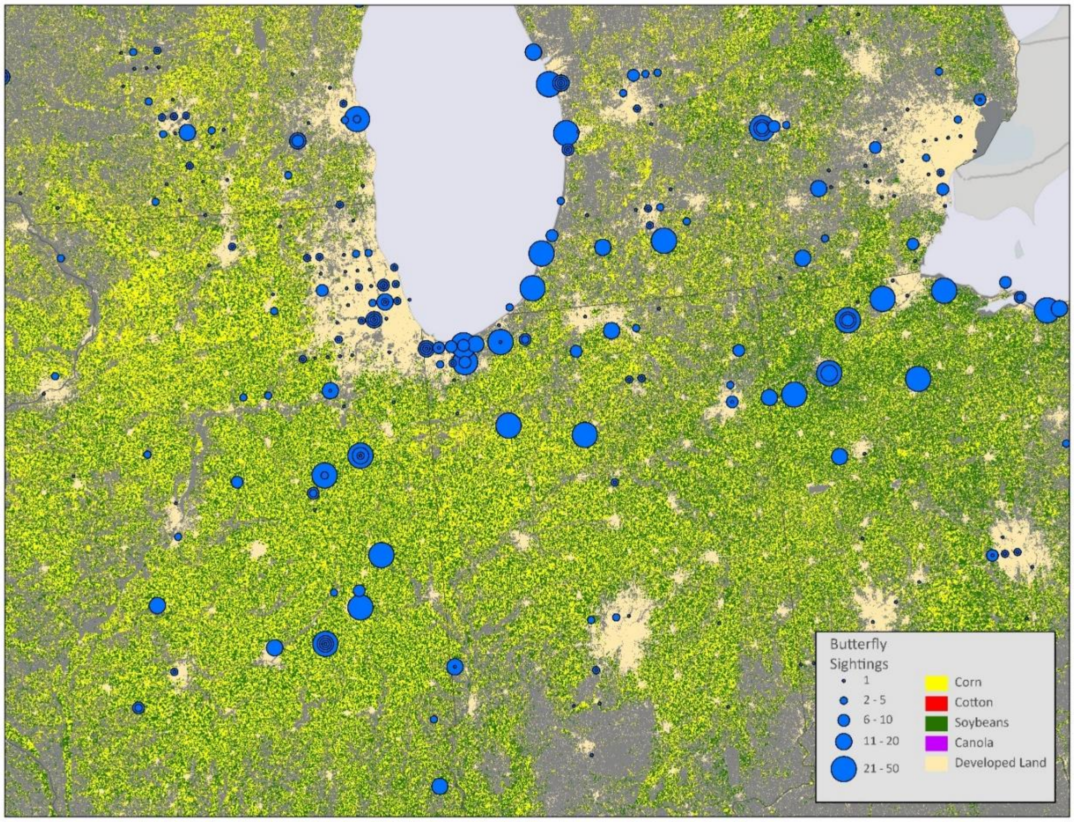
Mississippi River Basin, while developed cells were far more dispersed (Figure 35). The clustering of these crops was a factor in the respective densities of corn and soy in the summer breeding grounds. While development is not ideal for butterflies or milkweed, the footprint of corn and soy crops was likely more harmful than densely populated development due to the substantially larger cell count, overall anthropogenic footprint, and location in the summer breeding area.

Figure 35. Corn, Soy, Cotton, and Canola Versus Development



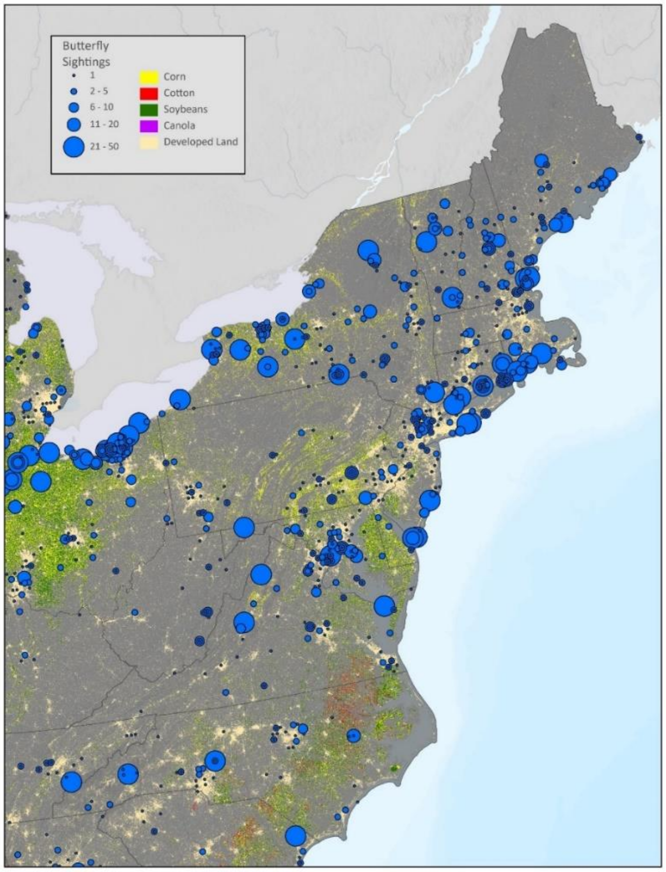
With less area containing milkweed due to herbicide use, female monarchs were forced to oviposit on fewer plants which created competition for larval food sources. This competition could be forcing butterflies into more constrained areas effectively squeezing their range and limiting recolonization opportunities (Flockhart et al., 2012). Figure 36 illustrates the density of corn and soy near Lake Michigan with the butterfly sightings during peak recolonization in 2022.

Figure 36. Peak Recolonization, Butterfly Sightings, Corn, and Soy



With land in the Midwest becoming less habitable for milkweed and monarch larvae, butterflies were likely being forced to seek host plants further east to avoid overcrowding. This displacement was effectively relocating the butterflies from the unfavorable conditions in the Corn Belt area towards the densely populated and developed East Coast (Figure 37).

Figure 37. Eastern Monarch Butterfly Sightings at Peak Migration in 2022



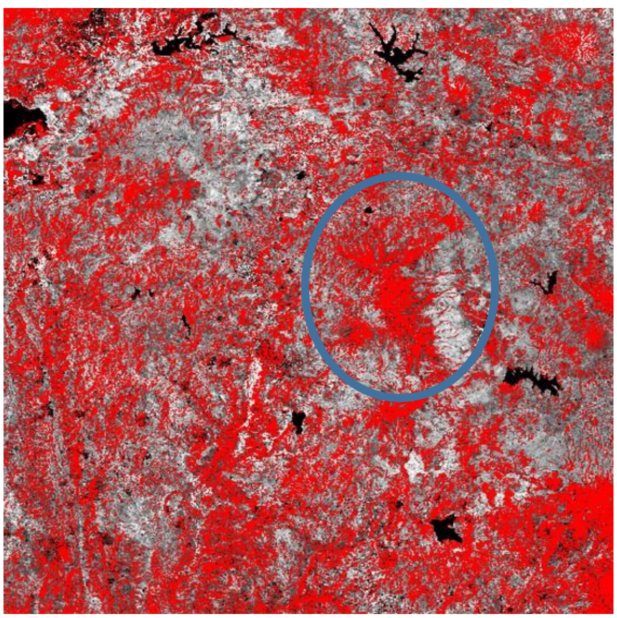
4.2. Overwinter Sites in Mexico

As the population in and around Mexico City continues to grow, the surrounding area has transformed from dense mountain forests to cleared lands to support the growing local population. As trees have been clear-cut for energy and lumber, large areas have been turned into pastures, farmland, and housing. While orthophotos leave little room for doubt regarding the degradation of the land adjacent to the MBBR, the full extent of the damage is less readily available. This study was able to extract an approximation of the amount of butterfly habitat that has been lost between 1986 and 2020, as well as obtain the density and health of the vegetation during that same time frame. Both the loss of dense forests and the declined health of the remaining vegetation indicated that the overwinter forests have been substantially degraded, which has constrained the suitable habitat needed for overwintering monarchs.

4.2.1. Classification

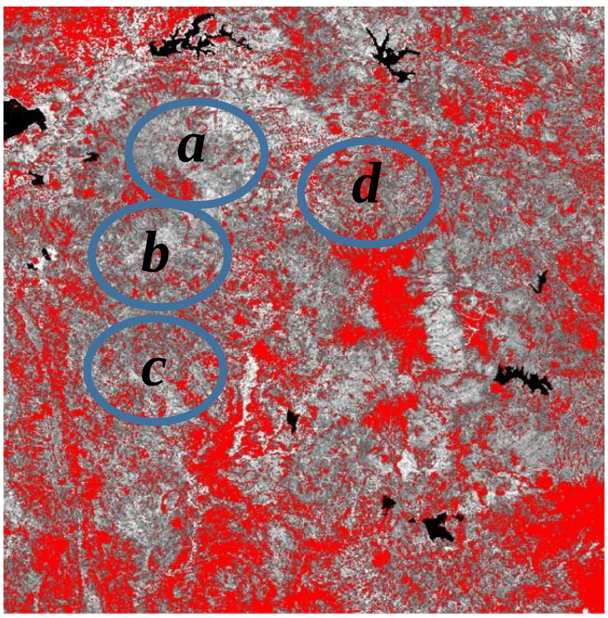
The classification was able to identify urban/developed areas, dense forests, water bodies (once reclassified), and land with little vegetation due to agriculture, pasture, and timber clearing. The first image reflected conditions from March 1986 (Figure 38) and visualized conditions six years after the establishment of the Monarch Butterfly Biosphere Reserve (MBBR) with widespread, dense butterfly habitat. The blue circle identified the MBBR, which is nearly undiscernible from the surrounding forest habitat outside of the reserve.

Figure 38. Classification Results - March 1986



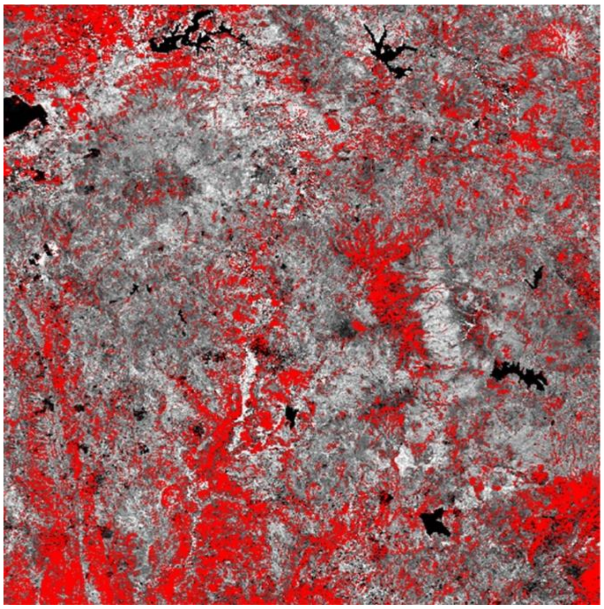
The second image reflected the change that occurred over the subsequent 14-years (Figure 39). There was considerable loss of habitat during this time frame with substantial forest loss in the land directly bordering the reserve; however, the MBBR itself remained largely intact. The blue circles identified particular loss of forest land due to urban growth and development in the cities of Acámbaro (a), Ciudad Hidalgo (b), Tuxpan (c), and Los Reyes (d). However, it is important to note that the 2000 image was taken in May, not March due to cloud cover during March and April of that year. This variance is less critical as the preferred roost trees for monarchs (oyamel fir (*Abies religiosa*), holm oak (*Quercus ilex*), and pine trees (*Pinus spp.*)) are all evergreens and do not experience leaf-off cycles; however, all dense forests were counted as suitable habitat for roosting butterflies, so any deciduous trees could slightly skew the results when accounting for the two extra months of leaf-on vegetation.

Figure 39. Classification Results - May 2000



The third image visualized the final classification result in March 2020 (Figure 40). This visualization displayed further loss of butterfly habitat as urban areas continued to develop, and land cover continued to degrade. In this final image, the MBBR was still intact; however, the overall loss of butterfly habitat had largely diminished beyond the reserve's borders.

Figure 40. Classification Results - March 2020



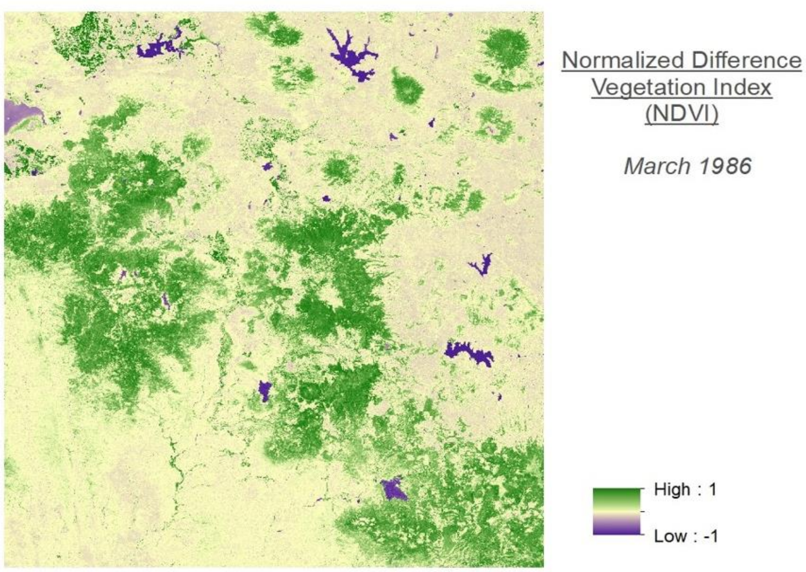
4.2.2. Butterfly Habitat Areal Calculations

To calculate the total butterfly habitat in each image, the number of cells with suitable butterfly habitat was multiplied by the spatial resolution of a single cell (900-m²). For the 1986 image, there were 6,103,696 cells in the targeted class which resulted in a total butterfly habitat area of 549,333-ha. The 2000 image had 4,145,033 cells of butterfly habitat which translated to a total suitable habitat area of 373,053-ha, which was a loss of 176,289-ha from 1986 to 2000. The final image from March 2020 revealed a total of 3,293,984 cells of suitable habitat, which translated to a total area of only 296,459-ha. This indicated an additional loss of 76,594-ha over the last 20 study years. Ultimately, the region lost a total of 252,874-ha of butterfly roost habitat between 1986 and 2020 with 70% of the total lost butterfly habitat occurring in the first 14-years. The results indicated that while forest loss has slowed, it was still being degraded in the areas surrounding the protected reserves. With population in the area continuing to grow, unprotected lands will not likely recover without intervention (López-García & Navarro-Cerrillo, 2020; Flores-Martínez et al., 2019)

4.2.3. Normalized Difference Vegetation Index (NDVI) Results

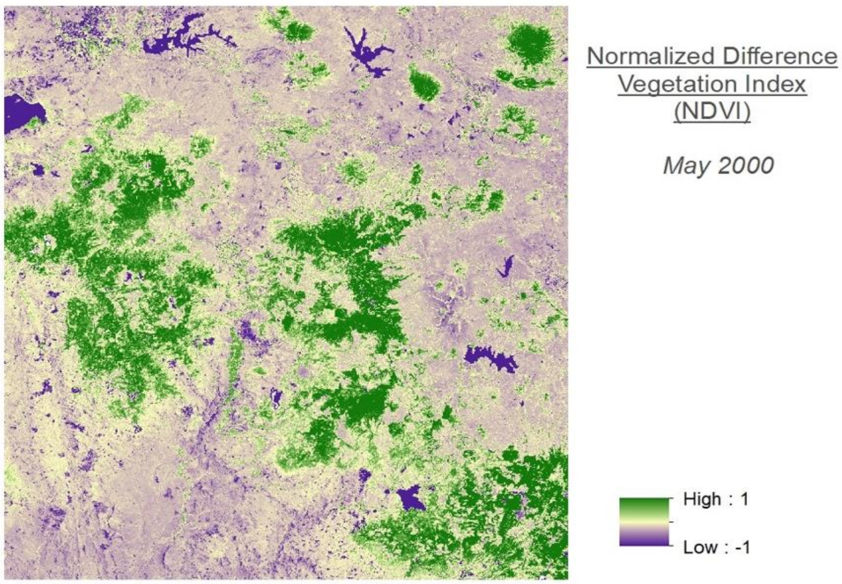
The NDVI analysis provided another form of visual analysis as it highlighted the normalized ratio of vegetation health and density in each of the three analysis years. The 1986 image displayed ample suitable butterfly habitat with the MBBR clearly visible in green (score of 1) indicating dense, healthy forest vegetation (Figure 41). The lakes were visible in purple and reflected the score of -1 indicating no vegetation. The NDVI was much better at discriminating between water bodies and dry land than the land cover classification and was generally accurate when depicting forested areas outside of the protected zones.

Figure 41. NDVI - March 1986



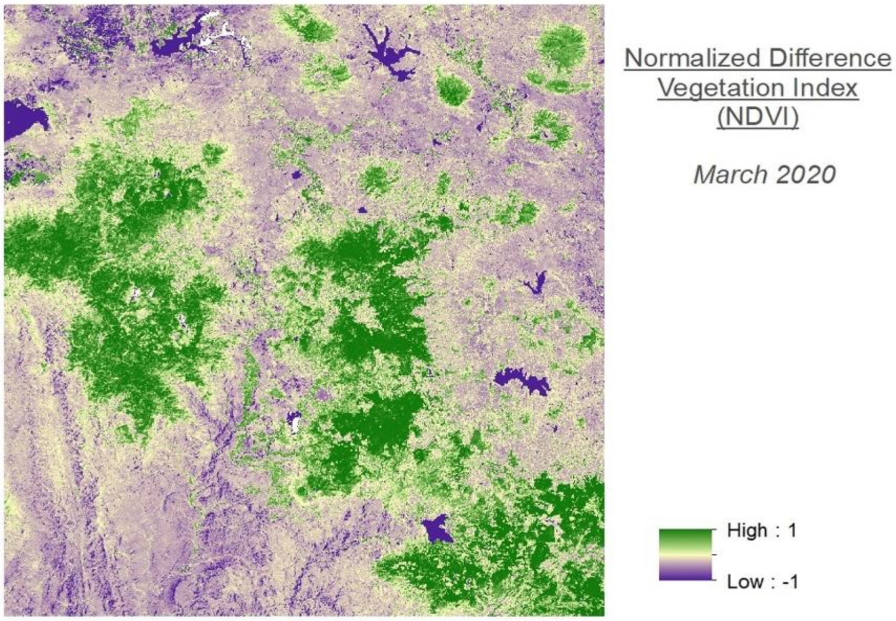
The NDVI image for 2000 displayed a large amount of land degradation across the study area which was in agreement with the land use classification analysis (Figure 42). While the water bodies and the MBBR remained unchanged, the surrounding unprotected area lost a large amount of its healthy, dense vegetation. The loss during this 14-year time period highlighted the substantial land clearing for development and agriculture as well as timber extraction from the local forests. When compared to the land use classification, this image did appear to reflect that most of the loss of forested vegetation did occur in this 14-year period with nearly all forests except those located within protected areas suffering substantial degradation.

Figure 42. NDVI - May 2000



The final study's NDVI image reflected no overall improvement in vegetation and land cover from 2000 to 2020 (Figure 43). This was also consistent with the land use classification method; however, while total vegetation was not improved, there were isolated locations that did appear to experience some improvement for dense vegetation. Locations surrounding the MBBR as well as forested areas to the immediate west of the reserve appeared to reclaim some of their denser vegetation that had been lost between 1986 and 2000. This was reasonable as the western forests did contain monarch protected sanctuaries including the San Andres and Mil Cumbres sanctuaries, but this localized improvement was not enough to decrease the overall loss of vegetation from the last two decades. While it did indicate that some areas could possibly be reforested, many areas may be beyond repair depending on the type of current land use and the extent of the degradation.

Figure 43. NDVI - March 2020



4.3. Non-Migratory Populations

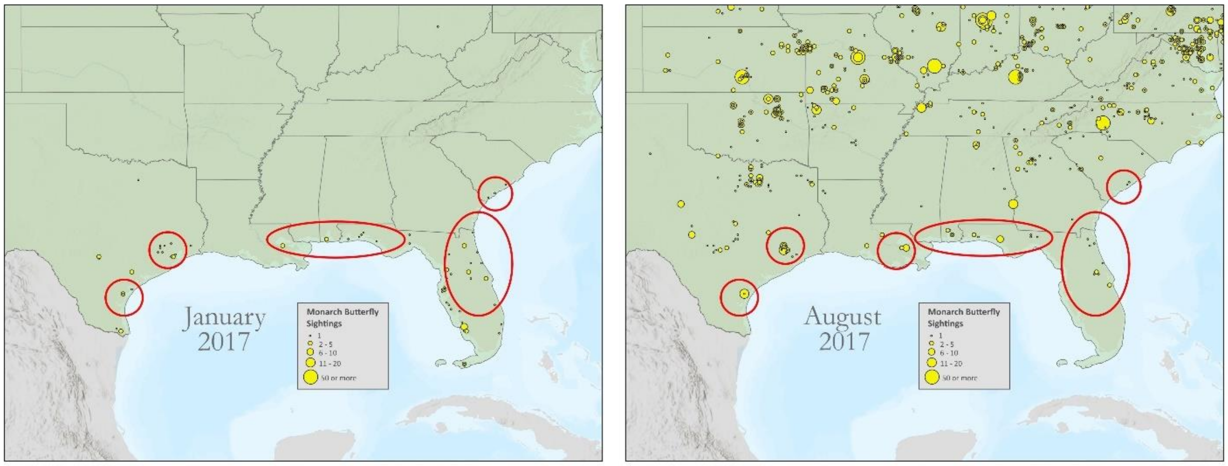
While the population follows a predictable migratory pattern north to the summer breeding grounds, an abnormal trend has been reported in recent years of monarchs that are no longer migrating (Freedman et al., 2018; Altizer & Davis, 2010). These butterflies have abandoned their migratory instincts and remain in one location while recolonizing year-round. With milkweed continually available, questions have arisen regarding the health of monarchs that have formed non-migratory sink populations (Majewska et al., 2019; Altizer et al., 2015). For this behavior to be substantiated, sightings would need to remain in the same areas consistently throughout the peak migration and peak overwinter months when they should reasonably be located elsewhere.

4.3.1. Eastern Population

Reports over the last several years have raised concerns that there were isolated populations of monarch butterflies along the South Atlantic and Gulf coastlines that were not overwintering but were instead breeding year-round (Majewska et al., 2019; Peterson, 2019; Altizer et al., 2015). For this to be possible, environmental characteristics needed to be habitable for both butterflies and their host plants during the overwinter months. A previous site suitability model ranked environmental and anthropogenic factors as they contributed to monarch butterfly migration, recolonization, viability, and mortality (Kesler & Bunch, 2020), which revealed that some locations in the Southern United States could possibly provide an environment that could support monarchs and milkweed through the winter and migration months. With favorable conditions established, sightings data was used to determine if monarch butterflies were present at locations in Southern Florida and along the Gulf and South Atlantic Coasts in all months of the migratory flight year, including peak migration and peak overwinter periods.

For this analysis, January was identified as a peak overwinter month, while August was used to represent peak migration (Figure 44). For the Eastern migratory population, monarchs should be in a state of reproductive diapause in Mexico during January; while in August, they should be located in the Northern United States in the Great Lakes and Corn Belt regions. The circles in Figure 45 represent areas of interest where monarch sightings were consistently logged year-round despite the larger migratory population being located elsewhere. While January and August 2017 did locate butterflies outside of the traditional migration, more years of data would be needed to differentiate non-migratory populations from singular migratory outliers that appear one time and then subsequently die or rejoin the migration later in the cycle.

Figure 44. Sink Population Areas of Interest



Notes. Peak Overwinter and Peak Migration with Monarch Butterfly Sightings (2017).

Full migrations were mapped from January 2017 to December 2022 to establish a continuous, multi-year visualization to identify if there was consistency in the abnormal butterfly sighting locations (Appendix A). Using the same months to represent peak overwinter (January) and peak migration (August) to establish possible non-migratory butterflies, it was confirmed that sightings were consistently located in Florida and along the South Atlantic and Gulf Coastlines during the entire study period.

The sightings data in Appendix B (Figures B66-B71) confirmed the existence of monarch butterflies that were too consistently located in the same area to be designated as singular outliers over the six-year data period. When coupled with research regarding physical morphology (Altizer & Davis, 2010) and parasitic infestations (Geest et al., 2019; Majewska et al., 2019; Altizer et al., 2015; Satterfield et al., 2015) in non-migratory butterflies, the presence of these suspected populations was concerning and has likely had negative impacts on population counts at the traditional overwinter sites in Mexico.

4.3.2. Western Population

Western monarchs have been declining at an accelerated rate over the past 20 years (Dingle et al., 2005; Xerces Society, n.d.). Their decline was so rapid between 2018 and 2021 that scientists were concerned that the Western population had breached the quasi-extinction benchmark where their population was unrecoverable (Figure 45) (Semmens et al., 2016; Engen & Sæther, 2000). Western non-migratory populations were analyzed in the same manner as the Eastern population by comparing sightings at peak overwinter and peak migration for each of the six years. The sightings circled in red are known overwinter sites where roosting monarchs begin their journey East and North to recolonize in the summer breeding grounds in Idaho and Nevada (Xerces Society, n.d.) (Figure 46).

Figure 45. Western Monarch Butterfly Counts by The Xerces Society

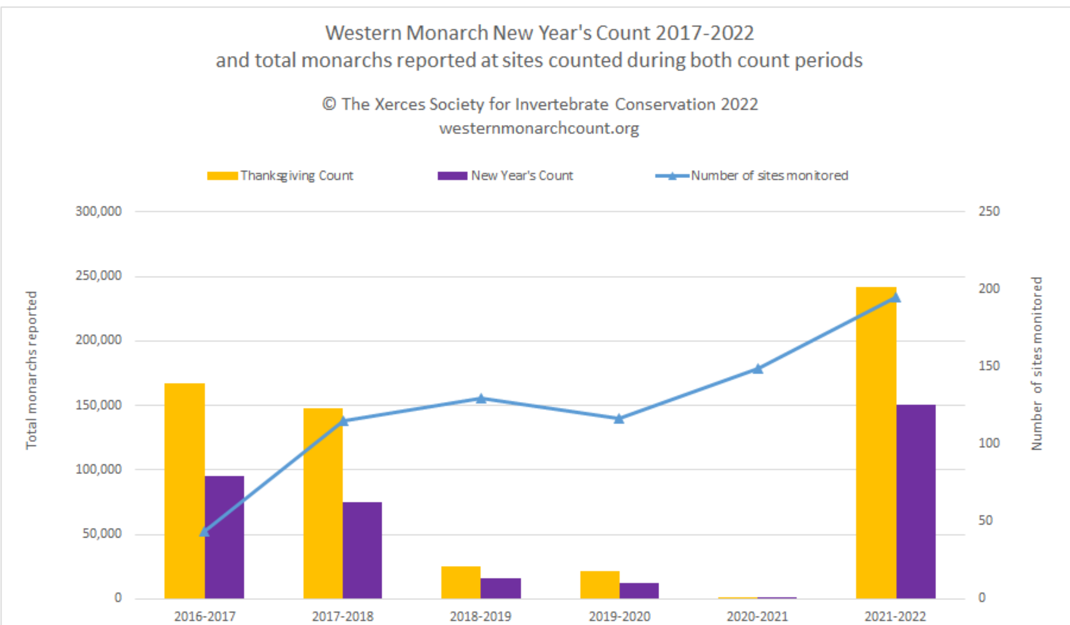
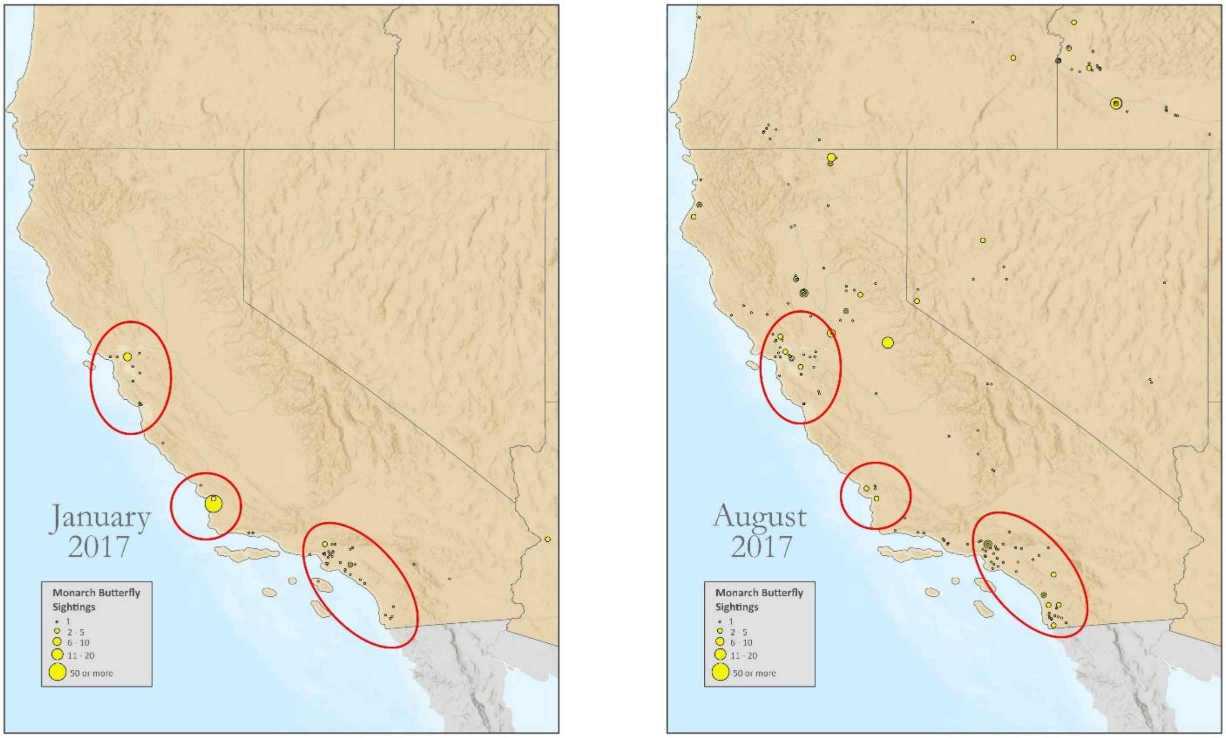


Figure 46. Areas of Interest During Peak Overwinter and Peak Migration



Unlike the Eastern population where the non-migratory sites were located away from the overwinter sites and summer breeding grounds, the Western population was more complicated. At the forefront of these difficulties was the reality that the Western population was rapidly declining. If there were substantially fewer butterflies, there should also be fewer sightings. The lower number of sightings lessened the dataset's ability to determine what was happening at the overwinter sites, but it was the most comprehensive dataset available at the time of this study.

Another issue was that it was impossible to differentiate the nature of the sightings at the overwinter sites. Whether a butterfly was overwintering, temporarily roosting, or actively breeding was indiscernible from the sightings alone, yet essential in understanding if the butterflies were in a consistent breeding resource mode, which has served as an indicator of migratory probability (Altizer & Davis, 2010). To gain some understanding as to whether or not the Western monarchs are losing their migratory behavior, the peak migration sightings were prioritized as the butterflies should not be at the overwinter sites, but instead moving East and North to the summer breeding grounds.

Using the same months to represent peak overwinter (January) and peak migration (August), sighting locations were reviewed to compare whether or not butterflies were appropriately located during the migratory cycle. Whether or not sightings were logged at the Central and Southern California overwinter sites when the butterflies should be migrating North could be the first step in verifying that Western monarchs may not only be losing their population numbers, they may also be losing their migration (Appendix B; Figures B72-B77).

While the argument can be made for the Eastern population that favorable conditions existed to support milkweed and monarchs year-round, the Western migration is more complex. The Western migration occurs at a smaller spatial scale and over fewer months (five-six months) than their Eastern counterparts (eight months). This difference could not be explained by environmental factors or conditions as the site suitability model indicated less optimal conditions in May 2017 as opposed to March or April, when the migration should have begun (Kesler & Bunch, 2023). Ultimately, the Western sightings were not dense enough in some study years to draw a formal and finite conclusion; however, the evidence was compelling that Western Monarchs were at least slowing their migration while some may not be exiting the overwinter sites at all.

5.0. Discussion

The results of the three individual studies regarding concerns identified through the previous site suitability analyses (Kesler & Bunch, 2023; Kesler & Bunch 2020) and accompanying literature reviews do have merit as major contributors to the decline in migratory North American monarch butterflies. While each of these impediments would negatively impact overall population numbers, the three in unison could be largely responsible for much of the decline. Herbicide resistant crops are responsible for considerable land degradation and a reduction in critical Eastern population summer breeding habitat; development and resource extraction has negatively altered the landscape surrounding the Monarch Butterfly Biosphere Reserve (MBBR) sites including the loss of unprotected critical habitat typically occupied by overwintering Eastern monarchs; and the presence of non-migratory butterfly populations could be providing an exodus from the overall migratory phenomenon.

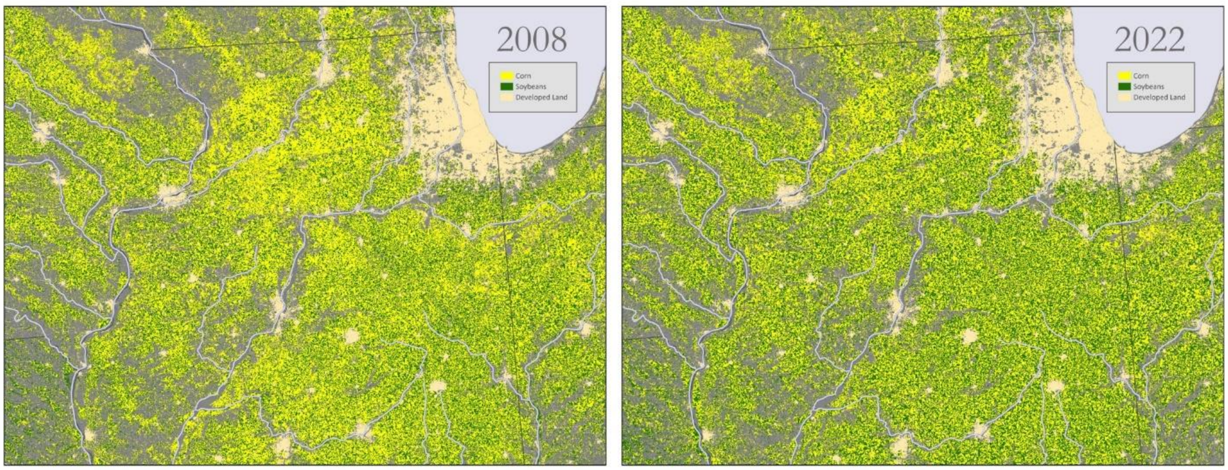
5.1. Herbicide Resistant Crops

Herbicide resistant crops have reduced the availability of milkweed, particularly in the Midwest Corn Belt region, which has historically served as the Eastern monarch summer breeding grounds. Female monarchs oviposit up to 300 eggs (Oberhauser, 2004)

on the undersides of milkweed leaves so that newly hatched larvae have an immediate food source. The larvae will consume milkweed non-stop for approximately two weeks before entering the pupa stage of development and emerging as a fully developed adult butterfly (Nail et al., 2015). When an excess number of larvae consume too few milkweed plants, foliage is completely consumed rendering the plant incapable of supporting future larvae until the shoots regrow and produce new leaves. The competition for an adequate food supply could lead to higher larval mortality rates if there are no other milkweed plants in close proximity (Flockhart et al., 2012).

As smaller individual farms have been replaced with large, consolidated commercial farms, the means and methods of agricultural management have changed to incorporate more mechanized and chemical maintenance and pest control (Pleasants & Oberhauser, 2012). With the overall footprint of agriculture becoming more densely occupied, small pockets of milkweed that used to grow freely have been eradicated. This densification was apparent in this study as the overall footprint of corn and soy did not grow in size, but instead cells within the larger footprint began to tip towards agriculture, especially corn and soy that tend to use the herbicide resistant varieties (Pleasants, 2015) (Figure 47).

Figure 47. Corn and Soy Crop Density



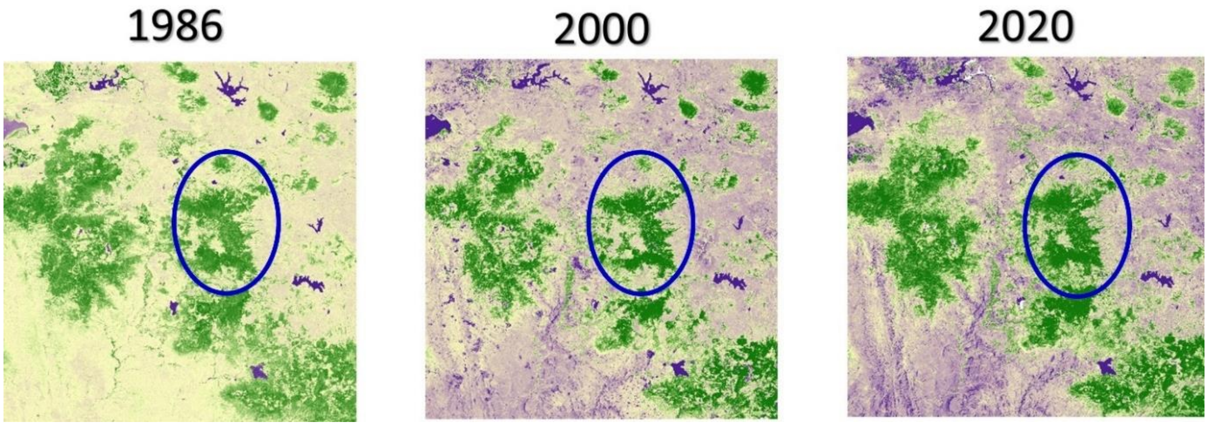
While the degradation of the summer breeding grounds has been almost completely attributed to genetically modified corn and soy, there is evidence that the downturn in recolonizing populations began before the negative impacts of herbicide resistant crops had been realized. Boyle et al. (2019) identified that specific species of milkweed began to decline in 1945 and again in 1955, which was immediately followed by a decline in monarch butterfly populations. Genetically modified crops with herbicide resistance were not introduced until 1996 and were not initially widely used (approximately 2%) (Boyle et al., 2019). However, as the use of genetically modified variants has increased, the decline of milkweed has intensified. So, while agricultural practices may be a substantial contributor in the decline of several milkweed species, there may be more factors involved in the larger milkweed decline in the Eastern summer breeding grounds (Lemoine, 2015).

5.2. Overwinter Sites in Mexico

The degradation of the overwinter habitat has been well documented and has gained national protection as a UNESCO World Heritage Site. Aerial and satellite imagery have helped visualize the extent of the loss that has been largely due to anthropogenic development and agriculture. With the population continuing to grow in nearby Mexico City, it is reasonable to believe that the need for land, raw materials, and natural resources will continue.

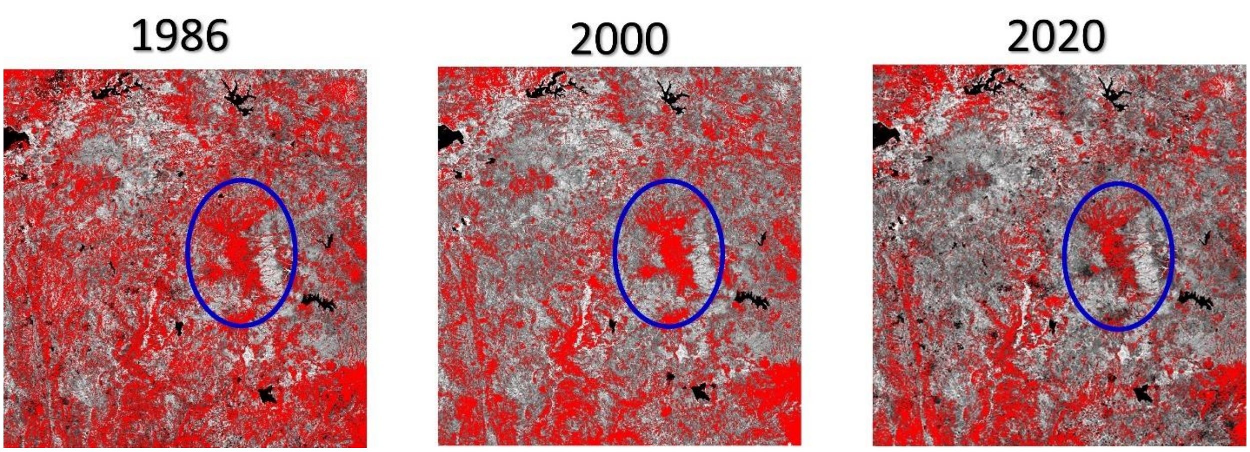
While the loss of forested area is very concerning, there is a simultaneous loss of vegetation density and overall “green” health (Pei et al., 2021). This means that not only are there areas where trees and vegetation have been removed, but the remaining trees and vegetation may be less dense and less healthy. Figure 48 illustrates the overall loss of dense, healthy vegetation over the past 35 years with the protected MBBR lands circled. The depletion of green vegetation is apparent as the amount of unhealthy, less dense vegetation (purple) greatly increased. It is also important to note that not all area that is purple is actual vegetation. The deepest purple areas are open water, empty fields, and developed spaces. While most of the loss occurred in the first 15 years, the healthy vegetation (green) did appear to become more dense in the last 20 years indicating that some vegetation had been regained; however, most of the area that was not healthy or the vegetation had been removed (purple) also became more developed leading to a higher density of unhealthy/no vegetation area. Overall, the protected sites remained intact with most of the degradation occurring in unprotected areas outside of the MBBR.

Figure 48. Results of NDVI Analysis



With a loss of 252,874-ha of overwinter habitat in and around the MBBR protected overwinter sites over the last 35 years, there is little that can be done except to protect and conserve the remaining habitat (Figure 49). With several areas clear-cut for pasture, agriculture, and illegal lumber extraction, butterflies are being squeezed into the remaining viable roost habitat. Further complicating the need to police and protect these critical areas, local government and law enforcement has developed a history of corruption and violence towards butterfly conservationists (Wamsley, 2020).

Figure 49. Critical Habitat Loss Analysis



With the fragile state of the remaining vegetation and illegal extraction of resources, ecotourism has likely added additional strain on the environment and could be endangering the protected sites within the MBBR if not managed properly (Russell & Wallace, 2004). While ecotourism does promote environmental conscience and provide a source of income for local communities, it can inadvertently damage the fragile ecosystems that they are trying to protect (Ibrahim et al., 2019). The only course of action moving forward is to protect the remaining forests and overwinter sites, while perhaps striking a planned balance between areas that are targeted for development and areas targeted for reforesting programs that will become additional butterfly habitat.

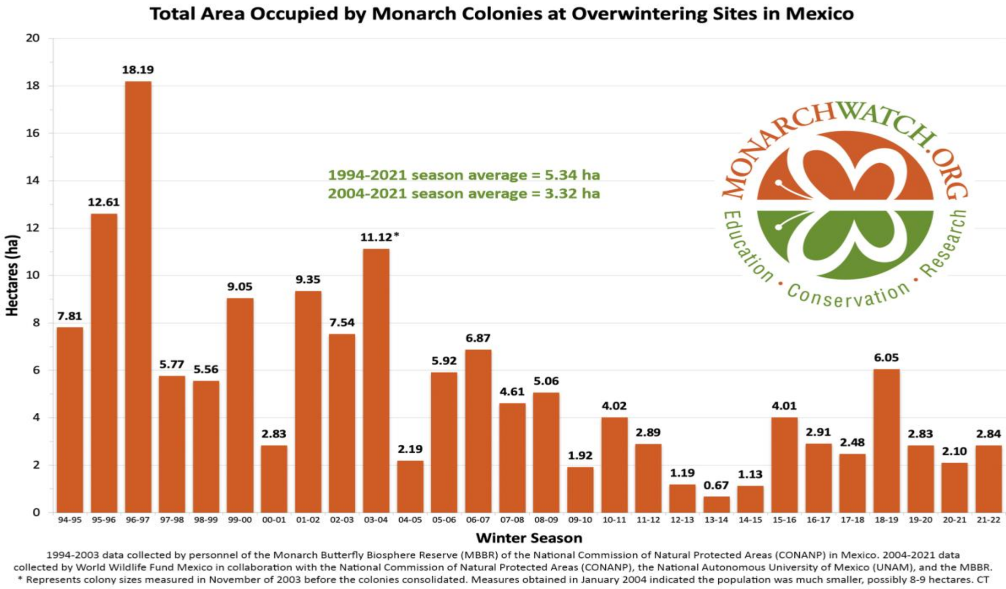
5.3. Non-Migratory Populations

While the herbicide resistant crops and degradation of the overwinter sites analyses left little room for doubt as to the widespread negative impact on migratory monarch butterflies, the analysis regarding non-migratory populations only led to more questions. As scientists have grappled with understanding why some monarchs migrate and others do not, there may be some reasons emerging that could identify why butterflies were sighted in certain locations while exhibiting no migratory or overwintering behaviors (Vidal & Rendón-Salinas, 2014). While it is impossible to know if specific butterflies were sedentary, sightings were consistent throughout all twelve months indicating that there was a population that was breeding and occupying the locations in Florida and along the Southern coastlines (Peterson, 2019; Williams, 2015).

5.3.1. Causes and Concerns

Despite this analysis aiding in the validation of the existence of non-migratory populations within the larger North American population, it did little to help understand why some butterflies were behaving abnormally. There are several theories detailing the causation of the loss of the migratory impulse; however, there may be multiple causes that are creating this anomaly. The most popular theory hypothesizes that migratory responses are triggered by weather, particularly temperature (Baumle, 2017; Nail et al. 2015). Temperature was heavily weighted in the previous site suitability models (Kesler & Bunch, 2023; Kesler & Bunch 2020) as butterflies become inanimate below 13°C (Nail et al., 2015); therefore, for non-migratory populations to survive, sink locations would need to also maintain an average temperature above 13°C. This theory was tested during this analysis while assessing the number of sightings in the suspected sink locations. 2018 and 2019 had fewer sightings when compared to the other four study years, but when the sightings were compared to the mean temperatures for January, there was a correlation between lower temperatures and lower sighting counts. While this seemed to easily address the lack of sightings that year, the reduced sightings in 2022 seemed unaffected by lower temperatures (Appendix B; Figures B78—B83). The low counts in 2018 could be due to temperatures that were substantially lower than the normal range, while 2022 was more borderline low. If it were more borderline, the actual daily temperatures may have been more suitable than their aggregated monthly dataset visualized. But it is also interesting that 2018/2019 also recorded the highest overwinter count in Mexico since 2006 (Figure 50). Therefore, it is questionable if the higher number of overwintering butterflies were perhaps an artifact of monarchs that would have otherwise overwintered along the Gulf Coast but could not due to significantly cooler temperatures. If the sink locations were essentially becoming new overwinter sites due to climate change (i.e. warmer temperatures at higher latitudes), could this ultimately translate into the lower counts in the overwinter sites in Mexico that have been recorded in recent years (Espeset et al., 2016)?

Figure 50. Eastern Monarch Butterfly Overwinter Counts



Note. Retrieved from MonarchWatch.org

Another theory regarding the underlying cause of the loss of migratory behavior is that non-migratory monarchs are physically *built* differently. Altizer and Davis (2010) noted that non-migratory butterflies tended to have different body and wing morphology than their migratory counterparts. After studying specimens and images of both captive-raised and wild monarchs known to be either migratory or non-migratory, they noticed that the wings of the non-migratory butterflies were less fit for long-distance flight. Migratory Eastern monarchs also had larger bodies (better suited for lipid storage to survive the long flight to Mexico and the overwintering months) and elongated wings (better suited for gliding), while non-migratory butterflies were smaller in size and had rounded wings (Altizer & Davis, 2010). Could this be a matter of *"form fits function"* where non-migratory monarchs are not migrating because they have developed in ways that are not compatible for lengthy flights; or inversely, have the Eastern migratory population migrated because they were simply able to?

Other theories regarding the loss of migratory behaviors included: (1) variations in reproductive development which typically occurs in the final generation of butterflies that will migrate to Mexico; (2) underdeveloped sensory, neural or physiological systems that trigger the butterfly to quit recolonizing and begin the Southern migration; and (3) captive breeding programs that created emergent butterflies that were temporally and geographically disoriented within the larger migratory cycle. Freedman et al. (2018) discovered that while there were some variations in the reproductive development of non-migratory monarchs, the butterflies retained their reproductive plasticity indicating that subsequent butterflies could theoretically receive cues to enter reproductive diapause and resume the migration. Freedman et al. (2018) also investigated the theory that non-migratory butterflies may lack the sensory and neural capability to receive migratory triggers; however, their research indicated that physiologically, non-migratory butterflies retained all sensory and neural networks that were required to receive the migratory trigger.

Wilcox et al. (2021) studied whether captive-raised butterflies were disoriented as a product of controlled breeding that deposited the adult butterflies at disjunct intervals and locations along the migratory cycle. If the butterflies could not locate themselves within the migratory flyways, perhaps they would remain sedentary. Wilcox et al. (2021) were able to conclude that while the butterflies may have experienced temporary disorientation, once they were able to orient themselves with their internal sun compass, they began to migrate south to overwinter in Mexico effectively resuming the migration.

While each of these studies introduced reasonable theories regarding the change in migratory behavior, they were also confronted with no overarching solution. The wing and body morphology study by Altizer & Davis (2010) produced compelling results in the sense that maybe butterflies have somehow mutated or evolved past long-range migration tendencies. If some butterflies cannot physically complete a 3000-mi migration, it could mean that non-migratory populations could be dangerously close to one adverse weather event or natural disaster from extinction. But while temperature was investigated in conjunction with lower counts at sink locations and higher counts in Mexico, it was still inconclusive as there was no clear cut-off from year to year as the 2022 population was still present with lower temperatures. Freeman et al.'s (2018) results added more complexity by revealing that non-migratory butterflies still retained neural and sensory networks and reproductive plasticity that could allow them to theoretically resume migratory behaviors should the right conditions present themselves. And finally, Wilcox et al. (2021) confirmed that captive-reared and other disjunct butterflies were capable of resuming the migration once they were able to freely use their internal compass. Ultimately, there was no singular factor that determined "which butterflies will migrate and which will not". These studies illustrated that there are likely multiple causes for the loss of migratory activity, and that each variable could be interacting with other factors and tipping points that collectively set future behaviors in motion.

6.0. Conclusion

As North American monarch butterflies await protection and resources from the Endangered Species Act (ESA) (Pocius et al., 2018; Brower et al., 2014), scientists, conservationists, and concerned citizens are diligently looking for ways to stabilize the declining Eastern and Western populations. Efforts to protect migratory butterflies while simultaneously providing conservation relief at all stages of the migration is not only difficult due to the large spatial footprint, it is also dynamic as changes with weather, climate, land cover, land use, and physical terrain create a moving target.

This study was conducted to continue the research and analysis regarding herbicide resistant crops, loss of overwinter habitat in Mexico, and the impacts and viability of non-migratory population sinks. Using Geographic Information Science, cartography, remote sensing, spatial analysis, and statistics, each threat was confirmed as a substantial impediment to migratory monarchs. While any one of these threats could have a sizable impact on overall monarch populations, the verification that all three could be impacting migratory butterflies indicates that the current state of the migration is in dire need of support. Genetically modified crops that have been engineered to be herbicide resistant have eradicated milkweed within spray zones and anywhere from 30-ft to over a mile depending on the type of herbicide and application technique (Brain et al., 2017; Vecchia et al., 2009). While the overall footprint of corn and soy has not grown larger, crops have increased in density removing the small habitable pockets that could support milkweed including ditches and public right-of-ways (ROWs) (Ozcan et al., 2020; Baum & Mueller, 2015; Xerces Society, 2015). More concerning is the fact that the corn belt region is geographically located within the Eastern summer breeding grounds, and the planting season aligns with months associated with peak migration and peak recolonization. With less milkweed, fewer larvae have an adequate food source resulting in fewer adult butterflies.

Degradation at the overwinter sites has been monitored and analyzed for several years. Aerial imagery has frequently been used to visualize how much forest has been lost due to development and natural resource extraction; however, the situation may be worse than these images alone have portrayed. Using satellite imagery, land cover classification techniques helped provide a quantity for the loss that has occurred over the past 35 years. That number is 252,874-ha, which indicated that roughly half of the unprotected forests have been lost since 1986. Further compounding the loss of forests, according to NDVI calculations, the remaining habitat has declined in density and was less healthy and less suitable for overwintering monarchs. With less adequate roost habitat, overwintering monarchs were more susceptible to exposure to the elements and predators which will undoubtedly lead to further reductions in population counts.

Sites associated with non-migratory monarchs have been the topic of several discussions, and researchers and conservationists question if the migration may be coming to an end (Brower et al., 2012). As climate change and anthropogenic factors continue to alter historic migratory trends, several monarch sightings have been logged at locations in Florida, along the Gulf Coast, and at the overwinter sites in California. These populations present several issues as they perpetuate parasitic infestations by consuming milkweed that grows year-round and are generally producing smaller butterflies that may be less healthy and less capable of undertaking the 3000-mi migration (Geest et al., 2019). While several theories have been considered regarding why some monarchs migrate and others do not, the reality is that there are probably multiple factors that collectively result in groups of non-migratory, constantly recolonizing butterflies. This study also contemplated the possibility that Eastern monarchs may be relocating to overwinter sites further north as climate change can bring warmer temperatures to higher latitudes. While this shift has definite correlations to the decline in counts at the overwinter sites in Mexico, it could be how Eastern monarchs have adapted to their changing environment. At the other end of the migration, Western monarchs may not be wholesale leaving the overwinter locations in Central and Southern California. This invokes questions regarding the viability of the Western habitat, especially when coupled with the critical drop in butterfly numbers that occurred in 2020/2021. While there has been evidence that the Western population may have rebounded in 2022, whether or not that trend will be sustained in 2023 is yet undetermined.

With multiple threats impacting the migration at various stages, studies such as this are needed to help isolate threats, understand root causes, and aid in the mitigation process. Since migrations add a geographic element to all analyses, using GIS, cartography, and remote sensing can be useful in guiding limited resources to threats and locations that could deliver the highest return in butterfly and flyway health. Despite the conclusions of each of these studies, monarchs have proven resilient in the past. With the proper conservation measures and protections, new strategies and new technologies could help restore monarch populations ensuring that they will remain and inspire future generations.

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CHAPTER V: WHERE IS THE MILKWEED? LOCATING NATURALLY OCCURRING MILKWEED USING REMOTE SENSING

1.0. Introduction

Recent studies have indicated that the North American population of monarch butterflies (*Danaus plexippus*) have been declining at an accelerated rate over the last decade. While there are multiple impediments that impact monarch butterflies including climate change (Melles et al., 2011), anthropogenic development (López-García & Navarro-Cerrillo, 2020; Pleasants & Oberhauser, 2013), and agriculture (Pleasants & Oberhauser, 2013), these factors all flow into one overarching concern, the loss of milkweed. As the sole host plant for monarch larvae, the prevalence of milkweed will always be at the center of annual recolonizations. Some scientists even use milkweed's growth range as the single driver that delineates monarch flyways, breeding grounds, and other critical habitat (Agrawal & Inamine, 2018).

Milkweed (*Asclepias spp.*) has a diverse number of species that are well adapted to survive in most areas of the United States; however, a host of anthropogenic factors have degraded the viable land that milkweed had previously occupied. Commercial, industrial, and residential development has led to the removal of large areas of naturally occurring milkweed, while agricultural endeavors have created large spaces that are uninhabitable due to practices linked to genetically modified crops that have been engineered to be herbicide resistant (Pleasants & Oberhauser, 2013). While there is a benefit to milkweed as it entices pollinators to fertilize crops which increases plant biodiversity and resiliency, milkweed has been considered dangerous for grazing livestock due to toxic cardenolides and as a pest plant in commercial croplands (Woodson, 1954; Züst et al., 2018). In Central and Eastern Europe, milkweed has been branded as an aggressive invasive species where it has been associated with negative impacts on native plant species (Papp et al., 2021) and native wildlife (Altizer et al., 2015; Geest et al., 2019). However, conservation initiatives have been established to support milkweed availability and connectivity along migratory routes, but once they are planted, little is often done to monitor future growth. While there are established ranges where milkweed species can grow, the reality is that the location of naturally occurring plants is largely unknown. Citizen science reporting platforms, such as the *Journey North* (n.d.) and the *Western Milkweed Mapper* (n.d.), have been useful in providing reported sightings, but they are not extensive enough at this time to make assertions to the current population status of wild milkweed.

Remote sensing and satellite technology have revolutionized the ability to identify and monitor vegetation using spectral signatures and various sensors without being in contact with the actual vegetation (Kuenzer et al., 2019; Papp et al., 2021). This allows for widespread analysis that can be specialized to identify specific plant species and ground cover; however, given the low profile of milkweed as a flowering, understory vegetation, satellite imagery is too coarse to locate individual plants or stands. Commissioned aerial photography can be costly and could not be run on a continual basis, leaving the use of unmanned aerial vehicles (UAVs) as the most viable option. Drones have gained a large user base as an affordable method of gathering aerial imagery, and with the availability of specialized sensors, cameras, and other equipment, UAV imagery has become the most cost-effective option for locating smaller plants.

2.0. Milkweed (*Asclepias spp.*) Biology and Ecology

Milkweed is vital to the recolonization and survival of monarch butterflies; however, environmental and anthropogenic threats have decreased the amount of naturally occurring milkweed which has led to declining monarch population counts at the overwinter sites in

Mexico and along the Central and Southern California Coast (McKnight, 2021; Xerces Society, n.d.). Agricultural practices have attributed to milkweed losses in the summer breeding grounds, while development footprints have removed natural land cover creating large spatial gaps in migratory flyways (Borders & Lee-Mäder, n.d.).

2.1. Importance to Monarch Butterflies (*Danaus Plexippus*)

Milkweed has always been associated with monarch butterflies and their annual recolonization as it is the sole food source for developing larvae. Following a reproductive diapause, female monarch butterflies exit the overwinter sites between late February and March (Eastern population) and between March and May (Western population) (Baumle, 2017). Eggs are oviposited on the undersides of milkweed leaves so that the newly hatched larvae will have an immediate food source as they will consume up to 2000 to 3000 times their initial bodyweight (Baumle, 2017; Oberhauser, 2004; North Carolina Wildlife Federation [NCWF], n.d.). After consuming milkweed for eleven to eighteen days non-stop, the larvae will molt one last time entering the pupa stage of development. After pupating for an additional eight to fourteen days, a fully developed adult butterfly will emerge and continue the migration.

Milkweed is so irrevocably intertwined with monarch butterflies that some conservationists have used milkweed prevalence to delineate flyways and habitable ranges (Waterbury et al., 2019; Xerces Society, n.d.). Inversely, the year-round presence of milkweed in certain locations in Florida and along the Southern Atlantic and Gulf Coastlines has been associated with monarchs that have ceased migrating (Freedman et al., 2018). These sedentary butterflies do not appear to enter a reproductive diapause and instead breed year-round in a constant recolonization mode. Milkweeds in these locations do not typically experience the annual plant die back that occurs in cooler regions and therefore grows unimpeded year after year. This type of growth has negatively impacted the butterflies as the milkweed is often infested with parasites that are passed to the butterflies during the larval stage of development (Geest et al., 2019). Non-migratory butterflies tend to be smaller and due to parasitic and protozoan infestations are believed to be less healthy than their migratory counterparts (Altizer et al., 2015).

2.2. *Asclepias* Species

Contrary to its common name, milkweed (*Asclepias spp.*) is typically classified as an herb or wildflower as opposed to an actual weed and encompasses a diverse number of species that have adapted to survive in a wide array of physical and environmental conditions (USDA, n.d.; USFS, n.d.). Milkweeds range in appearance from single, leafless plants to large, leafy colonies and have adapted to survive in a variety of landscapes from arid deserts and prairies to swamps and coastal wetlands (Borders & Lee-Mäder, n.d.). Milkweed received its name from the milky sap that oozes from the stems and seed pods and are largely perennial plants that experience an annual die back and return the following year (Woodson, 1954).

With over 100 species of milkweed available within the United States and Canada, it would seem that milkweed should be available throughout the migratory flyways and at the summer breeding grounds; however, less than half of the milkweed species have been designated as monarch host plants. Further narrowing the list of host plants, female monarch butterflies have exhibited a preference to specific species including common milkweed *(Asclepias syriaca)*, Butterfly weed *(Asclepias tuberosa)*, and Swamp Milkweed *(Asclepias incarnata)* (Pocius et al., 2018; USDA, n.d.).

2.2.1. Common Milkweed (Asclepias syriaca)

Common milkweed *(Asclepias syriaca)* is perhaps the most abundant of the preferable milkweeds and is native to the Eastern United States, especially in the Northeast and Midwest Regions (Figure 51) (Monarch Health, n.d., USFS, n.d.). It is often found in fields and along roadways in and around the summer breeding grounds (Fisher et al., 2020) and has small pink and white flower clusters. Common milkweed is unusual in the sense that unlike several milkweed species that grow as individual plants, common milkweed develops lateral rhizome shoots that create moderate to large stands of clonal plants (Wilbur, 1976).

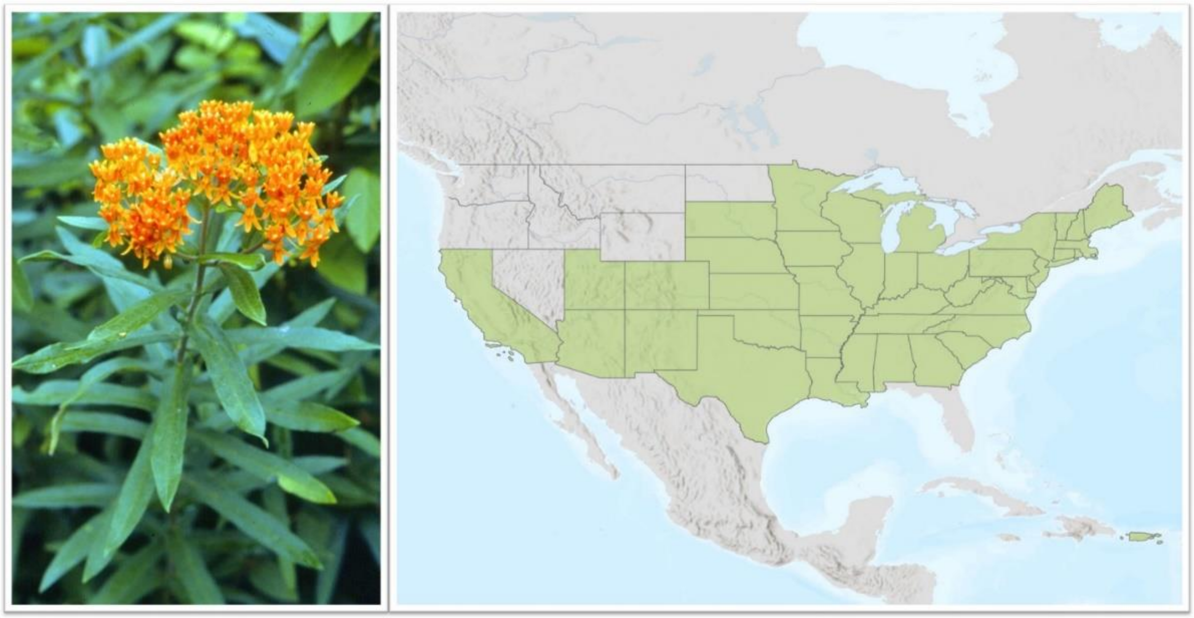
Figure 51. Common Milkweed *(Asclepias syriaca)* and Habitable Range

Note. Retrieved from USFS; Photo Credit: David Taylor

2.2.2. Butterfly Weed (Asclepias tuberosa)

Butterfly weed *(Asclepias tuberosa)* is also preferable due to its ability to support monarch larvae and adult monarchs as a larval food supply and nectar-producing plant. The bright and plentiful orange flowers make this an attractive plant for butterfly and pollinator gardens as well as the fact that the stems do not ooze sap as prominently as some other species (Monarch Health, n.d., USFS, n.d.). Butterfly weed has a wide viable range and is prominent East of the Rocky Mountains (Figure 52).

Figure 52. Butterfly Weed *(Asclepias tuberosa)* and Habitable Range

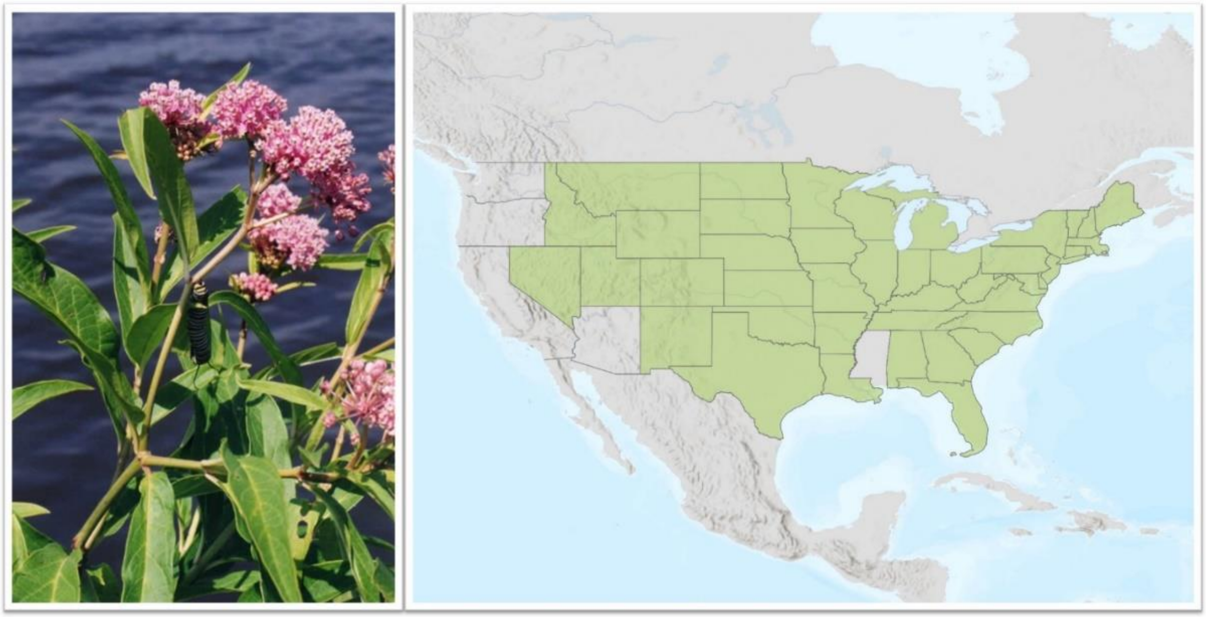


Note. Retrieved from USFS; Photo Credit: Larry Stritch

2.2.3. Swamp Milkweed (Asclepias incarnata)

Swamp Milkweed *(Asclepias incarnata)* tends to grow in wetland areas where the ground stays wet during the growth season and has pink and purple flower clusters (Figure 53). Swamp milkweed is native to the Eastern states and is not common west of the Rocky Mountains. Similar to common milkweed, swamp milkweed multiplies via lateral rhizomes that produce multiple shoots of clonal stems (Monarch Health, n.d., USFS, n.d.).

Figure 53. Swamp Milkweed *(Asclepias incarnata)* and Habitable Range



Note. Retrieved from USFS; Photo Credit: Jennifer Anderson

2.2.4. Cardenolides

As a deterrent from predators, monarch butterflies are typically unpalatable due to their bitter taste (Greenstein et al., 2022). Toxins known as cardenolides are acquired during the larval stage when a large volume of milkweed is consumed by the developing larvae (Züst et al., 2018). Monarchs are able to sequester the milkweed cardenolides which effectively transfers the toxic defense system to the larvae and ultimately to the adult butterfly (Adams et al., 2021). These cardenolides are toxic to livestock, predators, and humans if consumed; however, due to the unpleasant taste, most livestock will not voluntarily consume milkweed unless there is no other food supply available which can be avoided by proper pasture and range management (Borders & Lee-Mäder, 2014). The sequestered cardenolides lose potency over time and are therefore less effective against predators in older butterflies (Trigo, 2000).

2.3. Threats to Milkweed

While many resources have been focused on monarch butterflies, the ultimate threat to the monarch population is the decline and loss of wild milkweeds (Agrawal & Inamine, 2018; Pitman et al., 2018; Pleasants & Oberhauser, 2013). The largest contributor to milkweed loss in the Eastern summer breeding grounds lies with current agricultural practices (Brain et al., 2017; Pleasants & Oberhauser, 2013). As smaller farms have been incorporated into larger commercial farms, perimeter lands and small pockets of suitable milkweed habitat have been removed as the space has been encompassed into the larger crop footprint (Agrawal & Inamine, 2018). However, the largest threat is the large-scale use of genetically modified corn and soy crops that have been engineered to be herbicide resistant (Pleasants & Oberhauser, 2013; Vecchia et al., 2009). These varieties have been designed to allow sweeping application of herbicides over cropland areas eradicating all vegetation except for the planted crop. This practice has led to widespread loss of naturally occurring milkweeds that used to be prevalent around cropland perimeters and in-between rows of vegetation. Herbicide drift has been responsible for the loss of suitable land beyond the cropland perimeter and has been recorded at distances of 30-ft to over a mile depending on the type of herbicide (vapor or particulate) and the application method (Brain et al., 2017).

Other threats include climate change which could be responsible for milkweeds in the Southeastern coastal states that grow year-round with no annual dieback. This diversion from the normal milkweed growth cycle has led to parasitic infestations and could be the root cause of isolated non-migratory monarch populations (Altizer et al., 2015; Geest et al., 2019). Another threat to multiple insect species and vegetation is anthropogenic development. Lawns in residential and commercial areas are regularly treated with herbicides, pesticides, and other chemicals that eradicate unwanted species in developed areas, while structures remove natural landcover and replace it with impervious and other uninhabitable surfaces (Majewska et al., 2019). Ozcan et al. (2020) theorized that approximately 10% of the milkweed utilized by recolonizing monarchs existed in ditches, roadway medians, and other right-of-ways [ROW]; however, aggressive vegetation management and herbicide drift from croplands has led to a stark decline in milkweed in these areas (Brain et al., 2017).

3.0. Remote Sensing

Remote sensing allows scientists to observe and collect data while not in direct contact with the test subject (Aneece & Thenkabail, 2021). Satellite and aerial imagery have revolutionized vegetation, forestry, and conservation field work by allowing the passive monitoring of test subjects at both large spatial and temporal scales without having to perform in-situ field work which could be costly, difficult, and in some cases, impossible. These techniques have evolved in recent years from expensive, highly specialized sensors loaded onto satellites to comparatively inexpensive, commercially available cameras attached to unmanned aerial vehicles [UAVs] (Ragazzo et al., 2023; Djupkep Dizeu et al., 2022; Barrero & Perdomo, 2018). As technology has become more accessible, uses and applications have become more diverse. Common uses of remote sensing and spectral analyses include vegetation management (Dian et al., 2018), drought ((Samreen et al., 2023)), crop yield (Bandyopadhyay et al. 2014), precision agriculture (Ragazzo et al., 2023; Longchamps et al., 2010), biomass calculations (Casanova et al. 1998), weed and pest management (Basinger et al., 2020), land cover changes (Kuenzer et al., 2019), and general plant health and stress (Pei et al., 2021; Everman et al. 2008).

3.1. Spectral Sensors

Perhaps the most important piece of technology in any remote sensing analysis is the type and quality of sensor that will be used. Sensors are the component that detects and records an object's reflectance including bands that are able to detect ranges within the electromagnetic spectrum that are invisible to the naked eye (NASA, n.d.). Near infrared [NIR] sensors have been useful in identifying different types of vegetation beyond what the visible bands can detect as well as isolating factors that contribute to the health and density of vegetation.

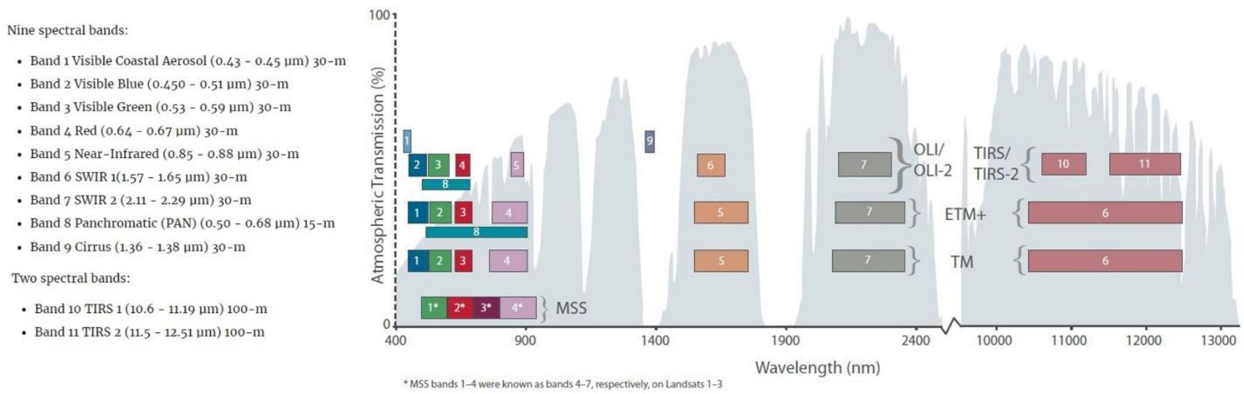
3.1.1. Multispectral Sensors Versus Hyperspectral Sensors

Multispectral sensors contain several bands that are capable of differentiating between various wavelengths and spectral bandwidths (Barrero & Perdomo, 2018). Certain bands are better equipped to visualize the spectral data depending on the type of analysis that is being conducted as well as the targeted feature. NIR bands are invisible to the human eye; however, they are very good at differentiating vegetation and non-vegetation land cover (Pei et al., 2021; Rosero-Vlasova et al., 2019). When coupled with the visible red band, vegetation health and density can be easily visualized with the aid of vegetation indices such as the Normalized Difference Vegetation Index [NDVI] (Pei et al., 2021).

The best example of a multispectral sensor is the current Landsat 9 satellite that launched in September 2021 (USGS, n.d.). The most recent Landsat imager utilizes a nine-band multispectral sensor named the Operational Land Imager-2 [OLI-2], which is the next generation of the OLI sensor aboard Landsat 8. Landsat 9 also has a two-band Thermal Infrared Sensor [TIRS-2] which is the next generation of the TIRS sensor from Landsat 8. The multispectral OLI-2 sensor has specialized bands including: visible coastal aerosol, visible blue, visible green, visible red, near-infrared, short wavelength infrared [SWIR 1], short wavelength infrared 2

[SWIR 2], Panchromatic [PAN], cirrus, and the TIRS-2 sensor with two additional thermal bands (Figure 54) (USGS, n.d.). The spatial resolution of spectral bands 1-6 is 30-m, while the spatial resolution for the PAN and TIRS-2 bands are 15-m and 100-m respectively. The data captured from this satellite is publicly available and free to download from the USGS website (USGS, n.d.). Plans are already in place for the next Landsat launch that will carry a super-spectral sensor that will have a total of 26 bands including 15 new bands that will aid in several agricultural and vegetation applications. “Landsat Next” will launch in 2030.

Figure 54. Multispectral OLI-2 Sensor Onboard Landsat 9



Note. Retrieved from USGS

Multispectral bands have allowed for multiple applications and analyses; however, the bandwidths can lead to overlap in vegetation spectral curves as bandwidth is averaged across a broad range of wavelengths making it too coarse to differentiate between closely related plants (Papp et al, 2021). For the purposes of this study, this type of sensor could have difficulty differentiating between grasses and other small, understory plants such as milkweeds and nectar-producing plants if the sensor has not been specifically designed to locate the target vegetation.

To provide more differentiation between spectral curves, hyperspectral sensors have been used for analyses that require more spectral precision to accurately discriminate spectral signatures using light properties, vegetation indices, and leaf profiles (Falcioni et al. 2020).

These types of sensors could theoretically contain thousands of bands with narrow bandwidths that would improve species identification by helping separate closely related curves and signatures (Basinger et al., 2020). The Hyperion sensor that was deployed onboard the Earth Observing-1 [EO-1] satellite is an example of a multispectral sensor that was launched in 2000 and decommissioned in 2017. This sensor contained 242 bands including 35 visible bands, 35 NIR bands, and 172 SWIR bands. The EO-1 satellite was originally part of a one-year National Aeronautics and Space Administration [NASA] Landsat demonstration project; however, the United States Geological Survey [USGS] approached NASA to continue the EO-1 mission to utilize the Hyperion sensor to capture imagery and to fulfill individual Data Acquisition Requests (DARs) that would be publicly available (USGS, n.d.).

However, the effectiveness of a sensor ultimately lies with the number of bands, the wavelengths captured within each bandwidth, and the spatial resolution (Papp et al., 2021; Basinger et al., 2020). Optical sensors typically contain bands within the visible range (300-700 nm) depicting visible green, blue, and red and can be used to create composite and false composite aerial imagery. NIR sensors can sense reflectance that is outside of the visible range (701-1300 nm) and can be used to differentiate vegetation and to access vegetation health and density. Short infrared sensors (1301-2500 nm) can be used to detect water and temperature and are often used for thermal feature detection (Basinger et al, 2020).

3.2. Spectral Signatures

Spectral signature refers to a plant’s unique reflectance and absorption of light and energy based on the plant’s biophysical make-up (Price, 1994). Living plants can be isolated using the visible blue, green, and red bands to detect chlorophylls a and b (blue 430-453 nm; green 500-565 nm; red 642-662 nm) which are pigments that are present in live, photosynthesizing plants (Falcioni et al., 2020). The blue visible band can detect carotenoids (400-500 nm) which are yellow, orange, and red pigments in living plants that are also associated with chlorophylls a and b and photosynthesis (Swapnil et al., 2021; Falcioni et al., 2020). Other pigments such as anthocyanins (AnC) and flavonoids (Flv) can be identified using blue, green, violet, and ultraviolet bands (Falcioni et al., 2020).

As spectral sensor resolutions have improved and bandwidths have narrowed, the ability of a sensor to help discriminate one plant from another has continued to improve, but there are many factors that characterize the target vegetation as well as some conditions that can negatively impact reflectance data. According to Papp et al. (2020), characteristics such as the content of the leaf pigment of a specific species can be an integral factor in creating a reliable spectral signature, while the age of the plant and amount of dust and debris on the leaves and stems could hinder the collection of accurate reflectance data. When studying leaf spectral signatures and foliar pigments as a means of differentiating between closely related species, Falcioni et al. (2020) discovered that the shape and thickness of the leaves also contributed to how light was being absorbed and reflected. Other factors that could affect the accurate collection of spectral data include the angle of the light source and reflective surface as well as local atmospheric and environmental conditions (Papp et al., 2021). It is for these reasons that spectral signatures are recorded as ranges of reflectance as opposed to a single combination of wavelengths and reflectance percentages.

3.3. Sensor and Platform Selection

With the availability of more affordable remote sensing technology and the flexibility of UAVs as opposed to manned aircraft or satellites, localized vegetation analyses are becoming more commonplace, but there are still impediments that must be properly managed to create usable datasets that have the ability to properly discriminate between different types of vegetation and ground cover. The first decision that needs to be made is to identify what type of sensor is needed. In many cases, high resolution Red, Green, and Blue (RGB) imagery is acceptable (Turhal, 2022); however, if a visual range sensor is used, data collection will be limited to the visible wavelengths which do not always provide enough variation to discriminate vegetation that has similar reflectance percentages (Basinger et al., 2020).

Another factor to consider is the sensor height and spatial resolution needed to effectively analyze the study area and the target vegetation. While satellite imagery, such as Landsat OLI products, are often too coarse at 30-m, Shao et al. (2023) were able to develop an index and detect yellow flowering vegetation using Landsat 8-OLI imagery. However, other studies that have focused on understory weeds identified that a spatial resolution of 5-50 cm is needed to successfully discriminate between different types of groundcover vegetation. Since UAVs are capable of recording sites with spatial resolutions of 5-m or less, drones are a more practical and cost-effective option (Turhal, 2022; Fernández-Quintanilla et al., 2018; Castaldi et al., 2017). The next task would be to determine the appropriate sensor height that would be needed to provide the most efficient data collection while maintaining optimal sensor resolution. In 1985, Menges et al. were able to successfully discriminate climbing milkweed (*Sarcostemma cyanchoides*) in orange trees (*Citrus sinensis*); ragweed parthenium (*Parthenium hysteropborus*) in carrot (*Daucus carota*); johnsongrass (*Sorghum halepense*) in cotton (*Gossypium hirsutum*) and sorghum (*Sorghum bicolor*); and Palmer amaranth (*Amaranthus palmer*) in cotton at a height of 3050-m using color NIR film. As the Federal Aviation Administration [FAA] does not allow drones to operate in airspace above 400-ft (121.92-m), drones should be able to capture usable data at this altitude or lower.

4.0. Proposed Methods

4.1. Study Site

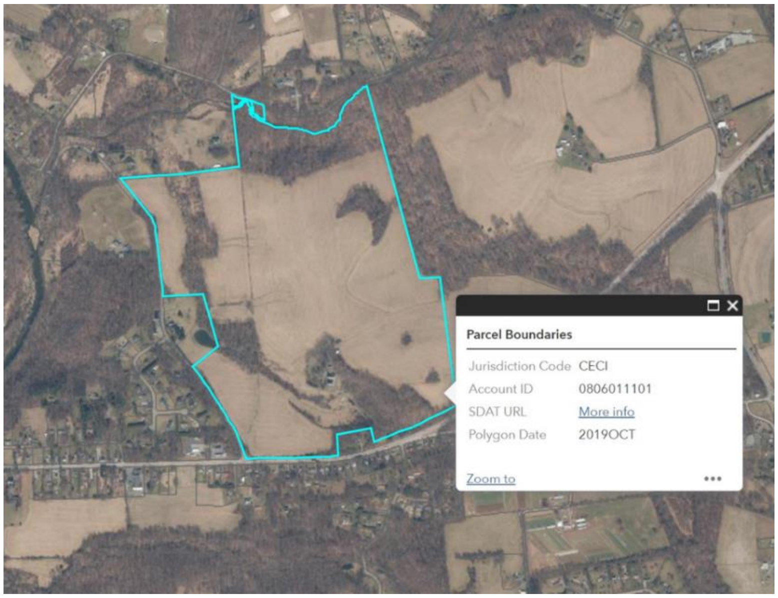
The purpose of this study was to create a method to monitor, document, and protect naturally occurring milkweeds. Before selecting sites for this pilot study, there were certain criteria that needed to be met. The site must: 1) be within the viable range of all three preferable milkweeds; 2) currently or recently have milkweed(s); 3) have milkweed that is naturally occurring and not planted or in a maintained pollinator garden; 4) have large, open pasture/field areas that are conducive to drone flight; 5) be on privately owned property that is not near protected airspace; and 6) be along a migratory flyway or within the summer breeding grounds.

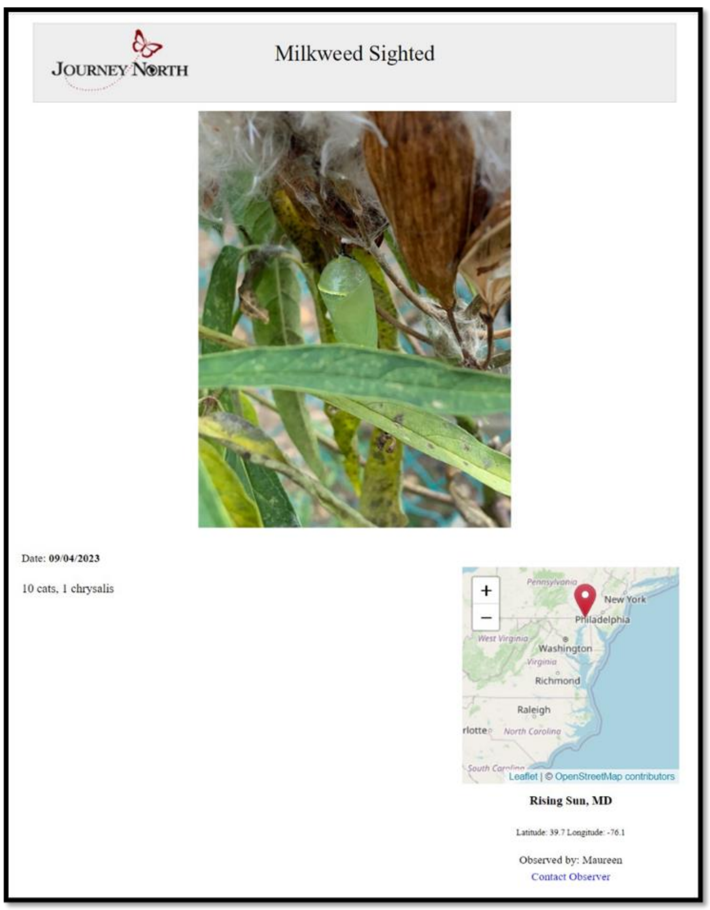
The Journey North database has a citizen science reporting interface that allows individuals to report milkweed sightings with information including the date and location of the sighting, notes, a link to contact the sighting contributor, and the ability to upload an image of the sighting (Journey North, n.d.). Using sightings that have occurred since August of 2023, three sites were selected as possible candidates for the pilot study.

4.1.1. Site A - Rising Sun, Maryland

This site contains ± 226-acres of farmland with a wooded perimeter. The parcel is privately owned and free from any protected airspace. This location is situated along the Eastern monarch migratory flyways and logged a milkweed sighting on September 9, 2023, with larvae and a pupa also present (Figure 55). This site was the first choice due to the presence of the recent naturally occurring milkweed and active presence of monarch larvae as well as the open space with little understory providing drone accessibility and line of sight.

Figure 55. Site A with Recent Milkweed Sighting





Note. Sightings data and imagery retrieved from the Journey North database

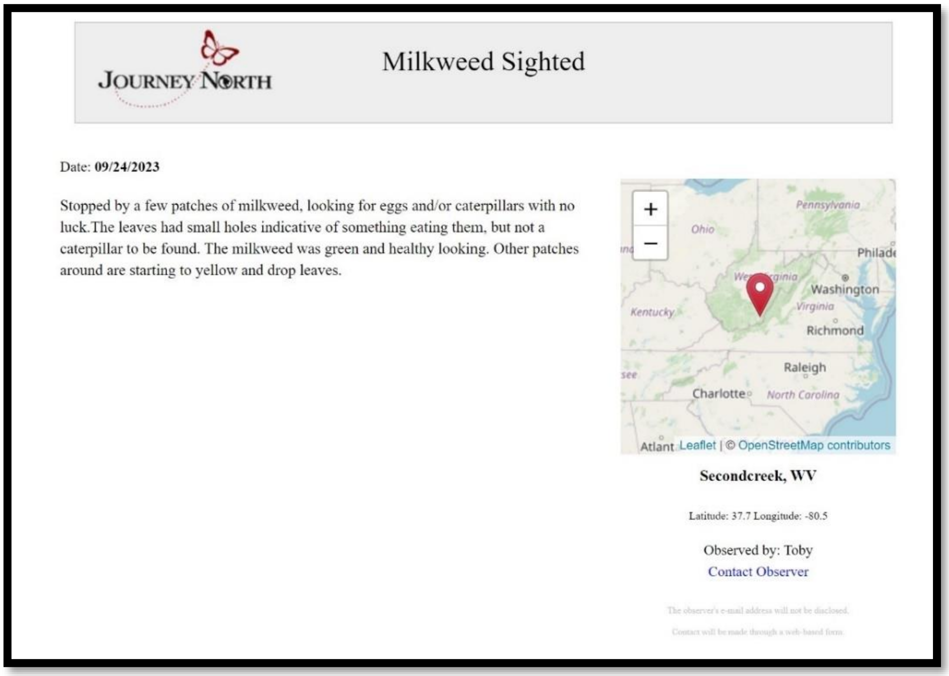
4.1.2. Site B - Second Creek, West Virginia

Site B contains ± 162-acres of agricultural land with some wooded areas. It is privately owned and is primarily open fields which are suitable for milkweeds and drone flight. This area appears undisturbed which makes it a good candidate for natural landcover and pollinator interactions. Multiple stands of milkweed were sighted on September 24, 2023, and the site is located within the Eastern monarch migratory flyways and adjacent to the southeastern edge of the summer breeding grounds (Figures 56-57).

Figure 56. Site B

Note. Sightings data and imagery retrieved from the Journey North database

Figure 57. Recent Milkweed Sighting at Site B



Note. Sightings data and imagery retrieved from the Journey North database

4.1.3. Site C – Schencksville, Pennsylvania

This site contains ± 49-acres of agricultural land with some wooded areas and a small creek. The parcel is adjacent to large residential developments on each side and is located along the Eastern monarch butterfly flyways. The parcel is privately owned and logged a milkweed sighting on August 19, 2023 (Figure 58). If Sites A and B are unavailable, Site C would become the highest priority site due to its recent milkweed sighting and open area and drone airspace. This site is smaller than Sites A and B which would result in a smaller study area as not all 49-acres would be suitable for drone imaging due to canopy and wooded areas.

Figure 58. Site C with Recent Milkweed Sighting

Note. Sightings data and imagery retrieved from the Journey North database

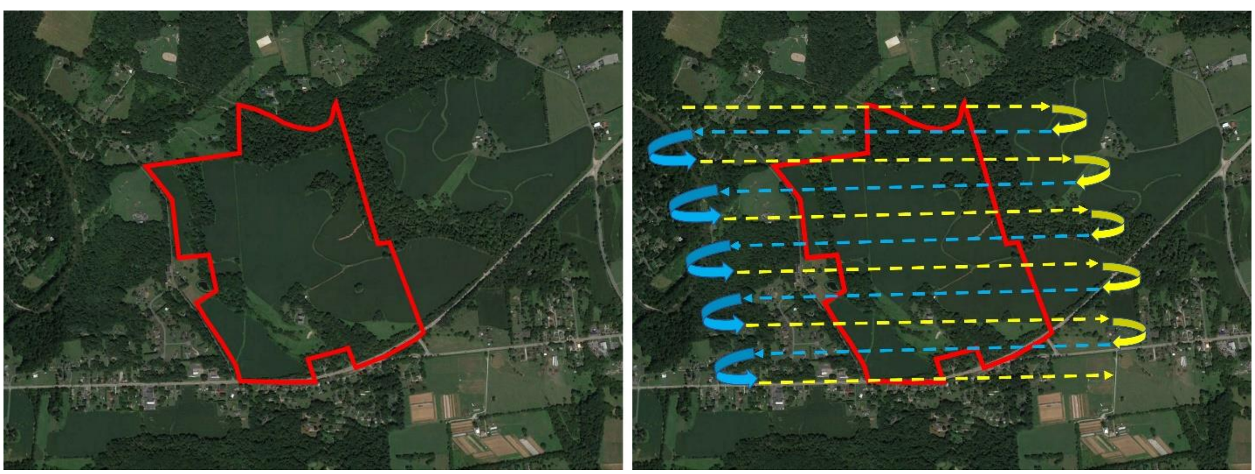
4.2. Equipment

Given the spatial resolution that would be needed to complete this study, the best and most cost-effective option would be to use a hyperspectral sensor mounted to a drone. The drone would need to be flown below 400-ft to comply with FAA regulations. The sensor would need to include the red, green, and blue visible bands as well as NIR bands that would be useful in analyzing the health and density of the targeted vegetation. Using a hyperspectral sensor should increase the ability for the narrow bands to isolate the target vegetation, reducing the number of false positives or negatives during image processing.

4.3. Data Acquisition

As a monitoring study, it would be ideal to acquire data from the same site multiple times throughout a flight year to map a baseline for the seasonal conditions and milkweed prevalence during those time ranges. Site suitability models could be run concurrently outlining composite milkweed suitability conditions (Kesler & Bunch, 2023; Kesler & Bunch, 2020) to provide more depth to the nature of the milkweed prevalence at that location. For the pilot study, it would be beneficial to survey the site in May, June, July, August, September, and October to get a full-range visualization of the recolonization and Southern migration. A second option would be to survey the site in August, September, and October primarily capturing the peak recolonization months and the Southern migration. Once the survey times are accepted and scheduled, data would be acquired using a drone in the typical "mowing the lawn" flight path strategy that allows for residual image overlap (Figure 59). It would also be beneficial to incorporate surveyed ground control points to aid in the image mosaic, georeferencing, and ground-truthing segments of the data processing activities. Efforts would also need to be in place to acquire the data under optimal conditions in order to provide unimpeded reflectance capture.

Figure 59. Study Site A with Proposed Drone Flight Path



4.4. Data Processing

Following data acquisition, the raw datasets would need to be cleaned and classified into vegetation groups based on similar spectral signatures. The use of a hyperspectral sensor has positive and negative factors associated with data processing. On the positive side, the narrow bandwidths tend to be more successful in identifying the target vegetation with fewer false positives and spectral curve overlap with other vegetation that has similar reflectance values (Aneece & Thenkabail, 2021); however, with the use of more bands, there can be data processing redundancy which would require, sometimes substantially, larger storage capacity to hold and process the acquired data (Liu et al., 2021).

The unsupervised classification technique does not require any training data or indices, but instead, the computer groups like reflectance values into a pre-set number of classes following a set number of iterations. A supervised classification informs the process by providing training data or creating machine learning devices often coupled with vegetation indices to identify baseline species signatures (Pei et al., 2021). Machine learning [ML] techniques have been incorporated into some classifications which guide the data processing to make generalizations or to "learn" from past iterations (Aneece & Thenkabail, 2021; Silva et al., 2021; Chen et al., 2003). Support vector machine [SVM] learning was developed in the 1990s and used various algorithms, statistical analyses, and binary decision-making structures to sort land cover into different classes. This technique improved in the years that followed becoming more complex while also gaining the ability to manage multiple classes simultaneously (Iqbal et al., 2023; Papp et al., 2021). Later techniques have included Artificial Neural Networks [ANN] (Papp et al., 2021; Silva et al., 2021), Discrimination Common Vector Approach [DCVA] (Turhal, 2022), and the Spectral Angle Mapper Method [SAM] (Ozcan et al., 2020) to locate the minute differences in reflectance that would ultimately lead to an accurate classification. As the pilot study, this analysis would execute both unsupervised and supervised classifications to gage which method provided the best classification; however, the supervised classification has performed better in similar studies (Aneece & Thenkabail, 2021; Papp et al., 2021; Chen et al., 2003).

5.0. Discussion

While this study was theoretical in substance, it was designed to be easily transformed into an active study at a future date. Decisions were outlined and paths selected whenever possible including the first steps in identifying an appropriate site for the field analysis. The ultimate goal of this study was to outline a method that could be used to locate milkweed and to create a schedule that data would be collected following the pilot analysis in order to monitor and manage gaps in migratory flyways. With areas that already have naturally occurring milkweeds being protected by citizens and conservationists coupled with private pollinator gardens, it may be possible to rebuild some areas in the summer breeding grounds and migratory flyways. Precision Agriculture was noted multiple times in associated literature referencing this type of remote sensing. While conservation was rarely the goal in those studies, specialized sensors, drones, classification models, training data algorithms, and other criteria and methods may be occurring concurrently in other fields that could be directly applied to this study.

5.1. Data and Classification Errors

As with any remote sensing study that has a target species, the crux of the analysis lies in the validity of the data and the accuracy of the classification. While the various spectral bands in hyperspectral sensors are preferable, there can still be issues with spectral curve overlap where it may become impossible to distinguish the target species from other vegetation that was also present (Falcioni et al., 2020). This becomes more complicated in that spectral signatures always exist as reflectance ranges which leaves room for interpretation and locational variations (Shao et al., 2023). Adding further complexity, plants can themselves vary their spectral signature during different seasons and stages of development and can behave differently in each spectral band (Papp et al., 2021). Another issue for milkweed is that flowering and non-flowering stages can reflect differently (Shao et al., 2023) which requires various adjustments to algorithms and vegetation indices that assist in the classification stages (Turhal, 2022). Furthermore, there is also an argument that spectral signatures are not actually unique, and that plant species can have unlikely doppelgängers through locational factors or the randomness of the universe (Longchamps et al., 2010; Price, 1994). Price (1994) conducted a study comparing multiple species that had similar spectra but were biologically unrelated. While the spectral curves for corn, soybeans, and winter wheat did not possess identical reflectance percentages, the curves were so similar in shape and wavelength that it could realistically lead to false positives when considering factors that could affect or diminish field reflectance readings.

While these concerns are not without merit, there will always be instances where differentiation between plant species will be difficult as several plants can possess similar biophysical characteristics as well as have similarities related to their shared environment and species ranges (Basinger et al., 2020; Fleishman et al., 2001). There will also be field factors that will affect proper data collection including dust and debris, light angle, plant age, leaf thickness and shape, and atmospheric conditions (Papp et al., 2021; Falcioni et al., 2020).

5.2. Limitations

While some studies have opted to use Landsat and Hyperion satellite imagery, the available datasets were too coarse for this analysis. But with the availability of hyperspectral sensors and drones capable of carrying multiple high-resolution cameras, drones were ultimately the most cost-effective and viable option; however, there are some limitations to using drone imagery. One issue inherent to the use of UAVs is that they cannot run infinitely and will require an energy source to function. As such, the flight time will be limited to the type of energy source that the drone uses. If the study area is large, it could take multiple launches to gather all of the necessary data which would require more time, funding, and resources. This factor alone makes drone remote sensing unsuitable for large spatial regions and would require a substantial collaboration involving hundreds of individual analysts to cover a single flyway segment.

5.3. Connection with Precision Agriculture [PA]

Precision Agriculture [PA] has been at the forefront of technologies designed to provide larger crop yields while using fewer chemicals, herbicides, fertilizers, and pesticides (Ali et al., 2022). Drones with onboard remote sensors have been used successfully to analyze soil composition (Ragazzo et al., 2023), provide moisture and nutrient content (Samreen et al., 2023), locate weeds and undesirable vegetation (Longchamps et al., 2010), identify pest infestations (Kanwal et al., 2022), isolate invasive species (Papp et al., 2021), and monitor overall crop health (Pei et al., 2021). Using highly discriminatory spectral bands that have been designed to specifically identify the study's target has helped streamline this technology making it more readily usable in everyday farm and crop management strategies (Pei et al., 2021). PA technologies have been well received as a means of saving energy, boosting efficiency, and lowering material and application costs which have positive implications for commercial agriculture and environmental sustainability (Turhal, 2022). Specialized remote sensing methodologies developed as an integral component of PA forecasting and management; however, it is in the monitoring that it has proven particularly useful (Kanwal et al., 2022).

While typical PA strategies have been designed to boost commercial agriculture, the techniques could be easily converted to support conservation. Papp et al. (2021) used a drone equipped with a hyperspectral sensor coupled with Artificial Neural Networks [ANN] and Support Vector Machine [SVM] methods to delineate training data to locate common milkweed in the Southern Great Plains region of Hungary; however, this study was monitoring milkweed as an invasive species to assess its spread and encroachment on native vegetation. While the purpose of Papp et al.'s (2021) study was very different than this study's conservation goals, the methods could be laterally applied to locate common milkweed in the United States along butterfly flyways and at the summer breeding grounds. This process could theoretically be adapted to locate the three preferable milkweeds (common milkweed, butterfly weed, and swamp milkweed) in designated conservation areas, protected areas, and parks to ultimately begin to visualize the locations of known naturally occurring milkweed stands as they affect flyway connectivity and butterfly recolonization. Once spectral signatures are isolated, specialized sensors could be created to streamline data acquisition and processing which would preserve target species identification accuracy across different study sites by creating a baseline sensor. With this type of development occurring concurrently, different applications are able to take advantage of the research and development that has already been done.

6.0. Conclusion

While much attention and resources have been given to monarch butterflies, the overarching issue with declining populations is firmly linked to the loss of naturally occurring milkweeds along migratory flyways and at the summer breeding grounds. Threats such as unfavorable agricultural practices, anthropogenic development, and climate change are all negatively impacting milkweed prevalence which has led to declines in overwintering butterfly counts. Conservationists and concerned citizens have been planting milkweeds and creating pollinator gardens throughout the Eastern and Western migratory ranges; however, many scientists wonder if it is merely too little, too late to save the migratory populations. Despite population counts suggesting that quasi-extinction benchmarks have been breached, Western and Eastern monarch populations have rebounded providing hope that they are resilient and worth the resources and effort to save. As pollinators, monarchs are important in preserving plant biodiversity and are members of several food webs that support multiple species of plants and animals. They also hold religious and cultural significance to Central American families that believe that monarchs returning to the overwinter sites are the souls of their ancestors returning to Earth during Día de los Muertos [Day of the Dead] festivities.

This study was a theoretical pilot study that would incorporate drone-based remote sensing methods to locate and protect areas where naturally occurring milkweed has already been established. Using a hyperspectral sensor, pilot study sites were selected to create the first draft of field and classification methods that could be used at multiple locations in an effort to stitch together flyways to repair some of the milkweed loss that has previously occurred. While this study was designed to be implemented in the near future, there is still a need for economical and reliable application-specific sensors that will help automate the analysis and make it more accessible to other analysts and conservation studies of like kind. Precision Agriculture [PA] has already established methods and technologies that could easily be transferred and adapted to meet this study's goals while providing consistency at other study sites in both the Eastern and Western migratory ranges. Monarch butterflies have a long and unique history of scientific, biological, ecological, religious, cultural, and migratory significance, which makes them worth conservation and protection; however, if efforts are not made to locate, assess, and protect currently established milkweeds, the future of monarch butterflies will remain uncertain.

CHAPTER VI: CONCLUSION

North American monarch butterfly numbers have been declining for several decades. While their migration was once so predictable that Native Americans harvested their crops based on their return to Mexico (Baumle, 2017), the future for these migratory butterflies has become grim and uncertain. As pollinators, monarchs provide an important environmental service and hold a base-level spot in many food webs. Culturally they hold deeply rooted significance for Native Americans and have become the most recognizable butterfly in North America. They defy nature every migratory year and are still a scientific enigma that is not wholly understood.

While not all monarch populations migrate, the North American populations undertake a substantial migration of approximately 3000-miles in the East and 700-miles in the West. This migration is unique in that no other insect species travels as far during a single migratory year, but it is in this migration that monarchs are encountering threats ranging from loss of host plants in their summer breeding grounds to loss of range and suitable habitat along flyways and at the overwinter sites. After the petition for threatened species status under the Endangered Species Act [ESA] failed to gain protection, funding, and other resources, scientists and conservationists had to shift their efforts to find other means to protect monarch butterflies, their host plants, flyways, and critical habitat. But how exactly do you protect a moving target (Bull et al., 2013), or could it be that the migratory phenomenon is simply coming to an end (Brower et al., 2012)?

This body of research utilized Geographic Information Science, cartography, spatial analysis, and remote sensing technology to assess the decline of migratory monarch butterflies from a geographic perspective. The very nature of the migratory process requires a geographic lens to truly view the threats at a wider angle across time and space. The first study followed a previous model to incorporate various elements of individual locations along the Western migratory flyways to visualize how temperature, land use, precipitation, elevation, and agriculture interact with the vital needs of monarch butterflies over the course of a single migratory year. These factors were ranked and weighted in lieu of basic entomological needs while also incorporating wildfire, solar farms, and drought as threats specific to the Western study area. Monthly maps were created to visualize site suitability throughout the entirety of the Western migratory range and were compared with concurrent geolocated monarch butterfly sightings obtained from the Journey North citizen science database. The study results indicated that while the Western migration was substantially smaller than the Eastern migration, the Western butterflies were not behaving as expected. They were leaving the overwinter sites along the Central and Southern California Coast late and returning early, if they were migrating at all. Sightings data indicated that there were sightings logged year-round at certain overwinter sites which could indicate that the butterflies, at least in part, could be becoming non-migratory. Other findings included the possibility that some butterflies could be migrating to Mexico, as well as possible sites in Arizona that could be serving as new overwinter and/or non-migratory sink locations. If the norm is to exit the overwinter sites in early spring, migrate, recolonize, and return to the overwinter sites in late October/early November, Western monarchs were either behaving abnormally, or the severely declining numbers were too small to make any formal decisions.

The second study used geographic information systems (GIS), cartography, and remote sensing to investigate the three most substantial threats that were identified in the previous Eastern and Western site suitability models (Kesler & Bunch, 2023; Kesler & Bunch 2020): 1) the effects of herbicide resistant crops on milkweeds in the Eastern summer breeding grounds, 2) land degradation at the overwinter sites in Mexico, and 3) the advent of populations of non-migratory monarchs. Corn and soy have been known varieties of crops that have been engineered to be herbicide resistant which allows for the application of widespread herbicides that eliminate all understory and emergent vegetation with no harm to the planted crop. When coupled with the density of corn and soy agriculture in the Midwest and Great Lakes Regions, which also doubles as the Eastern monarch summer breeding grounds, milkweed losses have been substantial. With fewer milkweeds available to monarch larvae, competition for host plants would become severe resulting in increased larval mortality rates which would effectively truncate recolonization numbers.

The second analysis addressed the loss of overwinter habitat in and around the Monarch Butterfly Biosphere Reserve [MBBR]. Imagery was obtained and classified with a separate Normalized Difference Vegetation Index [NDVI] analysis conducted for each analysis year. The first year, 1986, showed dense, healthy vegetation both inside and outside of the MBBR; however, by 2000, analyses indicated that 176,289-ha of butterfly habitat had been lost due to anthropogenic development, agriculture, and the extraction of natural resources. The final analysis year, 2020, indicated that while the loss of dense forest had slowed and recovered in some locations, there was still an overall net loss of 76,594-ha. The NDVI analysis reflected similar findings that indicated that while butterfly habitat was being lost, the remaining vegetation was less dense and less healthy.

Reports of non-migratory monarchs in Florida and along the Southern Atlantic and Gulf Coasts have been increasing in recent years. Not only are these monarchs not migrating, but they are breeding year-round with no signs of reproductive diapause. For this to occur, there would have to be suitable temperatures and a year-round source of milkweed and nectar-producing plants to support the local butterfly population. This study was able to substantiate the consistent presence of sightings when the butterflies should be reasonably located elsewhere. Eastern sites could be a mixture of non-migratory butterflies as well as migratory butterflies who were using the sites as new overwinter locations. The Western population indicated a mixture of migratory and non-migratory butterflies that never exited the overwinter sites. Sightings appeared at the overwinter sites throughout the year, while some butterflies exited the sites and continued on the traditional migratory and recolonization routes. While non-migratory monarchs may not appear alarming, several studies indicated the milkweeds that do not experience an annual die back have a tendency to become infested with parasites that are consumed by monarchs during the larval stage as well as changes in wing and body morphology that could make these butterflies less suitable for long-distance migrations.

The final study described a methodology for using unmanned aerial vehicles [UAVs} with onboard sensors to locate naturally occurring milkweed with the intent to monitor and protect the vegetation to begin to rebuild the natural networks of monarch host plants. With the coarse nature of publicly available satellite imagery, drones equipped with specialized hyperspectral sensors proved to be the most accessible and cost-effective method to capture milkweed spectral signatures. With similar work being done with Precision Agriculture [PA], the development of methods and inexpensive, application specific sensors could be available in the near future. As the technologies develop and become more accessible, it may be possible to run multiple milkweed searches while building datasets to visualize where the wild milkweed is actually growing while preserving it for future migrations.

The overarching conclusion incorporating findings from all three studies is that monarch butterflies are experiencing threats at every stage of the migration; however, the research falls to two root causes: loss of naturally occurring milkweed and loss of critical habitat. The loss of milkweed during recolonization has driven larval mortality rates, while milkweed that does not die back could be the driving factor in non-migratory populations. With climate change bringing warmer temperatures to higher latitudes coupled with anthropogenic development and agricultural impacts, the quality and amount of milkweed throughout the migratory range has substantially decreased. Migratory range and critical habitat have also suffered due to degradation of natural landcover that will not be able to be quickly recovered. With the amount of viable space decreasing at overwinter sites and in the summer breeding grounds, butterflies have been squeezed into habitats that were less suitable which has negatively affected population numbers. However, monarch butterflies have proven resilient in the past, which provides hope that if resources are provided soon enough, we may be able to save them.

As of this publication, monarch butterflies remain on the "Warranted, but Precluded" list. Western monarchs experienced exceptionally low counts in 2020 but managed to rebound the following year. Insect populations have proven resilient and may respond positively to resources and protection if it is provided soon enough. In 2022, the International Union for Conservation of Nature [IUCN] (2022) added monarch butterflies to their *Red List of Endangered Species* indicating that the current status and future population trajectory has remained unimproved. If monarchs remain on the "Warranted, but Precluded" list until their numbers become too small, it may be too late to recover their populations, especially in the West. The Xerces Blue butterfly (*Glaucopsyche xerce*s), for whom the Xerces Society is named for, was the first North American butterfly to disappear due to anthropogenic impacts and was last sighted in the 1940s. If actions are not taken to protect monarch butterflies and to preserve and improve their habitat and host plant availability, they could also disappear in the years to come. It has all happened before, but the question that we must ask is if we can save the monarchs and stop it from happening again.

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APPENDIX A: SIX YEARS OF NORTH AMERICAN MONARCH BUTTERFLY

SIGHTINGS BY MONTH FROM 2017 TO 2022

The following maps visualize the North American Monarch butterfly population sightings as retrieved from the *Journey North* and *Western Milkweed Mapper* databases. These sightings allowed for an overall visualization of all migratory movement within the United States from January 2017 to December 2022.

Map References

ArcGIS Online, n.d. Hill shade and Base map Map Data Layers. Accessed September 7, 2023. https://www.arcgis.com/

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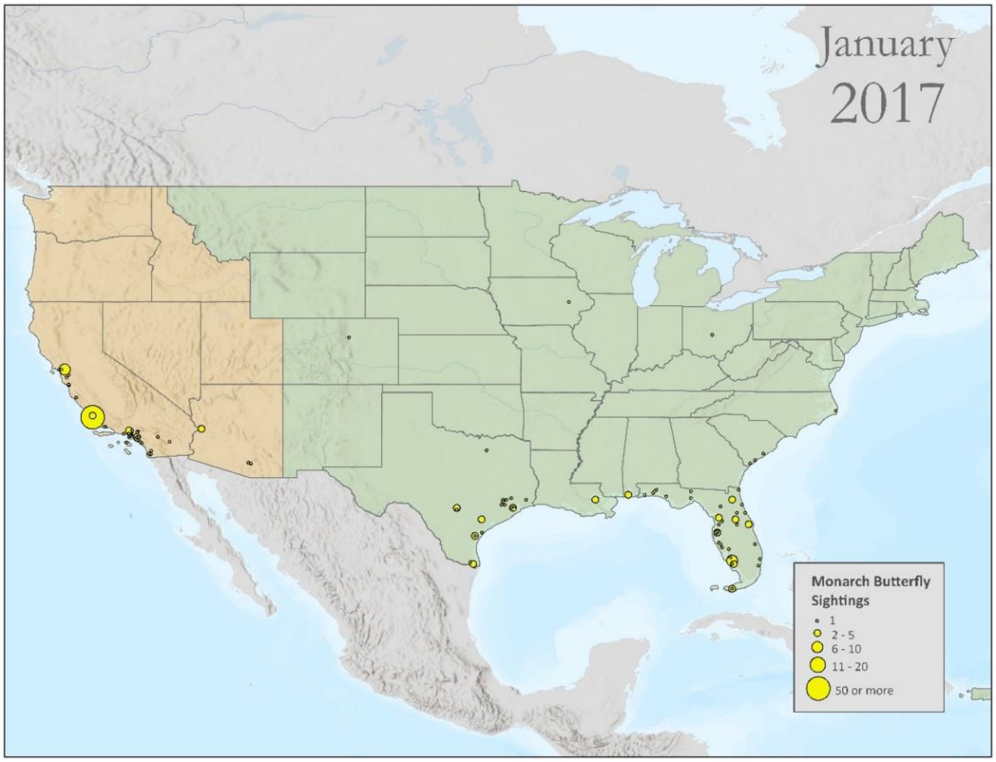
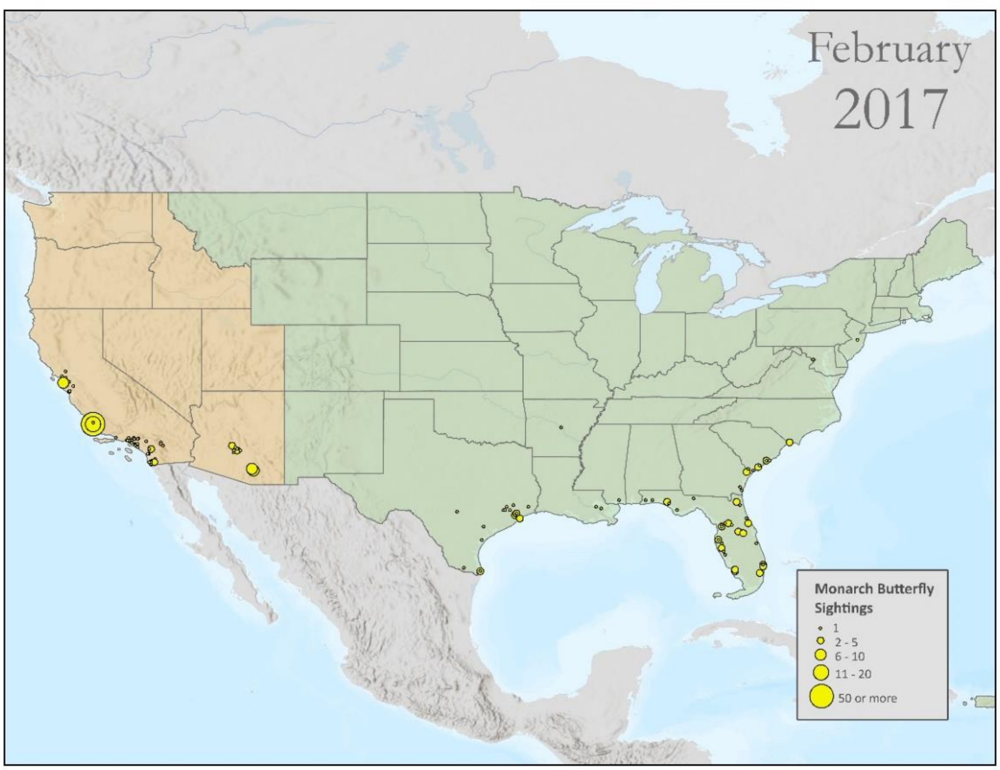
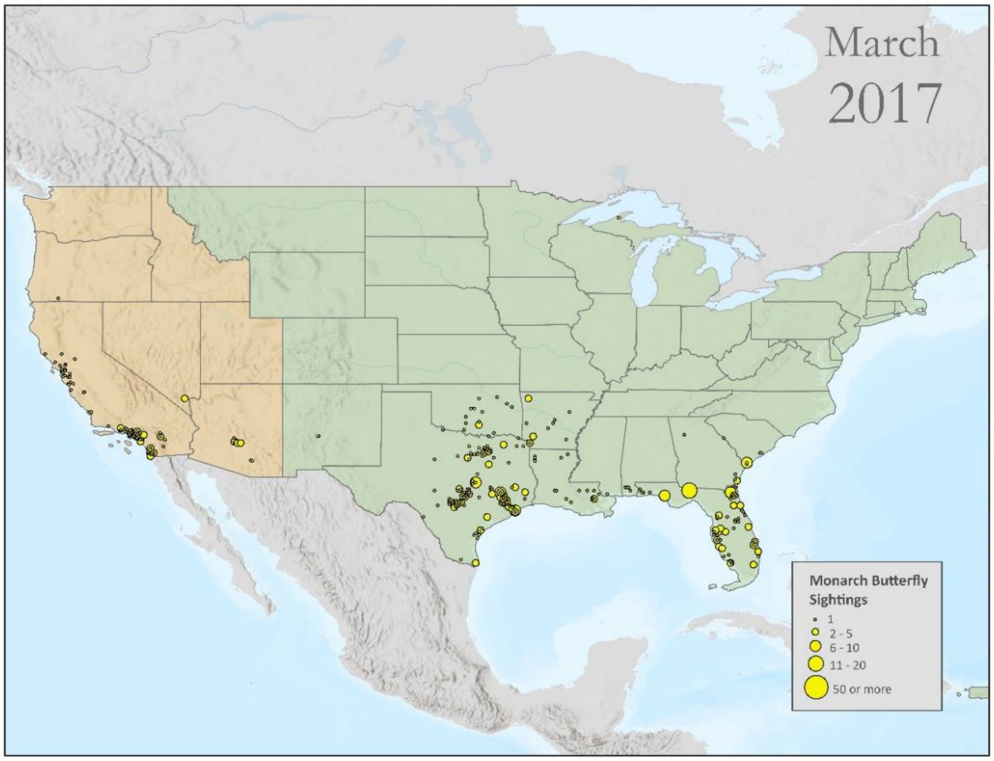
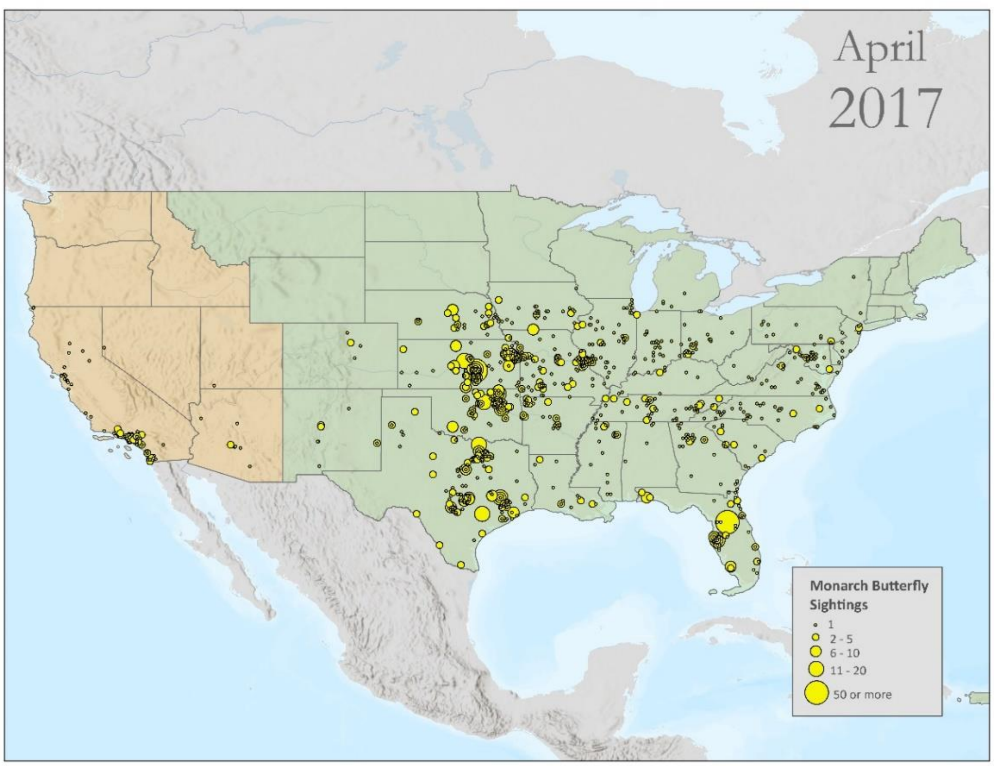
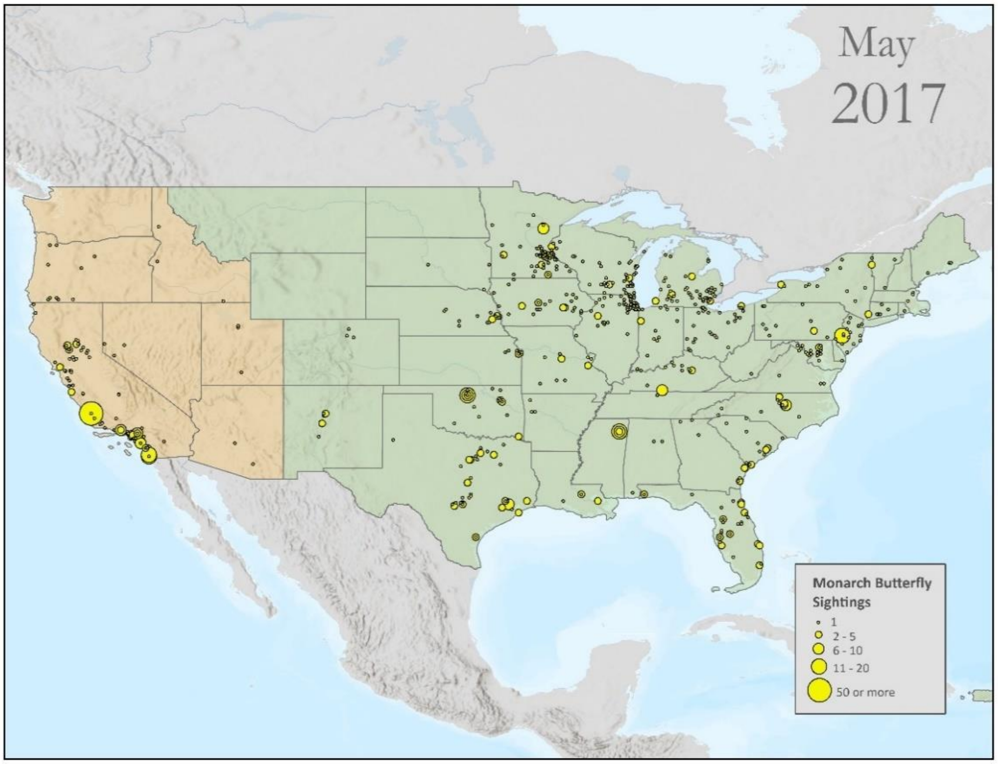
Figure A60. Monarch Butterfly Sightings - 2017

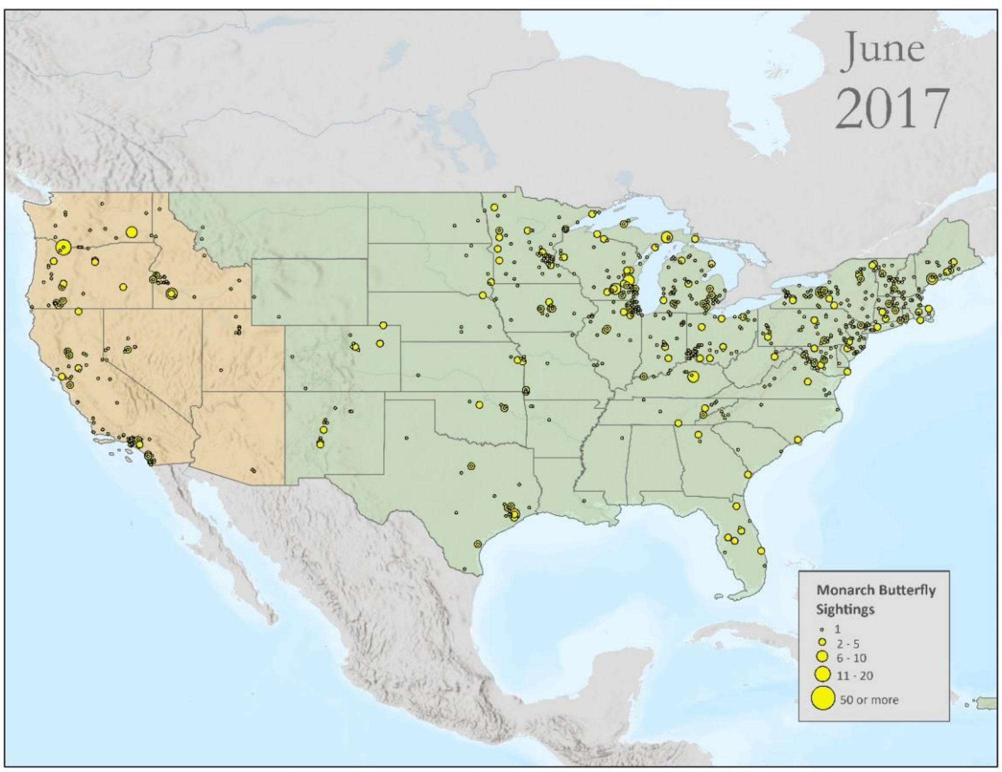


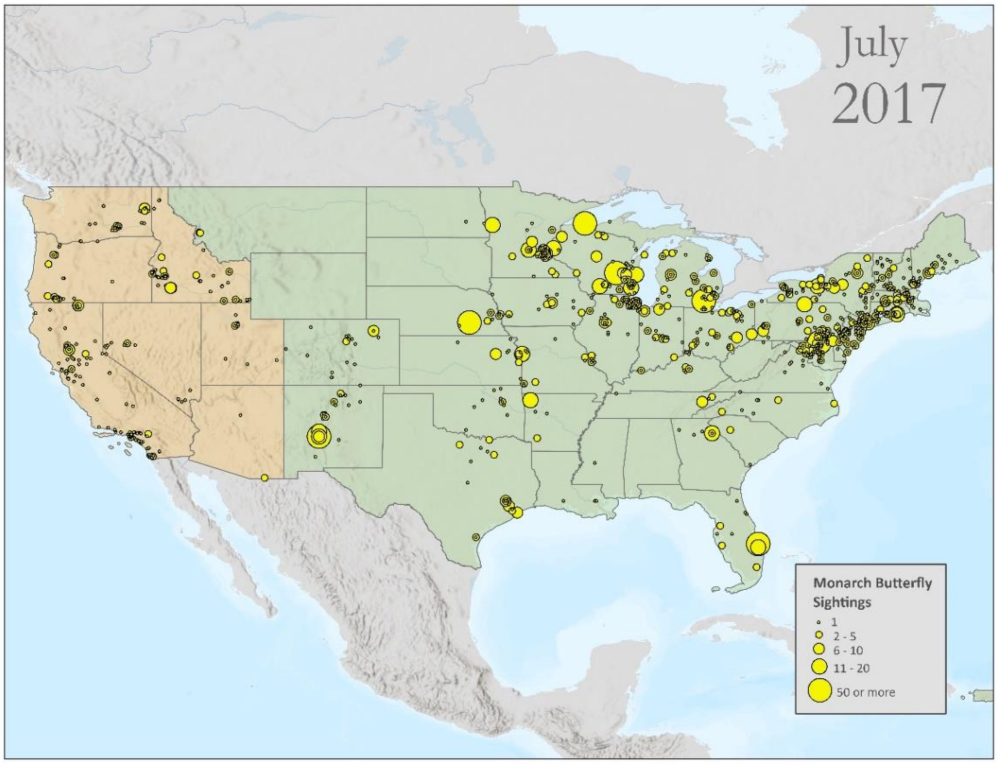


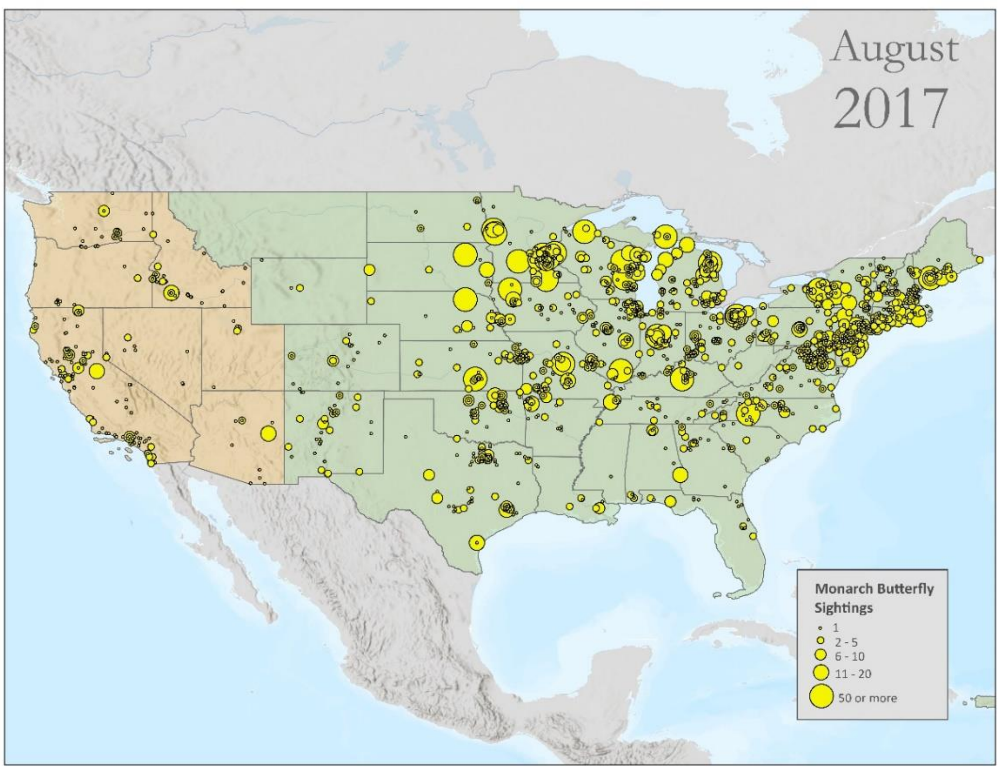

March
2017
Monarch Butterfly Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

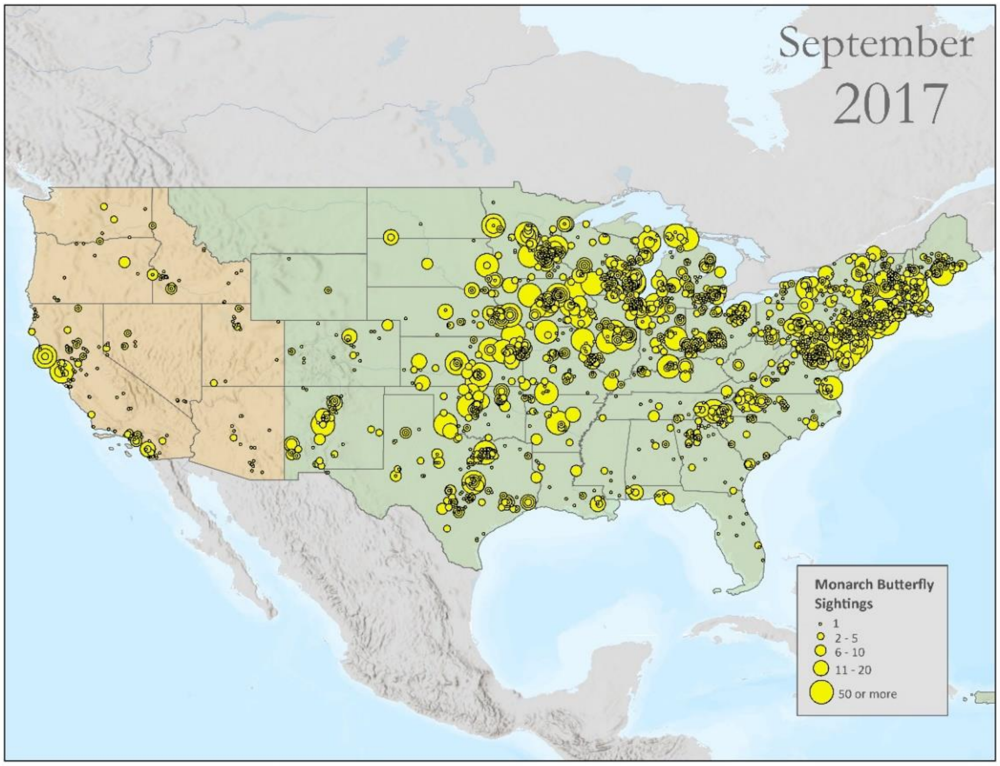

April
2017
Monarch Butterfly Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

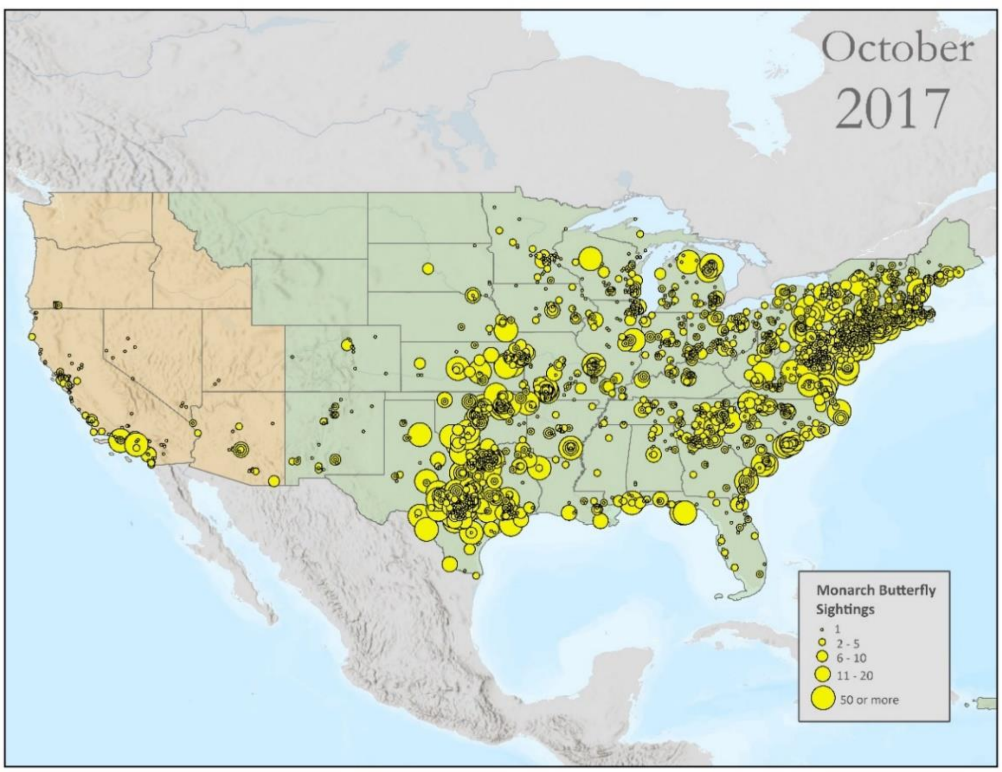

May
2017
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

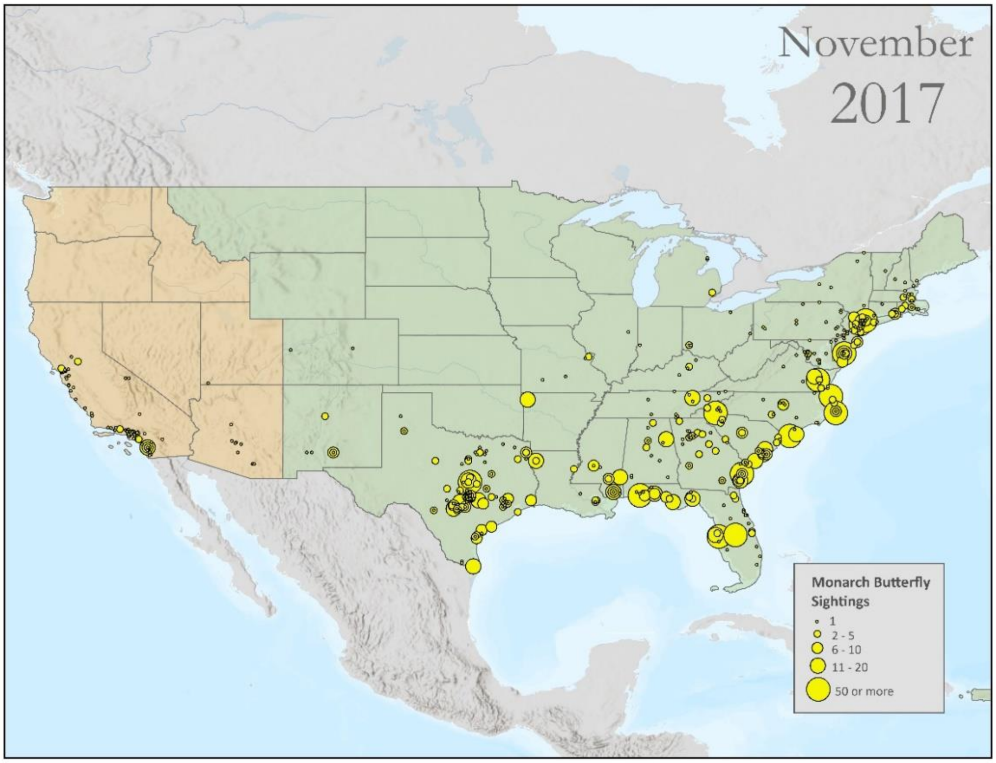

June
2017
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


July
2017
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


August
2017
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


September
2017
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


October
2017
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


November
2017
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

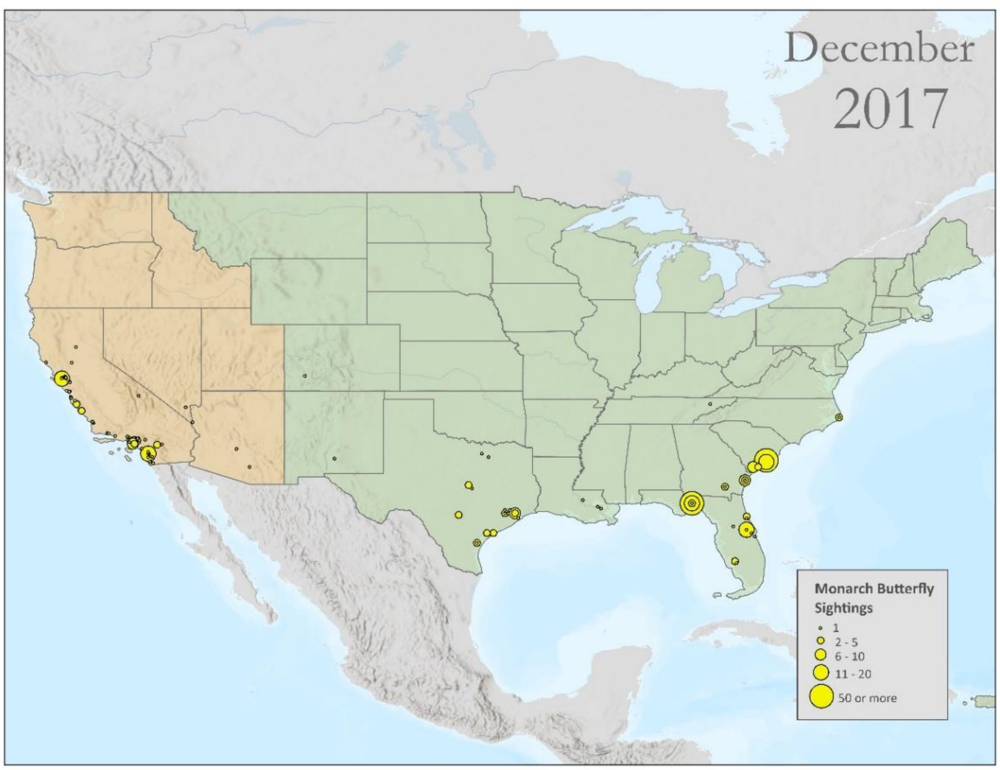
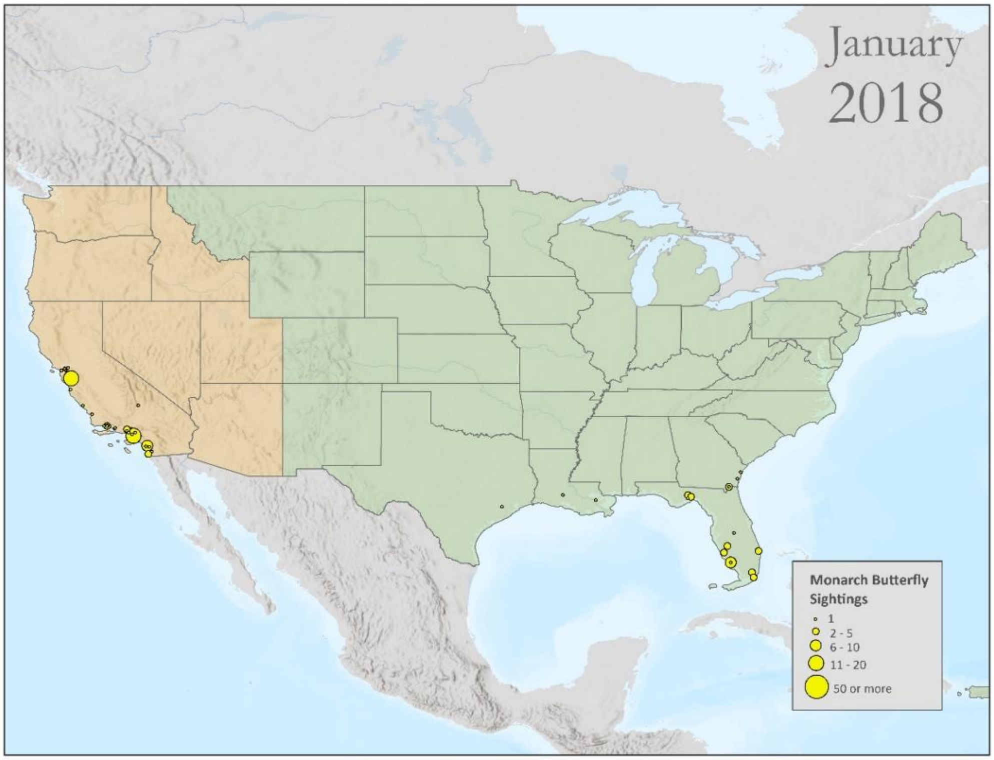
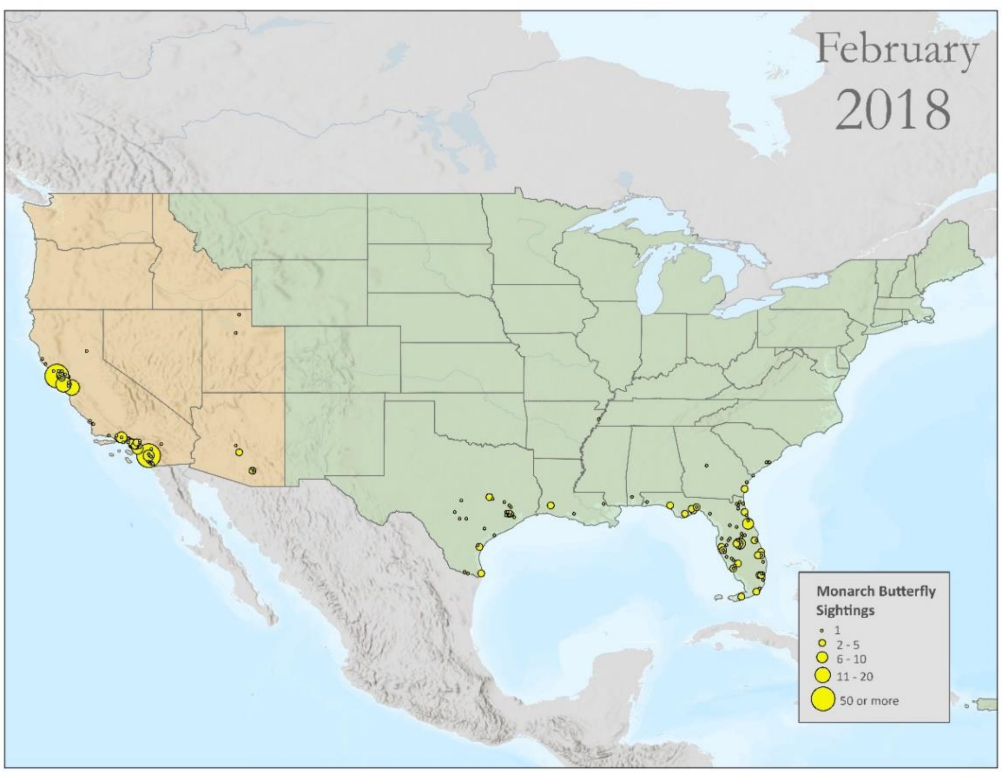
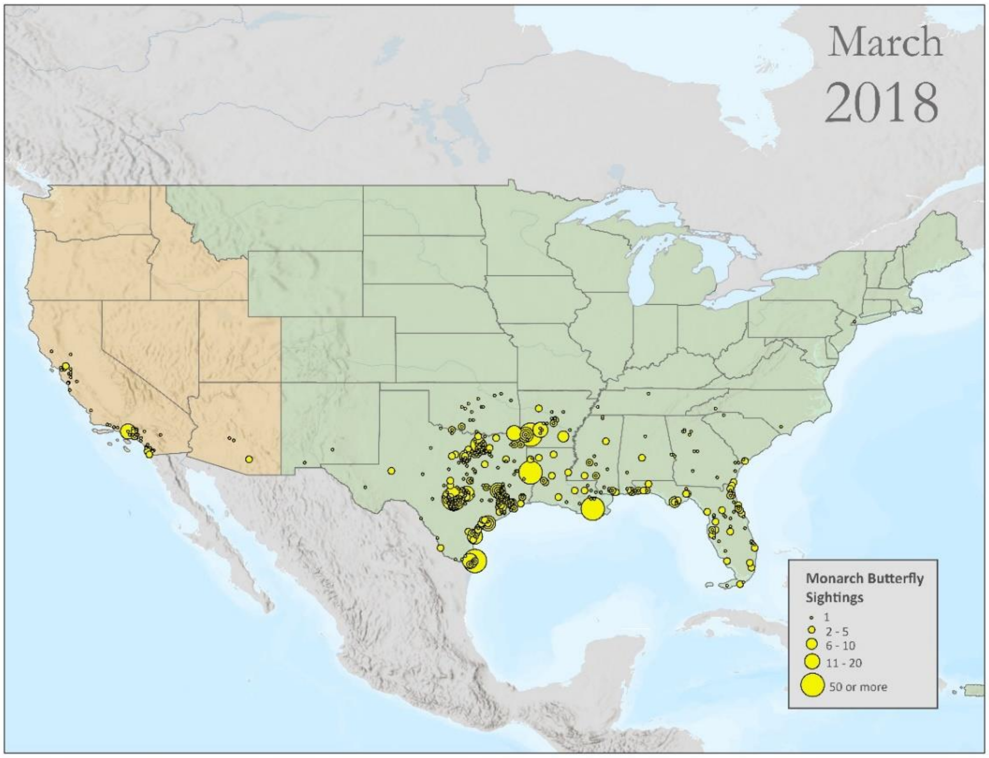
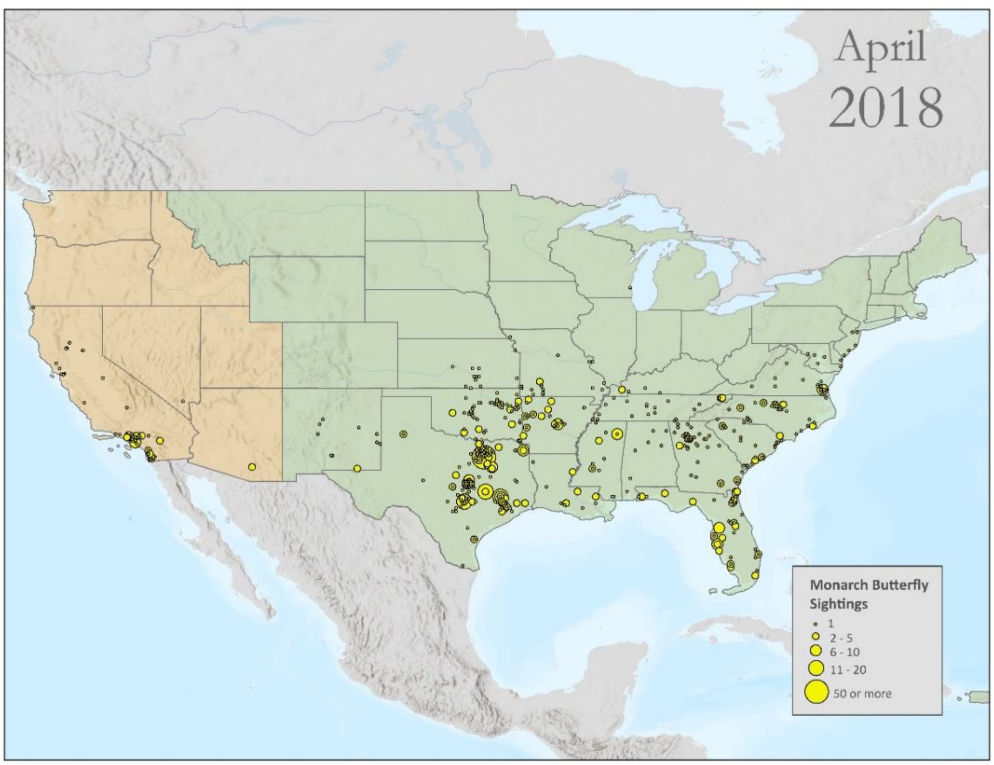

December
2017
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

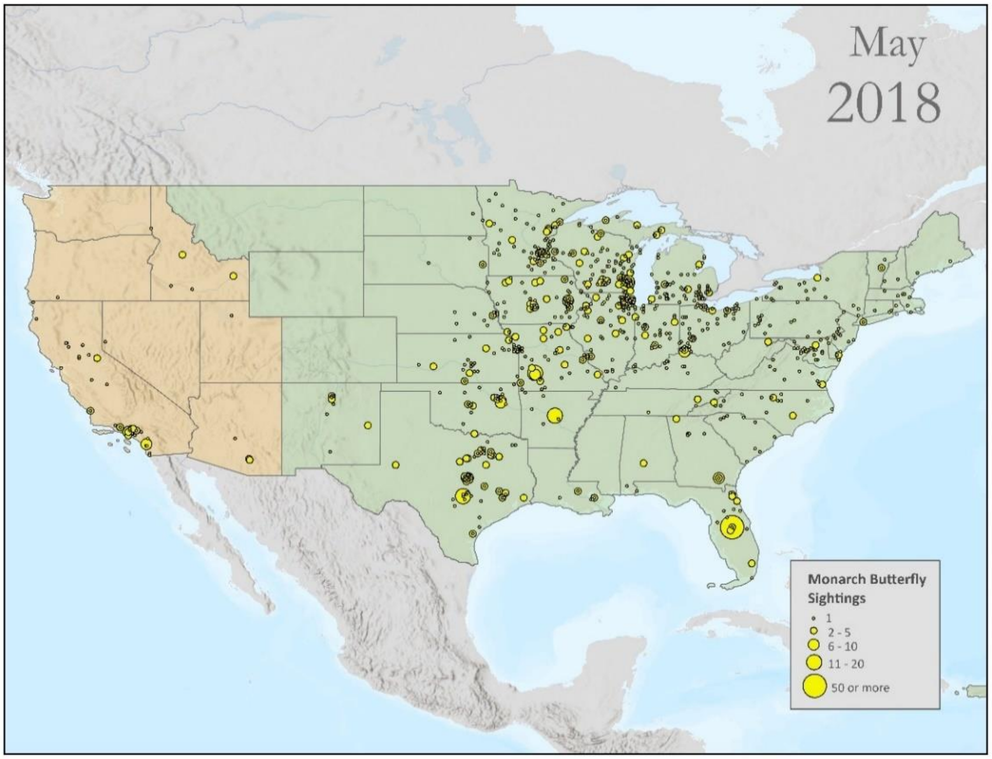
Figure A61. Monarch Butterfly Sightings- 2018

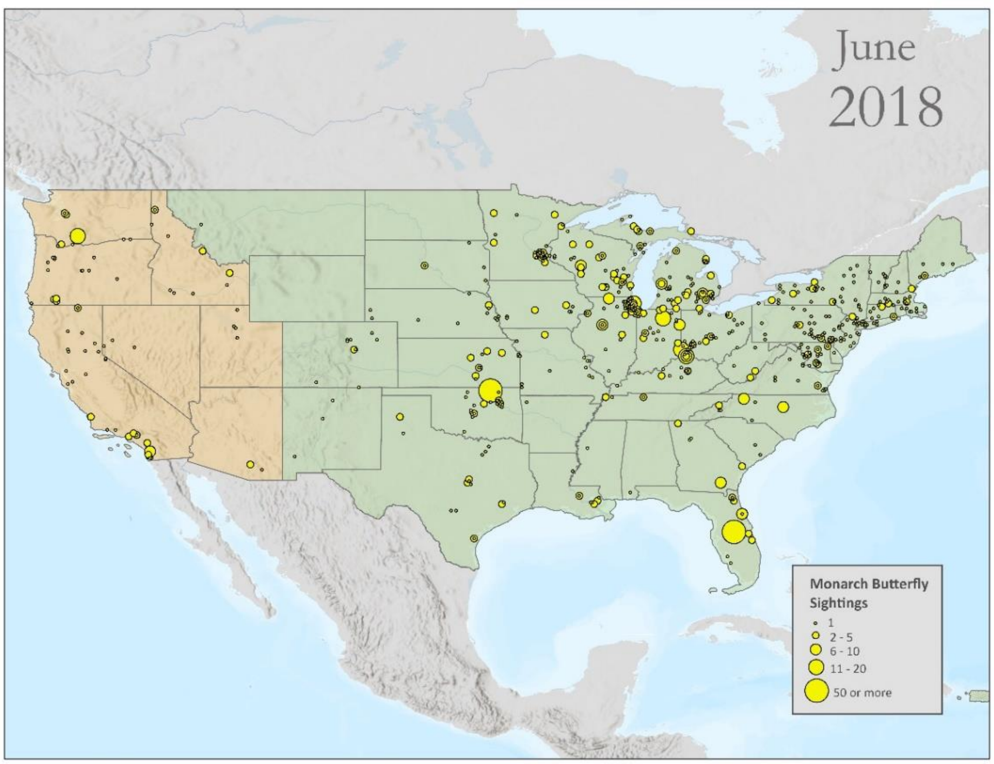


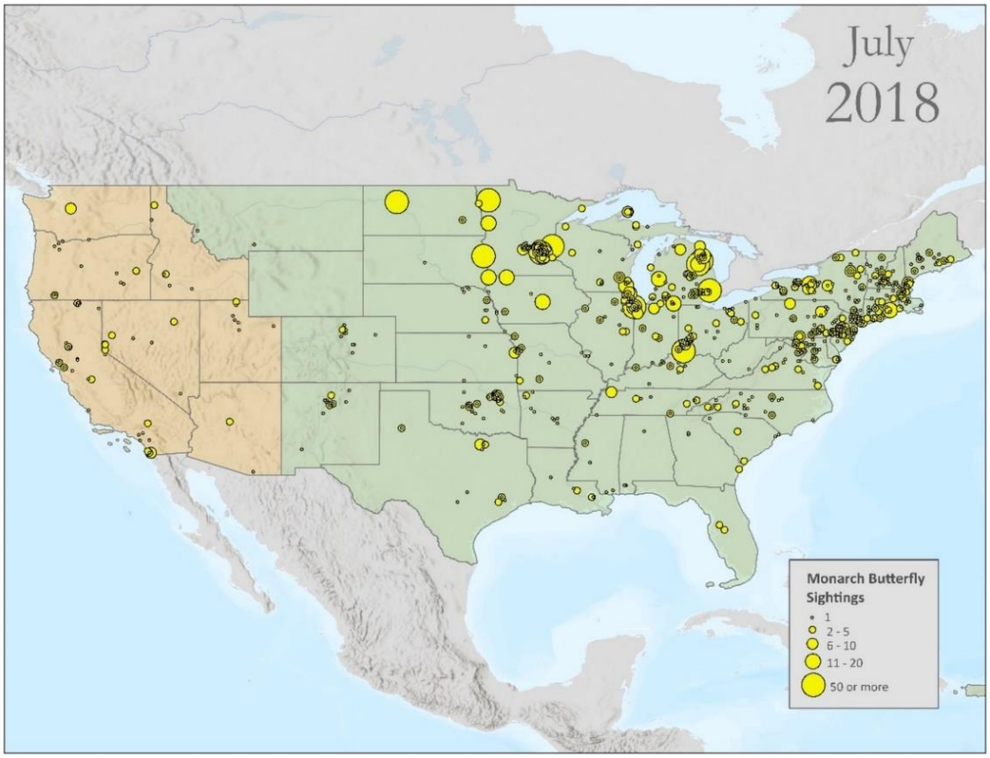


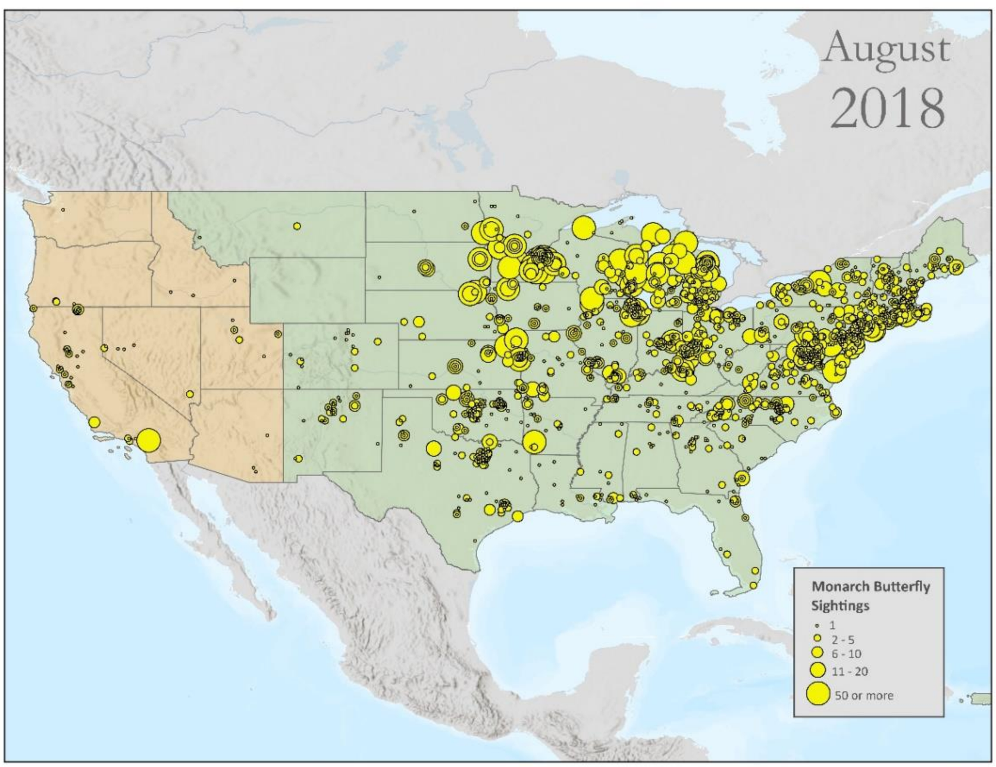

March
2018
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

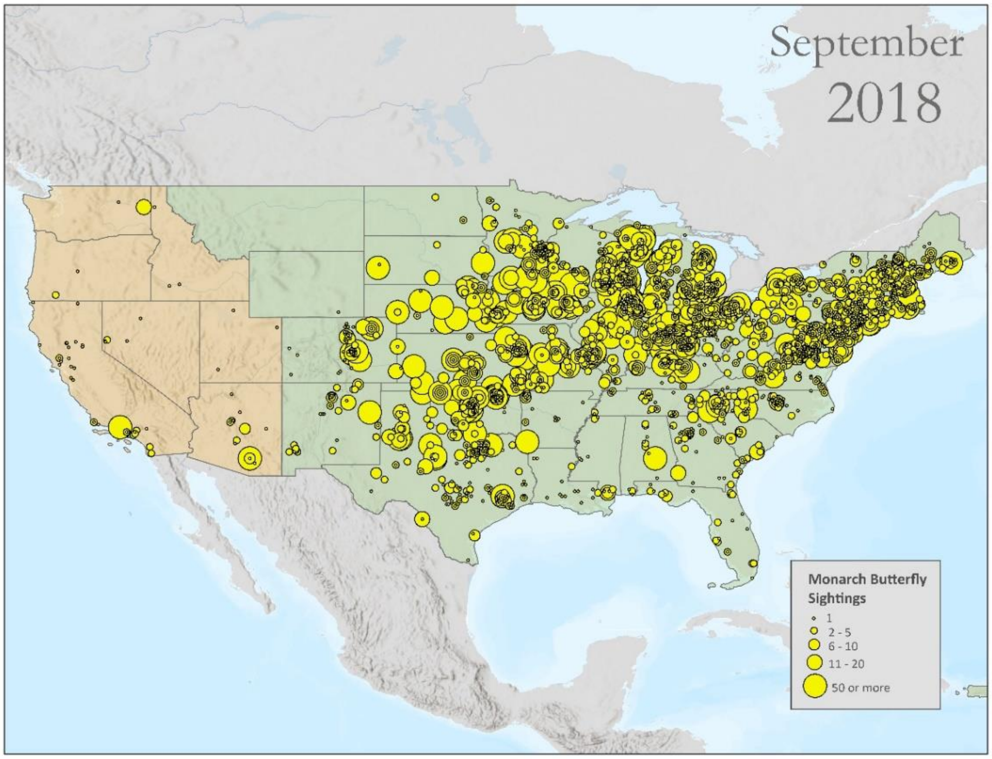

April
2018
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

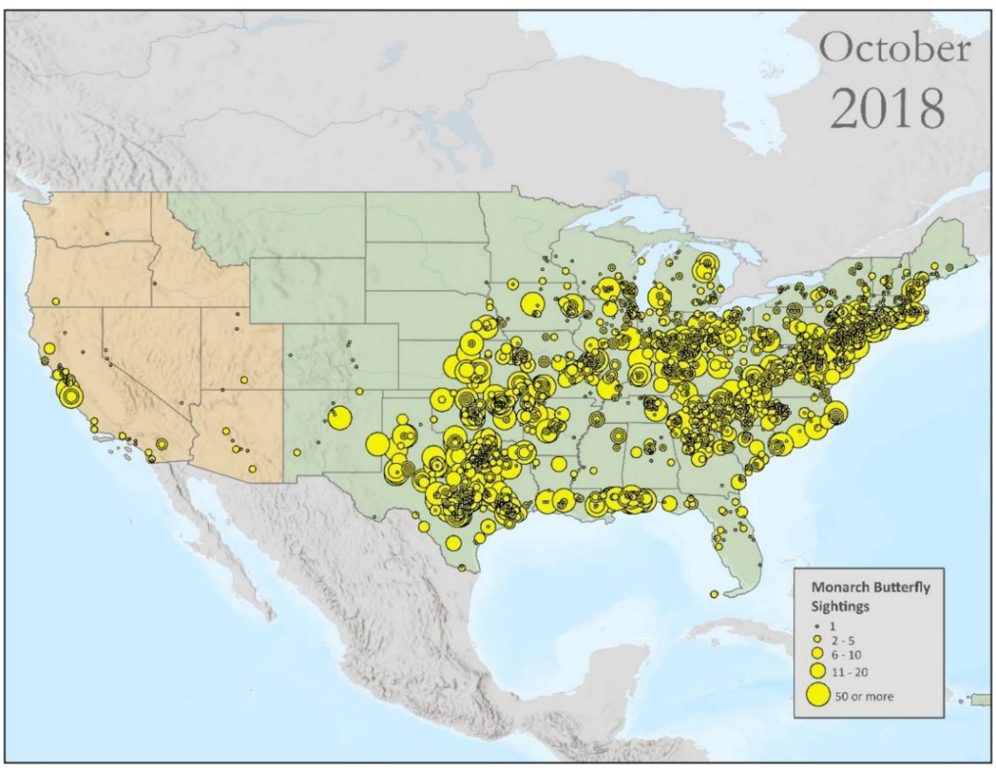

May
2018
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

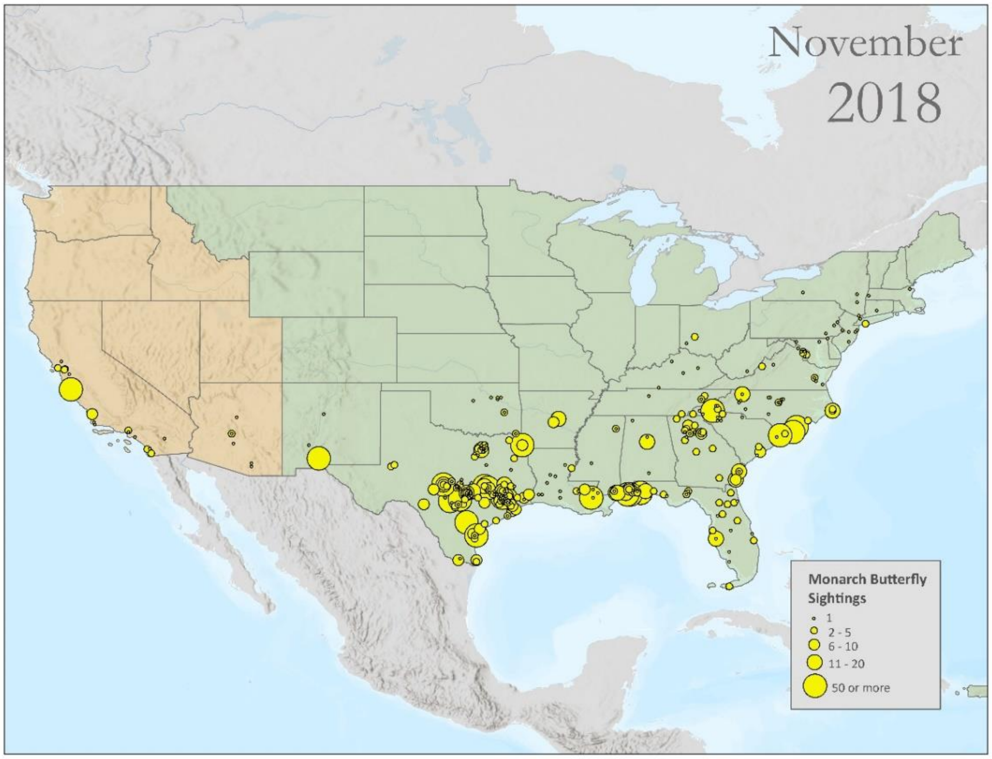

June
2018
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


July
2018
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


August
2018
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


September
2018
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


October
2018
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


November
2018
Monarch Butterfly Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

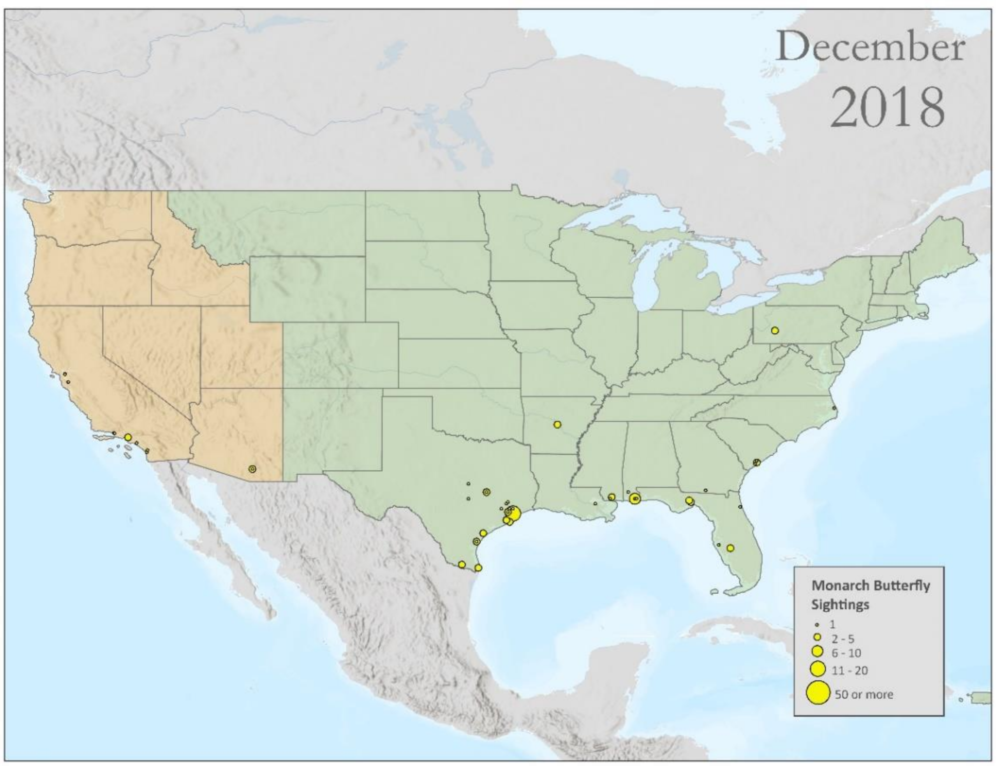
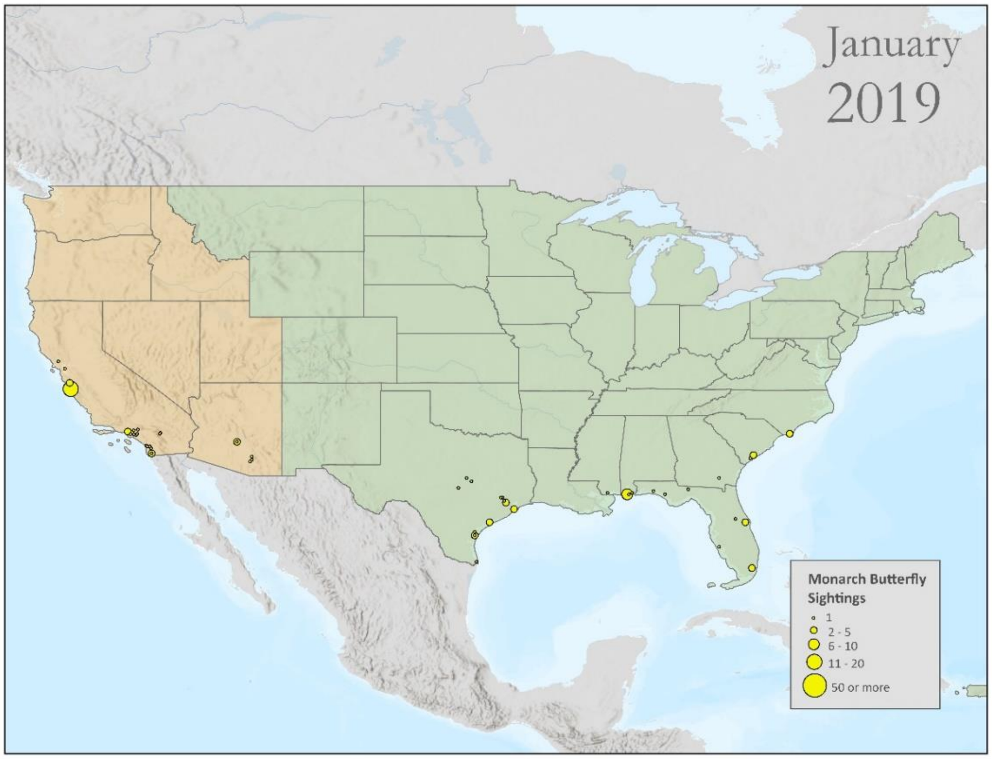
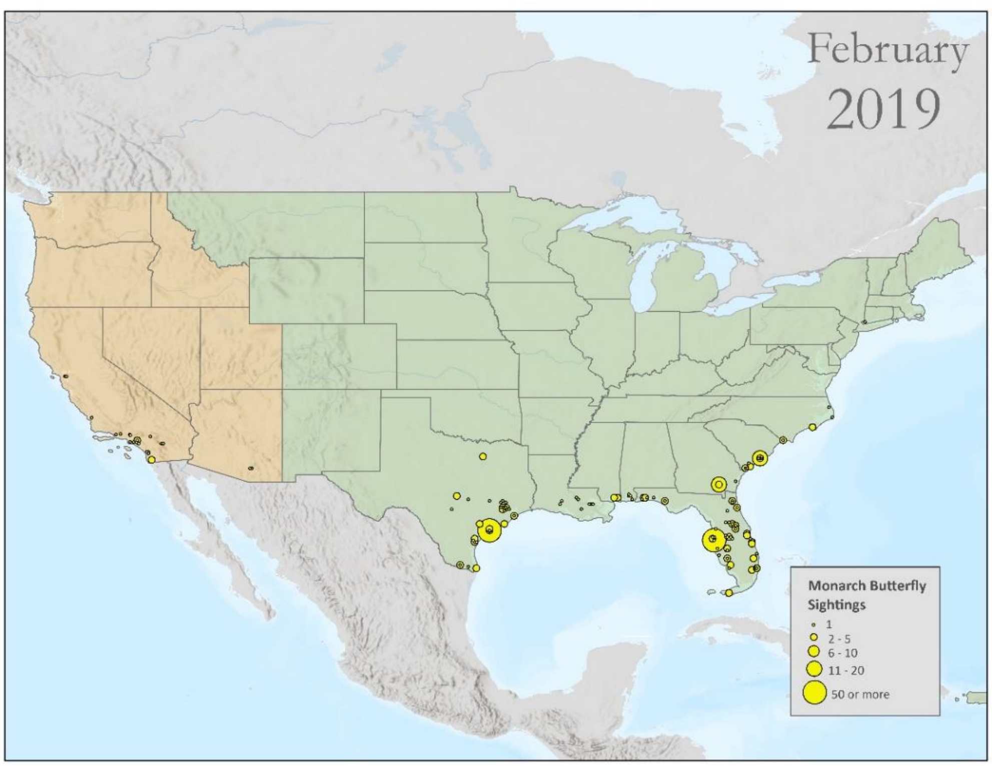
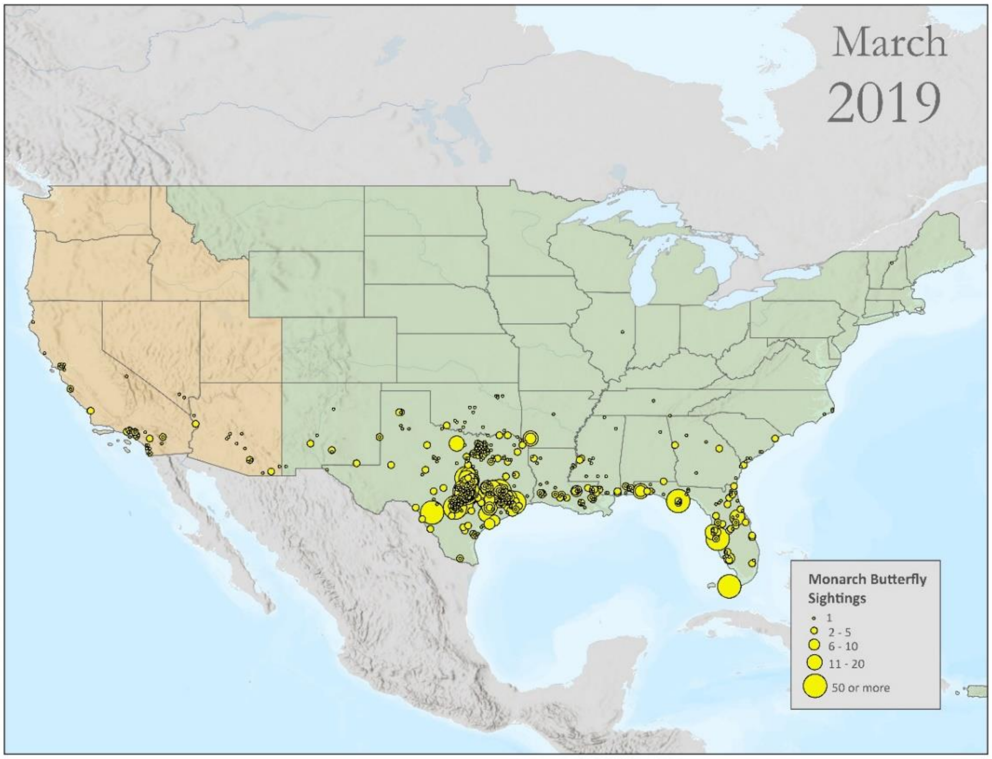
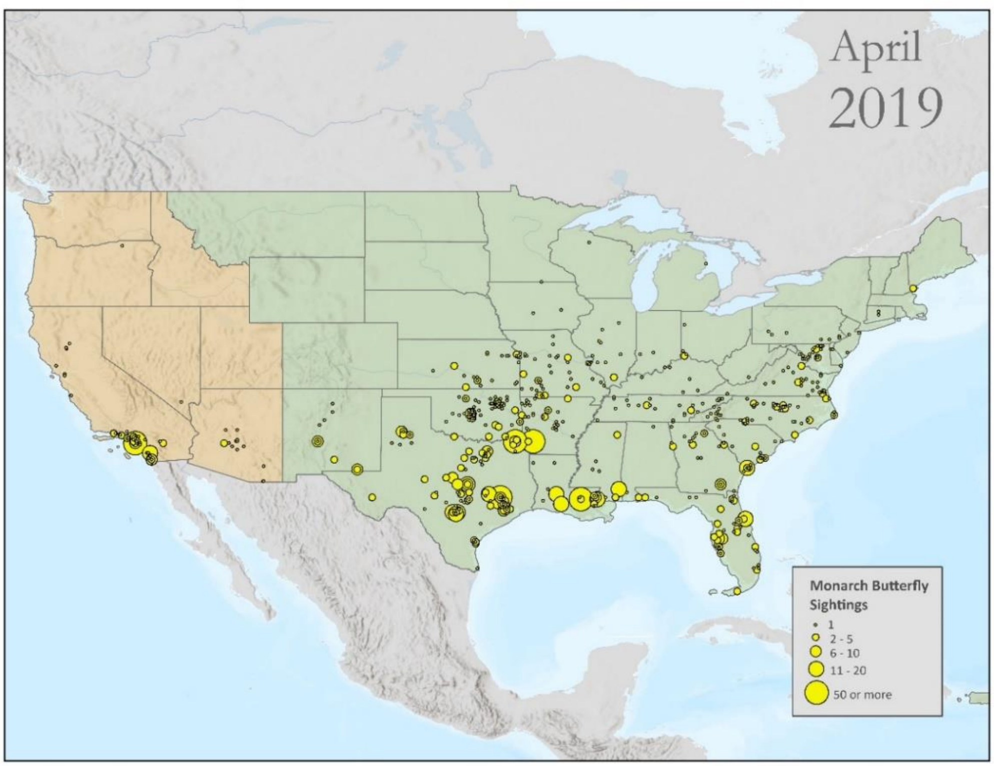

December
2018
Monarch Butterfly Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

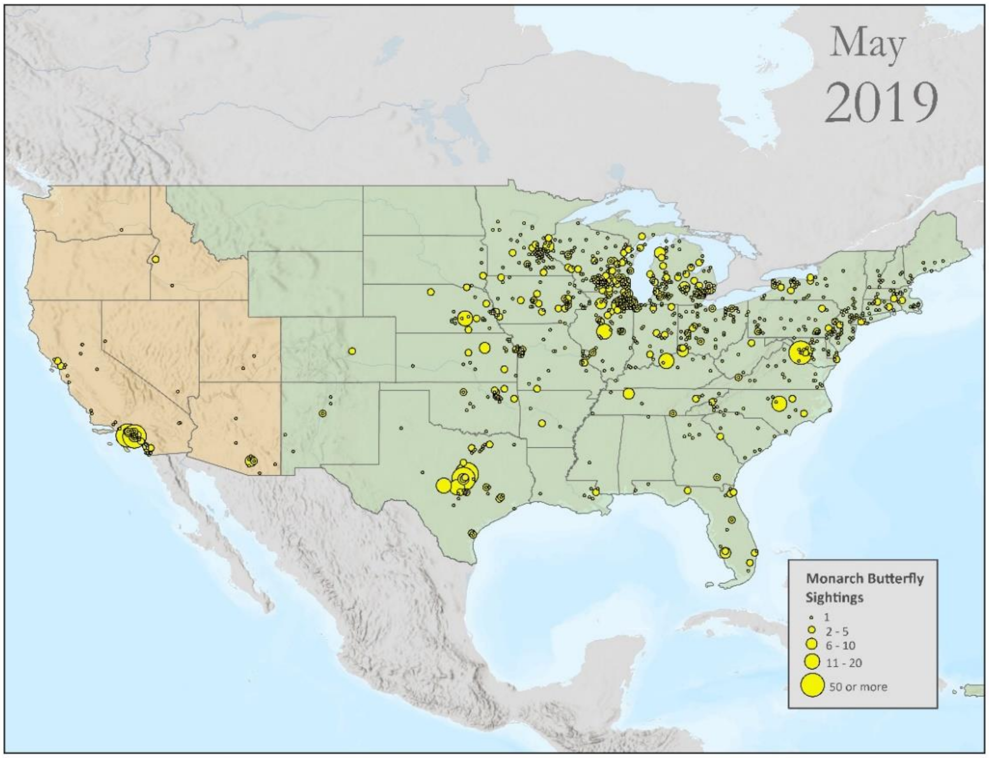
Figure A62. Monarch Butterfly Sightings - 2019

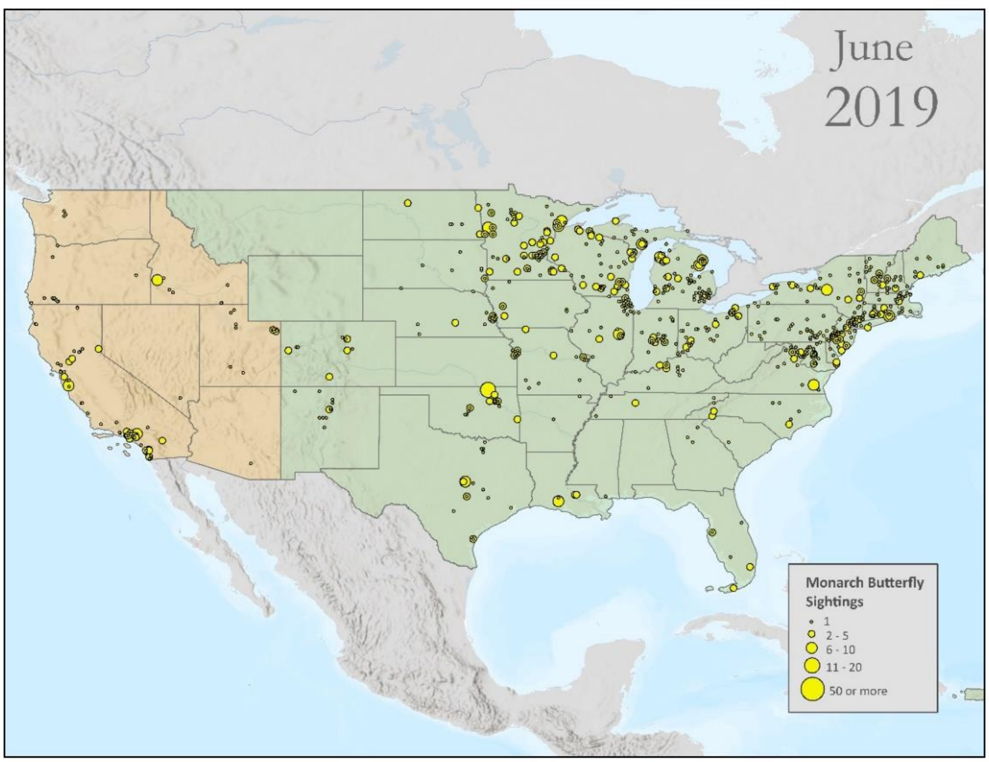


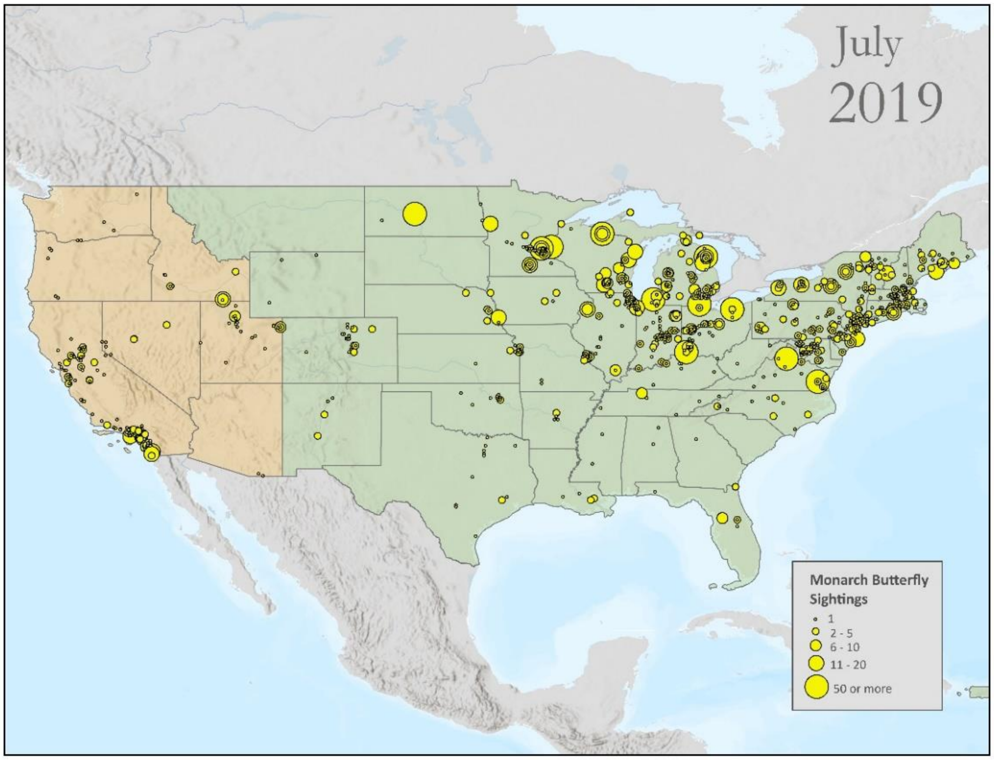


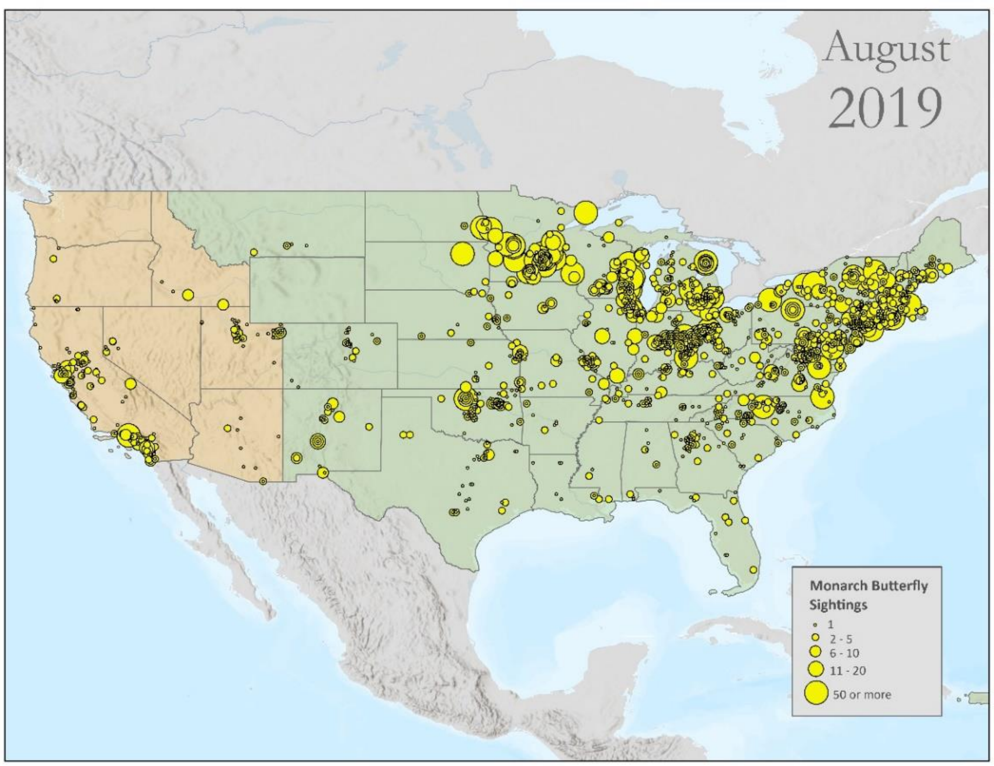

March
2019
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

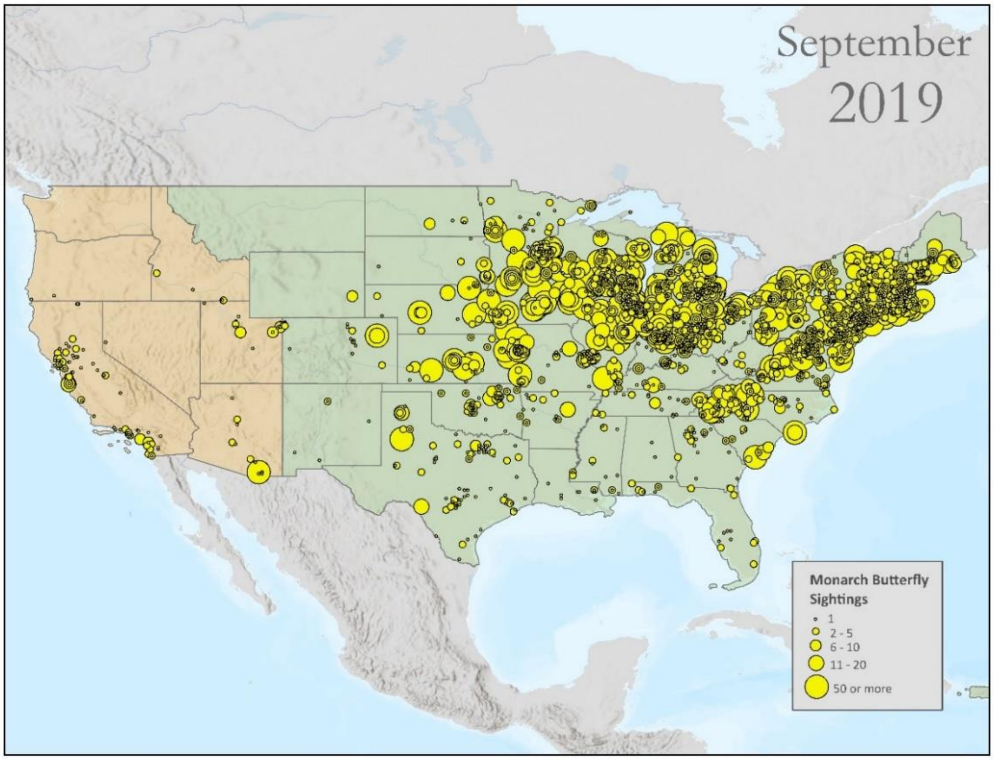

April
2019
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

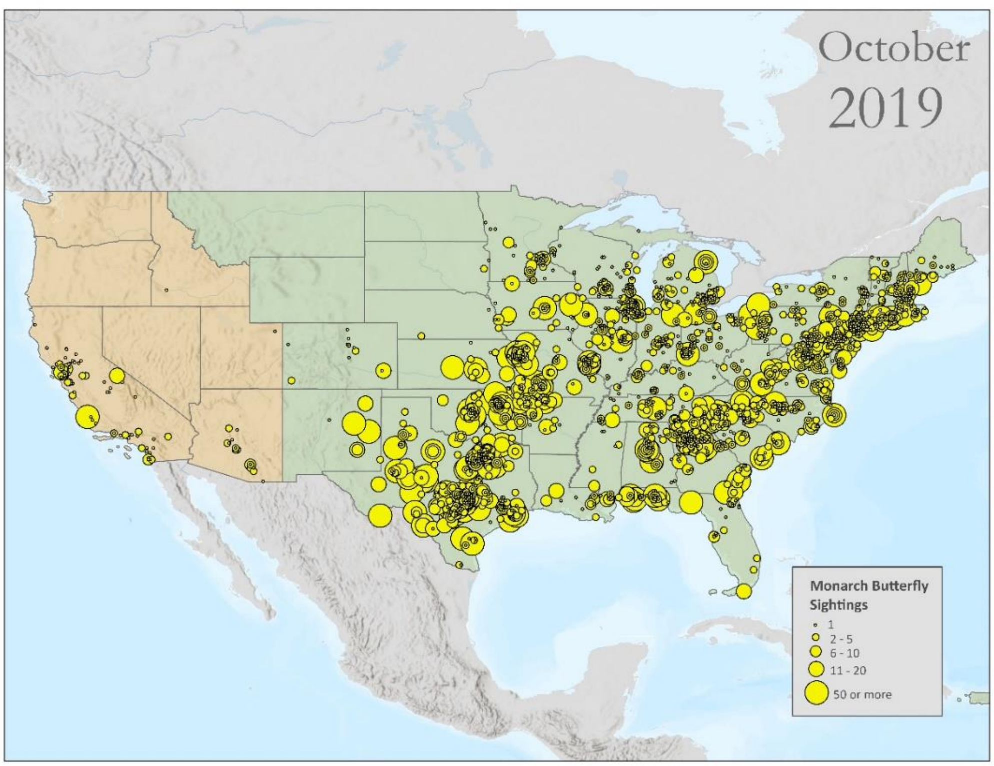

May
2019
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

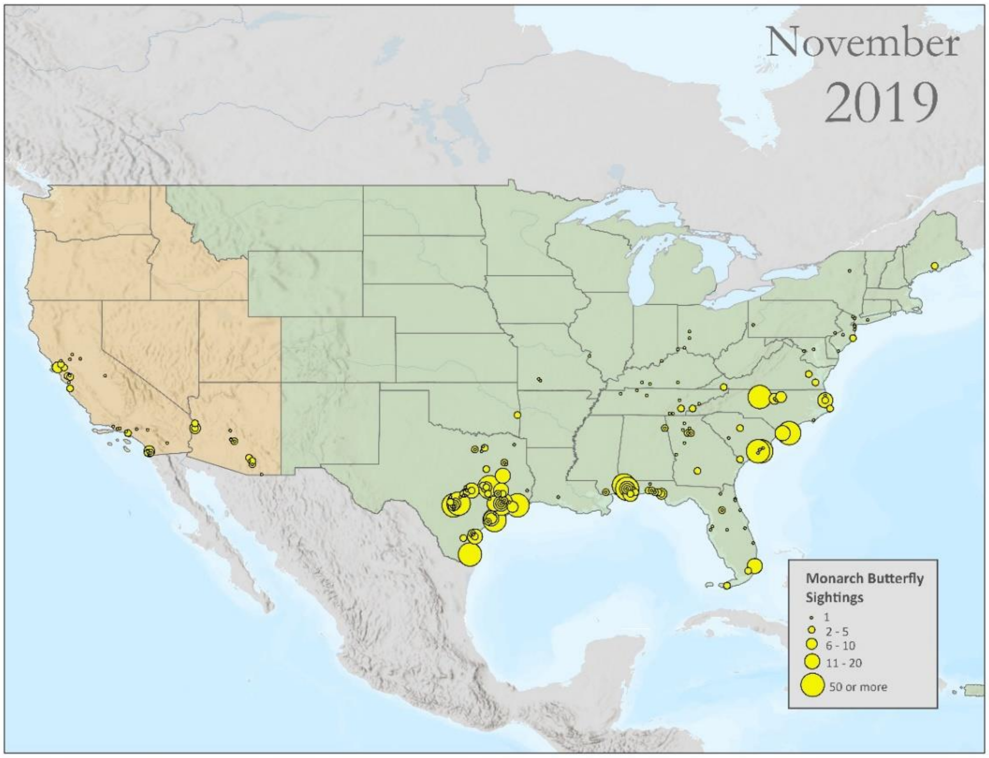

June
2019
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


July
2019
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


August
2019
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


September
2019
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


October
2019
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


November
2019
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

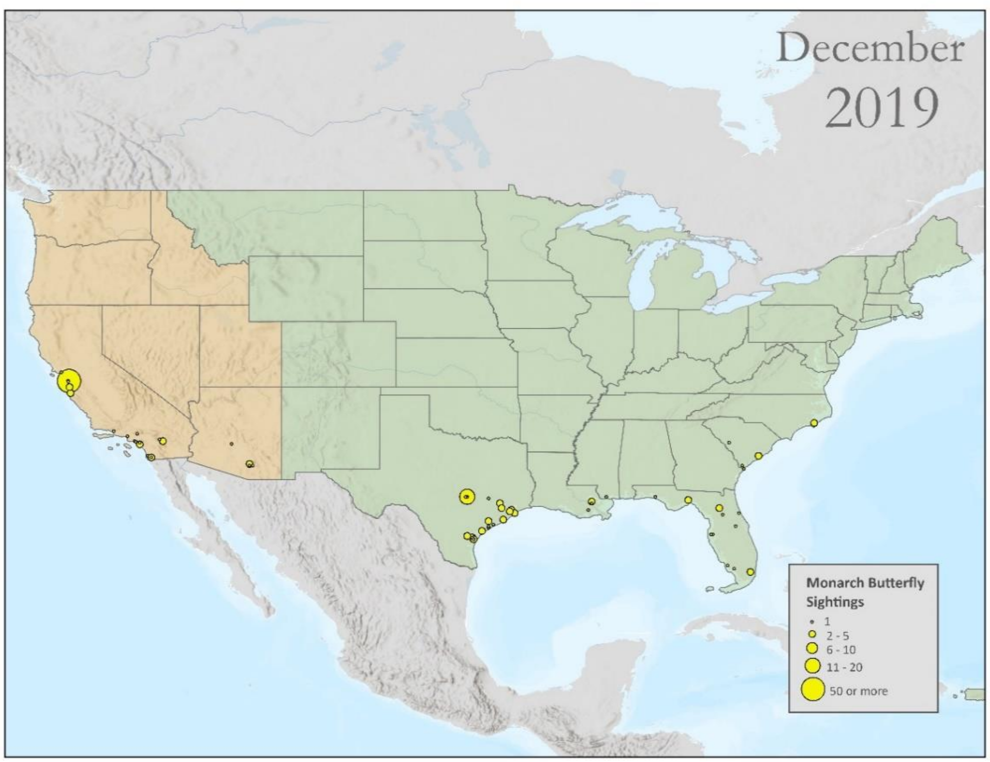
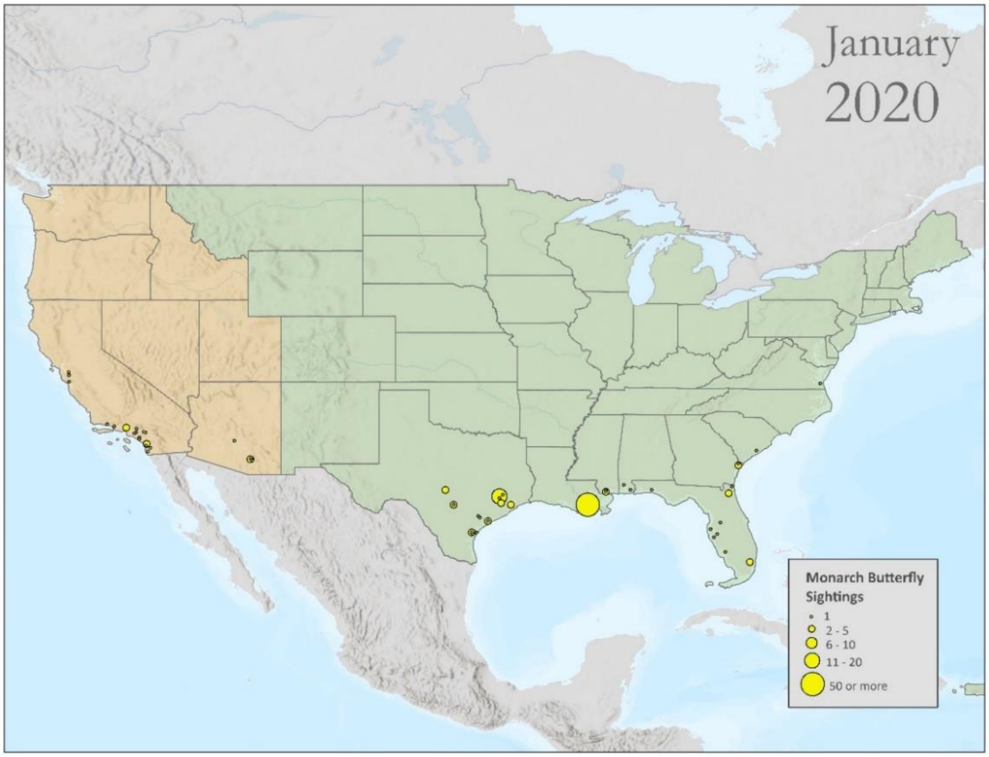
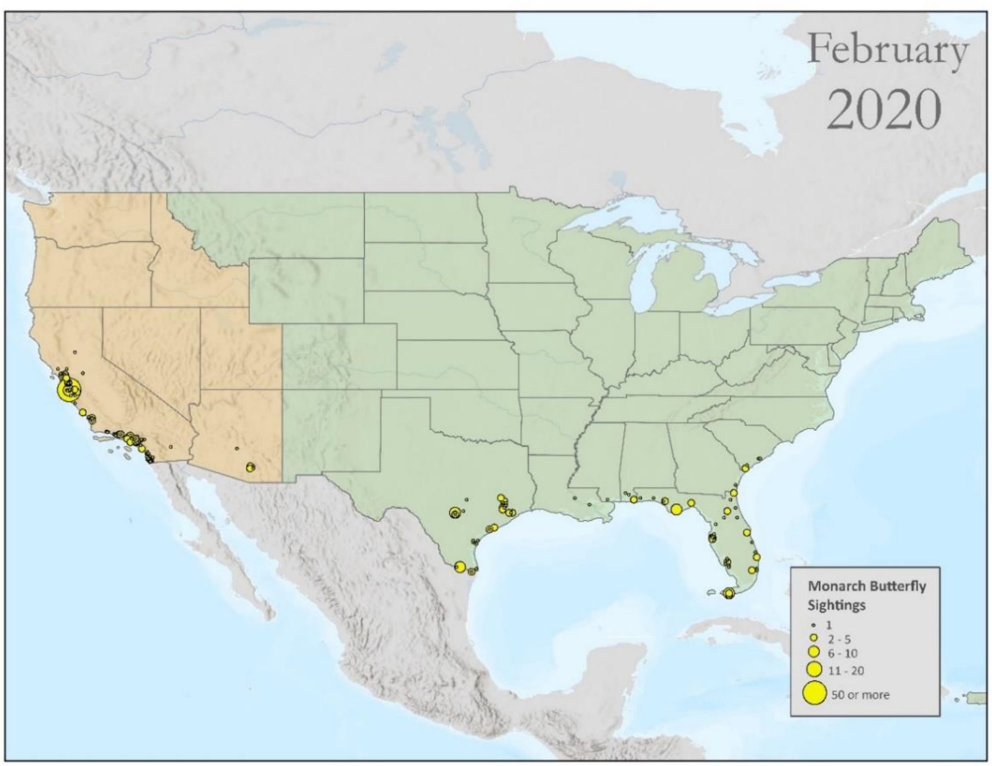
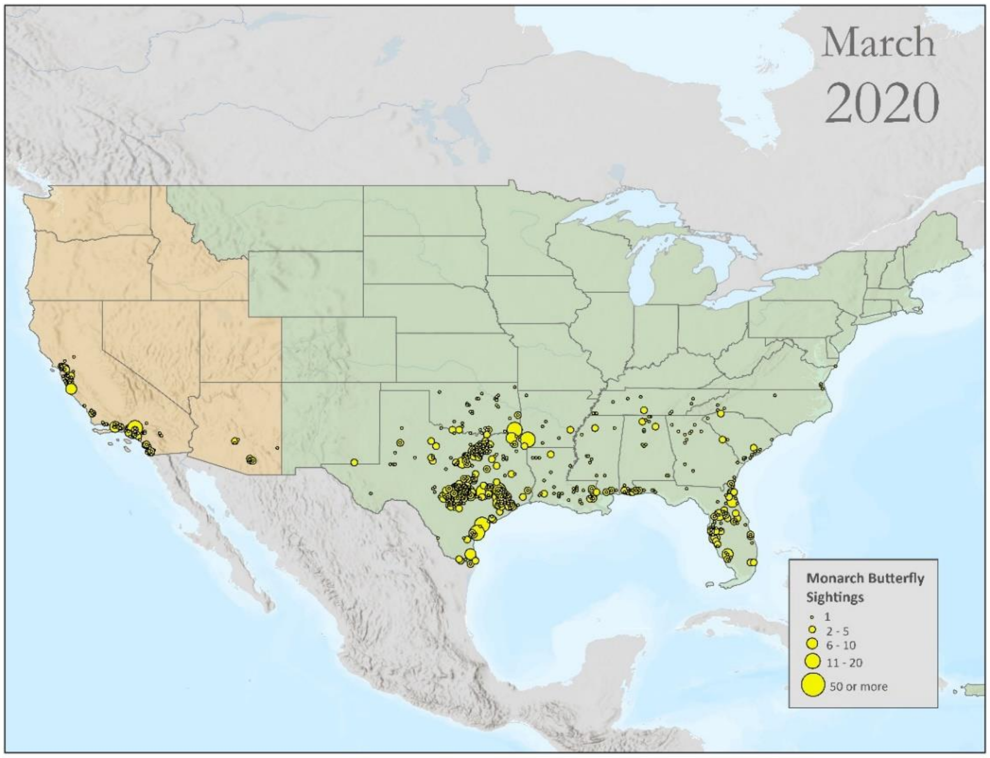
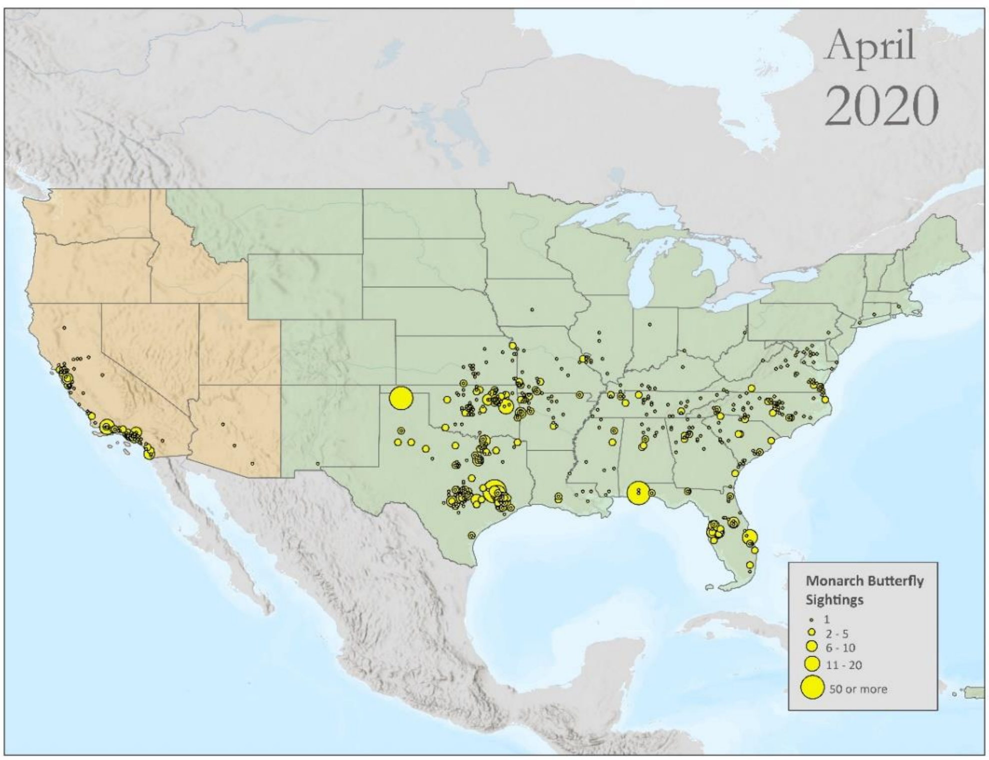

December
2019
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

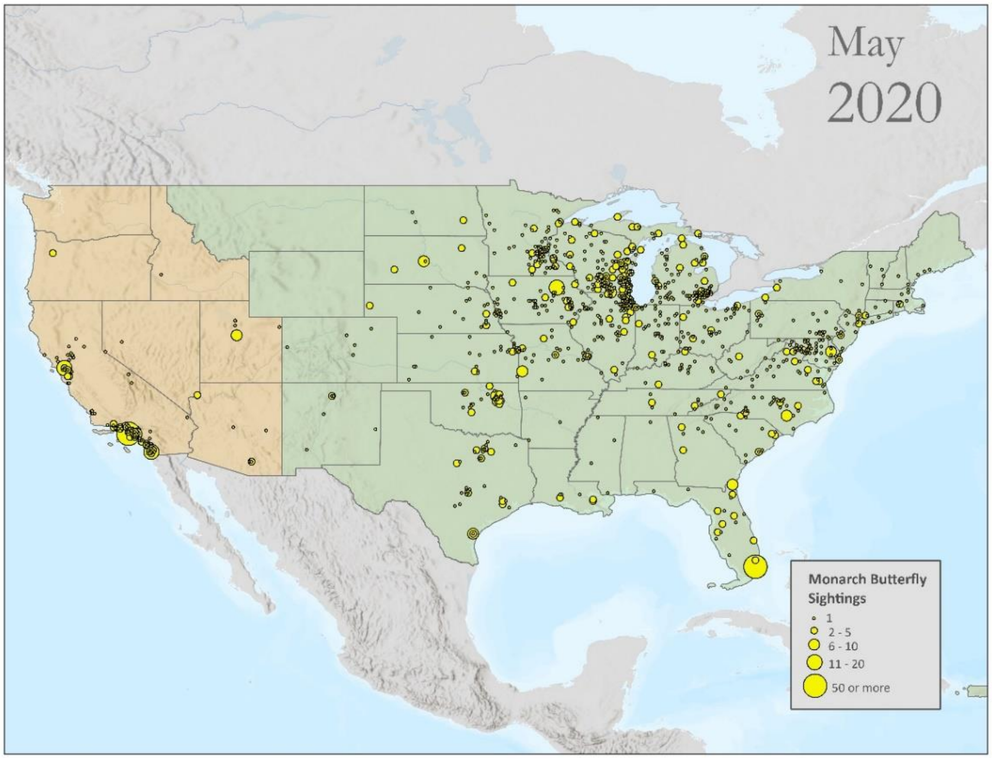
Figure A63. Monarch Butterfly Sightings - 2020

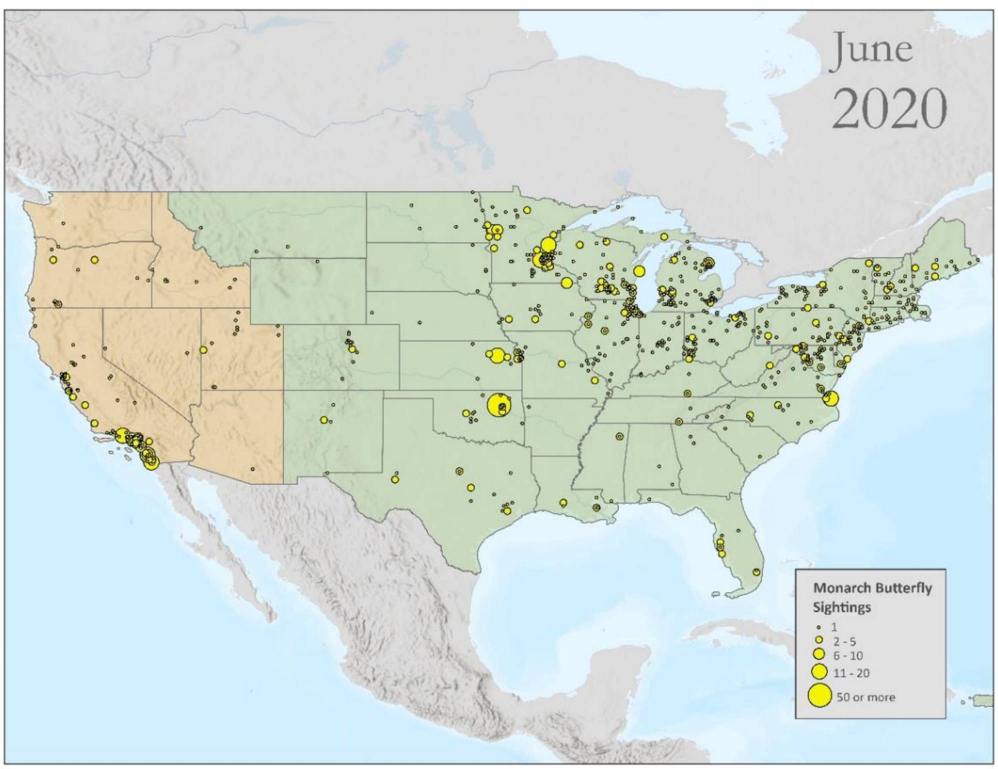


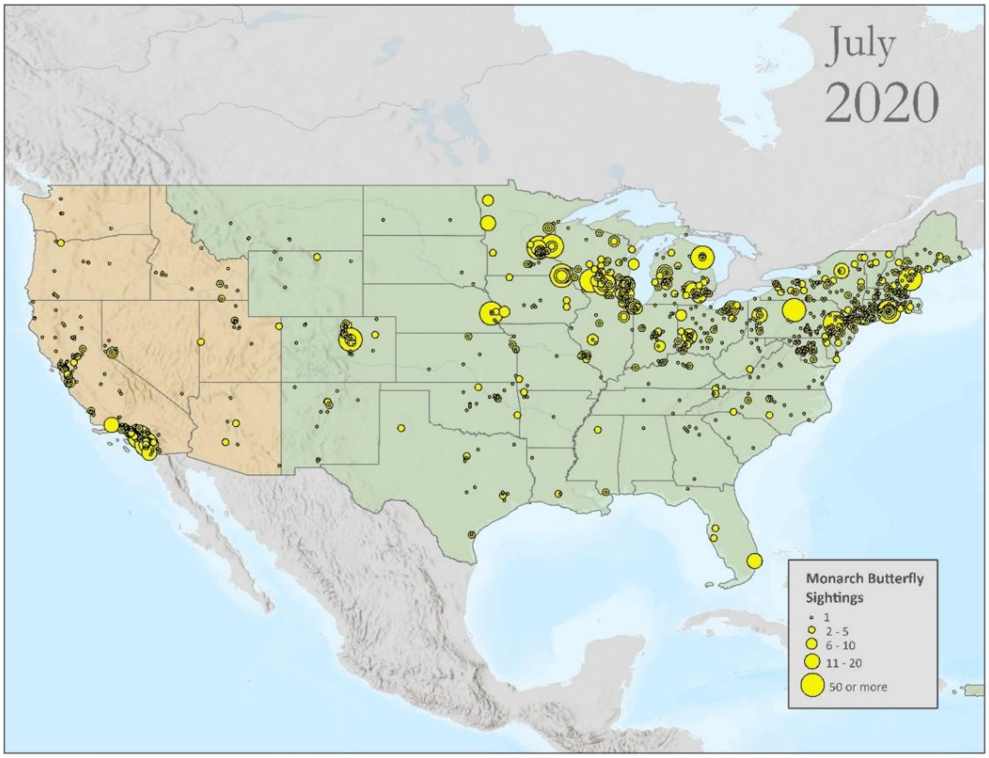


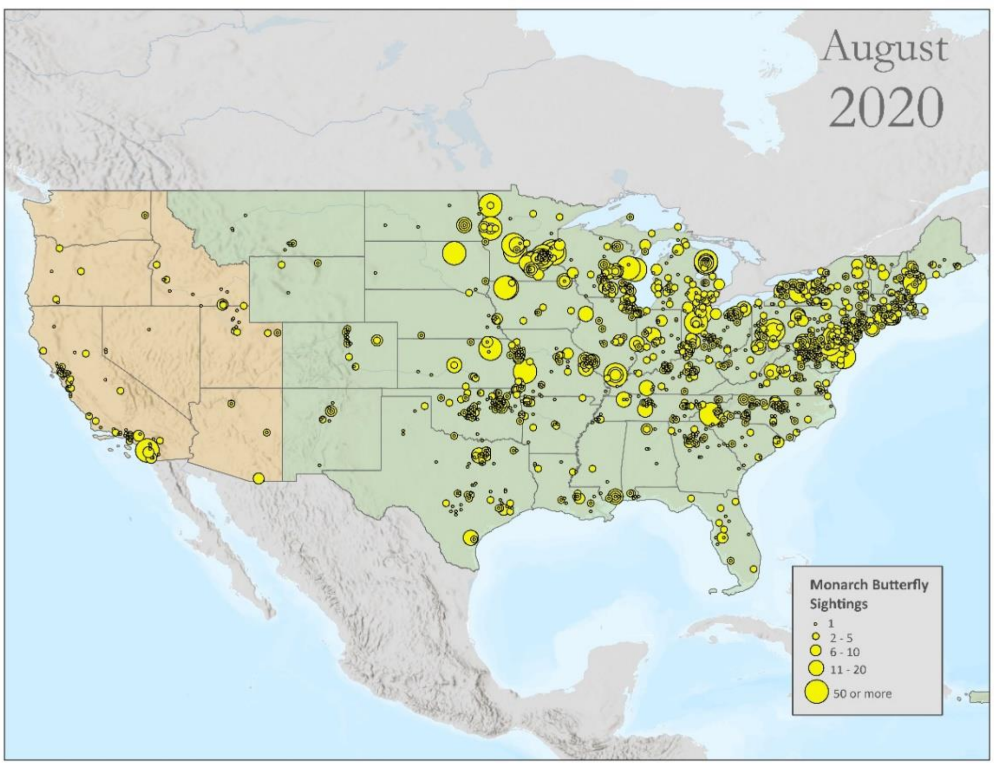

March
2020
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

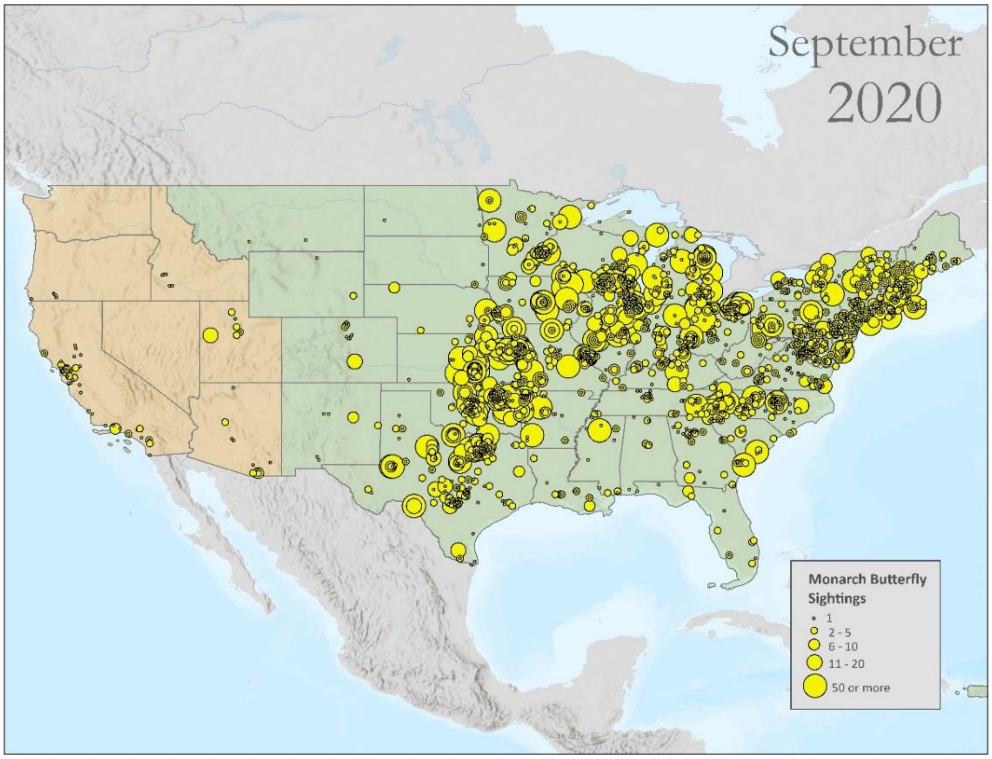

April
2020
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

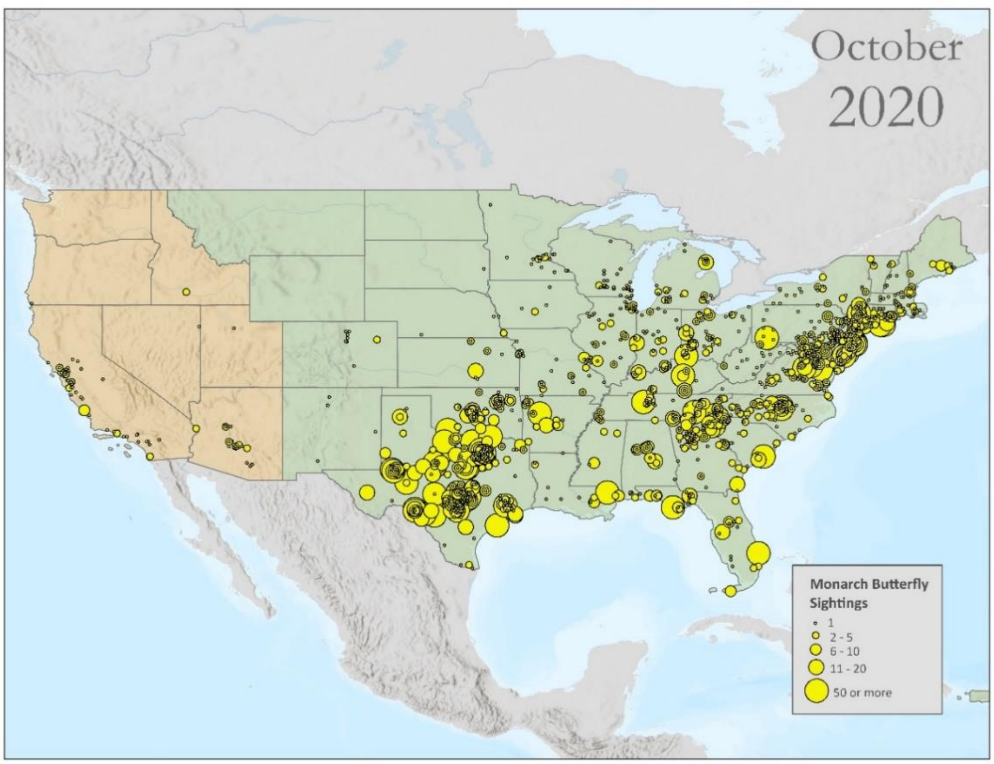

May
2020
Monarch Butterfly Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

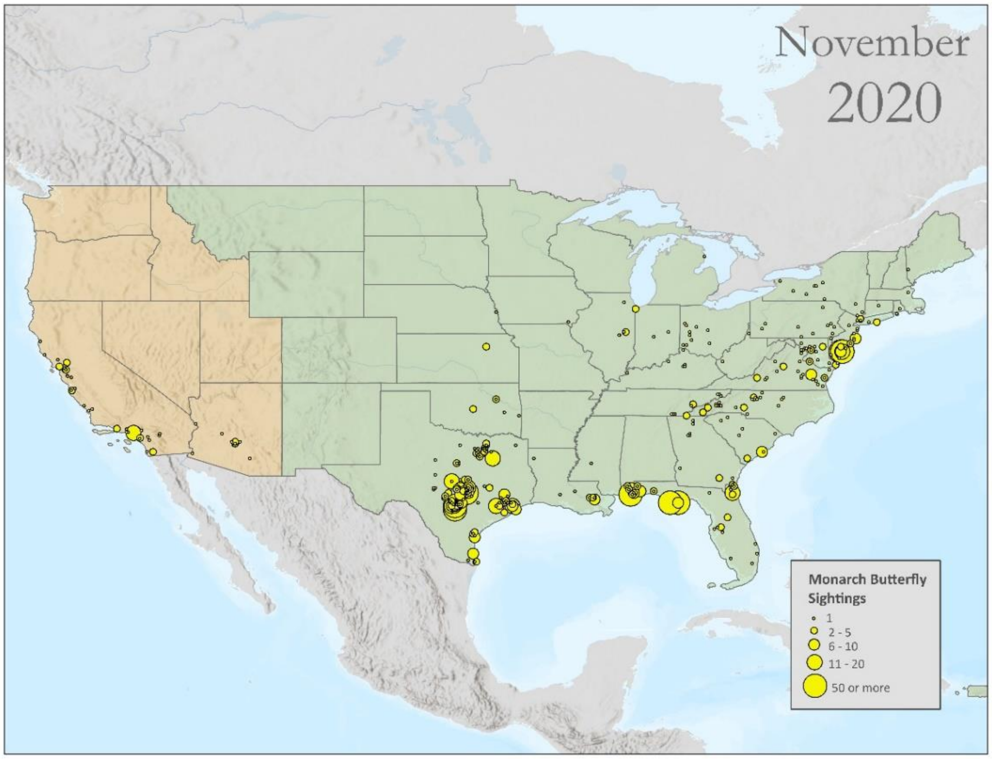

June
2020
Monarch Butterfly Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


July
2020
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


August
2020
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


September
2020
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


October
2020
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


November
2020
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

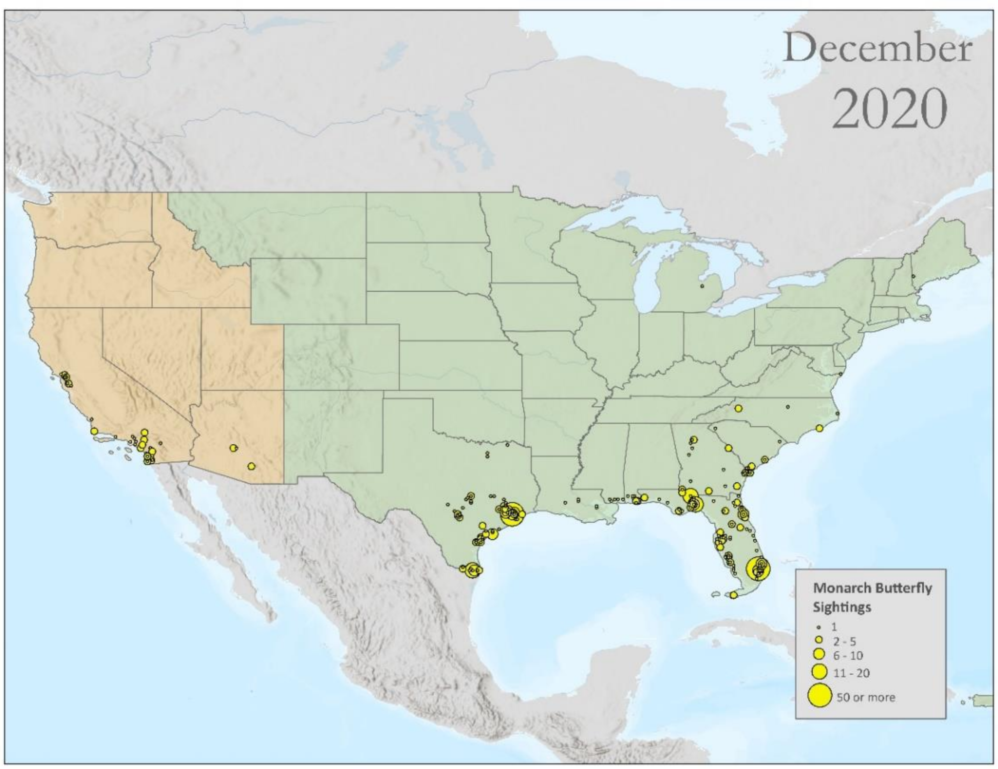
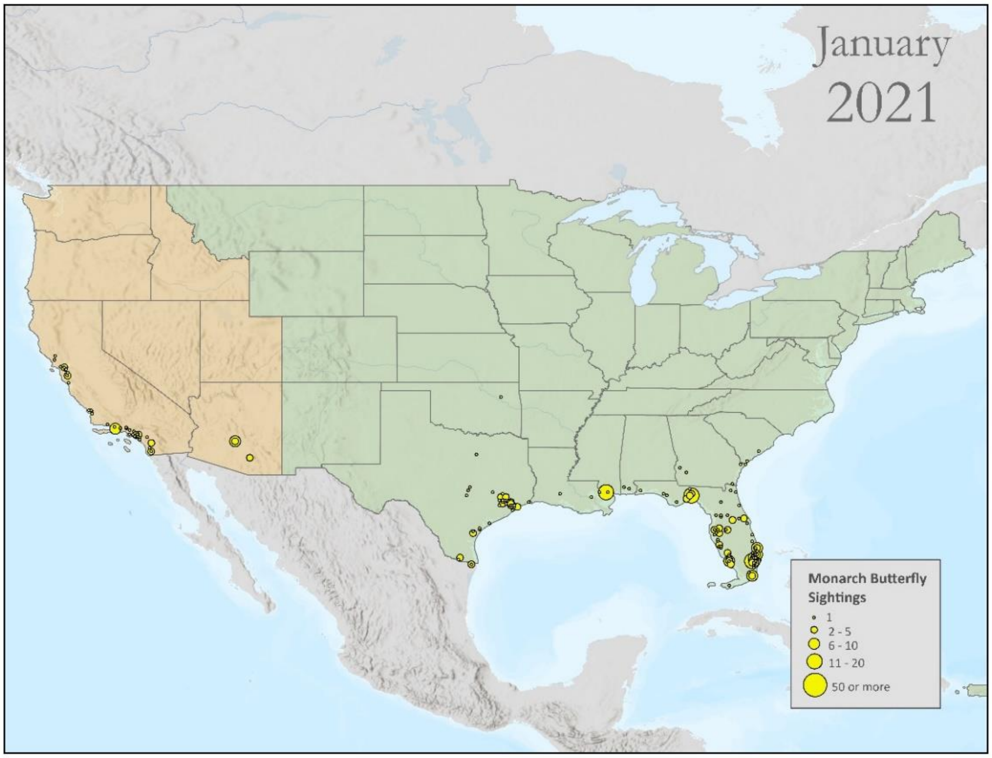
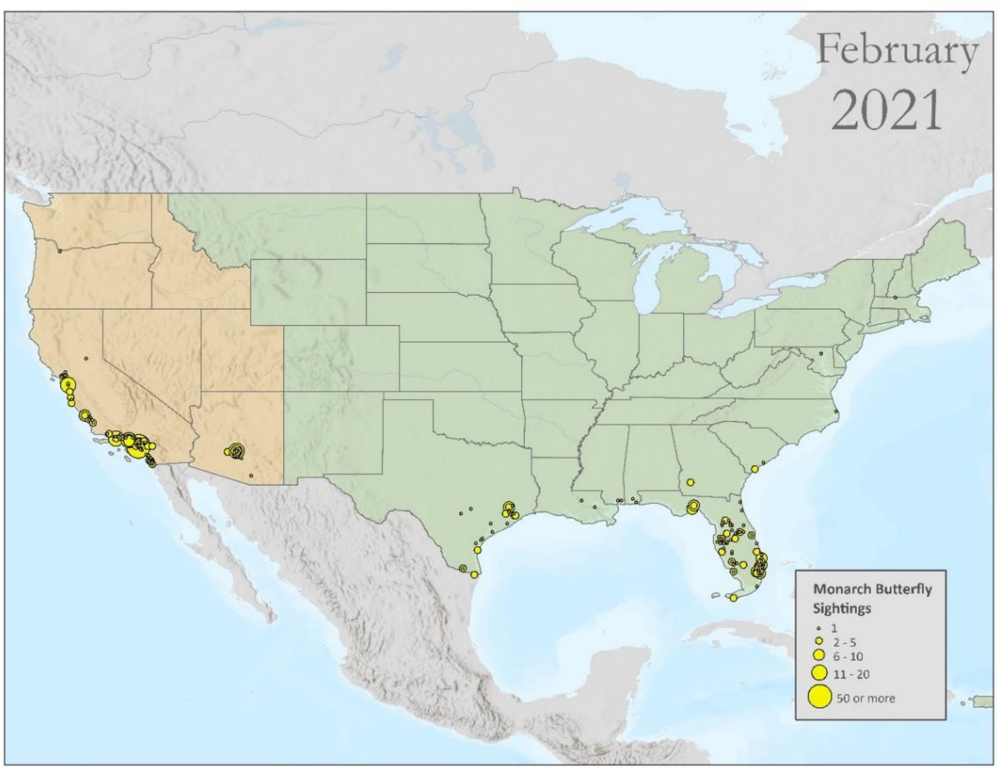
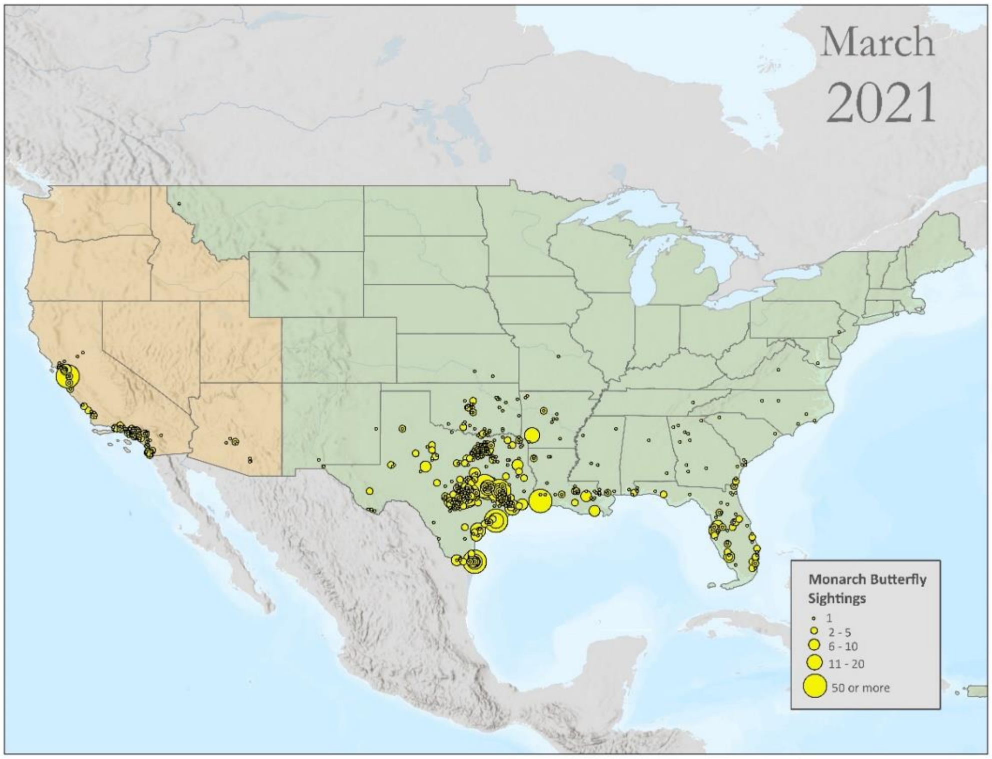
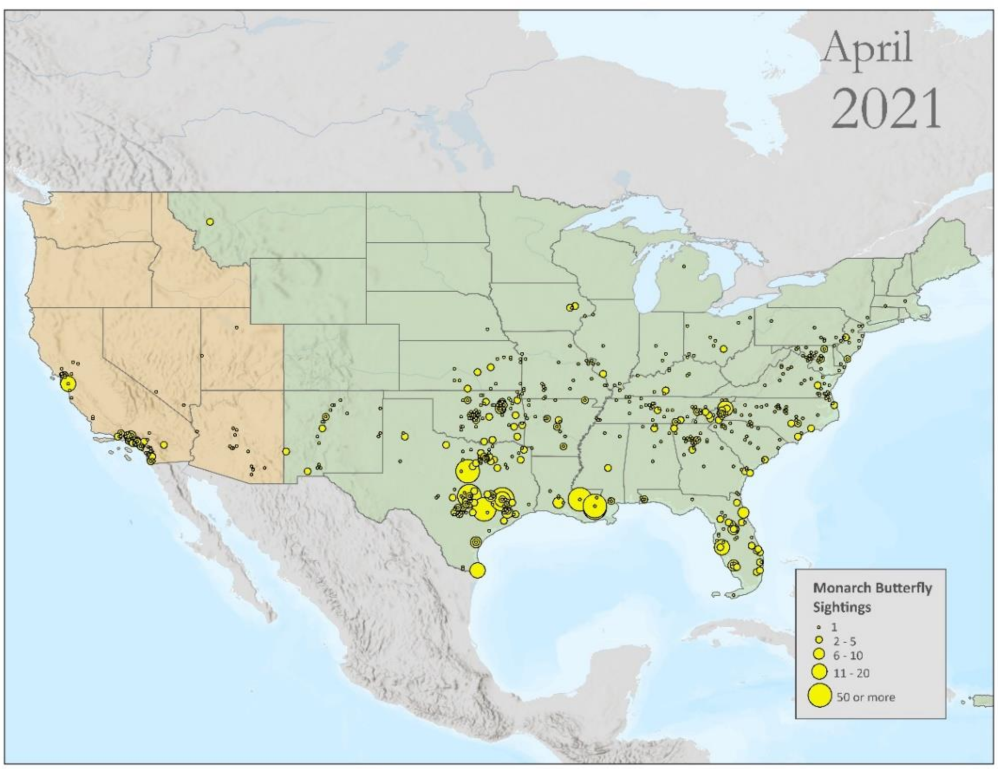

December
2020
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

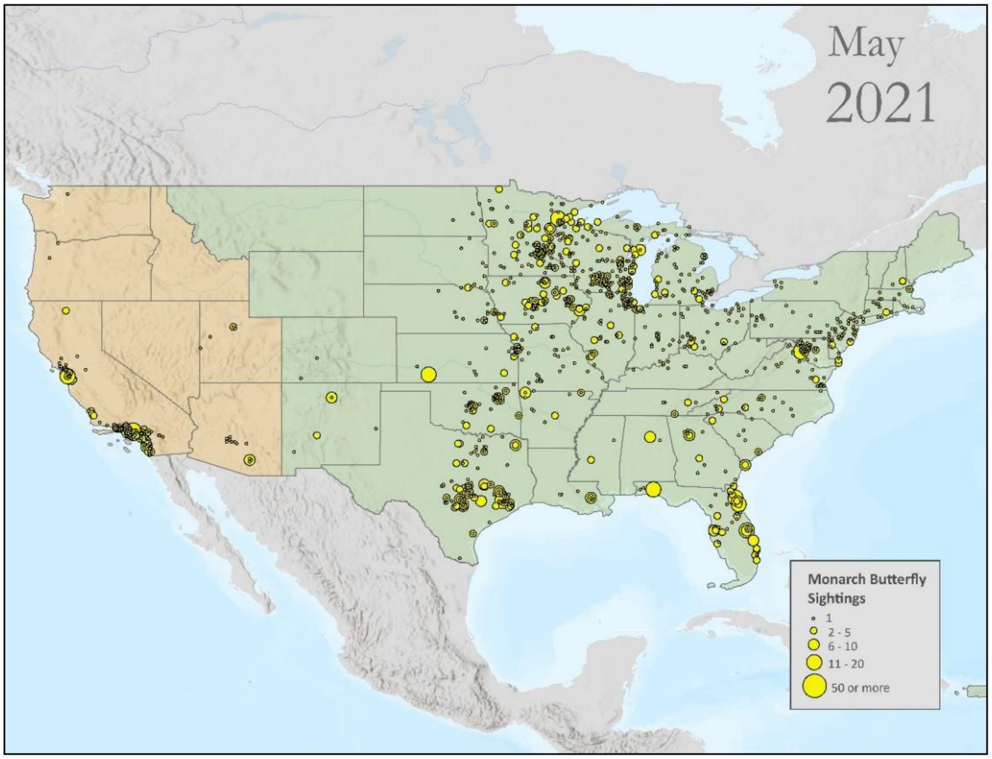
Figure A64. Monarch Butterfly Sightings - 2021

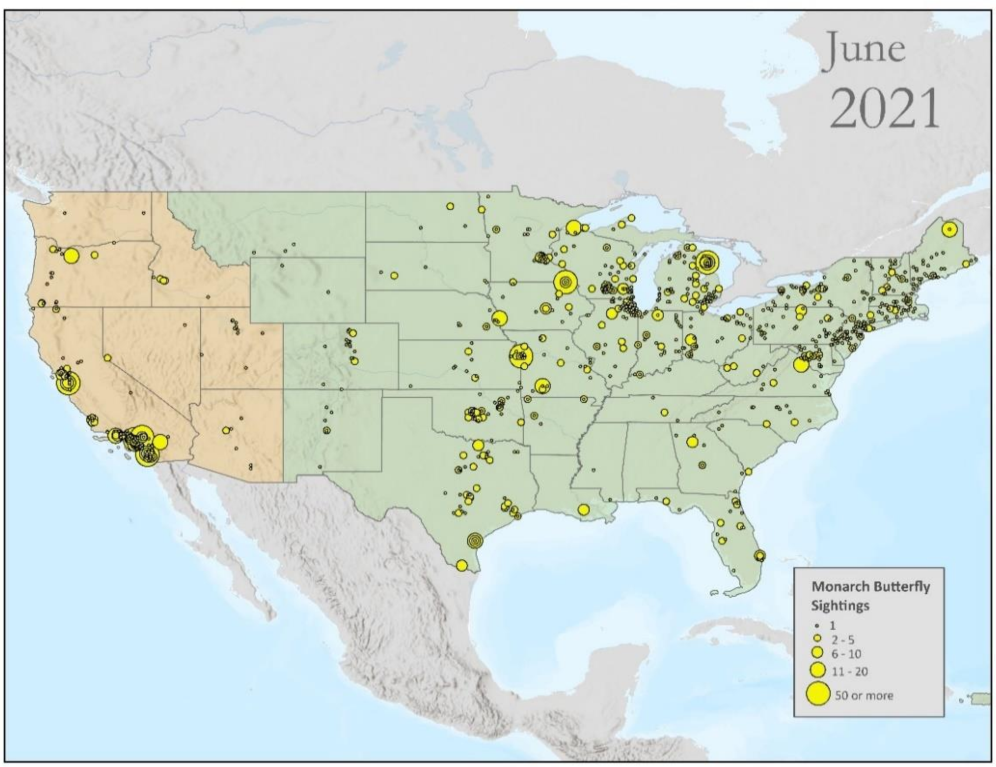


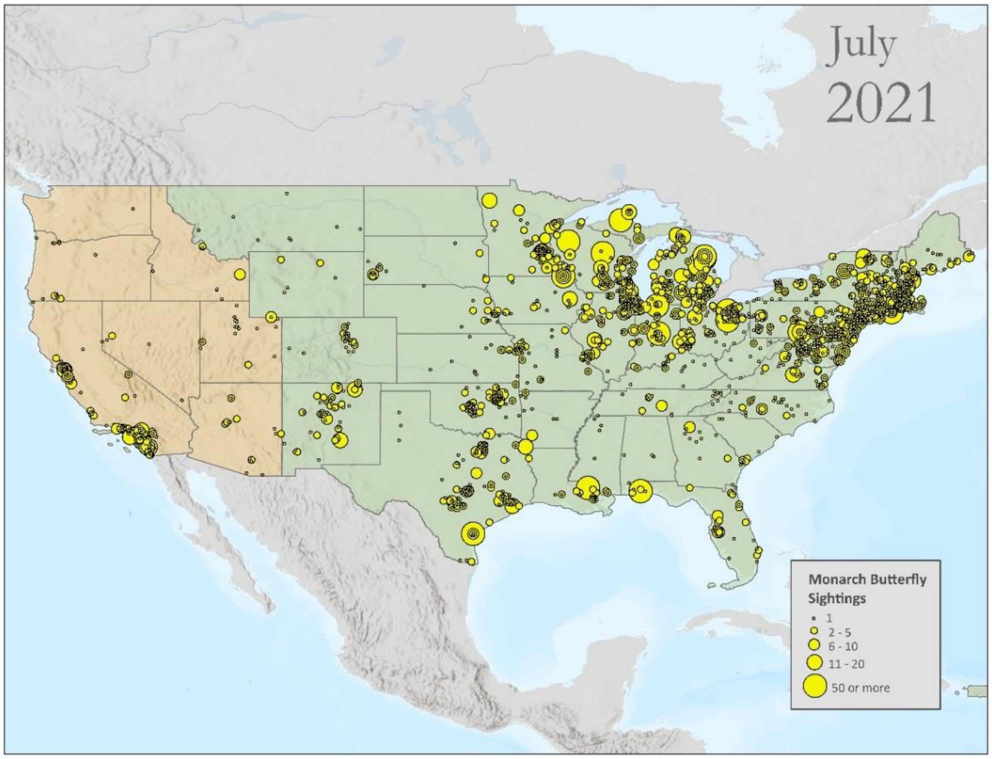


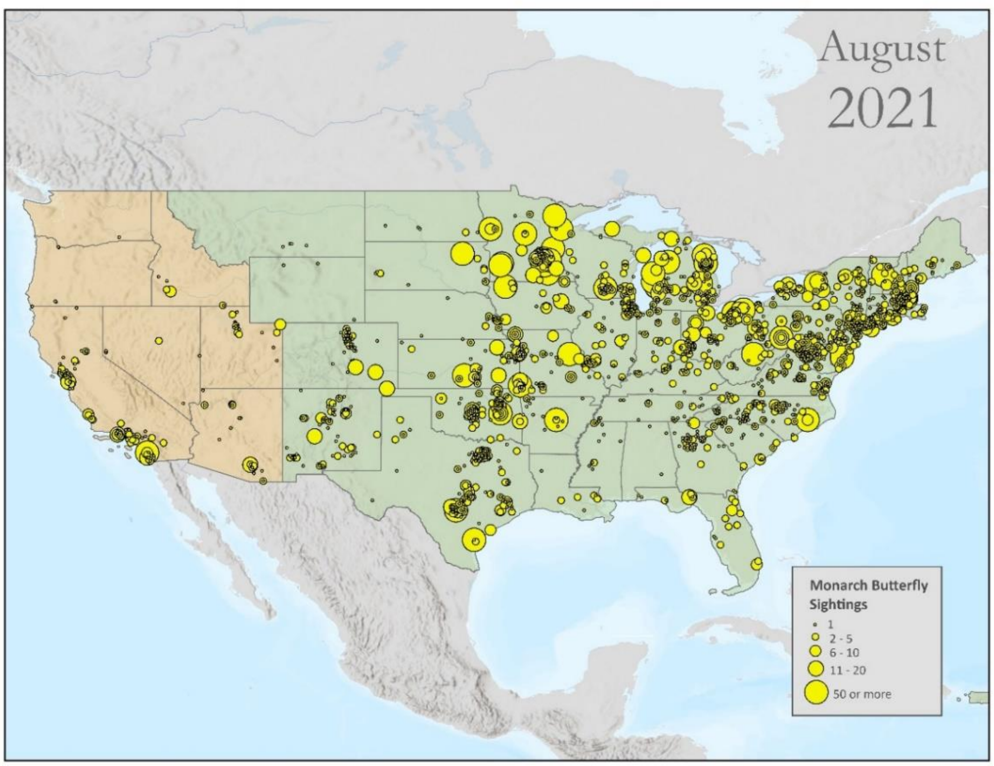

March
2021
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

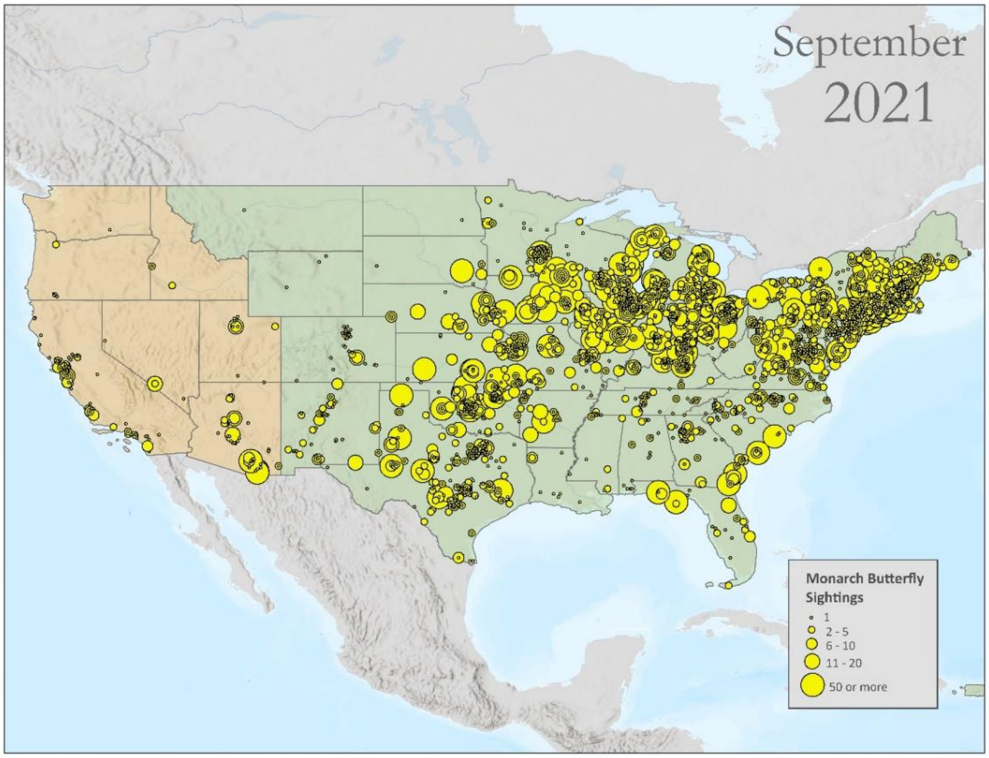

April
2021
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

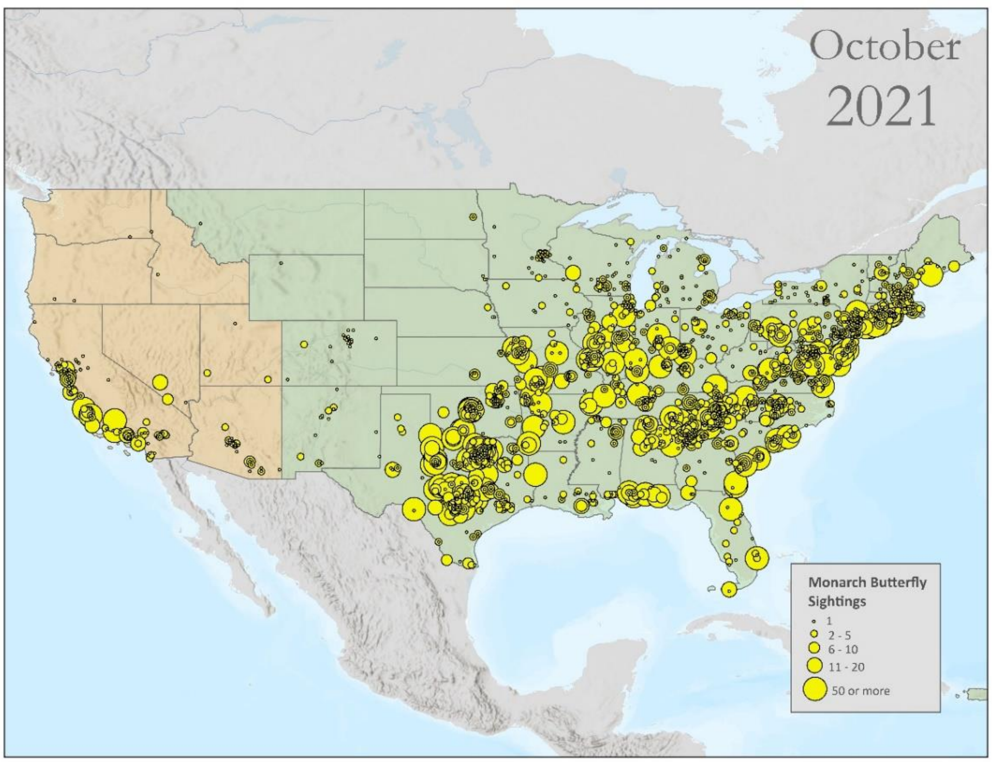

May
2021
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

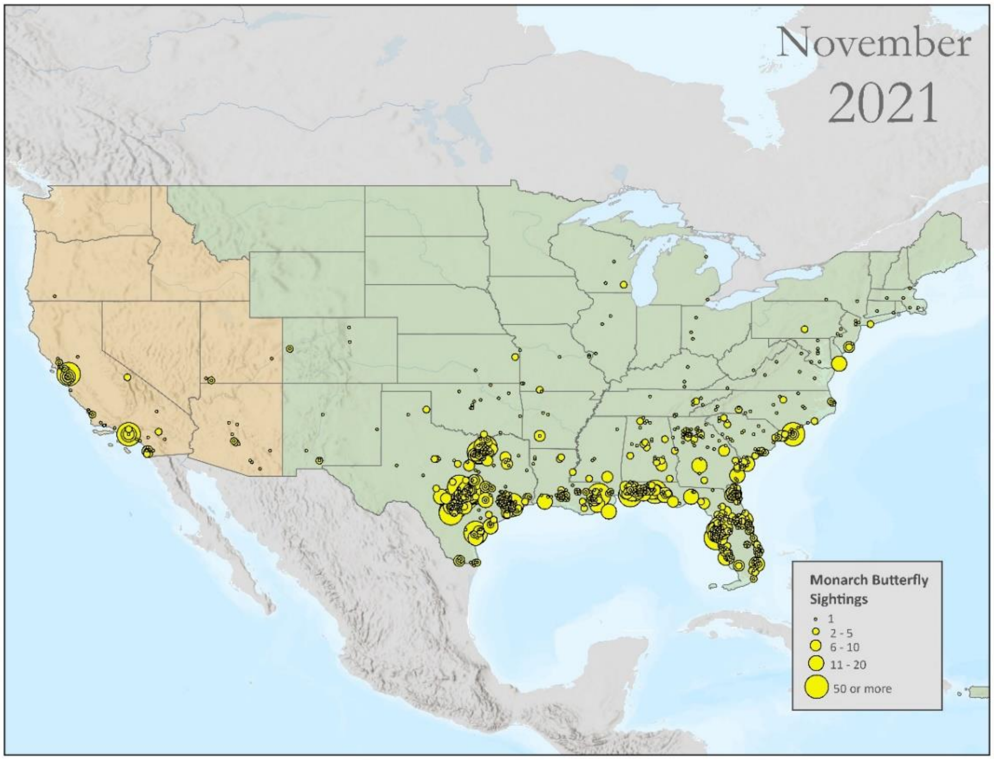

June
2021
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


July
2021
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


August
2021
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


September
2021
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


October
2021
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


November
2021
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

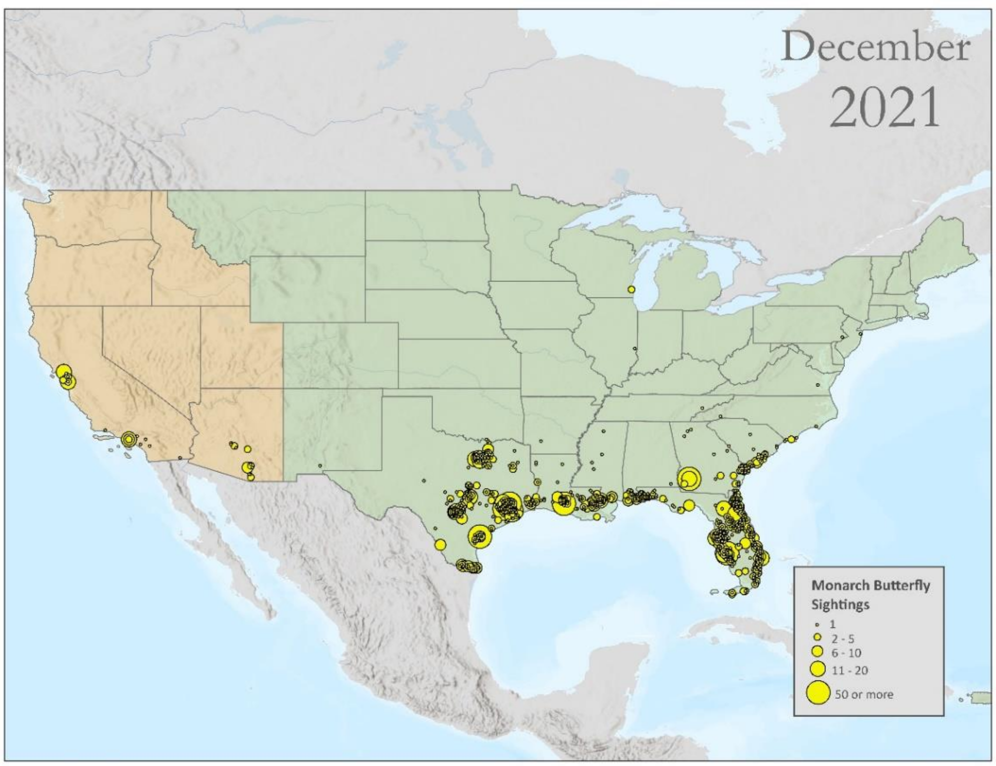
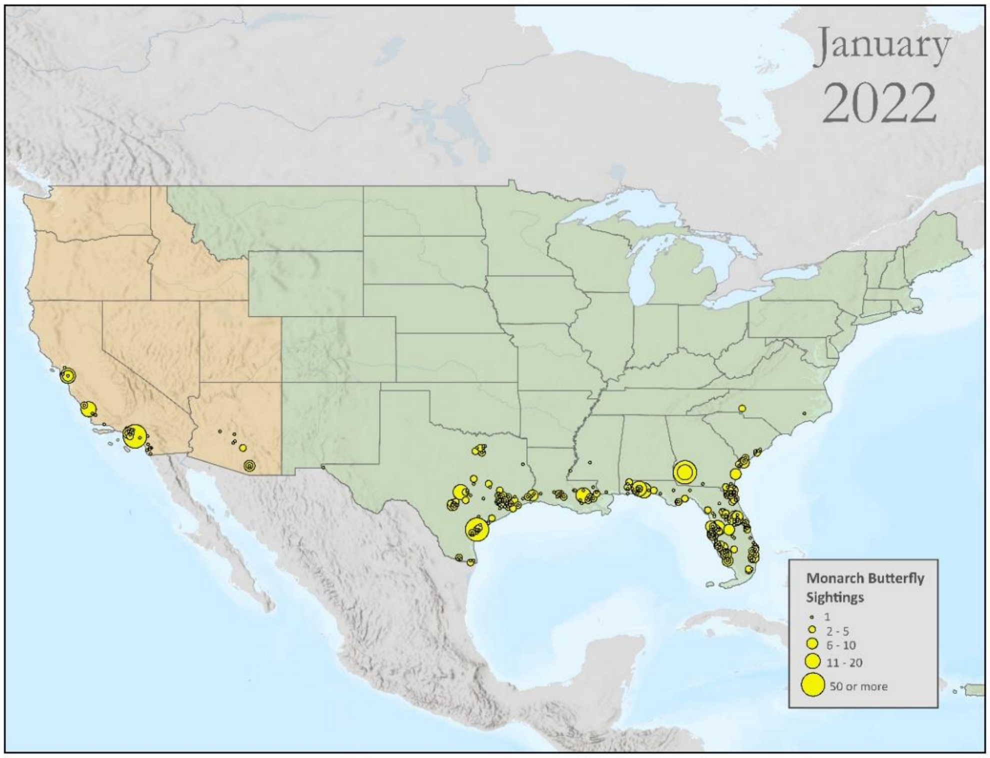
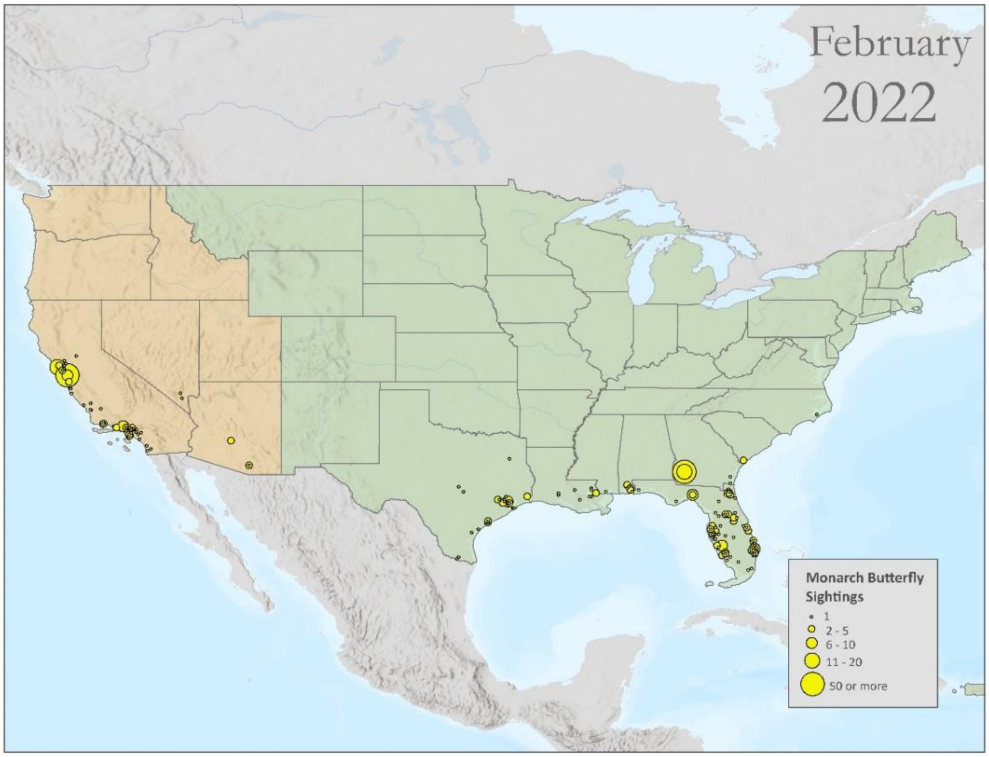
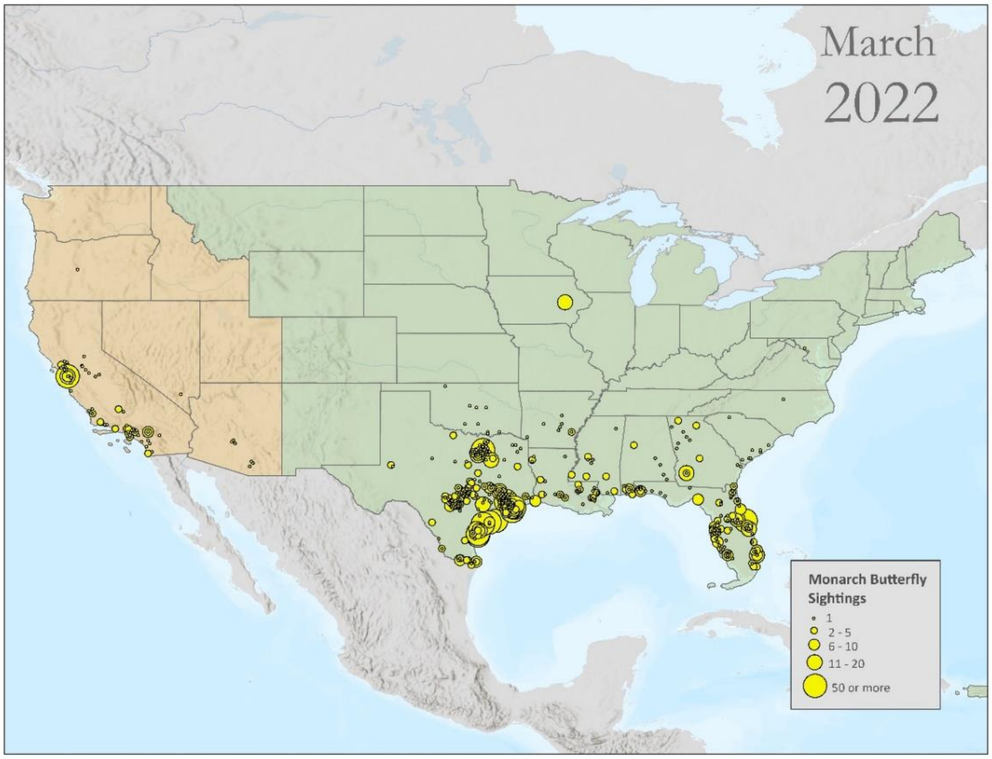
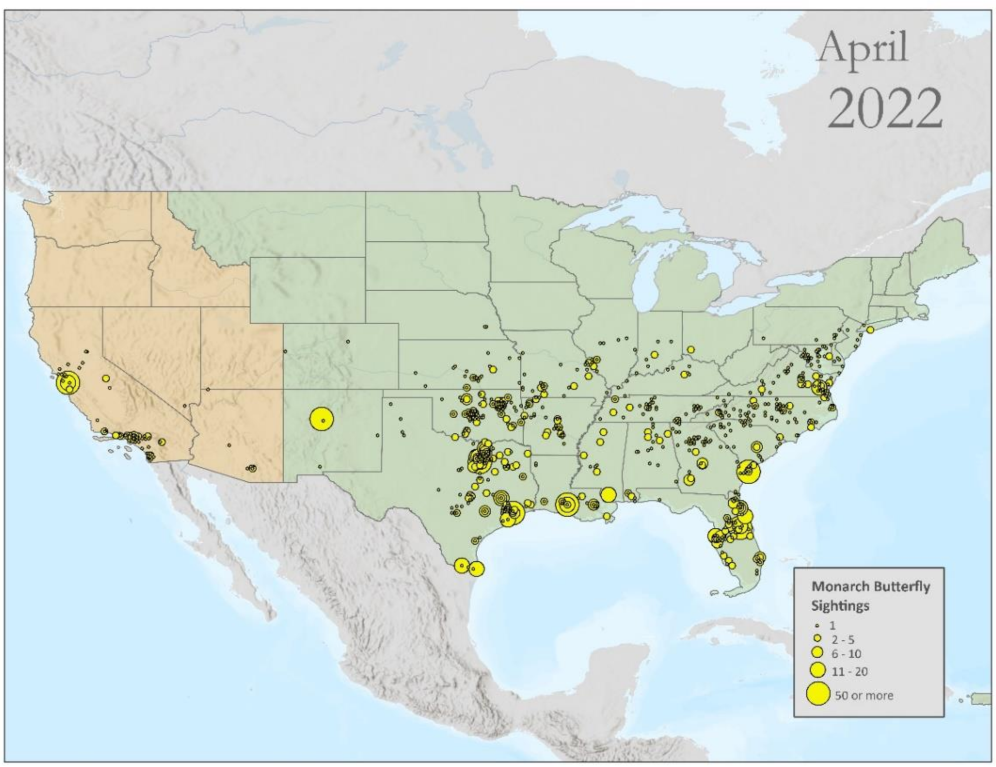

December
2021
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

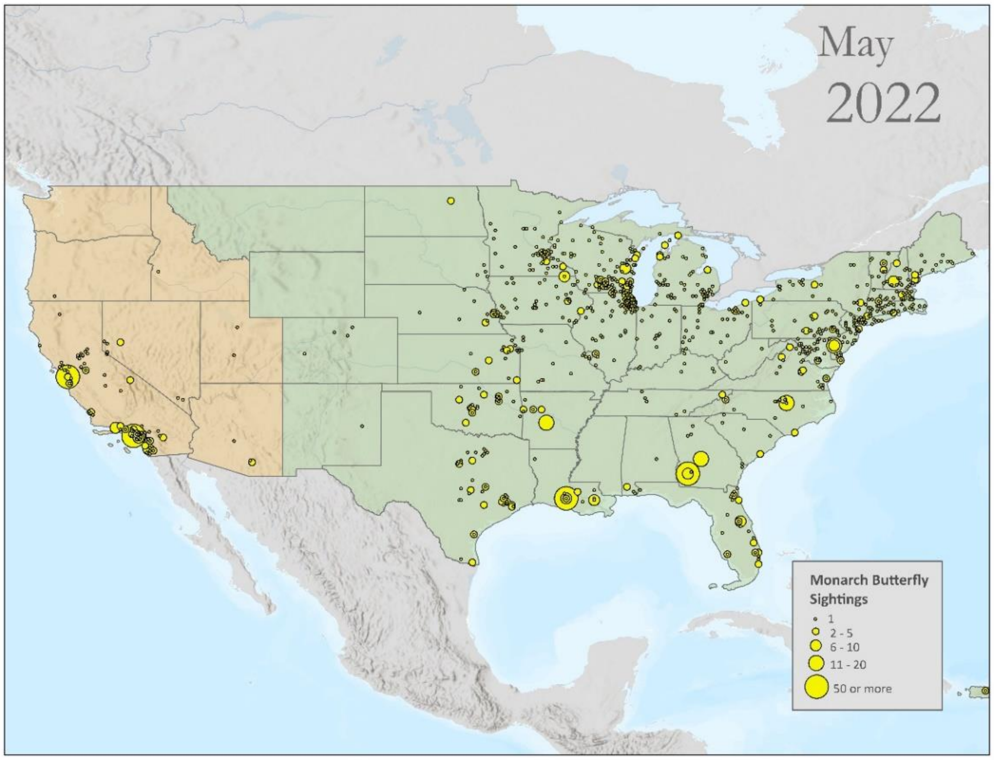
Figure A65. Monarch Butterfly Sightings - 2022

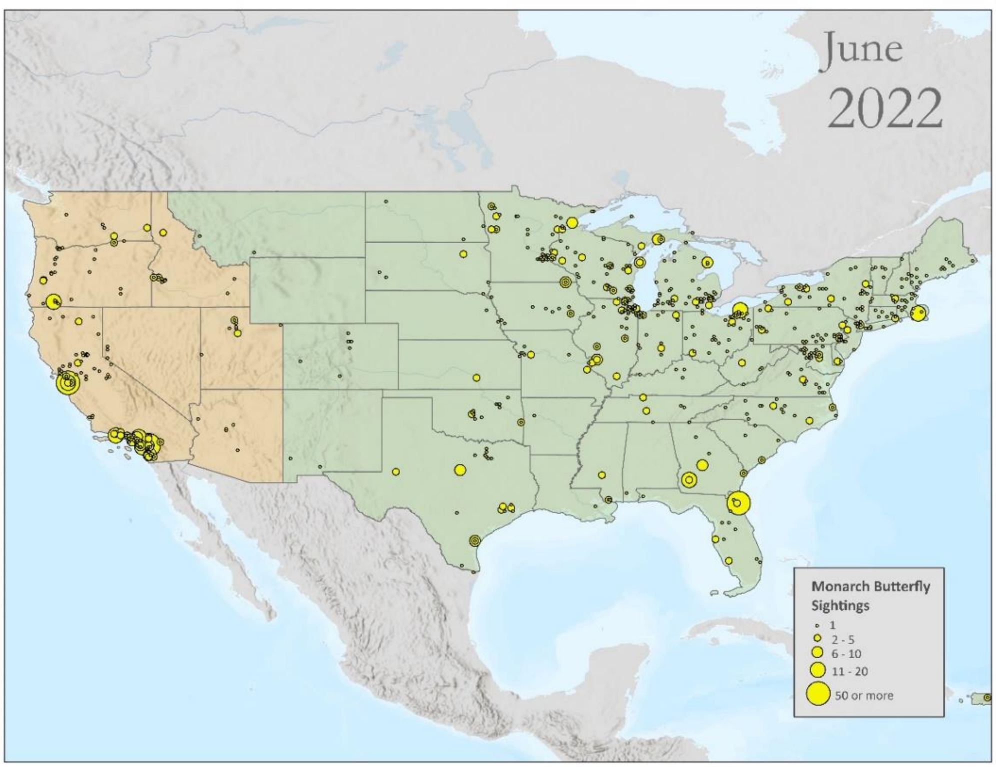


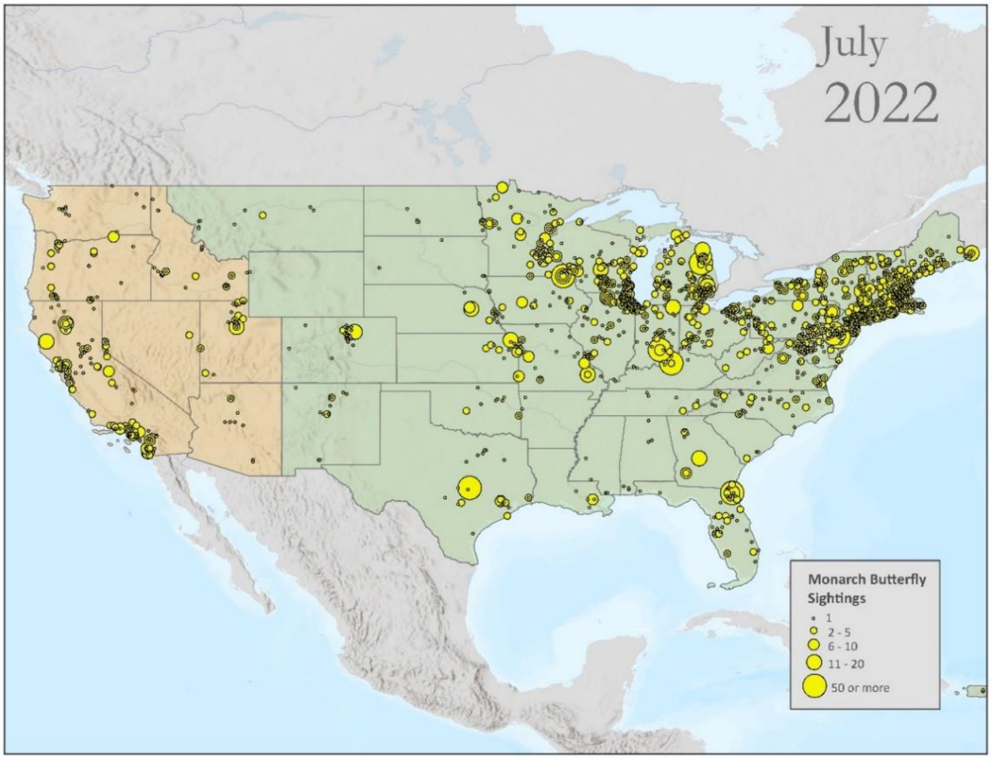


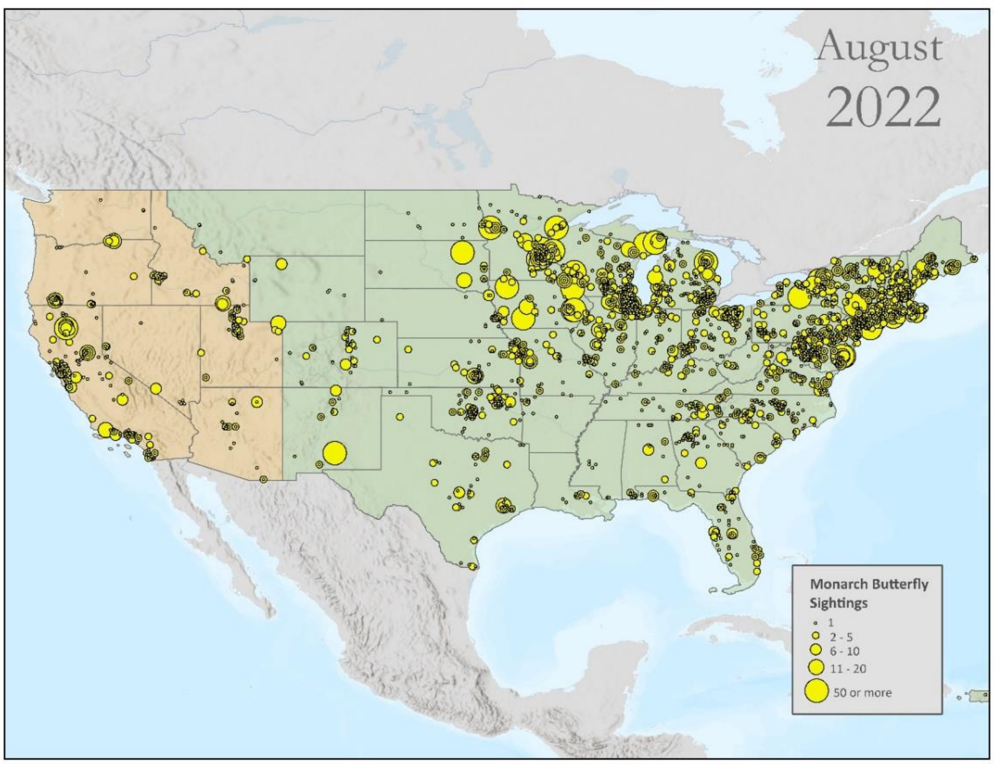

March
2022
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

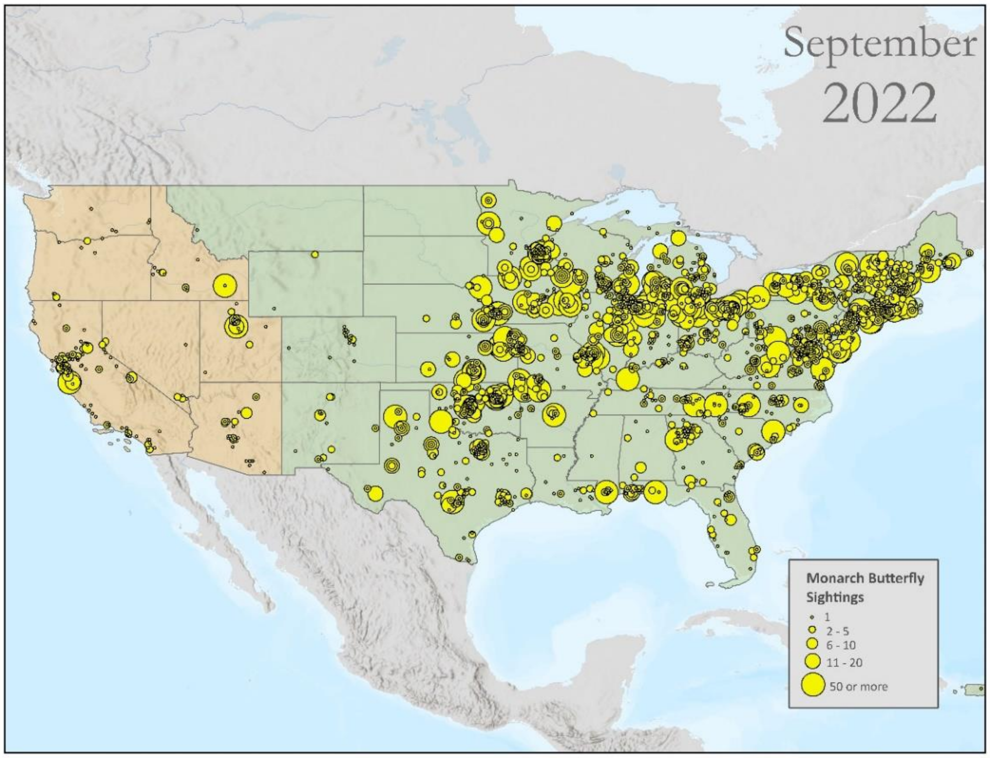

April
2022
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

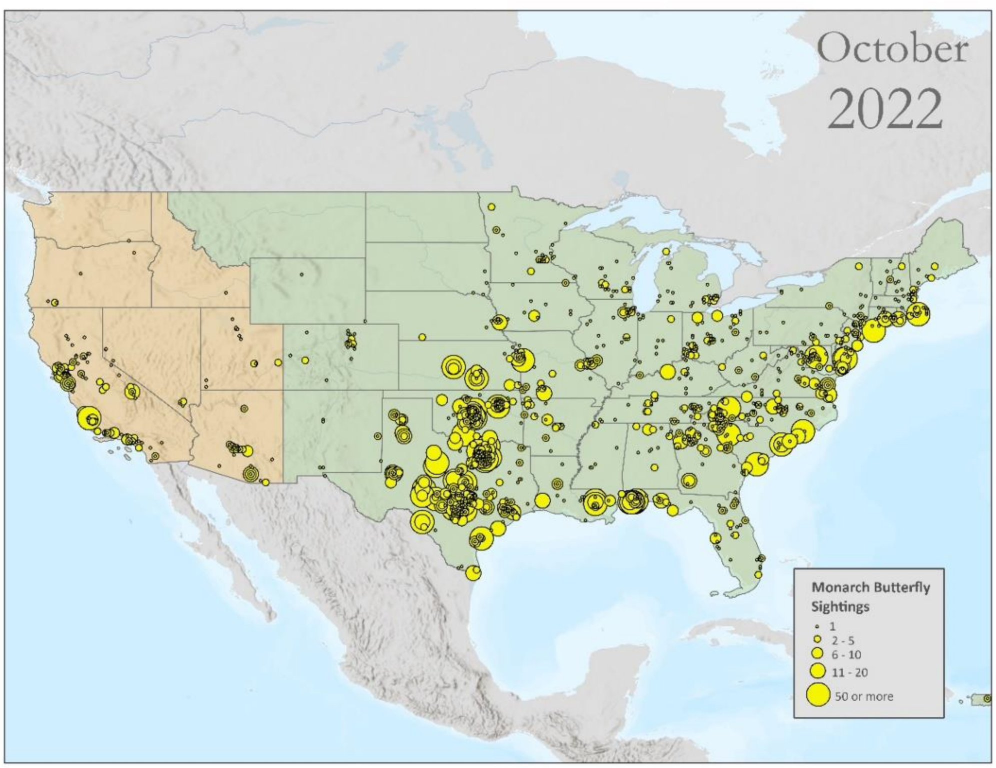

May
2022
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

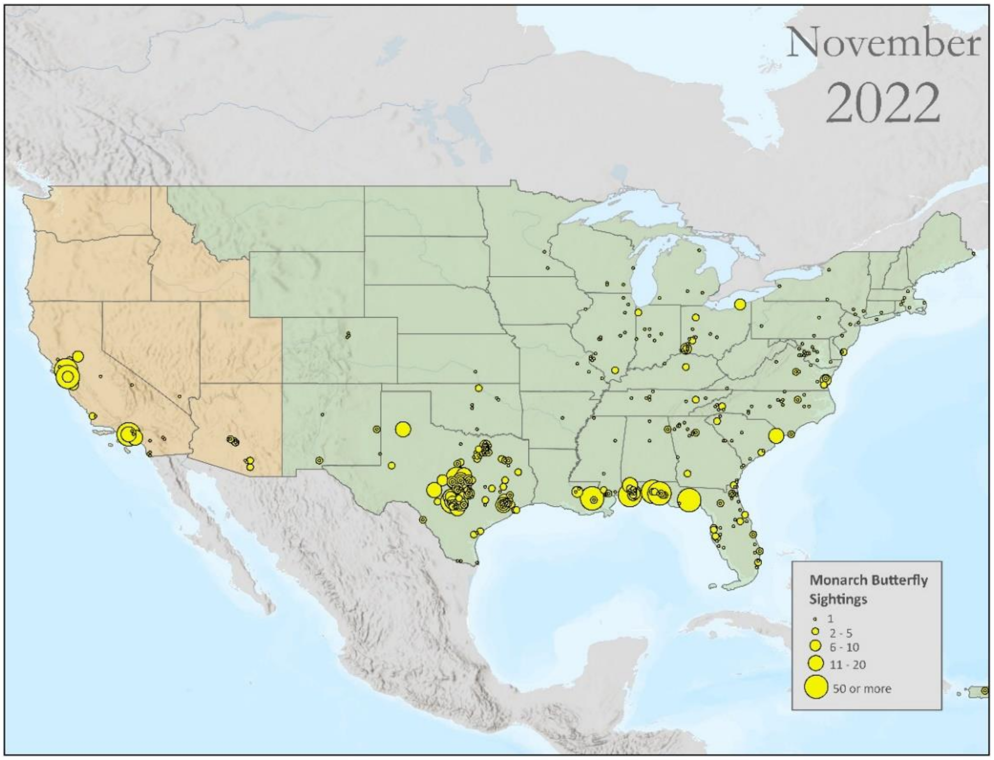

June
2022
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

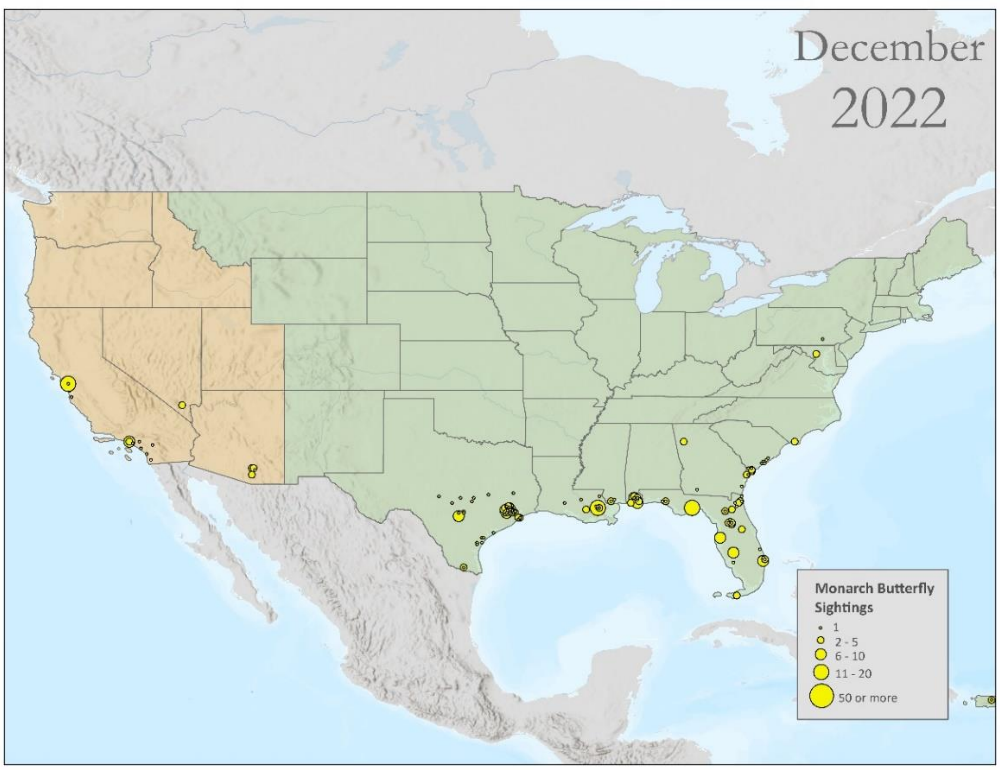

July
2022
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


August
2022
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


September
2022
Monarch Butterfly Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


October
2022
Monarch Butterfly Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


November
2022
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more


December
2022
Monarch Butterfly
Sightings
1
2 - 5
6 - 10
11 - 20
50 or more

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APPENDIX B: SINK POPULATION MAPS

Figures B66-B71 represent the Eastern monarch butterfly sightings which were retrieved from *The Journey North* monarch butterfly sightings database (journeynorth.org) and illustrate the butterfly locations during Peak Overwinter and Peak Migration months during the 2017-2022 flight years.

Figures B72-B77 represent the Western monarch butterfly sightings which were retrieved from *The Journey North* and *The Western Monarch Milkweed Mapper* (https://www.monarchmilkweedmapper.org/monarch butterfly) sightings databases. These maps illustrate the butterfly locations during Peak Overwinter and Peak Migration months during the 2017-2022 flight years.

Figures B78-B83 compare the mean temperature with the concurrent butterfly sightings data during the 2017-2022 flight years. The temperature data and map visualizations were retrieved from the PRISM Climate group at Oregon State University's data portal at *prism.oregonstate.edu.* The butterfly sightings used the same data from Figures B66 – B77.

Map Data Sources:

ArcGIS Online, n.d. Hill shade and Base map Map Data Layers. Accessed September 7, 2023. https://www.arcgis.com/

Journey North, n.d. Accessed September 7, 2023. https://journeynorth.org/.

PRISM Climate Group, n.d. Northwest Alliance for Computational Science and Engineering, Oregon State University. Accessed September 7, 2023. https://prism.oregonstate.edu/

Natural Earth, n.d. United States boundary and World Land layer. Accessed September 7, 2023. https://www.naturalearthdata.com/

Western Milkweed Mapper, n.d. Accessed September 7, 2023. https://www.monarchmilkweedmapper.org/.

Figure B66. Eastern Population Peak Overwinter and Peak Migration - 2017

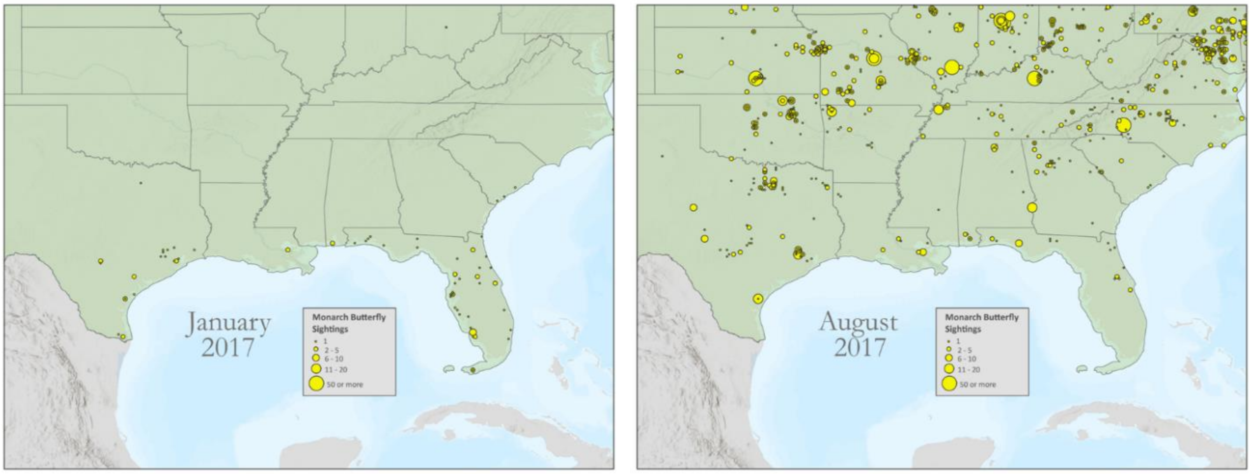

Figure B67. Eastern Population Peak Overwinter and Peak Migration - 2018

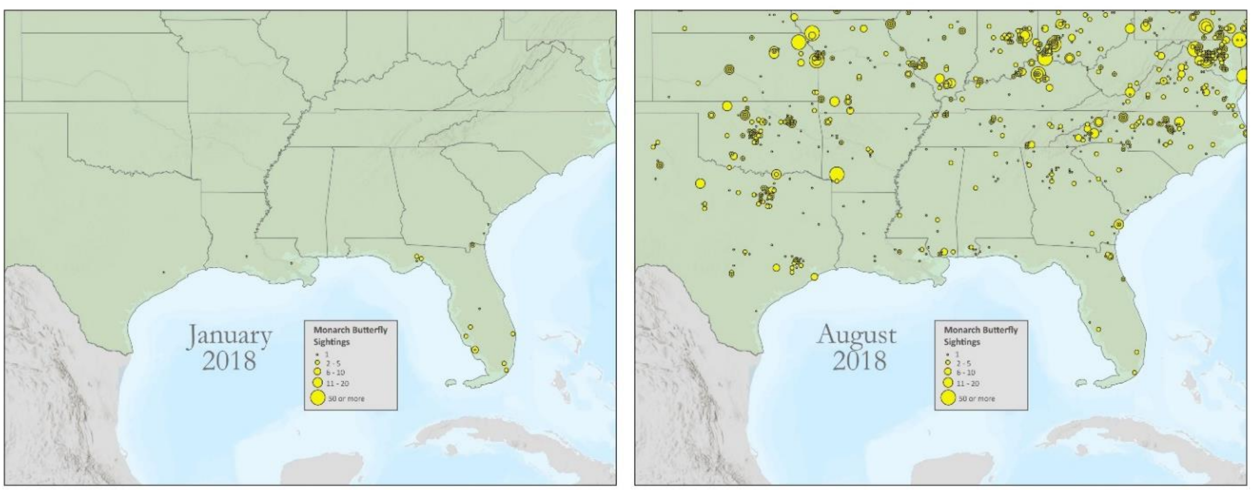

Figure B68. Eastern Population Peak Overwinter and Peak Migration - 2019

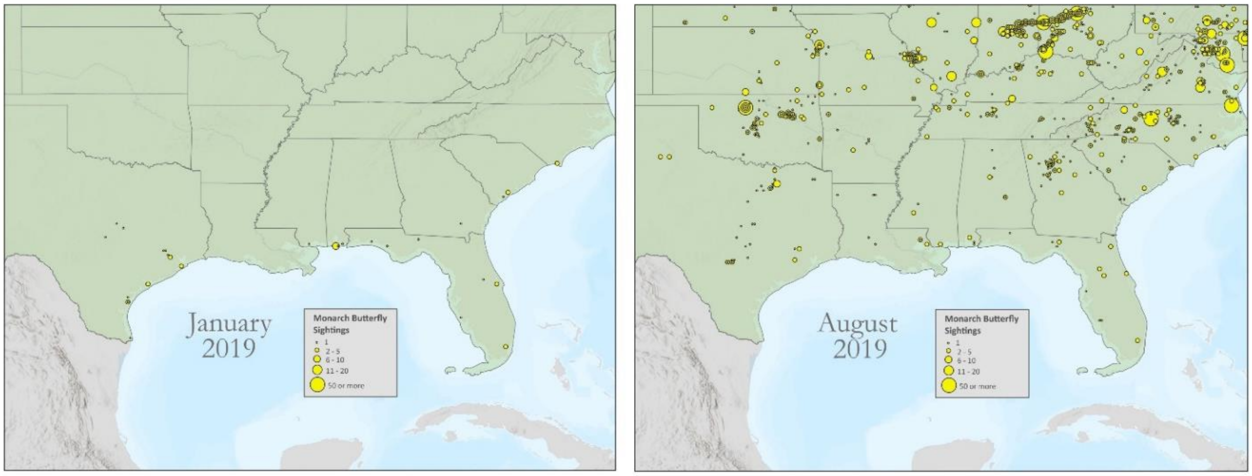

Figure B69. Eastern Population Peak Overwinter and Peak Migration - 2020

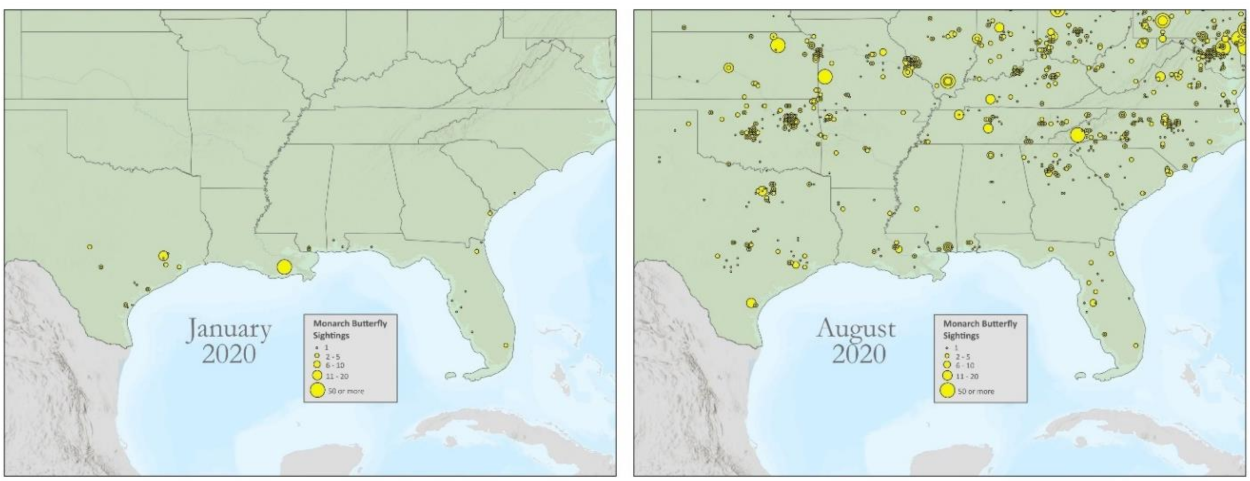

Figure B70. Eastern Population Peak Overwinter and Peak Migration - 2021

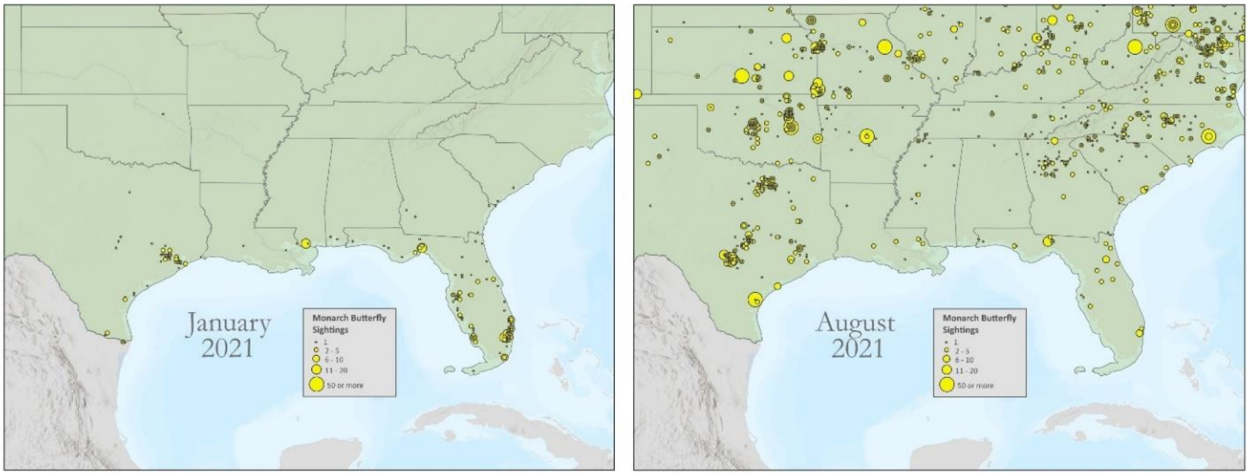

Figure B71. Eastern Population Peak Overwinter and Peak Migration - 2022

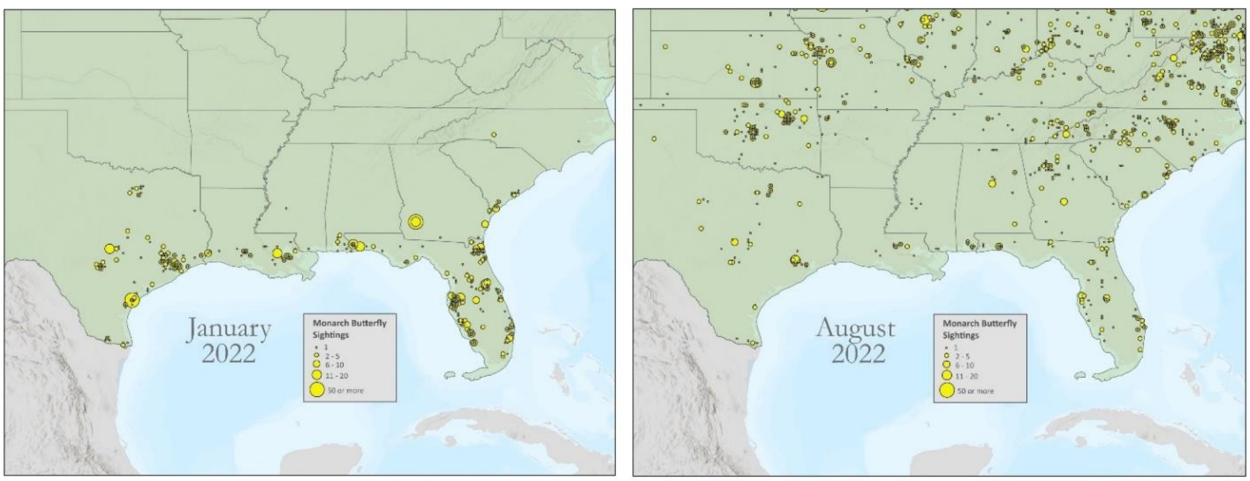

Figure B72. Western Population Peak Overwinter and Peak Migration - 2017

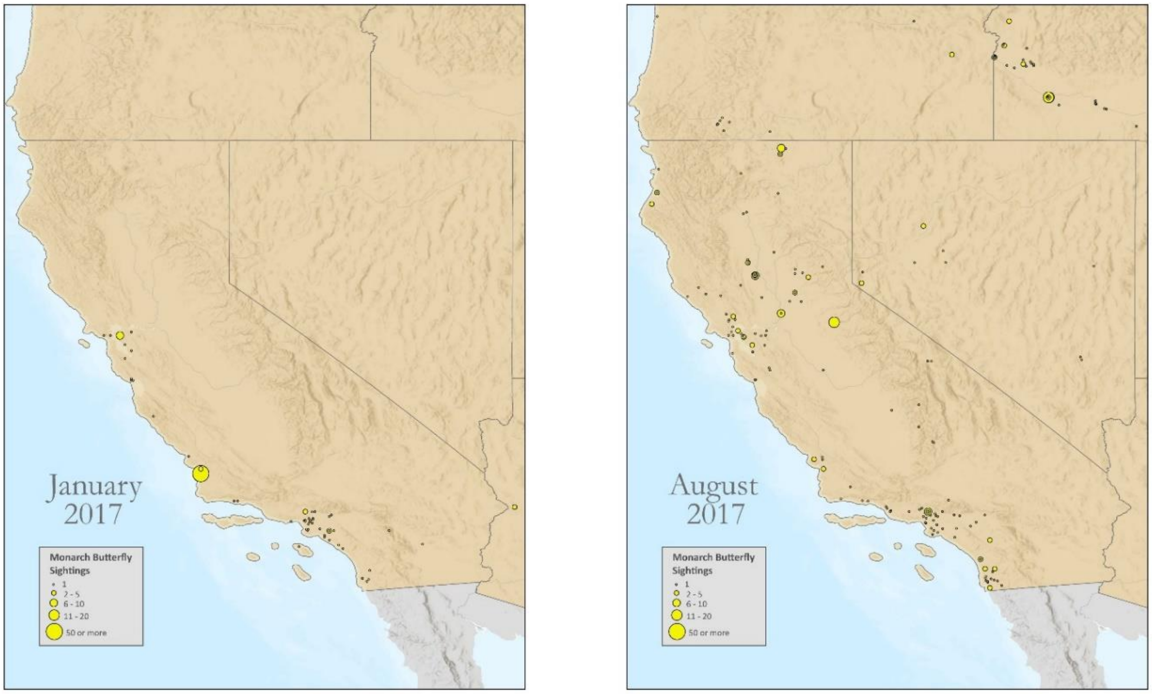

Figure B73. Western Population Peak Overwinter and Peak Migration - 2018

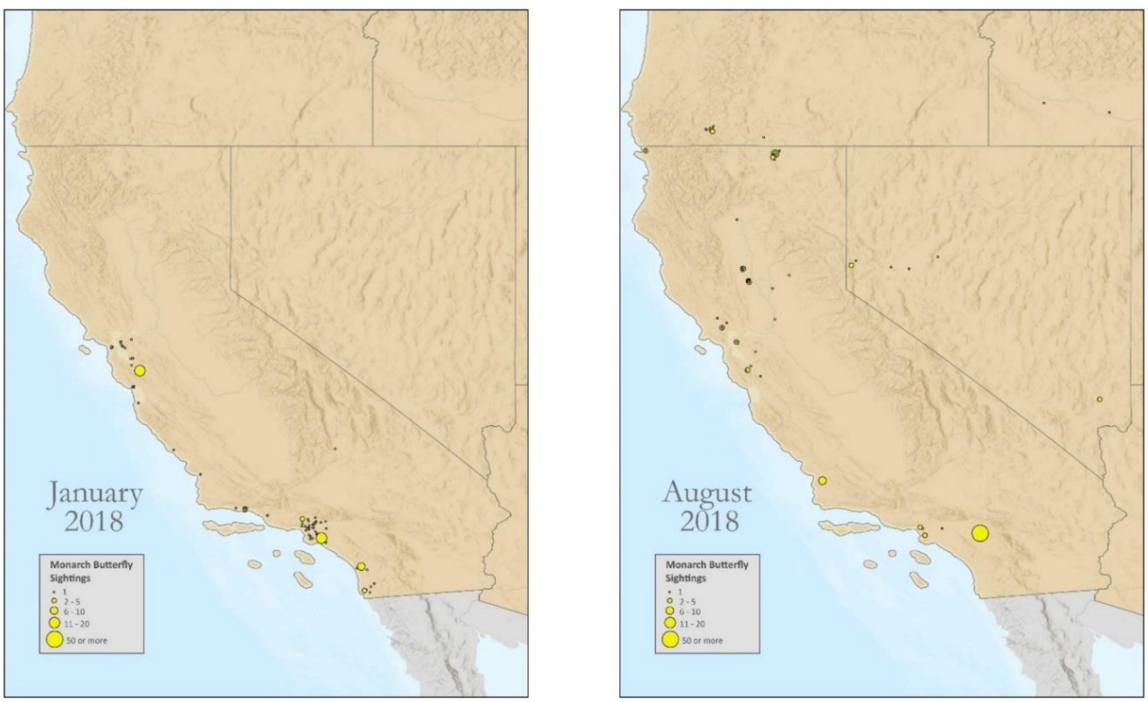

Figure B74. Western Population Peak Overwinter and Peak Migration - 2019

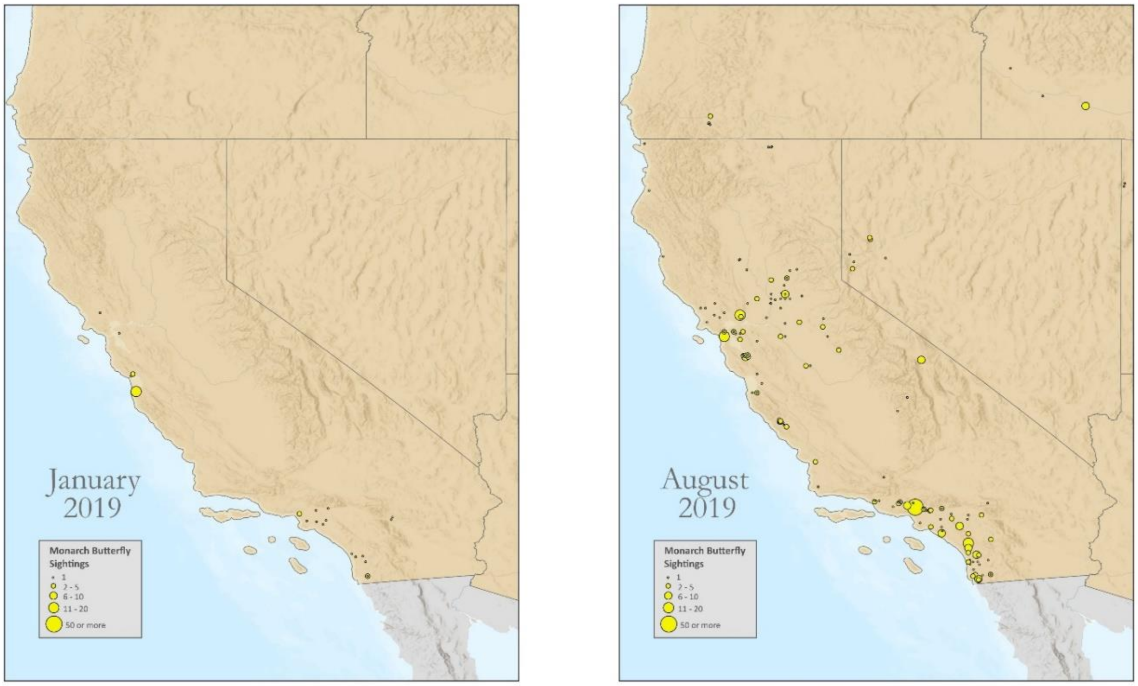

Figure B75. Western Population Peak Overwinter and Peak Migration - 2020

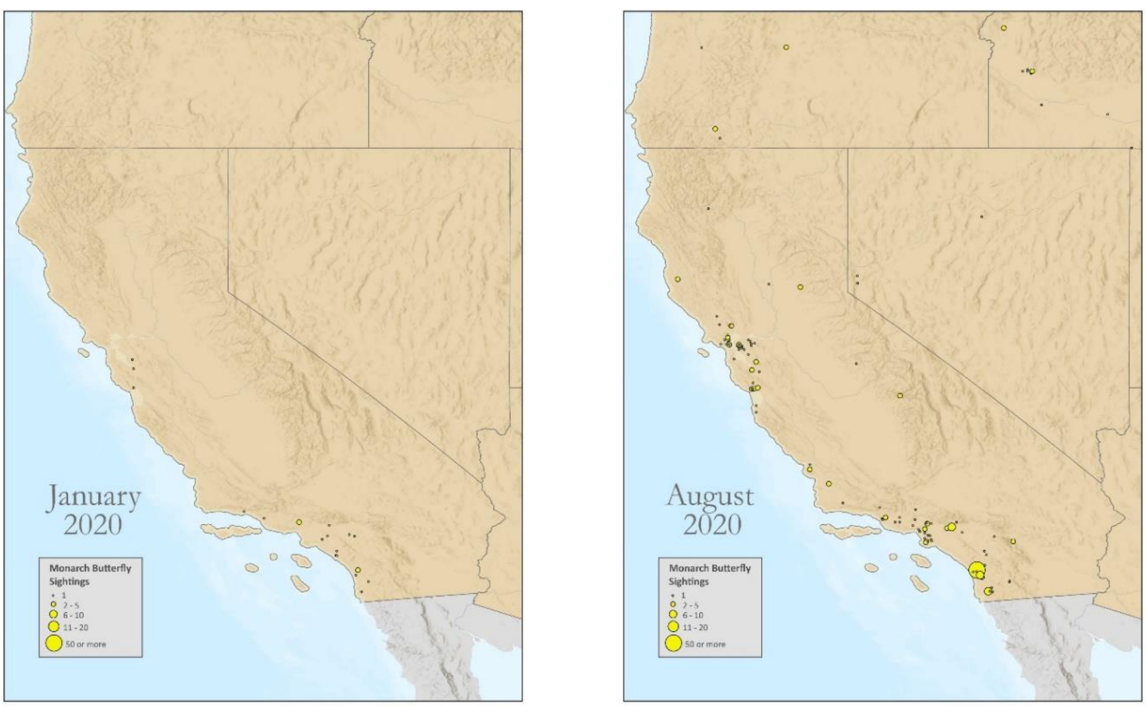

Figure B76. Western Population Peak Overwinter and Peak Migration - 2021

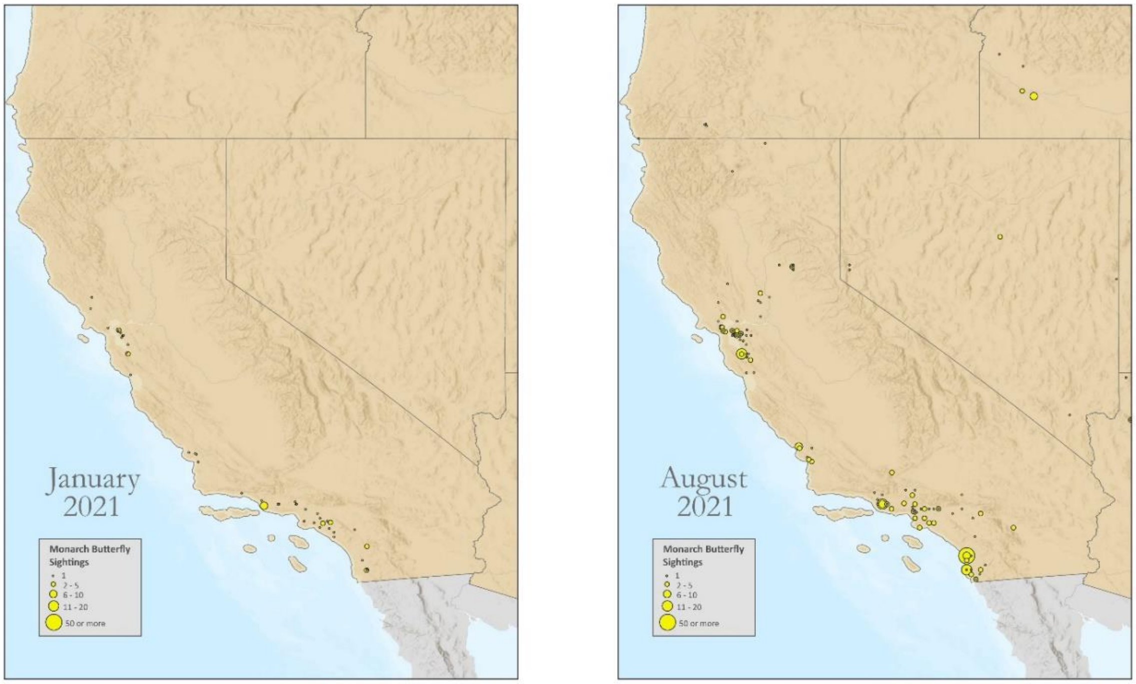

Figure B77. Western Population Peak Overwinter and Peak Migration - 2022

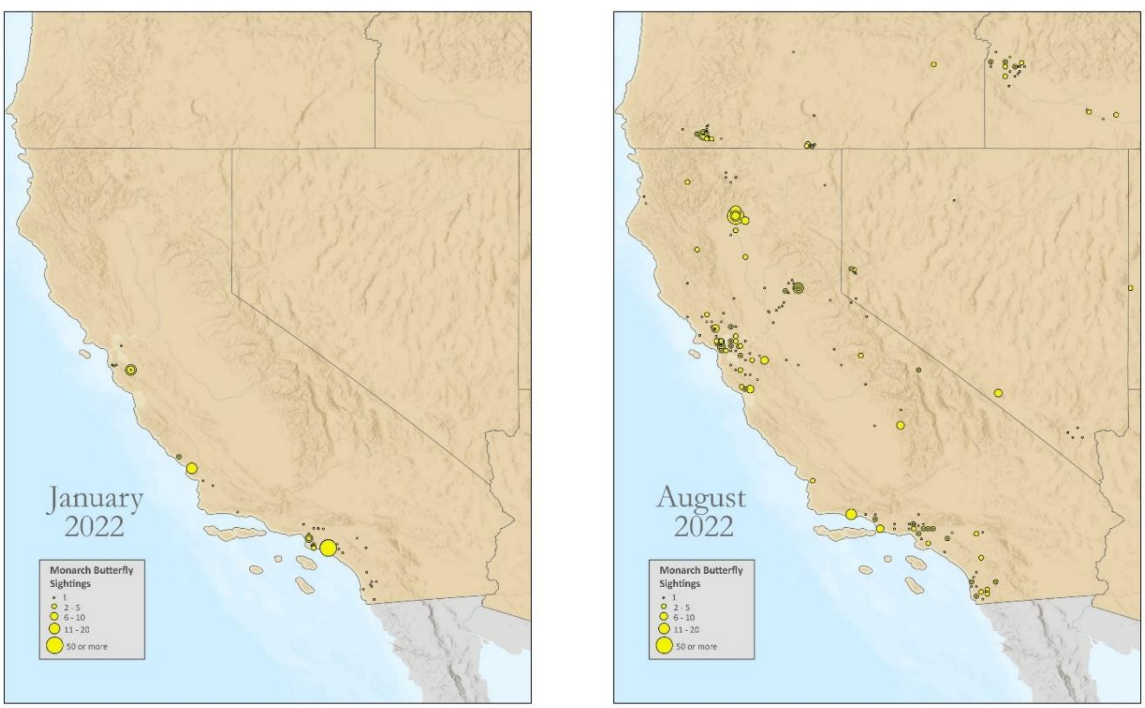

Figure B78. Peak Overwinter and Mean Temperature - 2017

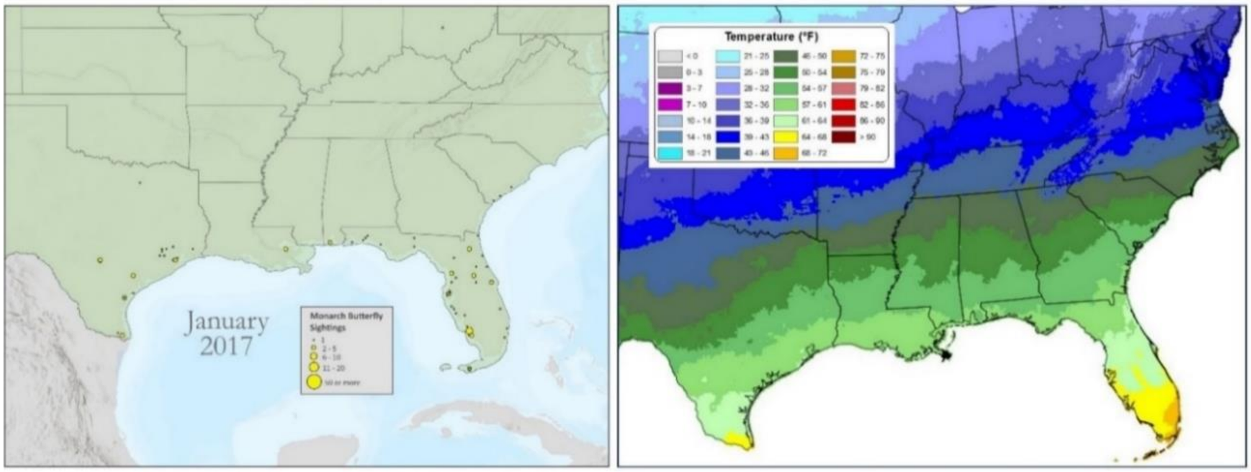

Figure B79. Peak Overwinter and Mean Temperature - 2018

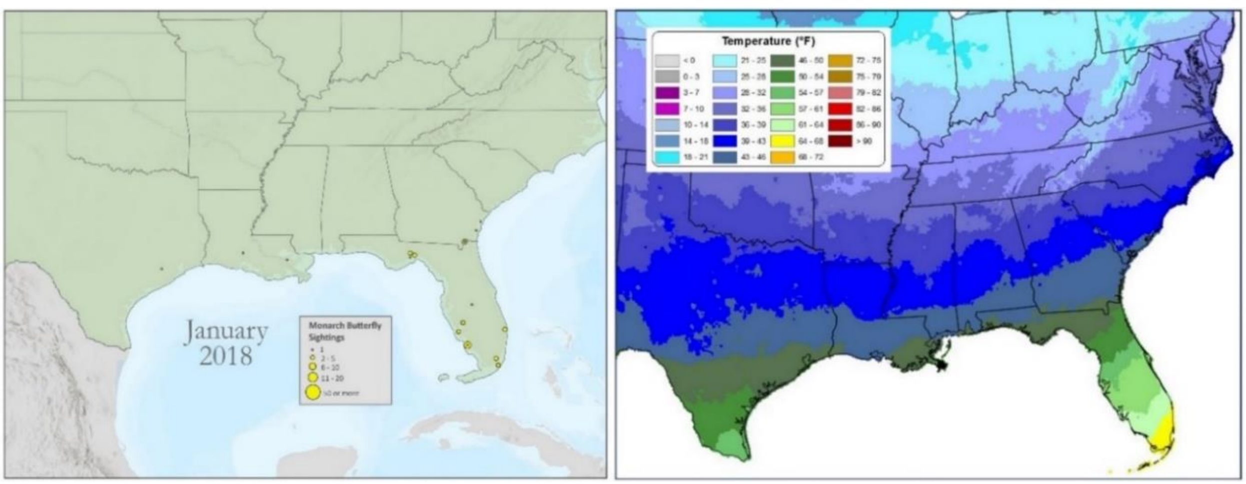

Figure B80. Peak Overwinter and Mean Temperature - 2019

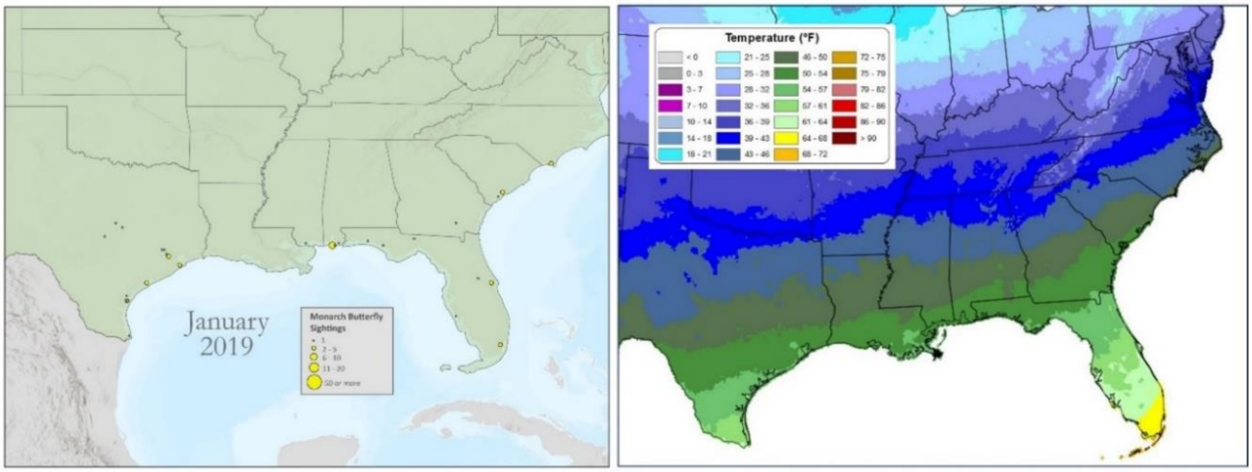

Figure B81. Peak Overwinter and Mean Temperature - 2020

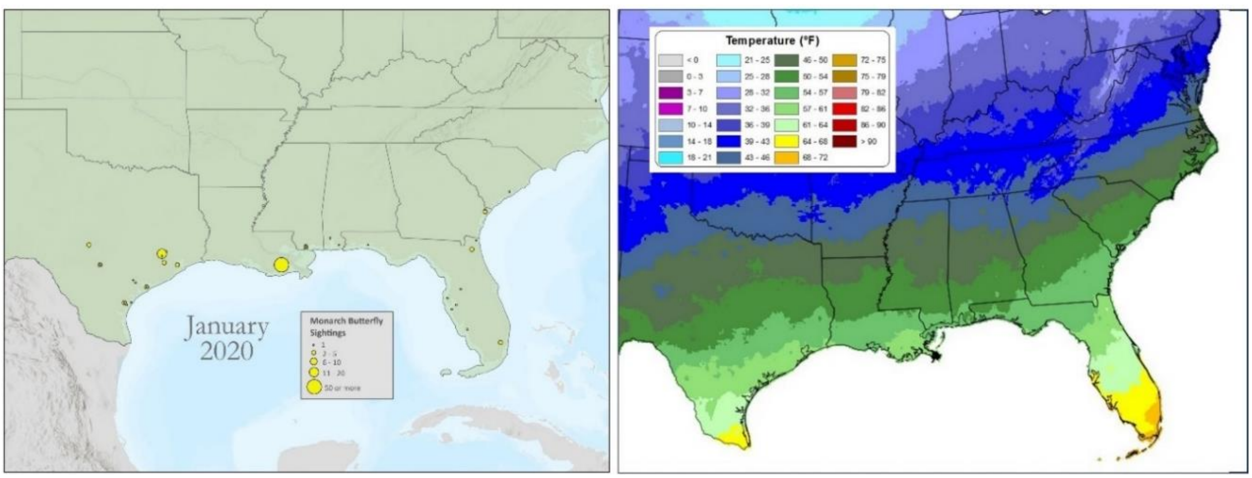

Figure B82. Peak Overwinter and Mean Temperature - 2021

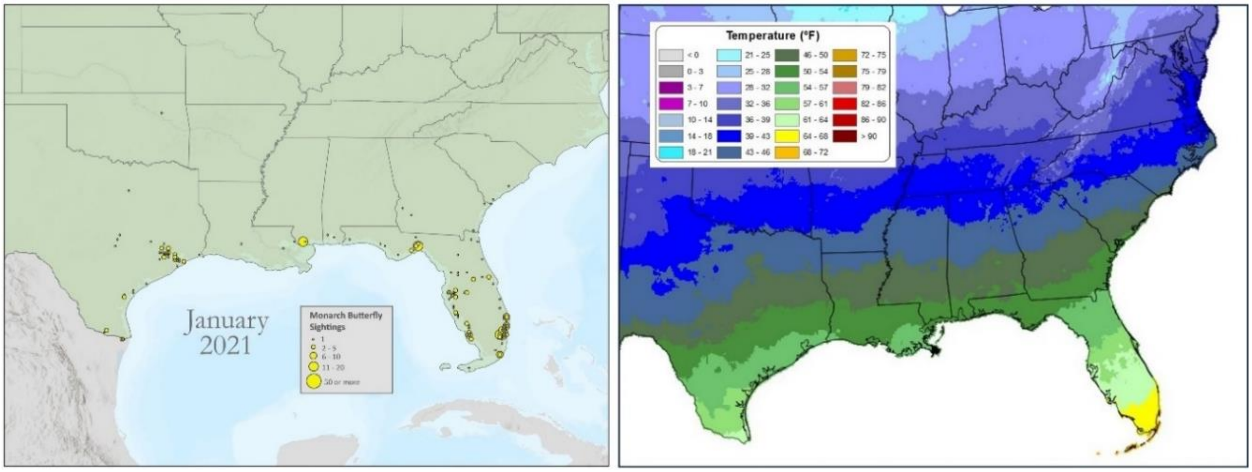

Figure B83. Peak Overwinter and Mean Temperature - 2022