# Applying Remote Sensing to Assess Habitat Viability for the Western Monarch Butterfly (Danaus plexippus plexippus) in California

# Applying Remote Sensing to Assess Habitat Viability for the Western Monarch Butterfly (*Danaus plexippus plexippus*) in California

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Abstract

Among the Lepidoptera, butterflies play a significant pollination role (Rader et al., 2016). Additionally, as widely regarded species that structure ecological communities, conservation biologists consider them "charismatic flagship" and "umbrella" species (Guiney & Oberhauser, 2008; New, 1997). The migratory monarch butterflies (*Danaus plexippus plexippus*) in North America have garnered much interest in the arena of education and ecology. Despite their significance, the abundance of western monarchs is susceptible to ecological and anthropogenic stressors, such as the loss or degradation of overwintering and of breeding sites, and climate change (Jepsen et al., 2015; Malcolm, 2018; Pelton et al., 2019). In addition, western monarch abundance has been in a continual decline for the last two decades, abruptly dropping in 2018, with low monarch abundance persisting the following year (Xerces Society Western Monarch Thanksgiving Count, 2022). Understanding what factors may be inducing this massive population decline is critical to conservation prospects for its reversal. Therefore, the main objective of my thesis research was to explore how the extent and role of large-scale habitat variation relates to overwintering monarch abundance.

To accomplish this objective, four hypotheses were tested: (1) habitat quality of coastal tree groves showed a downward trend during the study period, (2) the coastal groves showed an increase of negative anomalies in the recent decade as compared to the previous decade, (3) land cover changed in ways that are detrimental to monarch abundance, and (4) the overwintering habitat suitability in the recent decade has

decreased compared to the previous decade. Therefore, my specific aims were to conduct a two-decade spatiotemporal trend analysis of the groves along the California coast where western monarchs overwinter, as well as to evaluate whether the suitability in the recent decade has changed when compared to the previous decade. Satellite remote sensing datasets from MODIS and GPM, as well as western monarch Thanksgiving count datasets were acquired for this study. Software tools such as QGIS, Maxent, and Excel were used to process and conduct the data analysis.

The results indicated that not only the quality of the overwintering coastal groves has been deteriorating over time, but also the negative anomalies were more prominent during the recent decade (2010-2019). In addition, the dominant land cover types have been changing, and specifically: a decrease of overall canopy covered area of forest trees that provide roosting and protection to monarchs (adj $R^2$ = 83.85%; p-value = 2.61E-06); a compensatory increase in the proportion of woody savannas cover (adj $R^2$ = 82.13%; p-value = 2.71E-07); a decrease of shrublands (adj $R^2$ = 22.30%; p-value = .0271) that provide food sources to monarchs; and a steady increase of urbanization (adj $R^2$ = 97.04%; p-value = .0142). When comparing the suitability maps in 2003 with 2018, the overall extent of suitable habitat identified decreased by 20%, particularly along the south coast of California. For comparison of 2003 vs. 2018, the overwintering monarch distributions indicate a potential range shift. It is possible that this shift has occurred in response to precipitation & land surface temperature varying among study areas and, presumably throughout the monarch's tolerated range of habitats. Focusing study on California's entire coastal swath, as undertaken here, may facilitate stewardship planning by conservation planners and policymakers, with application to other pollinators as well.

## Dedication

To those who relentlessly pursue excellence for the greater good,

and appreciate the significance of little things.

For the want of a nail, the shoe was lost;

For the want of a shoe, the horse was lost;

For the want of a horse, the battle was lost;

For the failure of battle, the kingdom was lost; -

And all for the want of a horseshoe nail!

from *Fifty Famous People, A book of Short Stories*
by James Baldwin, 1912

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- Giovanni online data system, developed and maintained by the NASA GES DISC. https://giovanni.gsfc.nasa.gov/giovanni/
- NASA Applied Remote Sensing Training (ARSET) Program. https://appliedsciences.nasa.gov/what-we-do/capacity-building/arset
- MAXENT, American Museum of Natural History (AMNH). https://biodiversityinformatics.amnh.org/open_source/maxent/
- Xerces Society - Western Monarch Thanksgiving Count. https://westernmonarchcount.org/about/

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## Definition of Terms

Anomaly - the difference from a base period/ baseline. For this study (i.e., using the average of a base period of 20 years), a positive anomaly denotes the observed attribute was higher than the baseline; whereas the negative anomaly denotes the observed attribute was lower than the baseline. From the earth observation perspective, observing anomalies enables researchers to monitor the observed attribute departures from the average (base period) for a particular place and time.

Flagship Species - are commonly used to gain public interest (e.g., sympathy), enabling funding to support wider conservation needs and contexts beyond the species of immediate concern (Guiney & Oberhauser, 2008; New, 1997).

Maxent (Maximum Entropy) Modeling - species distribution modeling software that utilizes machine learning capability and a maximum entropy algorithm to generate a relative suitability rescaled value of 0 and 1, using user-provided known species presence records and environmental descriptors within a defined study area (Elith et al., 2011; Phillips et al., 2006).

Microclimate - a set of local atmospheric conditions that differ from those in the immediately surrounding areas. According to the California Coastal Commission (2021), five major climate types occur in close proximity in California are: desert, cool interior, highland, steppe, and Mediterranean.

Native vs. Non-native Trees - for this paper, the overwintering coastal groves/ forests along the California coast are primarily comprised of native tree species such as Monterey pine (*Pinus radiata*), Monterey cypress (*Cupressus macrocarpa*), western sycamore (*Platanus racemosa*), coast redwood (*Sequoia sempervirens*), and coast live oak (*Quercus agrifolia*); whereas non-native trees include eucalyptus (*E. globulus*) and red gum (*E. camaldulensis*) (Jepsen et al., 2015).

Non-bee Pollinators - insect pollinators such as flies, beetles, moths, and butterflies (Rader et al., 2016).

Overwintering Grounds - generally, the western migratory monarch butterflies overwinter at coastal groves/ forests along the Pacific coast of North America, with their main concentration at the California coast; whereas the eastern monarch butterflies overwinter in Mexico (Western Monarch Milkweed Mapper, 2022).

Satellite Remote Sensing - the process of capturing the physical attributes of an area by measuring the object's reflectance which is detected by the sensor(s) aboard a satellite (USGS, 2022).

Umbrella Species - their conservation is intended to foster persistence of co-occurring species that share habitat and other ecological resources (Guiney & Oberhauser, 2008; New, 1997).

Xerces Society Western Monarch Thanksgiving Count (2022) - since 1997, there has been a yearly organized initiative (three weeks surrounding the Thanksgiving holiday) of volunteers/ community-scientists to collect data on the status of the western monarch population along the Pacific coast, ranging from Mendocino to Northern Baja Mexico. The detailed methodology is found at https://www.westernmonarchcount.org/about/

# Chapter I

## Introduction

Among the Lepidoptera, butterflies play a significant pollination role (Rader et al., 2016). Additionally, as widely regarded species that structure ecological communities, conservation biologists consider them “charismatic flagship” and “umbrella” species (Guiney & Oberhauser, 2008; New, 1997).

A downward shift in abundance of such species could reflect changes in habitat conditions, perhaps signaling the need for assessment and conservation plans by researchers and policymakers.

Western monarch butterfly abundance at its overwintering sites has declined during the last two decades, reaching a markedly abrupt drop in 2018. Unlike preceding episodes, this decline was not followed by a recovery in 2019 (Figure 1). The low populations in 2018 and 2019 drew much attention from local policymakers and conservation communities. Two decades of data from the Xerces Society’s Western Monarch Thanksgiving Count (2022) reveal that the overwintering population dropped from 390,057 (across 139 overwintering sites) in 2000 to 27,721 (across 213 overwintering sites) in 2018 and 29,418 (across 240 overwintering sites) in 2019. Despite an increase in surveyed sites, observations of low monarch abundance persisted (Figure 1).

In addition, recent studies indicated that western monarch declines occurred predominately either while most monarchs were still roosting at their overwintering groves or immediately afterward (Espeset et al., 2016; Pelton et al., 2019).

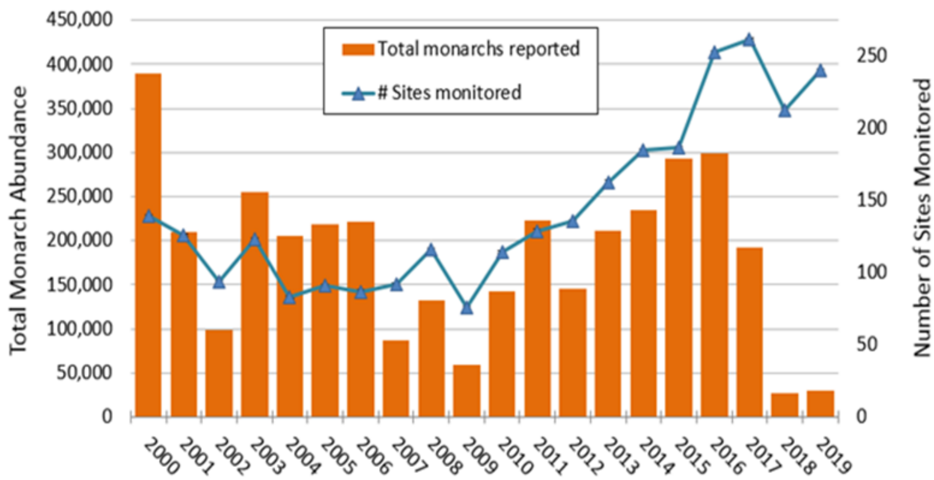



Figure 1. The Western Monarch Thanksgiving Count, 2000-2019.
Total monarch abundance from 2000 to 2019 (Extracted from the Xerces Society Western Monarch Thanksgiving Count, 2022).

Therefore, it is essential to gain insights into the conditions of these overwintering coastal sites, which occur along California's coast, and the nature of any reduction in monarch habitat quality.

## Research Objectives and Significance

Satellite remote sensing data and techniques were used to assess the potentially deteriorating condition of the coastal groves on which monarch survival depends. From two decades of observations of overwintering, this analysis was intended to facilitate stewardship planning by policymakers and relevant conservation organizations, with potential application to the management of other pollinators.

Accordingly, the research objectives were to:

- Improve understanding of how large-scale habitat variation relates to western monarch butterfly occurrence and abundance;
- Utilize satellite-based remote sensing methods to examine the past two decades of change in the potentially deteriorating condition of California's coastal groves that provide habitat resources for overwintering western monarch populations;
- Explore how variation in vegetation and other environmental descriptors could offer useful insights for conservation policy and regulatory decision-making.

## Background

Among the Lepidoptera, butterflies merit great interest due to their aesthetic, educational, and ecological significance. Spanning observations of 17 crops in 480 fields across five continents in 39 studies, a cohort research effort quantitatively analyzed the relative contributions of non-bee pollinators to crops dependent on pollinators (Rader et al., 2016). The authors concluded that non-bee pollinators are efficient in providing high pollination services (i.e., non-bees accounted for 38% [CI: 29–49%], honey bees 39% [CI: 29–50%], and other bees 23% [CI:15–33%] of visits to crop flowers). Since bees and non-bees respond to landscapes differently, they asserted that non-bee pollinators could supplement bees to provide more stable crop-pollination services as a buffer against the increased changes in land use. Thus, such pollinators play a vital role in crop production, particularly given declining bee populations (Rader et al., 2016).

Additionally, butterflies such as the migratory monarchs follow a migration path that spans their breeding to overwintering grounds (ranging from Canada to Mexico and California), across widely varying habitat types as delineated by vegetation and microclimatic conditions. The conservation of monarch nectar resources, as well as their breeding and overwintering grounds, will also benefit other species (Guiney & Oberhauser, 2008). In addition, attention to monarch butterfly decline reflects concern that a larger challenge is underway, especially in areas hosting significant crop production (California's over $50 billion agriculture industry represents over 13% of the U.S. 2018 total; CDFA, 2022). Therefore, the sections below address the current state of western monarchs in California and explore the likely challenges and stressors impacting monarch abundance.

## Monarch Butterfly Life Cycle and Distribution in the United States

The abundance of the migratory monarch butterflies (*Danaus plexippus plexippus*; hereafter "monarch") in North America has been studied and monitored for decades. They can be found across landscapes, such as roadsides, farmlands, deserts, prairies and meadows, open forests and woodlands, as well as in cities and gardens (Jepsen et al., 2015). At the breeding grounds, monarchs lay eggs on milkweeds (*Asclepias spp.*) that contain cardenolides that protect their larvae. It takes about 3-5 weeks to mature from egg to adult butterfly. As an adult, monarchs spend another 2-6 weeks to feed, mate, and lay eggs. The same life cycle is repeated throughout spring and summer, excepting the generation emerging in late summer/ early fall. The decreasing day length and temperature, and food abundance impact development of a "super generation." This monarch generation develops to be prepared for the migration and does not breed until overwintering is complete. They have a larger wingspan, and live an extended 6-9 months that enables them to fly to overwintering grounds, as well as to breed on their way back to inland breeding grounds (Brower, 2015; Guerra, 2020; Pyle, 2015; Western Monarch Milkweed Mapper, 2022).

For the fall migration, the eastern monarchs overwinter in Mexico, whereas the western monarchs generally overwinter at groves along the California coast (Figure 2). A wide variety of plants are nectar sources that sustain fall migration. The availability of fall- and winter-blooming nectar plants is particularly essential for allowing monarchs to convert nectars into energy and lipids during their fall migration, and for their winter survival (Jepsen et al., 2015).

When monarchs are at the coastal groves during winter months, they are mostly in productive diapause (i.e., reproductively inactive) and spend most of the time roosting in clusters which conserves their stored lipids. They limit their activities to basking in the sun, drinking water from nearby sources, and feeding on the winter-blooming nectar plants. This in turn, sustains monarchs throughout the winter and providing sufficient energy to mate and fly to their breeding grounds when the weather warms (Jepsen et al., 2015).

Both eastern and western monarchs begin departing their overwintering grounds in February and March, and arrive at their breeding grounds (the northern limit of their North American range) around early to mid-June (Jepsen et al., 2015; Pelton et al., 2016; Western Monarch Milkweed Mapper, 2022).

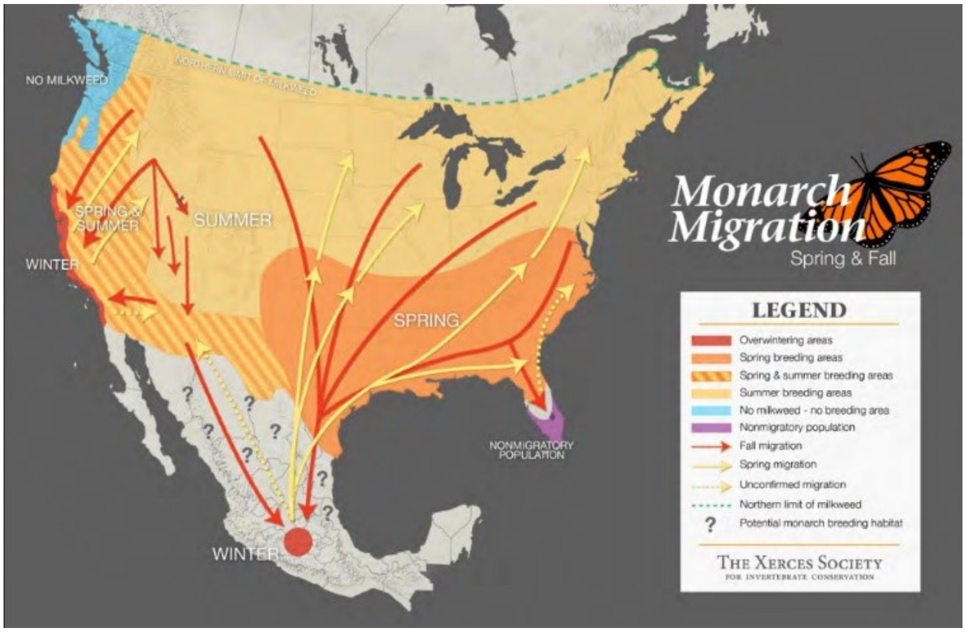



Figure 2. Monarch migration routes in North America.
For the fall migration, the eastern monarchs overwinter in Mexico, whereas the western monarchs generally overwinter at tree groves along the California coast (Jepsen et al., 2015).

Status, Challenges, and Stressors of Western Monarchs in California

Studies of the western monarch (*Danaus plexippus plexippus*) are sparse compared to the more widely examined eastern monarch (Crone et al., 2019; Xerces Society, 2022b). However, it is known that western monarchs are vulnerable to various stressors, such as the loss or degradation of overwintering sites (i.e., the availability and quality of overwintering habitat), climate change (e.g., increased drought and severe storms), the loss of breeding habitats (e.g., diminution of milkweed feeding and oviposition sites, and impacts of herbicides and insecticides) (Crone et al., 2019; Jepsen et al., 2015; Malcolm, 2018; Pelton et al., 2016; Pelton et al., 2019).

Census data collected from 2000 to 2019 by the Xerces Society show that Western monarch abundances at their overwintering sites have declined significantly, particularly in 2018 (Figure 1). By observing the Thanksgiving count and the New Year's count (i.e., six weeks after the Thanksgiving count), as well as analyzing daily survival rates, Pelton et al. (2019) found that the daily survival rates during the recent overwintering periods (2017-2019) were much lower (a drop in the range of 36-49%) when compared to the historical estimate (a drop of only 29-32%). In addition, by monitoring the summer breeding sites (i.e., monarch egg and larval abundances) across the West in 2017 and 2018, the authors' analysis suggests that the decline in the 2018 Thanksgiving count occurred prior to the beginning of the 2018 breeding season; i.e., the decline happened either late during the overwintering season in 2017 while monarchs were still roosting or very early in the breeding season in the early spring (of 2018) when monarchs began to take flight from their overwintering habitats back to their inland breeding grounds (Pelton et al., 2019).

This conclusion from Pelton et al. (2019) echoes the analysis of over 40 years of data showing western monarch declines were due to increased mortality concentrated either during or immediately after overwintering, when most monarchs were still at their overwintering grounds (Espeset et al., 2016). Thus, examination of the important role played by the coastal groves where western monarchs overwintering could illuminate possible causes of this increased mortality.

## The Importance of Overwintering Coastal Groves

The unique characteristic of monarchs is their wide distribution across vast inland breeding grounds of the United States from spring to late fall. However, in winter, they congregate en masse at very limited and specific coastal groves - the availability and quality of which is essential for protection and survival (Pyle, 2015).

In fact, western monarchs return to many of the same overwintering locations year after year. Generally, they arrive in mid-October and form dense clusters on tree branches, leaves, and at times tree trunks in the coastal groves along the California coast (Figure 3).

Unlike eastern monarchs that roost at their overwintering grounds in dense and high mountain forests in Mexico, western monarchs reside at the overwintering sites (tree groves) that are at low elevations (below 60-90m) and within 2.4km of the California coast. However, both eastern and western monarch overwintering grounds are characterized by microclimatic conditions that provide a mild and consistent temperature (both day and night) when compared to the surrounding areas that are beyond such climate conditions (Brower, 2015; Jepsen et al., 2015; Pyle, 2015).

Figure 3. Western Monarchs clustering at a California overwintering site.
Source: author, 2021.

These overwintering coastal groves along the California coast are primarily comprised of tree species such as eucalyptus (*E. globulus*), red gum (*E. camaldulensis*), Monterey pine (*Pinus radiata*), Monterey cypress (*Cupressus macrocarpa*), western sycamore (*Platanus racemosa*), coast redwood (*Sequoia sempervirens*), and coast live oak (*Quercus agrifolia*). Monarchs have been recorded clustering on these native and non-native trees. The composition and structure of both native and non-native tree species within a coastal grove that provides a suitable microclimate plays an essential role for their winter survival (Griffiths & Villablanca, 2015; Jepsen et al., 2015; Longcore et al., 2020; Pelton et al., 2016; Pyle, 2015).

In addition, western monarchs prefer a winter roosting habitat that provides a dense and mature canopy, and offers specific microclimatic conditions that shield them from wind and harsh weather elements (Brower, 2015; Jepsen et al., 2015; Pyle, 2015). The coastal groves supply specific microclimatic conditions that maintain certain temperature ranges during the day and night (i.e., a mild and consistent temperature throughout the winter -- cool during the day and warm during the night), and act as a blanket for the monarchs. The coastal fog/marine layer, sufficient sunlight, and protection from wind provide monarchs an ideal environment to overwinter (Pyle, 2015).

However, monarch mortality increases when they are wet and in freezing conditions (Brower, 2015). Thus, during the day, the overwintering sites should offer sufficient insolation to enable monarchs to thermoregulate by basking in the sun. Monarchs will cluster at a certain tree height to maintain ideal temperature and avoid treetops that are exposed to colder temperatures. Tall and mature trees with larger trunks that hold more heat and offer warm spots for monarchs if night temperatures become too cold. Therefore, tall mature trees are essential for the monarch to roost and survive (Brower, 2015).

## Application of Satellite Remote Sensing Data and Techniques

In order to assess the intricate conditions such as those found in coastal groves that span the entire swath of the California coast, data acquired from remote sensing satellites have been found useful, particularly for observing environmental dynamics, disturbances, and anomalies. Satellite-based remote sensing data offer valuable opportunities for assessing past and current habitat conditions in a large-scale and consistent manner within specified temporal intervals. In addition, satellite remote sensing observations not only provide information where ground-based measurements are absent, but also, they are generally a cost-effective means of assessing environmental phenomena (NOAA, 2022; Rose et al., 2014; Turner et al., 2015).

The MODIS vegetation index (VI) products such as NDVI (normalized difference vegetation index) and EVI (enhanced vegetation index) (NASA MODIS, 2022) have been a main data source used to monitor and assess regional or global vegetation dynamics to better understand vegetation and forest change over broad areas. Researchers have been using such indices for a wide variety of studies, such as to gain an understanding of the phenological variability in spring and fall across environmental gradients in Great Smoky Mountains National Park (Norman et al., 2017); to study the leaf phenology of tropical evergreen forests in South America (Xiao et al., 2006); to observe forest defoliation by gypsy moth outbreaks in the Eastern U.S. (Spruce et al., 2011); and to conduct rangeland planning in central Asia (Reeves & Bedunah, 2006).

Such remote-sensed data of forest conditions could help to overcome the challenges of observing forest change across regions due to variations in environmental conditions, where there may be a paucity of ground measurements of productivity (Waring et al., 2006). Moreover, the capability of producing consistent observation data for key drivers of biodiversity change at either the local or global level, has made satellite remote sensing techniques particularly useful (Turner et al., 2015).

In addition, satellite remote-sensed data that are consistent and provide even geographic coverage of bioclimatic and environmental descriptors, could also enhance knowledge of species distributions for biodiversity analysis and species distribution modeling (Phillips et al., 2006; Waltari et al., 2014). These techniques can be usefully applied to assess changes in the quality of the overwintering habitats of western monarch butterflies.

## Research Questions, Hypotheses, and Specific Aims

Therefore, this study centered on using remote sensing data and techniques to examine the potentially changing and deteriorating conditions of coastal groves across monarch overwintering habitats along the entire California coast. Accordingly, analyzing the anomalies and trends of vegetation and environmental variables for the last two decades (i.e., 2000-2019), as well as the degree to which these correlate with the observed monarch decline, holds particular interest. In this context, my proposed research addressed the questions and hypotheses listed below.

$Q_1$: What was the state of California's western monarch overwintering grounds (as detected in the study area) from 2000-2019?

$H_{1a}$: Habitat quality of coastal groves (the EVI and NDVI average) showed a downward trend during the study period.

$H_{1b}$: The coastal groves (the EVI and NDVI average) showed an increase of negative anomalies (i.e., lower than the 20-year average) in the recent decade as compared to the previous decade.

$H_{1c}$: Land cover type (LC) changed in ways that are detrimental to monarch abundance, such as a shift in vegetation species and an increase in urbanization.

$Q_2$: Has the California western monarch overwintering habitat suitability changed in the recent decade compared to the previous decade?

$H_2$: The overwintering habitat suitability in the recent decade (2013 and 2018) has decreased compared to the previous decade (2003 and 2008).

Specific Aims

In order to address these research questions and to test associated hypotheses, my specific aims were to:

1. Conduct a two-decade spatiotemporal trend analysis of coastal groves of western monarch overwintering habitat along the California coast by using satellite-based remote sensing data.
2. Determine if the overall trend pattern (the state) of coastal groves has changed over the period of the last two decades, and if so, what has changed and to what extent, specifically related to land cover types within the study area (e.g., evergreen needle forest, evergreen broadleaf forest, urban).

3. Generate time series trend charts over the entire study period to depict trend patterns, as well as anomaly (difference) charts to illustrate the intensity/ frequency of anomaly-occurrence years.
4. Evaluate whether the western monarch overwintering habitat suitability in the recent decade (2013 and 2018) has changed when compared to the previous decade (2003 and 2008) by using satellite-based remote-sensed environmental descriptors and the Maxent species distribution model.
5. Generate the respective habitat suitability maps to determine which areas/regions have changed, and whether the habitat suitability has increased or decreased.

# Chapter II

# Methods

The sections below detail the study area and selection, variables used, data analysis and high-level workflow.

## Study Area Description and Selection

A swath of the California coast encompassing monarch overwintering sites (Xerces Society, 2022a) was analyzed for this study. The study area (Figure 4) was defined based on the CALVEG mapping zones: three CALVEG zones were acquired and stitched into a swath as the study area/extent: north coast west, central coast, and south coast (USGS Forest Service, 2022). Therefore, one shapefile was generated using QGIS (2022) for the entire California coast.

Most of the overwintering sites are at low elevations (below 60-90m, i.e., 200-300 feet) and within 2.4km (1.5 miles) of the California coast, which has a mild winter climate. The main tree species at these sites are eucalyptus (*E. globulus*), red gum (*E. camaldulensis*), Monterey pine (*Pinus radiata*), Monterey cypress (*Cupressus macrocarpa*), western sycamore (*Platanus racemosa*), coast redwood (*Sequoia sempervirens*), and coast live oak (*Quercus agrifolia*) (Jepsen et al., 2015).


Figure 4. Map of the study area.
A swath of the California coast (darker green area) encompassing monarch overwintering sites (orange dots) (Xerces Society, 2022a) was analyzed for this study. The study area was defined based on the CALVEG mapping zones (USGS Forest Service, 2022).

Study Period and Data

Censuses are determined annually three weeks around Thanksgiving by Xerces Society members and community scientists in its Thanksgiving Count (Xerces Society Western Monarch Thanksgiving Count, 2022); therefore, yearly recurring November data from 2000-2019 were used for the present study.

Satellite remote sensing datasets were acquired via various NASA platforms that provide imagery and geophysical measures/quantities derived from MODIS (Moderate Resolution Imaging Spectroradiometer) land products and GPM (Global Precipitation Measurement) to conduct data analysis (Table 1).

The MODIS products that were used for this study have been available since 2000/2001, i.e., NDVI and EVI (2000-2019) and LC (2001-2019); Thus, this study was scoped to analyze observations for the last two decades (NASA EARTHDATA, 2022a-d). The improved LC v6 that has an overall accuracy of 73.6% for its Land Cover Classification System was used for better accuracy as compared to v5 (Sulla-Menashe et al., 2019). For details of various MODIS product maturity and validation stages, see Appendix 2.

Note that EVI and NDVI indices were used to complement each other to detect vegetation changes. NDVI is chlorophyll sensitive, whereas EVI is more responsive to canopy structural variations (Huete et al., 2002). NDVI and EVI are the proxy for the conditions of the coastal groves, and climate variables are denoted by precipitation (Precipitation L3) and temperature (LST_day and LST_night).

Table 1. Variables and their descriptions.

| | |
|---|---|
| Variable | NDVI (The Normalized Difference Vegetation Index): 1km_monthly_NDVI |
| Data Type/ Description | The Normalized Difference Vegetation Index (NDVI) measures the density of plant growth by using two key wavelengths, i.e., band 3 (red) and band 4 (NIR). Plants that are thriving absorb most of the red (visible light) and reflect most of the near-infrared light (NIR); whereas browning or sparse vegetation reflects most of the visible light (red) and less NIR. Thus, dense vegetation will have a high index (e.g., 0.9), whereas areas that have fewer plants will have a low index (e.g., 0.1).<br><br>NDVI formula:<br>NDVI = NIR - RED/ NIR + RED<br><br>Where:<br>NIR = Near-infrared band (band 4); RED = Red band (band 3) |
| Unit/ Value range | -1.0 to 1.0 |
| Data Source | NASA EARTHDATA, 2022b; Didan, 2015 |
| Dataset | MOD13A3.006 |
| Product Maturity | Stage 3 validation (for details, see Appendix 2) |
| Variable | EVI (The Enhanced Vegetation Index): 1km_monthly_EVI |
| Data Type/ Description | The Enhanced Vegetation Index (EVI) measures surface vegetation greenness that indicates the biomass/ density of a forest. It excludes both the background and atmospheric noises (i.e., it uses the blue band to remove atmosphere residual/ noises such as smoke and clouds). Thus, the bare ground will have a value of 0 and dense vegetation a value of 1.<br><br>Features:<br>• Improved sensitivity in areas that have high biomass.<br>• Reduces the influence of atmospheric conditions on vegetation index values.<br>• Corrects for canopy background signals.<br><br>EVI formula:<br>EVI = G * (NIR-RED) / (NIR+ C1 * Red- C2 * BLUE + L)<br><br>Where:<br>• Atmospherically corrected surface reflectance of red and blue bands |

|  |  |
|---|---|
|  | • G = 2.5 (a scaling factor)<br>• C1 = 6, C2 = 7.5, and L = 1 (coefficients to correct for atmospheric condition, and canopy background adjustment). |
| Unit/ Value range | -1.0 to 1.0 |
| Data Source | NASA EARTHDATA, 2022b; Didan, 2015 |
| Dataset | MOD13A3.006 |
| Product Maturity | Stage 3 validation |
| Variable | LC (The Land Cover Type): LC_Type2 |
| Data Type/ Description | The Land Cover Type (LC) provides yearly global land cover types from eight classification schemes.<br><br>Type-2 is based on the annual University of Maryland (UMD) classification. Each type (e.g., evergreen needleleaf forests, evergreen broadleaf forests, urban and built-up lands, croplands, etc.) will be a variable (See Appendix 1 for details). |
| Unit/ Value range | Pixel |
| Data Source | NASA EARTHDATA, 2022a; Friedl & Sulla-Menashe, 2019 |
| Dataset | MCD12Q1.006 |
| Product Maturity | Stage 2 validation |
| Variable | MOIDS/Terra Land Surface Temperature/Emissivity Monthly L3 Global 0.05° CMG:<br>• LST_Day_CMG<br>• LST_Night_CMG |
| Data Type/ Description | The Land Surface Temperature and Emissivity (LST&E) provides average monthly values in 0.05° latitude/longitude Climate Modeling Grid (CMG). A CMG granule is a geographic grid (7,2000 cols and 3,600 rows) for the entire globe. |
| Unit/ Value range | °K (Kelvin) |
| Data Source | NASA EARTHDATA, 2022c; Wan et al., 2015 |
| Dataset | MOD11C3 v006 |
| Product Maturity | Stage 2 validation |
| Variable | Merged satellite-gauge precipitation estimate - GPM IMERG Final: Precipitation L3 1 month 0.1° x 0.1° V06 |
| Data Type/ Description | The Integrated Multi-satellitE Retrievals for GPM (IMERG) provides the multi-satellite monthly precipitation estimates on a 0.1° x 0.1° (~10km x10km) grid over the globe. |

| | |
|---|---|
| Unit/ Value range | Millimeter (mm) |
| Data Source | NASA EARTHDATA, 2022d; Huffman et al., 2019 |
| Dataset | GPM_3IMERGM v06 |
| Variable | Yearly Total Monarch Abundance; Overwintering site coordinates |
| Data Type/ Description | Yearly Thanksgiving count from 2000 to 2019. |
| Unit/ Value range | Mean values; Coordinates |
| Data Source | Xerces Society Western Monarch Thanksgiving Count, 2022 |
| Dataset | Xerces Society Western Monarch society database |

Software and Tools

For this research, both QGIS (2022) and Maxent (Maximum Entropy Modeling) (Phillips, 2017; Phillips et al., 2022) which are open source software, as well as MS Excel, were used to process and analyze the datasets. QGIS v3.8, a geographic information system, was used as the main software to process and conduct spatial data analysis and to compose graphical maps from satellite remote sensing data that were acquired from NASA platforms. MS Excel was used to tabulate the processed spatial data from QGIS and then to conduct various trend and anomaly analysis.

In addition, Maxent software v3.4, a machine-learning tool for modeling species niches and distributions, was used to analyze the monarch dataset (i.e., the overwintering site coordinates) coupled with the satellite remote sensing environmental descriptors (e.g., temperature and precipitation), to generate western monarch habitat suitability maps. Key advantages of Maxent are its ease-of-use and speed when compared with other modeling methods. Maxent requires only the species presence data and the environmental variables for the entire study area. In addition, it is suitable for small sample sizes and training datasets (Phillips et al., 2006; Phillips, 2017).

### Data Analysis and Workflow

The workflow diagram below captures the steps to address the research questions and to answer the corresponding hypotheses (Figure 5). For detailed descriptions of the processing steps, see Appendix 3.

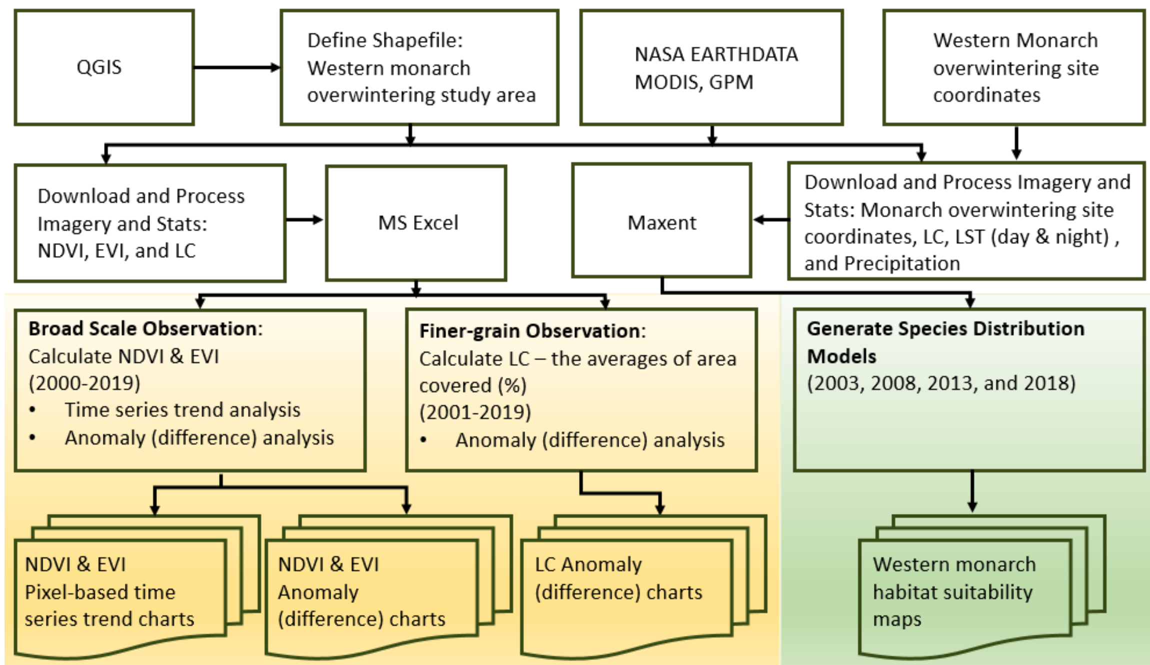



Figure 5. High-level workflow.
Note that the orange-shaded area depicts the processing for the first research question; whereas the green-shaded area depicts the second research question.

# Chapter III

# Results

The results are organized based on the order of my research questions and the corresponding hypotheses. To answer my first research question regarding the state of California's western monarch overwintering grounds (as detected in the study area) from 2000 to 2019, three hypotheses were suggested.

## Overall EVI and NDVI Trend Patterns

To test the first hypothesis that "habitat quality of coastal groves (the EVI and NDVI average) showed a downward trend during the study period," EVI and NDVI trend charts were generated in order to lay out in broad strokes the state of the coastal groves for the entire study area. The resulting trend charts showed that the EVI and NDVI trends respectively have substantial variations throughout the study period from 2000 to 2019 with slightly concave trend patterns (Figures 6 & 7).

When the EVI data points between the two decades (i.e., 2000-2009 vs. 2010-2019) were analyzed further, 2000-2009 shows an upward trend; whereas 2010-2019 shows a downward trend (Figures 8 & 9); the NDVI shows similar trend patterns (Figures 10 & 11).

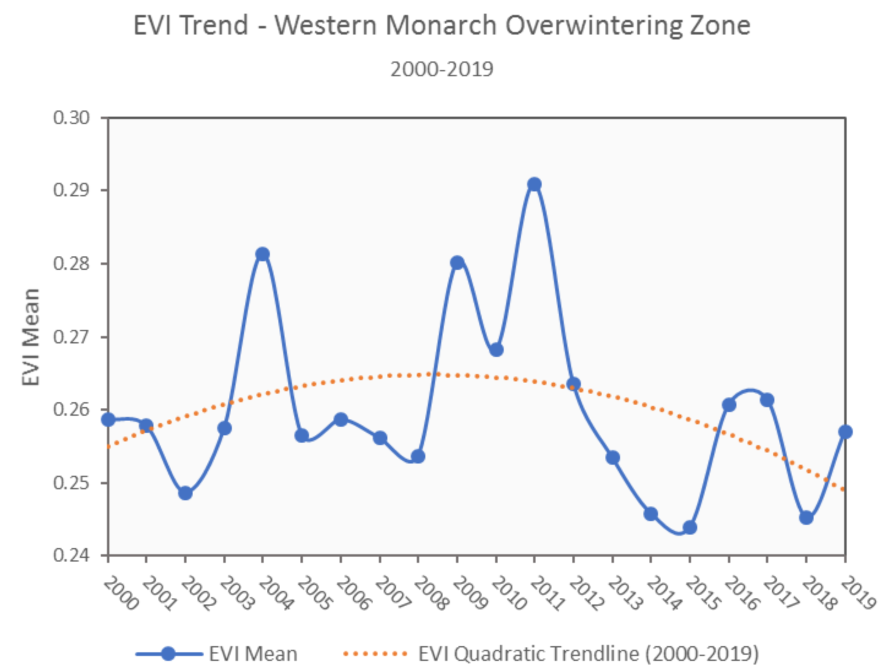



Figure 6. The Enhanced Vegetation Index trend chart (2000-2019).

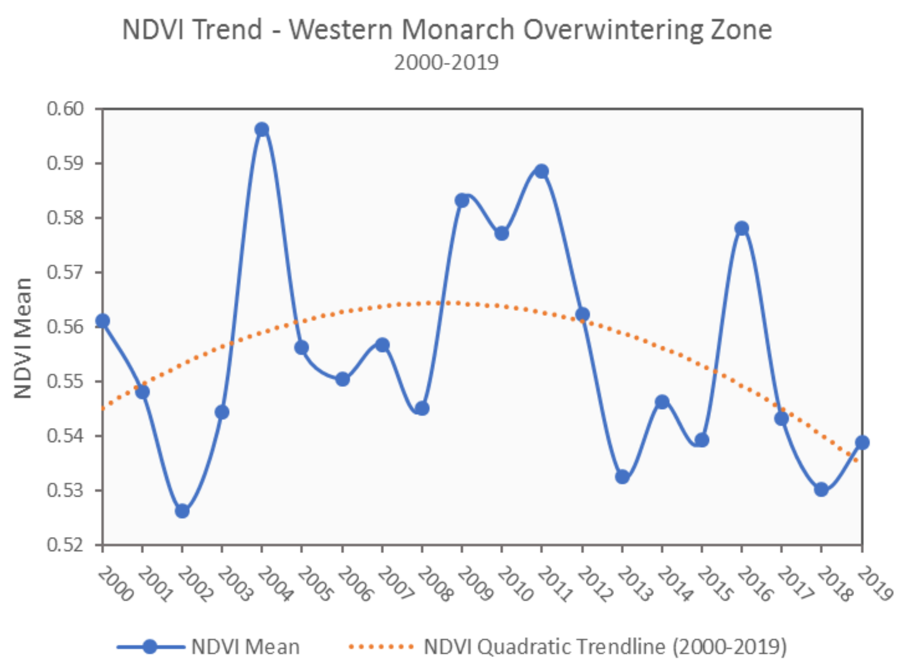



Figure 7. The Normalized Difference Vegetation Index trend chart (2000-2019).

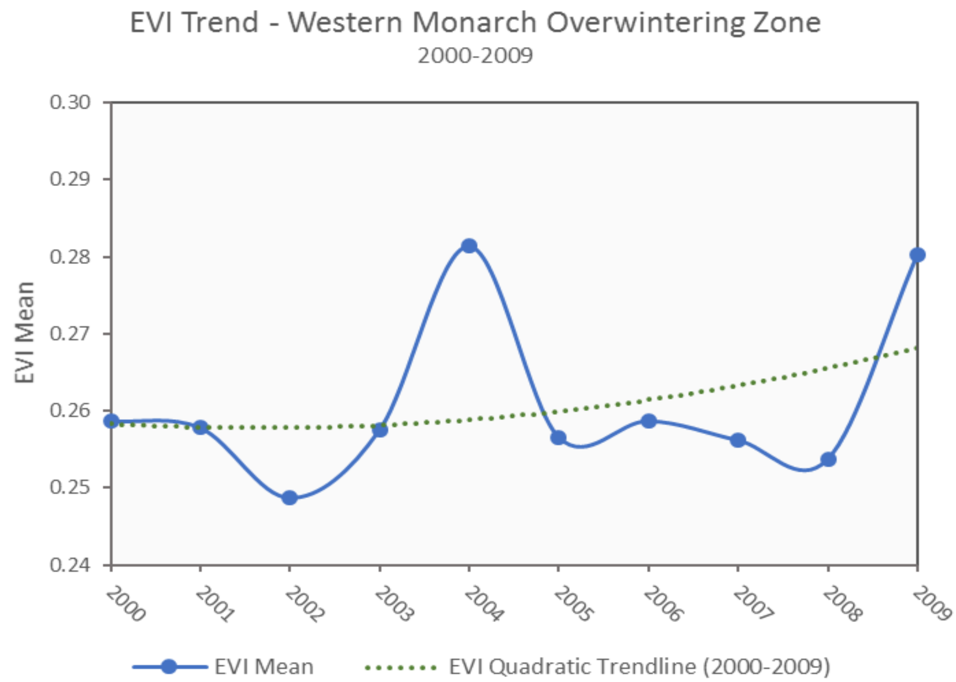



Figure 8. The Enhanced Vegetation Index trend chart (2000-2009).

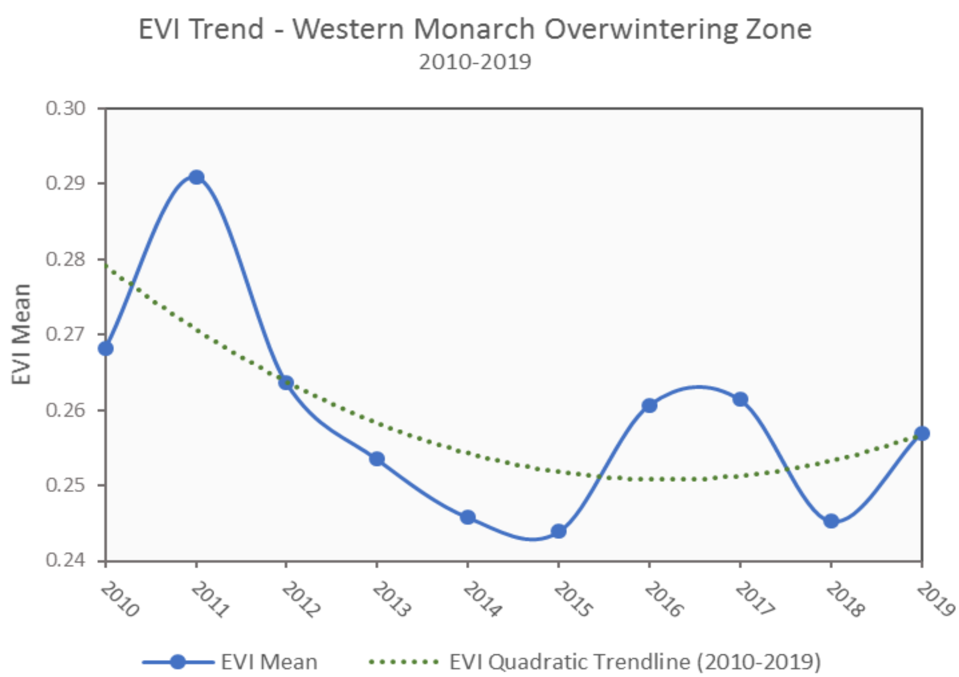



Figure 9. The Enhanced Vegetation Index trend chart (2010-2019).

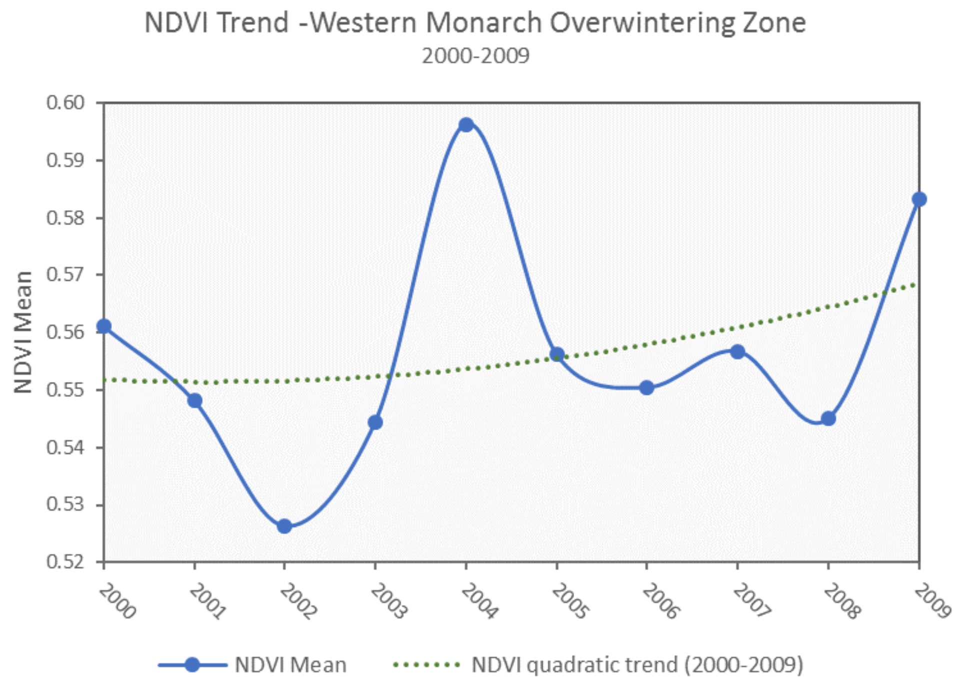



Figure 10. The Normalized Difference Vegetation Index trend chart (2000-2009).

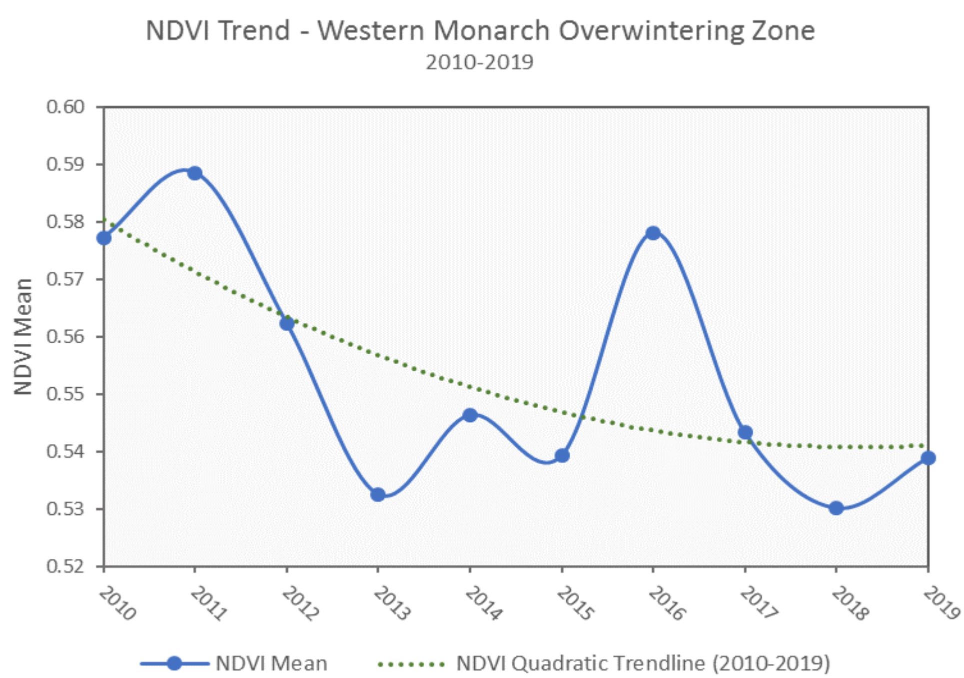



Figure 11. The Normalized Difference Vegetation Index trend chart (2010-2019).

To delve further into the dynamics of the EVI and NDVI trend patterns, and to test the second hypothesis: "The coastal groves (the EVI and NDVI average) showed an increase of negative anomalies (i.e., lower than the 20-year average) in the recent decade as compared to the previous decade," EVI and NDVI anomaly charts were generated.

Respective anomaly charts were computed by comparing the mean value of each individual year with the 20-year average. By observing the chart patterns, the EVI anomaly chart shows an increase and more intense negative anomaly years during the period 2010-2019 as compared to the period 2000-2009. The NDVI anomaly chart echoes a similar trend pattern (Figures 12 & 13).

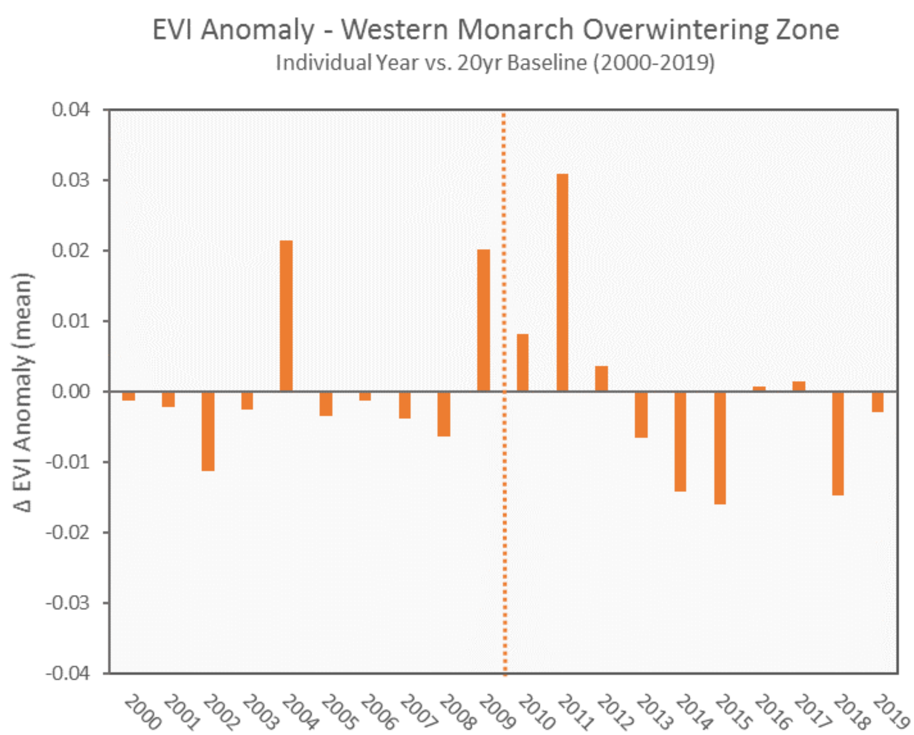



Figure 12. The Enhanced Vegetation Index anomaly chart (2000-2019).

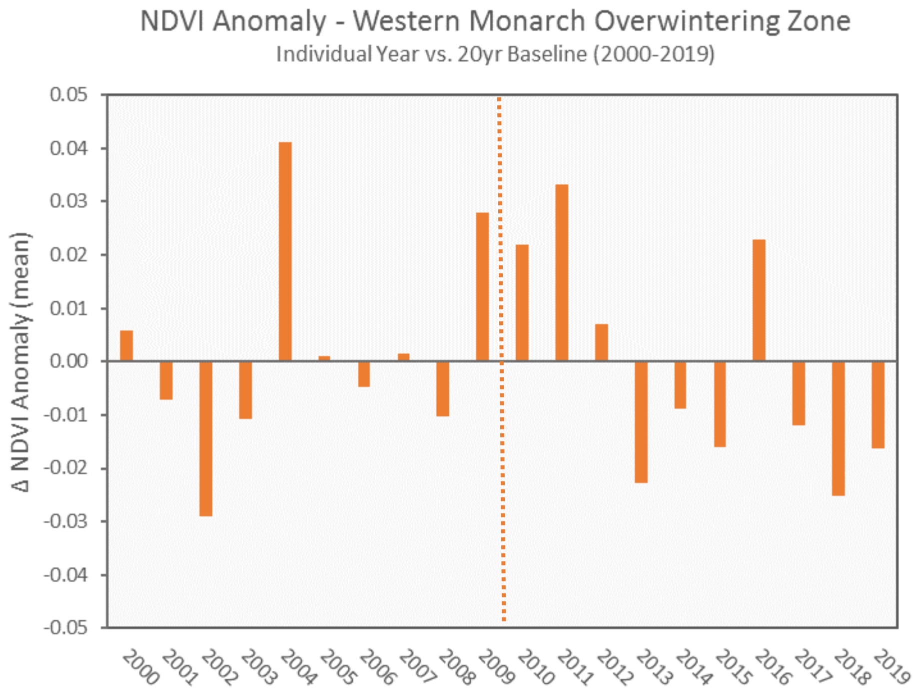



Figure 13. The Normalized Difference Vegetation Index anomaly chart (2000-2019).

Land Cover Type Dynamics

The third hypothesis explored and determined if the coastal groves (i.e., from a detailed land cover type (LC) perspective) have changed in ways that are detrimental to monarch abundance, and if so, what has changed and to what extent. To test this hypothesis, the average area covered (%) of various land cover types for the entire study period (2001-2019) were calculated.

The following charts were created to assist in analysis and visualization:

- The land cover trend chart shows the relative change of each land cover type evolving over time in relation to all other land cover types (2001-2019) (Figure 14);

- The land cover anomaly chart shows the difference of each individual year of a particular land cover type when compared with the corresponding baseline average (2001-2019) (Figure 15);
- Pareto charts were also generated to give context about the dominant land cover types in the study area (Figures 16a & b).

Note that the parenthesized numbers (e.g., (1) Evergreen Needleleaf Forests; (2) Evergreen Broadleaf Forests) in Figures 14 to 16 correspond to the Land Cover Type 2 Class Definition (refer to Appendix 1).

The land cover trend chart (Figure 14) provides an overall context of the relative change of each land cover type evolving over the last two decades. From the pareto charts, percentage area of each land cover type shows a slight difference when only comparing the first year of the study period and the last (i.e., 2001 vs. 2019) (Figures 16a & b); however, certain land cover types (e.g., grasslands, evergreen needleleaf forests, evergreen broadleaf forests) varied throughout the entire study period (Figure 14). The section below further analyzes the dynamics of each land cover type in detail to see whether such variations correlate with the observed monarch decline.

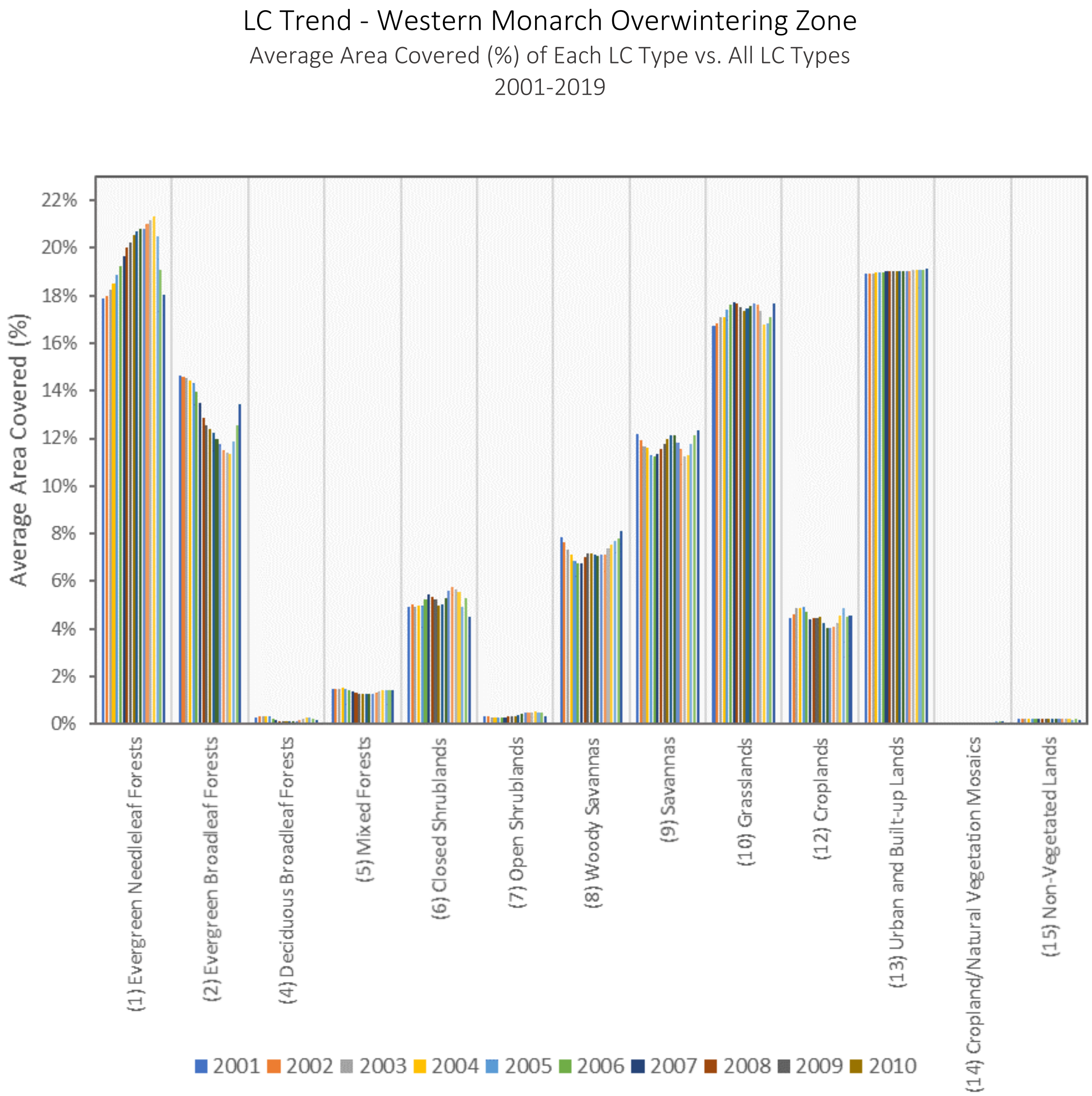



Figure 14. Land Cover trend chart (2001-2019).
The chart shows the relative change of each land cover type evolving over time in relation to all other land cover types.

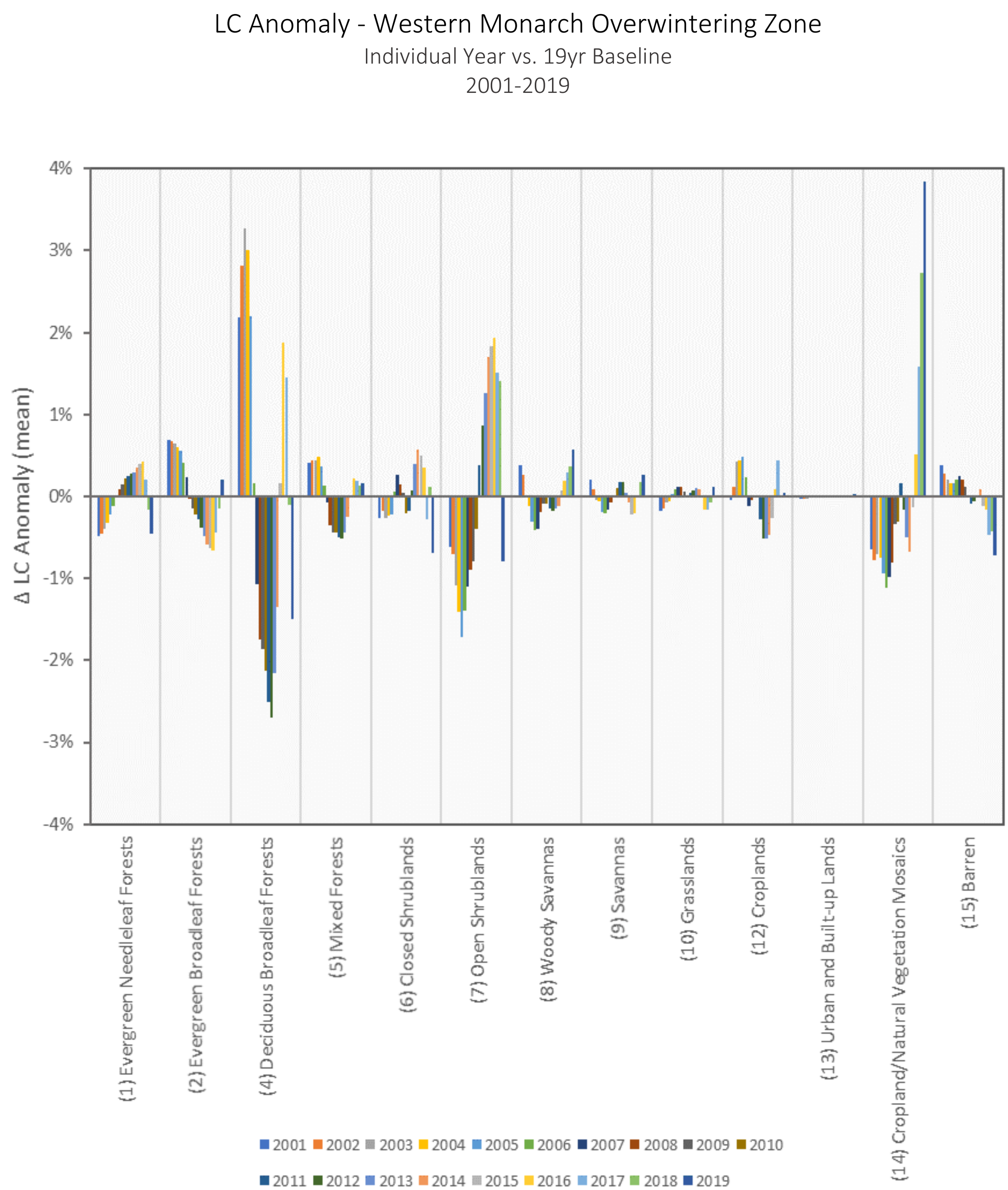



Figure 15. Land Cover anomaly chart (2001-2019).
This chart shows the difference of each individual year of a particular land cover type when compared with the corresponding baseline average.

Based on the 2001 and 2019 pareto charts, eight land cover types contributed to about 97.5% of the entire study area, namely, urban and built-ups, evergreen needle forests, grasslands, evergreen broadleaf forests, savannas, woody savannas, closed shrublands, and croplands (Figures 16a & b). Thus, these eight land cover types were further analyzed to gain a better understanding of the dynamics and changes in the study area. Individual trend charts and anomaly charts were generated to observe in detail the changes of these eight land cover types; adjusted $R^2$ and p-value ($\alpha = 0.05$) were also calculated based on each land cover type as a function of time (quadratic regression) (Figures 17a-l). Note that even though the deciduous broadleaf forests and the cropland/natural vegetation mosaics were showing a substantial anomaly in recent years (Figure 15), they only cover 0.3% and 0.1% respectively of the entire landscape. Therefore, they were excluded in the detailed charts below.

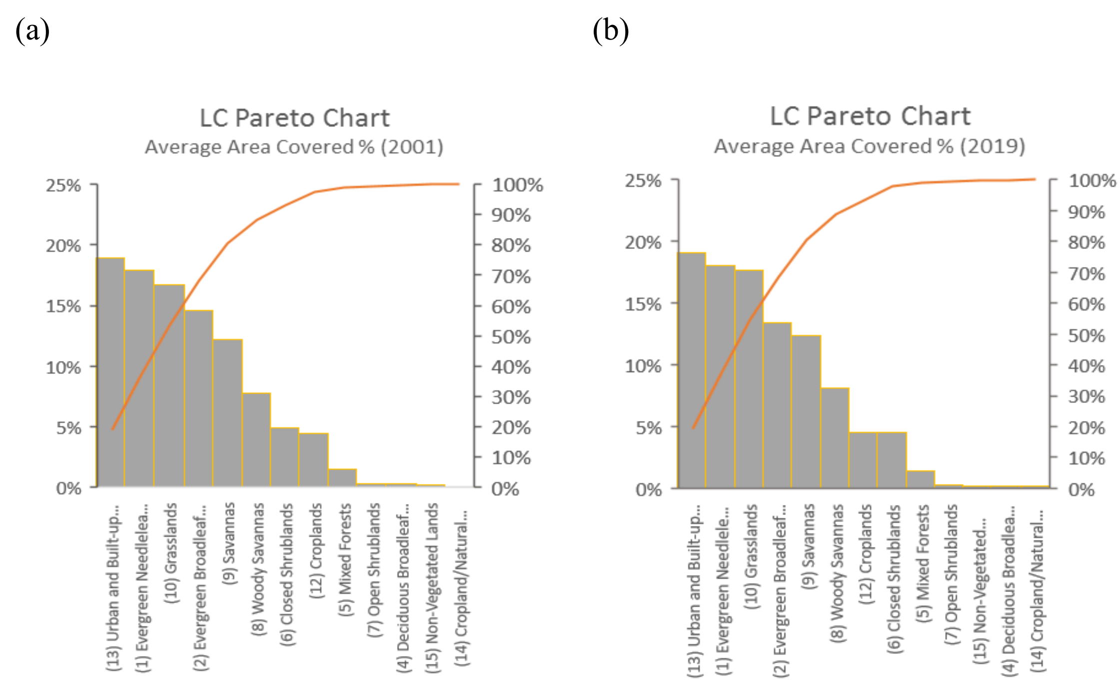
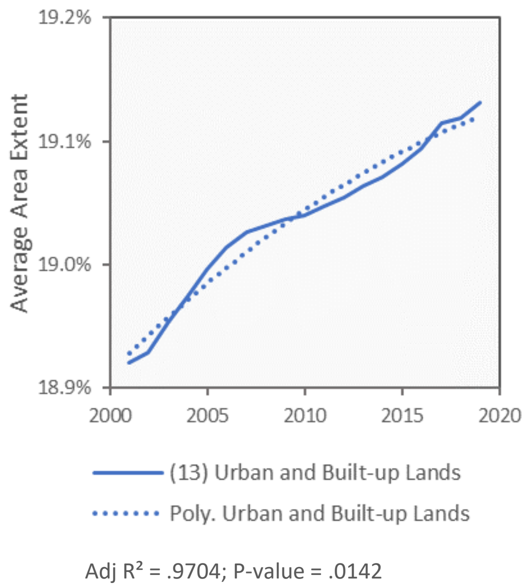


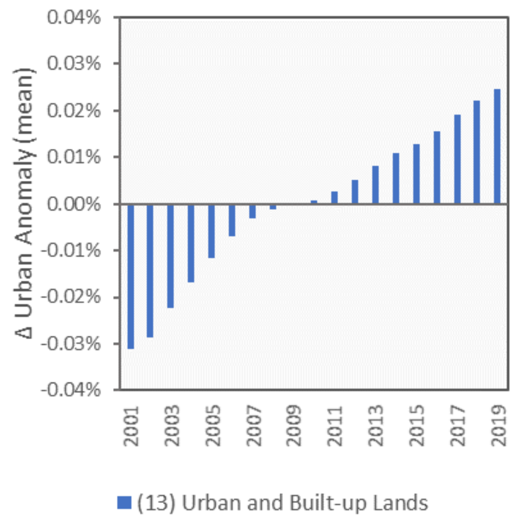

Figure 16. Land Cover pareto charts (2001 & 2019).
(a) Average area covered (%) in 2001 & (b) Average area covered (%) in 2019.

(a)



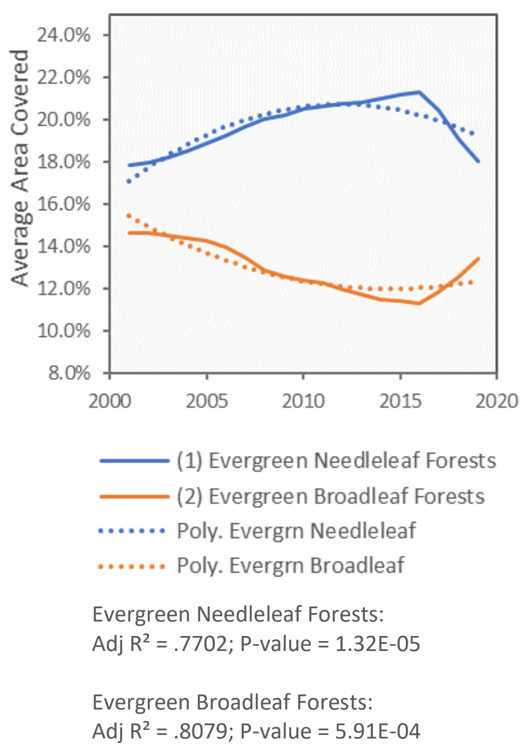
19.2%
19.1%
19.0%
18.9%
Average Area Extent
2000
2005
2010
2015
2020
(13) Urban and Built-up Lands
Poly. Urban and Built-up Lands
Adj R² = .9704; P-value = .0142


(b)



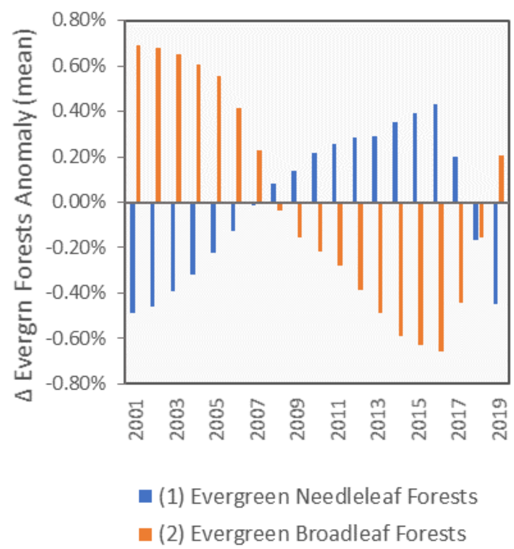
0.04%
0.03%
0.02%
0.01%
0.00%
-0.01%
-0.02%
-0.03%
-0.04%
Δ Urban Anomaly (mean)
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
(13) Urban and Built-up Lands


(c)



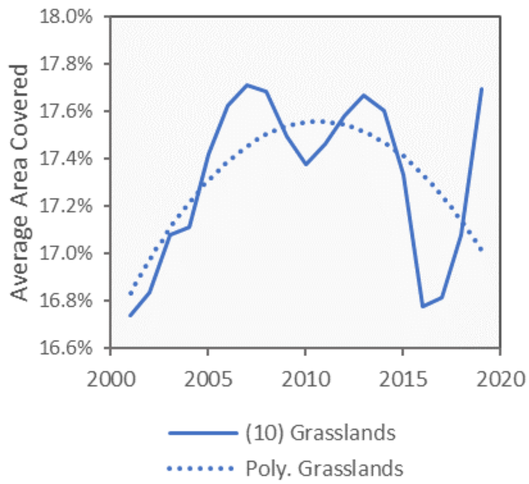
24.0%
22.0%
20.0%
18.0%
16.0%
14.0%
12.0%
10.0%
8.0%
Average Area Covered
2000
2005
2010
2015
2020
(1) Evergreen Needleleaf Forests
(2) Evergreen Broadleaf Forests
Poly. Evergrn Needleleaf
Poly. Evergrn Broadleaf
Evergreen Needleleaf Forests:
Adj R² = .7702; P-value = 1.32E-05
Evergreen Broadleaf Forests:
Adj R² = .8079; P-value = 5.91E-04


(d)



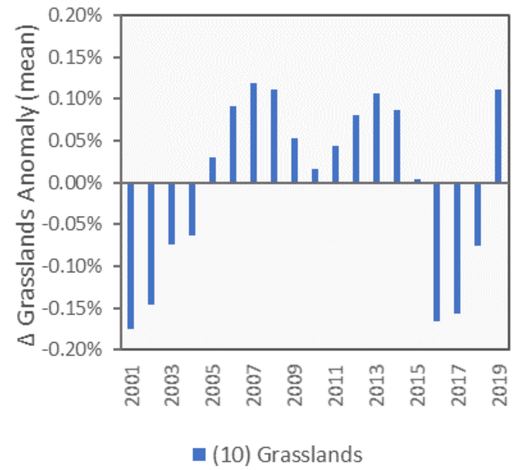
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
-0.60%
-0.80%
Δ Evergrn Forests Anomaly (mean)
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
(1) Evergreen Needleleaf Forests
(2) Evergreen Broadleaf Forests

(e)

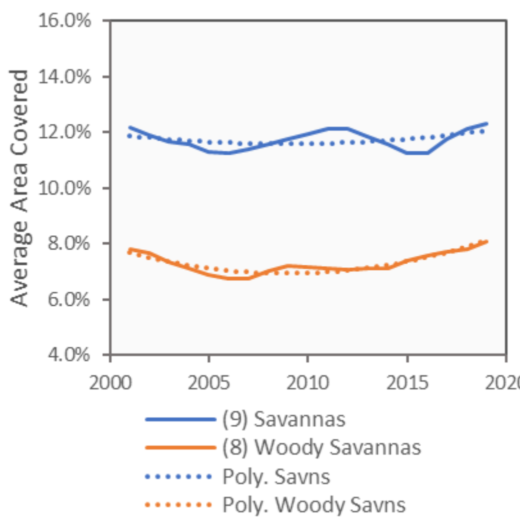



Adj $R^2$ = .3379; P-value =.0052

(f)



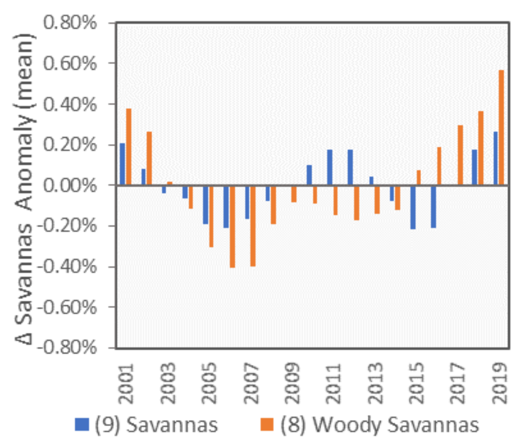

(g)




Savannas:
Adj $R^2$ = .0535; P-value = .1302

Woody Savannas:
Adj $R^2$ = .8213; P-value = 2.71E-07

(h)



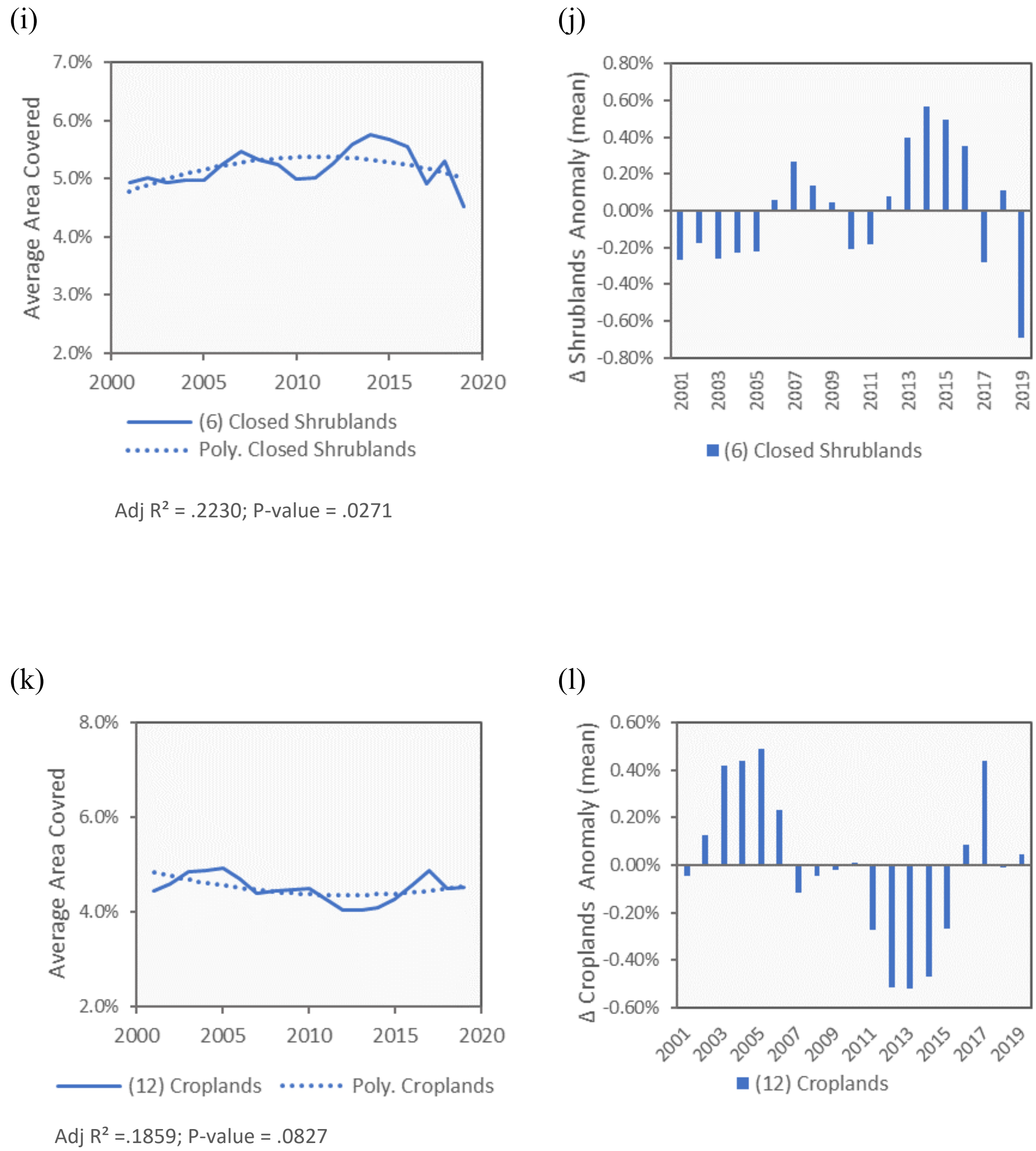



Figure 17. Key land cover types (2001-2019).
(a, c, e, g, i, k) are average area covered (%) trend charts, and (b, d, f, h, j, l) anomaly charts.

According to the pareto charts, the urban and built-up land is the most dominant land cover type in the study area (average area extent between 18.9 to 19.1%) (Figures 16a & b). Despite having a small scale of changes when compared to the baseline, it shows a steadily upward trend since 2001 and a positive anomaly since 2009 (Figures 17a & b). The evergreen forests (Figures 17c & d) show the dynamics of shifting between needleleaf forests and broadleaf forests. Since 2008 there was an interchange of needleleaf forests (positive anomalies) and broadleaf forests (negative anomalies).

One the other hand, grasslands (Figures 17e & f) show a fluctuation pattern with negative anomaly years clustered around 2001-2004 and 2016-2018. Both savannas and woody savannas show positive anomalies since 2017 and 2015 respectively when compared to the baseline (Figures 17g & h). Closed shrublands show a downward trend since 2015 (Figures 17i & j); whereas croplands show a fluctuation pattern, with negative anomaly years clustered around 2011-2015 (Figures 17k & l).

## Habitat Suitability Modeling

The second research question explored whether the California western monarch overwintering habitat suitability has changed in the recent decade when compared to the previous decade, and if yes, to what extent. Accordingly, the associated hypothesis was tested that "overwintering habitat suitability in the recent decade (2013 and 2018) has decreased compared to the previous decade (2003 and 2008)."

This involved generating four habitat suitability maps (i.e., 2003, 2008, 2013, and 2018) by using Maxent species distribution modeling software (Figures 18a-d). A difference map (i.e., 2018 vs. 2003) was also generated to show the change of habitat suitability in the study area (Figure 19).

Maxent output, as depicted by the habitat suitability maps, indicate suitable environmental conditions for monarchs. Note that the predicted potential geographic distributions for western monarchs at their overwintering grounds were generated using monarch site census records (presence data), climate variables (precipitation, day and night temperatures), and land cover type variables.

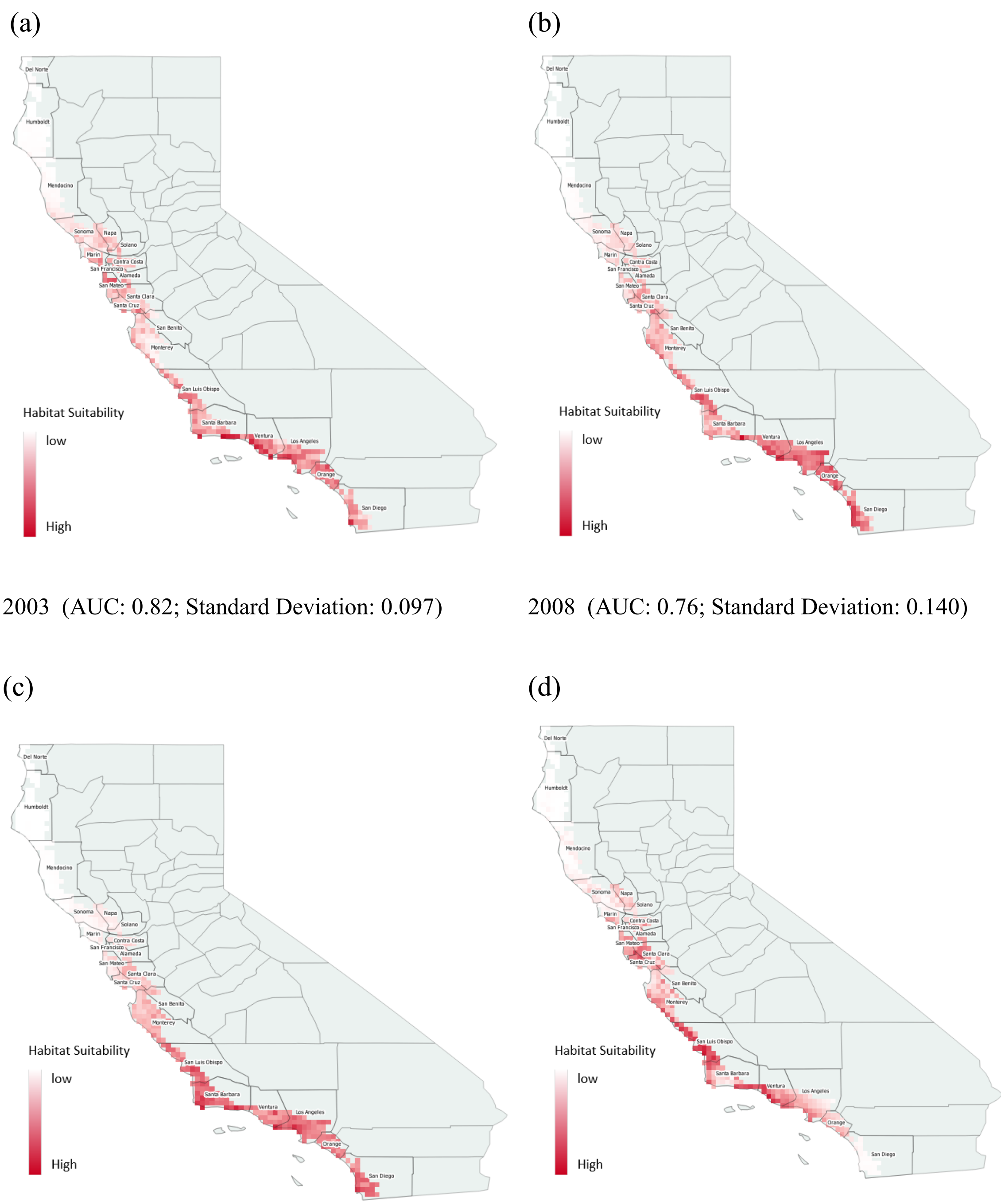
The output map produces a continuous prediction with values ranging from low (0) to high (1). The darker reds (from the color scale bar) indicate pixel areas which are considered high in suitable conditions for monarchs; whereas white to pale pink, are considered low in suitable conditions.

*Species distribution patterns*. Based on the habitat suitability map in 2003, Maxent indicated suitable conditions for monarchs for most of the entire swath of coastal counties, i.e., from south of Mendocino to San Diego county, with concentrations around the Bay Area, as well as in the south counties from San Luis Obispo to San Diego (Figure 18a).

In 2008, the habitat suitability extent retreated from Mendocino and the San Francisco Bay area; however, it still covered the entire swath of the coastal area from Santa Clara to San Diego, with the concentration in the central coast and south counties (Figure 18b).

In 2013, the habitat suitability extent continued to retract from the Bay Area and concentrated around the central coast and south coast (Figure 18c).

And in 2018, the habitat suitability extent retreated from the south counties such as Los Angeles to San Diego, as well as from part of Santa Barbara county (Figure 18d).




2003 (AUC: 0.82; Standard Deviation: 0.097)

2008 (AUC: 0.76; Standard Deviation: 0.140)

2013 (AUC: 0.79; Standard Deviation: 0.066)

2018 (AUC: 0.83; Standard Deviation: 0.073)

Figure 18. Habitat suitability maps (2003, 2008, 2013, and 2018).

When comparing the suitability maps in 2003 with 2018, the overall extent of suitable habitat identified decreased by 20%. In 2018, the habitat suitability extent reduced more prominently in the south counties, such as in Orange and San Diego (Figures 18a-d). To aid visualization, the habitat suitability difference map was generated (Figure 19). Note that areas in blue and green show an increase of suitability, and areas in orange and red indicate a decrease of suitability; whereas yellow indicates no difference.

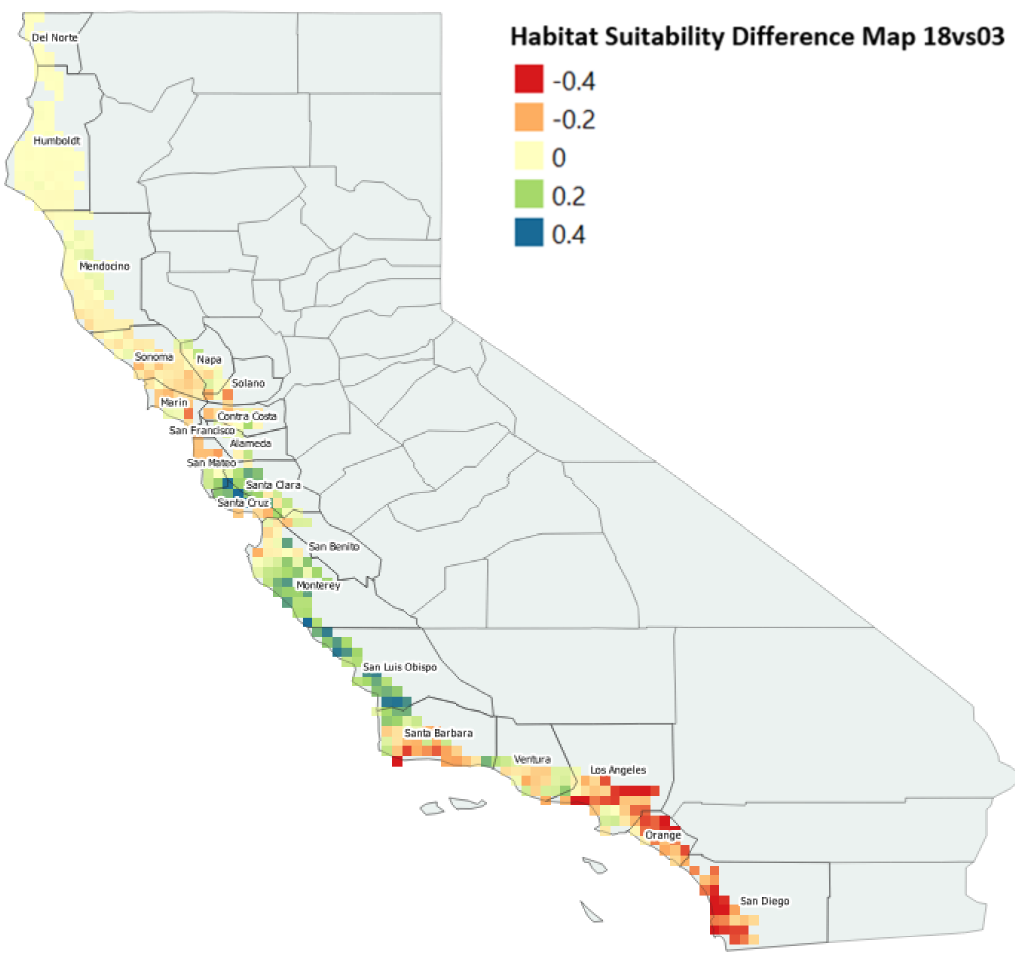



Figure 19. Habitat suitability difference map (departure from 2003 baseline in 2018).

*Maxent model performance and settings*. Table 2 details the settings used across all four maps, and the output summary statistics of the model fit. For the average test AUC (area under the receiver operating characteristic curve) scores, all four models were considered acceptable (above 0.75). Note that in order to adjust for the granularity of the environmental pixels and monarch coordinates, a 10% threshold was used to buffer for accuracy and variance.

Table 2. Maxent model processing and settings.

| Settings | | |
|---|---|---|
| Output format | Logistic | |
| Cross-validation replicates | 7x | |
| Background points | 6000 | |
| Regularization multiplier | 1 | |
| Training presence logistic threshold | 10% | |
| **Year** | **Average Test AUC for 7 Replicate Runs*** | **Standard Deviation** |
| 2003 | 0.82 | 0.097 |
| 2008 | 0.76 | 0.140 |
| 2013 | 0.79 | 0.066 |
| 2018 | 0.83 | 0.073 |

* Test AUC (area under the receiver operating characteristic curve) is the fit of the model to the testing data. AUC > 0.75 is considered acceptable; whereas AUC = 0.5 indicates that the output model performs similarly to a random model.

The maps above (Figures 18a-d & 19) capture and provide a snapshot of the monarch distribution patterns and habitat suitability extent at their overwintering grounds for the years 2003, 2008, 2013, and 2018, respectively. However, to observe the trend patterns (year-to-year) for the entire study period of the monarch abundance and its correlated factors, further analyses were conducted and presented in the later section: Monarchs, Coastal Groves, and Climate Change.

Monarch Distribution -- Two-dimensional Climate Characteristics

As mentioned in the previous sections, monarch mortality increases under wet and in freezing conditions (Brower, 2015). Additionally, monarchs are also sensitive to temperature and are dependent on environmental cues in their life stages (Brower, 2015; Green II & Kronforst, 2019; Guerra, 2020; Pyle, 2015; UN CMS, 2022).

Thus, this section also includes an assessment of precipitation and land surface temperature (day and night) to gain a better understanding of how these climate elements relate to the distribution of monarchs at their overwintering grounds. The two-dimensional climate characteristics (i.e., precipitation and temperature) depict the western monarch presence/distribution in the study area. These bivariate plots were derived from the monarch presence coordinates (occ) and the study area's background points (bkgrd) for both 2003 and 2018, to facilitate visualization of the area conditions that are modeled as suitable and unsuitable for monarchs (Figures 20 & 21).

PRCP_LST(Day) Bivariate Plot
2003 vs. 2018

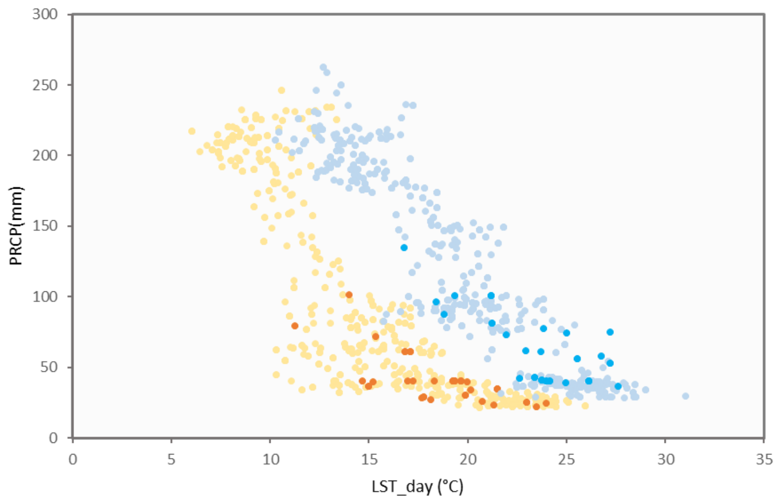



Figure 20. PRCP_LST(Day) bivariate plot.
Monarch's presence/distribution and study area background points based on two-dimensional climate characteristics: precipitation & day temperature (2003 vs. 2018). Note: light orange dots (2003) and light blue dots (2018) are background points (bkgrd) across the study area; whereas darker orange dots (2003) and darker blue dots (2018) pertain to sites where monarchs were censused (i.e., monarch occurrence).

PRCP_LST(Night) Bivariate Plot
2003 vs. 2018

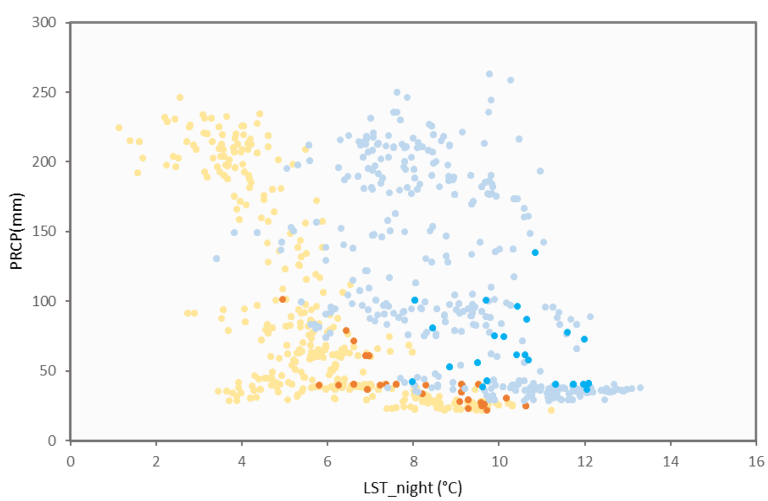



Figure 21. PRCP_LST(Night) bivariate plot.
Monarch's presence/distribution and study area background points based on two-dimensional climate characteristics: precipitation & night temperature (2003 vs. 2018). Note: light orange dots (2003) and light blue dots (2018) are background points (bkgrd) across the study area; whereas darker orange dots (2003) and darker blue dots (2018) pertain to sites where monarchs were censused (i.e., monarch occurrence).

In 2003, monarch occurrence (occ) could be found mostly clustering in areas where precipitation (PRCP) ranged from 20-40mm; day land surface temperature (LST_day) 15°-24°C; and night land surface temperature (LST_night) 6°-11°C; whereas in 2018, monarchs clustered in areas where PRCP ranged from 40-100mm; LST_day 19°-27°C; and LST_night 8°-12°C (Figures 20 & 21).

The overall study area (bkgrd) also demonstrates a shift in temperature and precipitation, i.e., in 2003, mean $PRCP_{03}$ = 91mm; $LST\_day_{03}$ = 17.85°C, and $LST\_night_{03}$ = 6.85°C; however, in 2018, the range had shifted: mean $PRCP_{18}$ = 112mm; $LST\_day_{18}$ = 20.85°C; and $LST\_night_{18}$ = 9.85°C (Figures 20 & 21).

Table 3 summarizes the change in the study area (background) and the monarch presence (occurrences).

Table 3. Changes in the PRCP_LST (2003 vs. 2018).

| | LST_day (°C) | LST_night (°C) | PRCP (mm) |
|---|---|---|---|
| 2003 Monarch occ | 15-24 | 6-11 | 20-40 |
| 2018 Monarch occ | 19-27 | 8-12 | 40-100 |
| 2003 bkgrd (mean) | 17.85 | 6.85 | 91 |
| 2018 bkgrd (mean) | 20.85 | 9.85 | 112 |

# Chapter IV

# Discussion

The main goals of this paper were to assess the condition of the coastal groves along the entire swath of California coast and to analyze the anomalies and trends of vegetation and environmental variables for the last two decades.

In particular, this involved seeking a better understanding of how large-scale habitat variation relates to monarch abundance, as well as how these phenomena are impacting the overwintering habitat suitability of the western monarchs. Applying habitat-related data produced via satellite imagery provided a lens with which to view a significant conservation issue: the steep drop in abundance of a species of "charismatic microfauna," the western monarch butterfly.

Thus, it is crucial to examine the potential stressors most likely responsible for the iconic western monarch's alarming population decline: particularly overwintering habitat condition.

## Coastal Grove Conditions

By using EVI and NDVI as proxies for assessing the overall condition of the coastal groves, a decrease in quality and biomass for the recent decade (2010-2019) was demonstrated. The EVI data trend for the last 20 years (Figure 6), showed a lower-highs pattern, i.e., the highest mean value was 0.29 in 2011, and since then, it has never reached such a peak for the rest of the recent decade. A similar pattern can be found in NDVI (Figure 7), where the highest mean value was 0.60 in 2004.

When comparing each individual year with the 20-year average, EVI and NDVI (Figures 12 & 13) showed increased intensity and frequency of negative anomalies for the recent decade, specifically starting from 2013.

Land Cover Type Alterations

Analyzing changes in land cover (Figures 17a-l), particularly focusing on the dominant land cover types in the study area, enabled several observations as highlighted below:

- The urban and built-up lands have been increasing at a steady pace during the past two decades, with an increasing positive anomaly over the recent decade (Figures 17a & b);
- The evergreen needleleaf forests have had a positive anomaly since 2008 and decreased abruptly in 2018. Interestingly, the evergreen broadleaf forests showed a reverse pattern (Figures 17c & d). In addition, the evergreen broadleaf forests had greater negative anomalies than the evergreen needleleaf forests for the past decade. Despite "recovery" of evergreen broadleaf forests (i.e., a positive anomaly) in 2019, this was smaller than the loss of evergreen needleleaf forests (a negative anomaly). From 2016-2019, the interchange trends showed an increase of broadleaf (+2.1%) and a decrease of needleleaf (-3.3%); however, the combined forests showed a loss of about 1.2%;

- The savannas and woody savannas had an increase of positive anomalies during the past decade, particularly the woody savannas (Figures 17g & h);
- Closed shrublands decreased (-1.2%) since the peak of 2014 and reached the lowest point in 2019 (Figures 17i & j).

When closely observing the land cover type dynamics, the urban and built-up lands have increased but at a slower pace; however, the vegetation showed a substantially increased variation and transformation.

In order to have a better understanding of these changes, it is essential to be aware of the various vegetation types. Based on the class definitions of land cover types used in this study (for details, see Appendix 1), forests are defined as trees over 2m in height with tree canopy-cover over 60%; whereas savannas/woody savannas are sparse trees standing out from an herbaceous layer. Savannas have tree canopy-covers of 10-30%, and woody savannas 30-60%. Thus, both savannas and woody savannas have less tree canopy-cover than forests. Closed shrublands are characterized by shrubs 1-2m in height, with shrub canopy-cover more than 60%.

Shrub species characterizing the study areas include black sage (*Salvia mellifera*), bladderpod (*Peritoma arborea*), bush sunflower (*Encelia californica*), common snowberry (*Symphoricarpos albus*), creeping blueblossom (*Ceanothus thyrsiflorus thyrsiflorus*), golden currant (*Ribes aureum gracillimum*), keckiella (*Keckiella corymbosa*), Santa Barbara Ceanothus (*Ceanothus impressus*), seaside woolly sunflower (*Eriophyllum staechadifolium*), silver lupine (*Lupinus albifrons*), and woolly bluecurls (*Trichostema lanatum*) (Calscape, 2021).

Western monarchs roosting at their overwintering habitats require tall trees with dense canopy to provide the microclimatic conditions that protect them from wind and harsh weather elements, yet supply sufficient insolation to allow them to thermoregulate; they also require sufficient nectar-rich food sources in their surrounding areas (Brower, 2015; Jepsen et al., 2015; Pyle, 2015).

However, over the recent decade (2010-2019), the study area underwent a decrease of tall and mature trees (i.e., forests); an increase of sparse-standing trees with a less-dense tree canopy (i.e., savannas); and a decrease of closed shrublands. This also means that there were fewer tall and mature trees for shelter and protection, and a reduction in flowering vegetation as a food source for the overwintering monarchs.

## Coastal Groves and Their Microclimate

The overwintering groves at the coast play an important role in delineating localized microclimate, and thus the survival of western monarchs. The western monarchs prefer a mild and consistent temperature throughout the winter, i.e., cool during the day and warm during the night. During this period, monarchs also are vulnerable to harsh weather elements, such as wet and freezing conditions. Thus, tall trees that are clustered closely with dense foliage are essential to provide buffering to shield monarchs from severe rainstorms and extreme weather (Brower, 2015; Pyle, 2015).

When comparing LST_day (day land surface temperature), LST_night (night land surface temperature), and precipitation for years 2003, 2008, 2013, and 2018 (i.e., an interval of five years for the previous two decades), all three variables showed changes throughout the years (Figures 22, 23, & 24). Note that the temperatures are presented in Kelvin (°K); whereas precipitation is in millimeter (mm).

The general gradient patterns of land surface temperature (day) show a cooler temperature range along the north coast and a warmer temperature range along the south coast. However, when comparing all four maps (2003-2018), there has been an increase of temperature, particularly from the Bay Area to the south counties (Figures 22a-d).

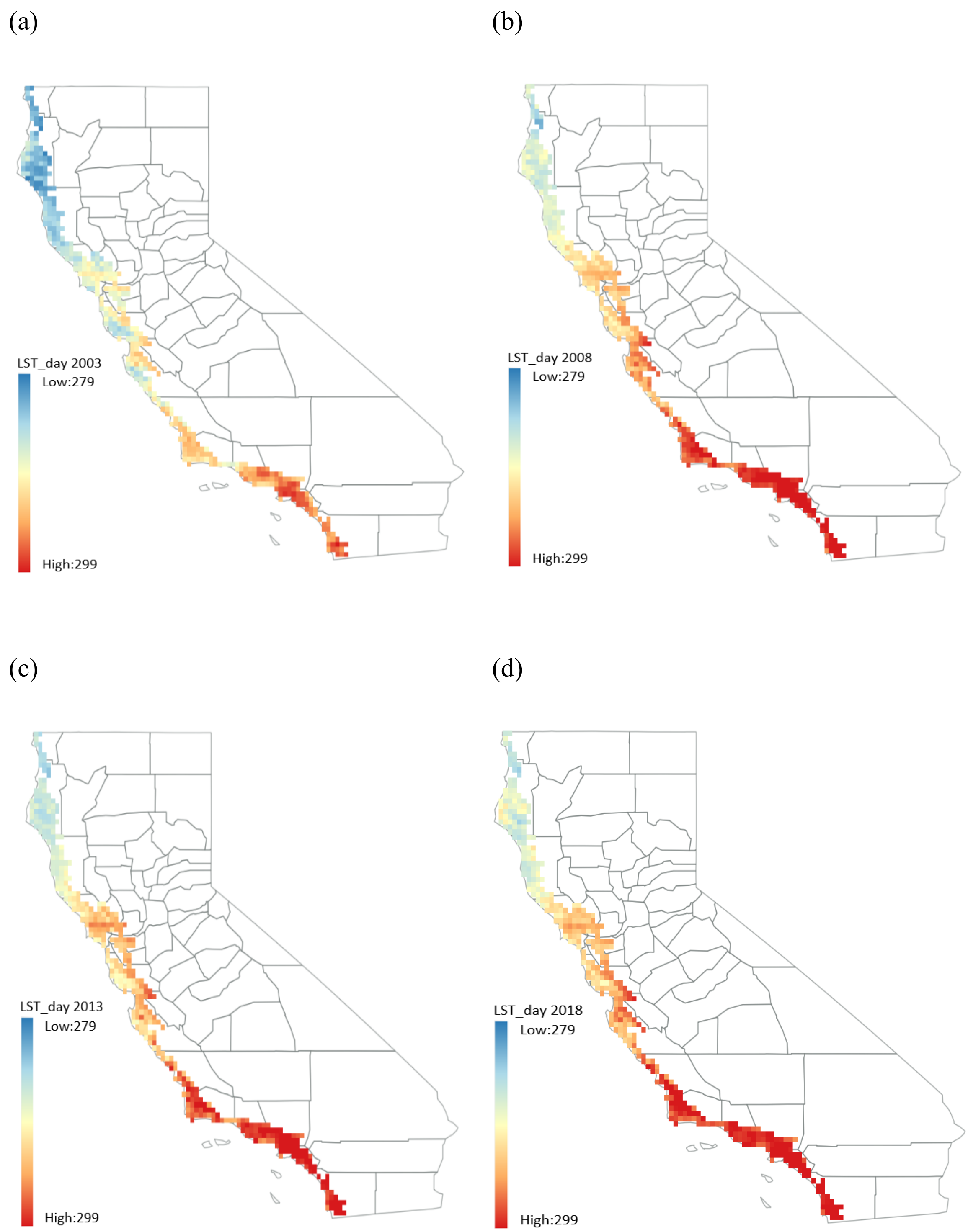



Figure 22. Day land surface temperature (°K) maps (2003, 2008, 2013, and 2018).

The night land surface temperature (LST_night) also shows significant changes, particularly an increase of temperature along the north and central coasts (Figures 23a-d).

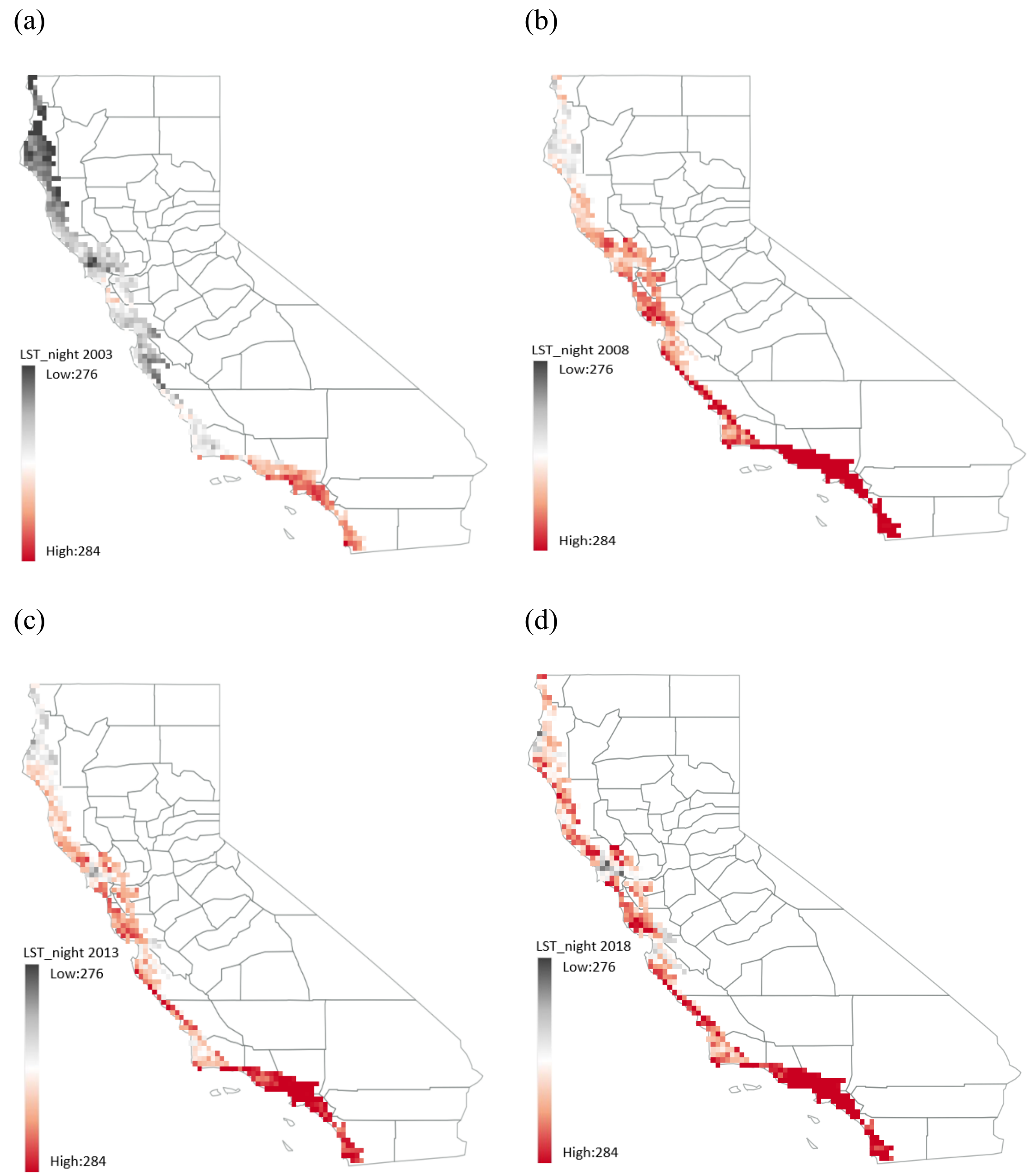



Figure 23. Night land surface temperature (°K) maps (2003, 2008, 2013, and 2018).

The general precipitation gradient patterns show a higher precipitation along the north coast than the rest of the coastal areas.  When comparing 2003 and 2018, the precipitation patterns show an increase in the Bay Area and the central coast (Figures 24a-d).

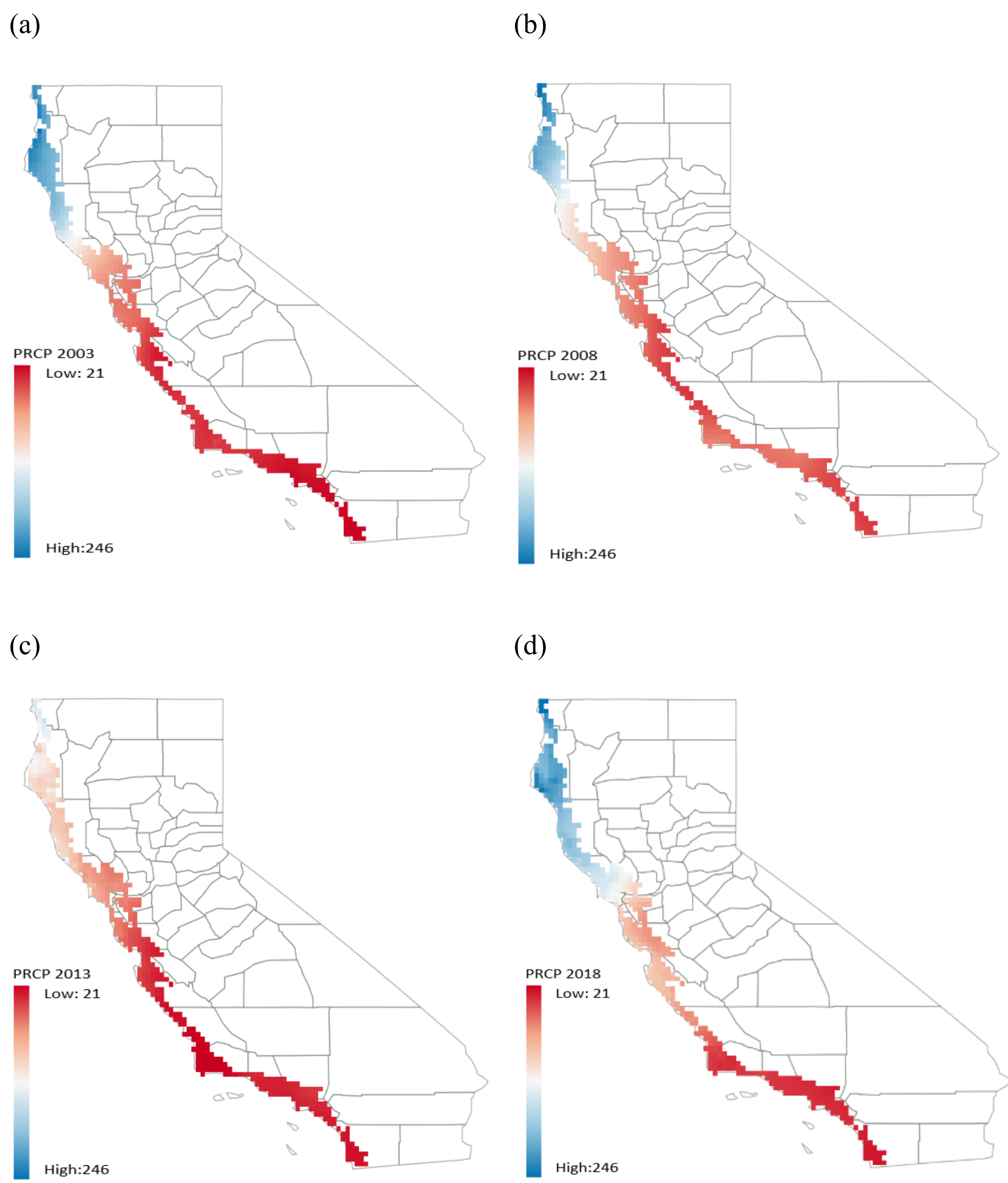
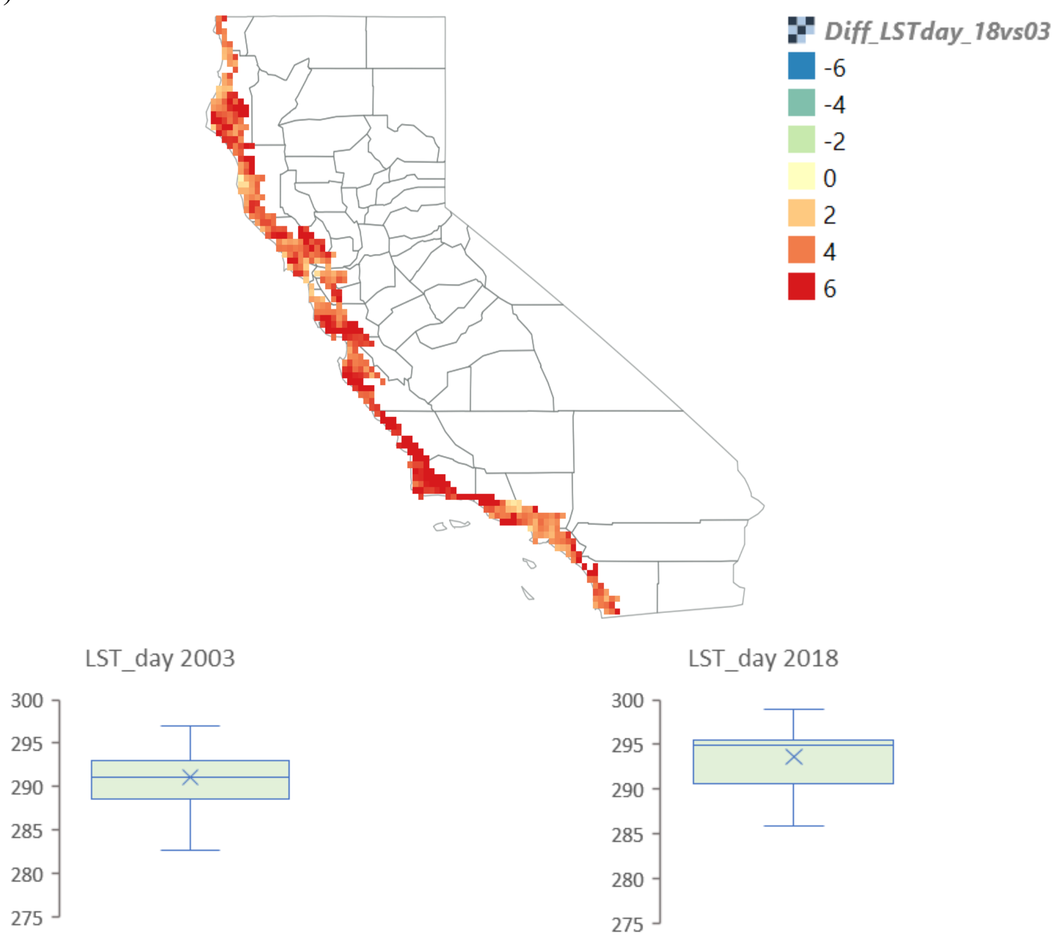


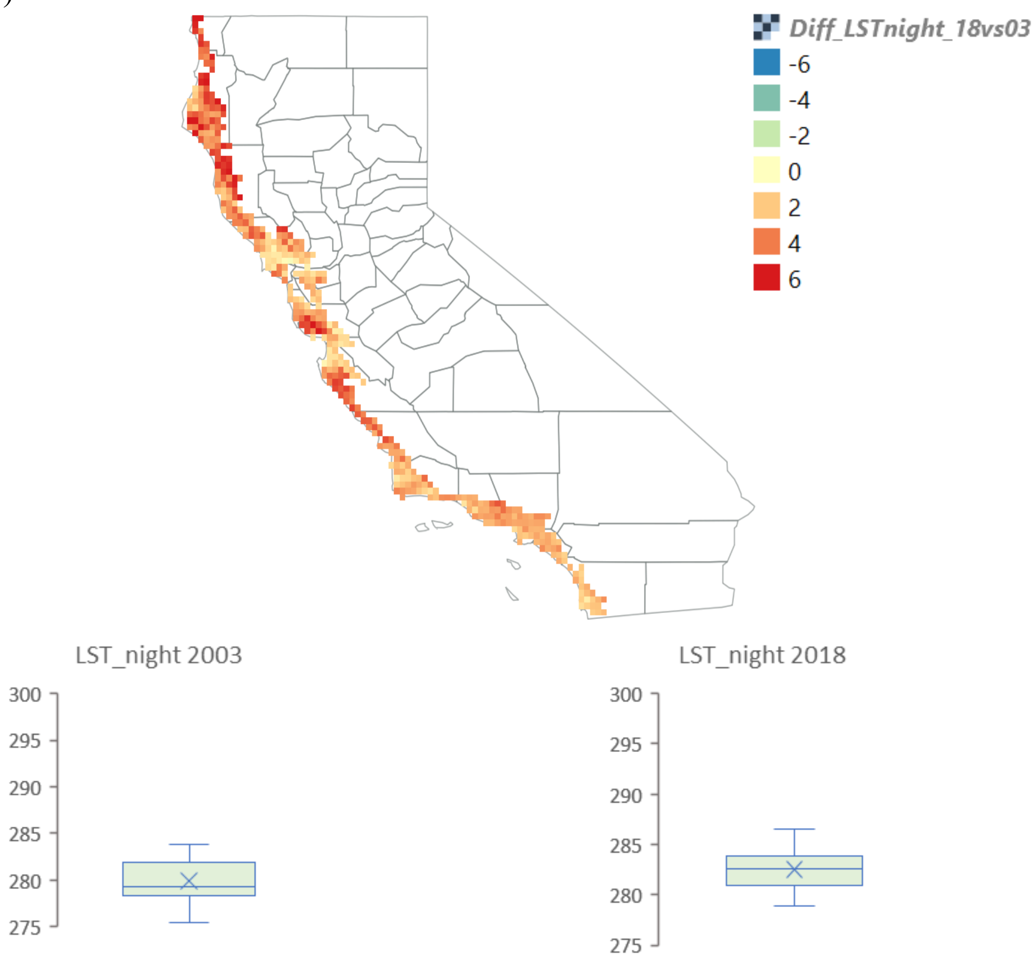

Figure 24.  Precipitation (mm) maps (2003, 2008, 2013, and 2018).

The difference maps and charts below depict clearly the variance between 2003 and 2018. Both the LST_day and LST_night difference maps show a positive anomaly (i.e. increased temperature) in 2018 throughout the entire coast when compared with 2003; while the precipitation (PRCP) difference map shows a substantial precipitation variation throughout the entire coast, with an increase of precipitation in the Bay Area and the central coast (Figures 25a-c).

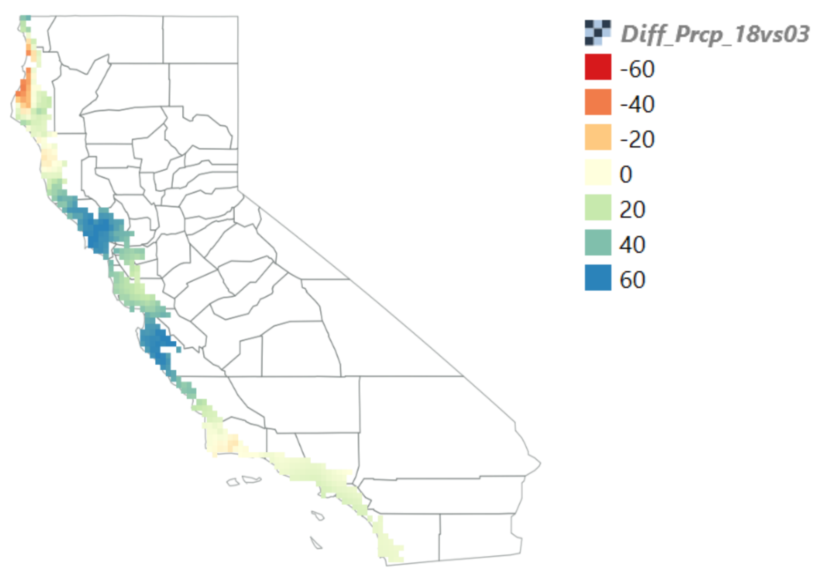
(a)

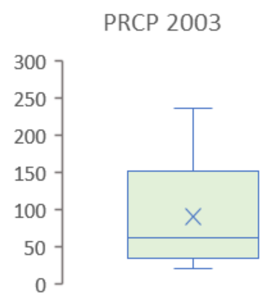


(b)


Diff_LSTnight_18vs03
-6
-4
-2
0
2
4
6
LST_night 2003
300
295
290
285
280
275
LST_night 2018
300
295
290
285
280
275

(c)


Diff_Prcp_18vs03
-60
-40
-20
0
20
40
60



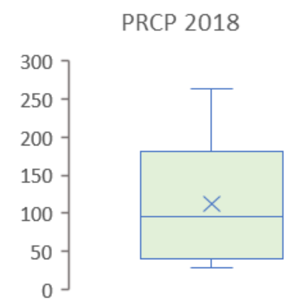



Figure 25. Difference maps (LST_day, LST_night, & PRCP) (2003 vs. 2018).

Monarchs, Coastal Groves, and Climate Change

As previously discussed, overwintering western monarchs are dependent on the coastal groves and requisite microclimatic conditions to survive through February/March when northward and inland dispersal begins. However, the coastal groves, as well as vegetation structure and composition are changing. Due to the increasing day and night temperatures, the substantial precipitation variation, combined with the lack of dense foliage tree groves throughout the entire coast, the overwintering grounds offered diminishing protection to overwintering monarchs from harsh weather elements over the study period.

Two scatter plots below depict the monarch abundance as a function of the forest canopy covered area (i.e., both types of evergreen forests: needleleaf and broadleaf) for the entire study period (2001-2019) (adj $R^2 = .8064$; p-value = .0112), and for the recent decade (2010-219) (adj $R^2 = .9393$; p-value = .0318) (Figures 26 & 27). The two outliers (i.e., 2018 and 2019 data points that are derived from the abrupt decline of monarch abundance) prompted the question of whether they are initiating a new significant cluster and trend, or are simply outliers to be ignored. When these two outliers were removed, adj $R^2$ values decreased by ~73% and ~71% respectively to adj $R^2 = .0774$ (p-value =

.9560) and .2316 (p-value = .3431); this could imply that the more prevalent trend from the recent years was substantially influenced by the coastal groves that monarchs are reliant on for roosting and wintering.

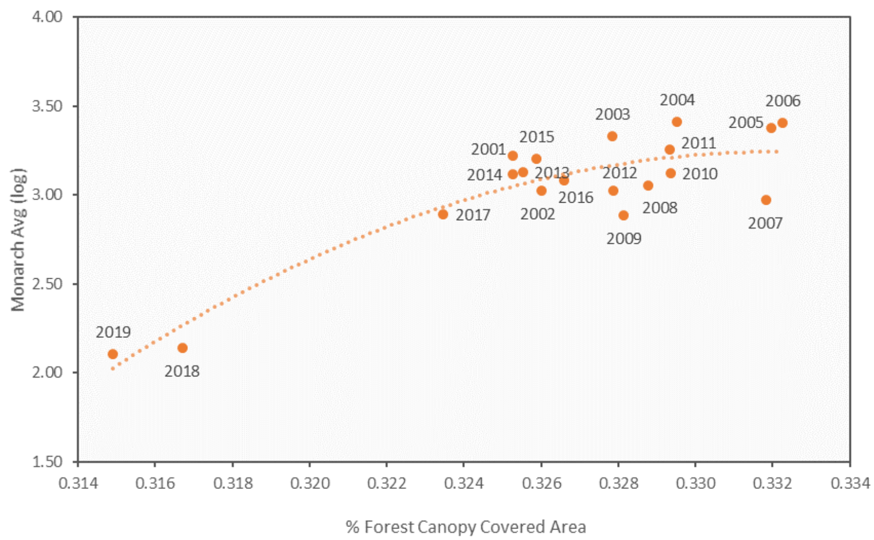



Figure 26. Scatter plot (2001-2019) - monarch abundance as a function of forest canopy covered area. Adj $R^2$ = .8064; p-value = .0112.

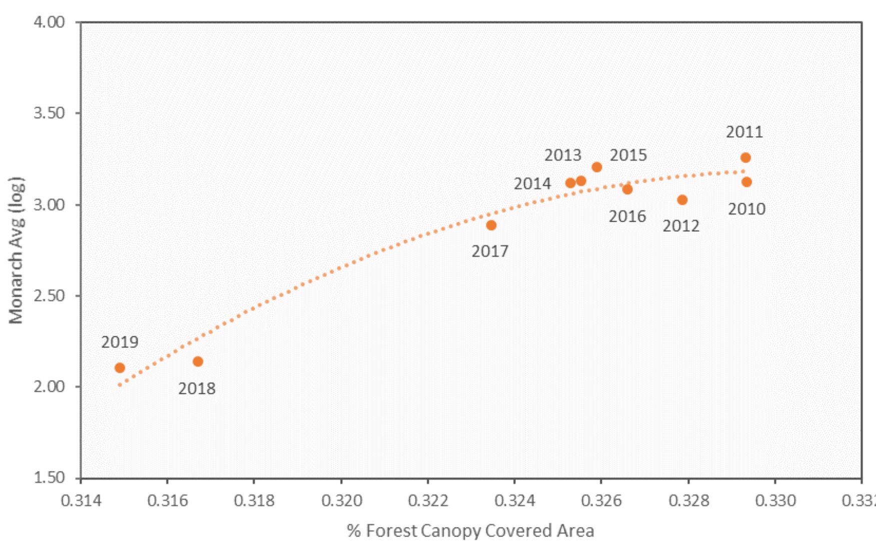



Figure 27. Scatter plot (2010-2019) - monarch abundance as a function of forest canopy covered area. Adj $R^2$ = .9393; p-value = .0318.

When scrutinizing further the dynamics of monarch abundance and their coastal groves (i.e., both evergreen needleleaf and broadleaf forests) that monarchs use for roosting and clustering, the combination chart below shows the evergreen forest canopy covered area (adj $R^2$ = .8385; p-value = 2.61E-06) and monarch abundance (adj $R^2$ = .5545; p-value = .0134) as a function of year respectively (Figure 28). In 2017, both the coastal groves and the monarch abundance show the onset of a departure from the previous lows. Interestingly, these trends show the evergreen coastal groves and the monarch abundance have been trailing each other closely for the last two decades (Figure 28).

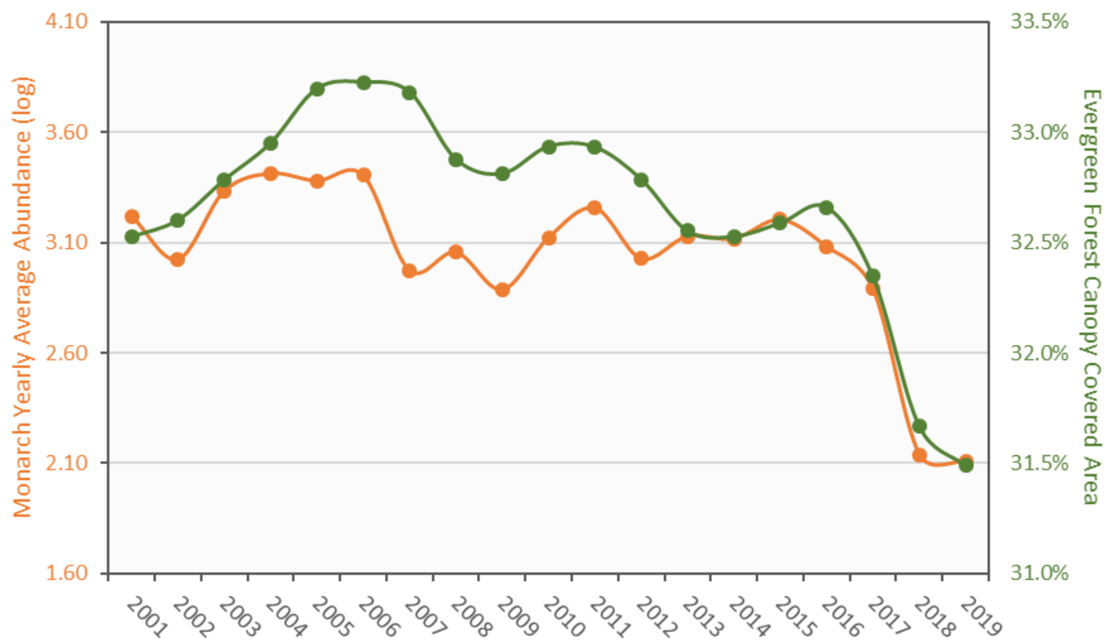



Figure 28. Evergreen forest canopy covered area and monarch abundance f2001-2019. Note: Green data points are forest canopy covered area (%) that shows significant decline since 2017 (adj $R^2$ = .8385; p-value = 2.61E-06); whereas orange data points are monarch abundance that echo a similar downward trend (adj $R^2$ = .5545; p-value = .0134).

In addition, the western monarch's habitat suitability extent has been decreasing throughout the past two decades (Figure 18). When comparing 2003 with 2018, the habitat suitability extent had a much smaller range in 2018 (Figure 19). Furthermore, when comparing 2003 with 2018, both the monarch census sites and the overall California study area underwent apparent shifts as indicated by the two-dimensional precipitation & temperature climate characteristics (Figures 20 & 21).

As migratory butterflies, western monarchs are dependent on environmental cues to achieve critical milestones in their life cycle. For instance, when monarchs sense the arrival of fall, the cues help them to produce the super generation with characteristics that are fit for migration (Brower, 2015; Guerra, 2020; Pyle, 2015). Thus, climate change and land use change could also lead to a lack of sensory cues that may hinder a successful migration (Guerra, 2020). The initialization and termination of diapause at the overwintering grounds are also closely related to how monarchs relate physiologically to environmental conditions. The onset and duration of western monarch diapause are critical to both survival and reproduction (Green II & Kronforst, 2019).

On the other hand, such unique sensitivity to environmental cues in their life stages and on the migratory routes, may signify environmental change at their overwintering sites (Green II & Kronforst, 2019; Guerra, 2020).

## Conclusions

This thesis examined the importance of the California coastal groves providing overwintering western monarchs the resources needed for overwintering and survival. However, these groves are also impacted by an array of stressors that could decrease their quality and biomass, and in turn, could adversely impact the associated monarch viability and abundance.

The results of this study highlight several key points:

- The quality and biomass of the overwintering coastal groves, which are crucial to the survival of western monarchs, appears to have deteriorated over time during the study period. Both EVI and NDVI data trends for the last 20 years displayed their highest peaks of mean values in 2011 and 2004 respectively, and never reached such peaks for the rest of the recent decade;
- The coastal groves (EVI and NDVI) showed more prominent negative anomalies during the recent decade (2010-2019);
- The dominant land cover types have changed in ways that are likely detrimental to monarch abundance, i.e., degradation of habitat quality and decrease of shrublands that provided nectar-rich food sources;
- Based on Maxent species distribution modeling, when comparing the overall habitat suitability in 2018 with 2003, 2018 indicated a smaller extent of suitable habitat;
- Both the monarch presence/distribution and the overall study area indicated a potential range shift when observing the two-dimensional climate characteristics (precipitation & land surface temperature).

Multiple factors contribute to the abundance of western monarchs and their overwintering habitats. Regarding the intricate relationship between the groves of California's coast, particularly their microclimates, and the consequential viability of monarchs, more intensive research is merited.

In addition, the climate pattern (e.g., the increasing day and night temperatures and substantial precipitation variation for the last two decades) that has become increasingly variable along the California coast requires close monitoring with respect to potential impacts on the coastal groves and monarchs.

This study spanned 20 years of observations using remote sensing data to analyze the trends and anomalies of large-scale habitat variation and their extent and impact in relation to monarch abundance for the entire swath of overwintering grounds. Its results underscore the need to institute a relevant and rigorous conservation program to enable coexistence of both the western monarchs and their coastal groves. As this study provides broad insights that cover a major portion (21 counties) of the California coast, further studies at the individual county level could assist policymakers to gain additional perspective of the dynamics and changes of their specific coastal grove conditions and land cover. Unique, more fine-grained forest dynamics, including varied species compositional changes, and variance in environmental resources and stressors are likely to impact associated populations of overwintering monarchs. Accordingly, observations at the county and state levels may, in turn, enable policymakers to develop better targeted strategies, while maintaining cohesive management policies across the entire California coast.

In addition, the baseline assessments and results established here could enable future, expanded observations of such trends and anomalies. Mapping projected outcomes vs. actual results could reveal relative effectiveness of conservation plans/ policies, thus facilitating more finely-tuned monitoring by researchers and improvements in conservation planning by policymakers.

The use of remote sensing in conservation initiatives can be a valuable tool to observe key drivers and environmental variables that are relevant to biodiversity conservation (Rose et al., 2014; Turner et al., 2015). By applying remote sensing to gauge habitat viability, this study identified correlations with western monarch butterfly abundance. The approach represents a further contribution of remote sensing to conservation.

The increasingly accessible and refined quality of satellite remote sensing imagery and output data, coupled with the availability of user-friendly, open source machine learning and GIS software, offers a practical and useful means for conservationists and policymakers to monitor significant swaths of landscape, such as the entire California coastline. Anomalies that would otherwise have been missed can now be detected. In turn, the assessment and results of such a pixel-based approach would allow conservationists and policymakers to pinpoint specific phenomena or areas of concern, and to conduct additional studies via a more resource-focused and detailed *in-situ* approach.

Beyond shedding light on the extent and dynamics of monarch habitat suitability, deploying machine-learning tools such as Maxent software may also enable researchers to discover and evaluate new locations as potential monarch overwintering sites.

From the results of this study, two emergent questions could readily frame future research initiatives:

- Was the 2018 and 2019 abrupt decline in western monarch abundance merely an outlier to be dismissed, or a more significant and potentially enduring population decline mediated by deterioration of the overwintering grounds?

- To what extent might the decline in western monarch abundance at the overwintering grounds also signal an alarming condition for lesser-known species, including other pollinators, that share habitat and other ecological resources with the monarch?

The coastal groves and monarchs are valuable assets to the local community and should be protected and given a chance to continue thriving for future generations. The findings of this paper, presented here, may offer insights to conservation planners and policymakers considering longer-term sustainability of the western monarch population.

Appendix 1

Land Cover Type 2 Class Definition

LC_Type2: Annual University of Maryland (UMD) legend and class definitions (NASA EARTHDATA, 2022a).

| **Name** | **Value** | **Description** |
|---|---|---|
| Water bodies | 0 | At least 60% of area is covered by permanent water bodies. |
| Evergreen Needleleaf Forests | 1 | Dominated by evergreen conifer trees (canopy >2m). Tree cover >60%. |
| Evergreen Broadleaf Forests | 2 | Dominated by evergreen broadleaf and palmate trees (canopy >2m). Tree cover >60%. |
| Deciduous Needleleaf Forests | 3 | Dominated by deciduous needleleaf (larch) trees (canopy >2m). Tree cover >60%. |
| Deciduous Broadleaf Forests | 4 | Dominated by deciduous broadleaf trees (canopy >2m). Tree cover >60%. |
| Mixed Forests | 5 | Dominated by neither deciduous nor evergreen (40-60% of each) tree type (canopy >2m). Tree cover >60%. |
| Closed Shrublands | 6 | Dominated by woody perennials (1-2m height) >60% cover. |
| Open Shrublands | 7 | Dominated by woody perennials (1-2m height) 10-60% cover. |
| Woody Savannas | 8 | Tree cover 30-60% (canopy >2m). |
| Savannas | 9 | Tree cover 10-30% (canopy >2m). |
| Grasslands | 10 | Dominated by herbaceous annuals (<2m). |
| Permanent Wetlands | 11 | Permanently inundated lands with 30-60% water cover and >10% vegetated cover. |
| Croplands | 12 | At least 60% of area is cultivated cropland. |
| Urban and Built-up Lands | 13 | At least 30% impervious surface area including building materials, asphalt, and vehicles. |
| Cropland/Natural Vegetation Mosaics | 14 | Mosaics of small-scale cultivation 40-60% with natural tree, shrub, or herbaceous vegetation. |
| Non-Vegetated Lands | 15 | At least 60% of area is non-vegetated barren (sand, rock, soil) or permanent snow and ice with less than 10% vegetation. |
| Unclassified | 255 | Has not received a map label because of missing inputs. |

Appendix 2

MODIS Validation

MODIS Validation Strategy (NASA, 2022).

| Validation Hierarchy | |
|---|---|
| Stage 0 validation | No validation. Product accuracy has not been assessed. Product considered beta. |
| Stage 1 validation | Product accuracy is assessed from a small (typically < 30) set of locations and time periods by comparison with in-situ or other suitable reference data. |
| Stage 2 validation | Product accuracy is estimated over a significant set of locations and time periods by comparison with reference in situ or other suitable reference data. Spatial and temporal consistency of the product and consistency with similar products has been evaluated over globally representative locations and time periods. Results are published in the peer-reviewed literature. |
| Stage 3 validation | Uncertainties in the product and its associated structure are well quantified from comparison with reference in situ or other suitable reference data. Uncertainties are characterized in a statistically rigorous way over multiple locations and time periods representing global conditions. Spatial and temporal consistency of the product and with similar products has been evaluated over globally representative locations and periods. Results are published in the peer-reviewed literature. |
| Stage 4 validation | Validation results for stage 3 are systematically updated when new product versions are released and as the time-series expands. |

## Appendix 3

## Research Process

To answer the first research question and test the related hypotheses, steps were taken as the following:

1. Processed the MODIS datasets for NDVI, EVI, and LC sub-types by using QGIS. Note: All land cover types were used for this study except type 0 (water bodies), type 3 (deciduous needleleaf forest), and 11 (permanent wetlands). For the entire list of LC various sub-types - see Appendix 1 for details.
2. Prepared a shapefile based on the defined western monarch overwintering study area, adapted from CALVEG mapping zones (USGS Forest Service, 2022).
3. Downloaded and generated imagery and statistics for variables mentioned above.
4. For a broader scale observation:
    a. Conducted NDVI and EVI time series trend analysis respectively for the entire study period. Succession trend analyses were conducted after the initial trend patterns have been analyzed.
    b. Calculated the NDVI and EVI anomaly by taking the difference of an individual year's average and the 20-year average (2000-2019).
    c. Generated the deliverables:
        i. Time series trend charts for NDVI and EVI.
        ii. NDVI and EVI anomaly (difference) charts that depicted the anomaly-occurrence years for the two-decade period to observe if the coastal

groves are showing a disproportionate increase of the negative anomaly-occurrence years (i.e., lower than the 20-year average).

5. For a detailed observation:
    a. Calculated the averages of area covered (%) for the entire study period (2001-2019).
    b. Generated the deliverable: A difference (anomaly) chart showing the changes of individual land cover types to observe if there was a shift in various land cover types (e.g., the abundance of evergreen needleleaf forests and evergreen broadleaf forests, taller and mature trees vs. shorter trees, and urbanization).

To answer the second research question and test its primary hypothesis, the following steps were conducted:

1. Processed the MODIS and GPM datasets for climate and environmental descriptors: LC sub-types, LST_day, LST_night, precipitation, using QGIS.
2. Prepared a shapefile based on the defined western monarch overwintering study area, adapted from CALVEG mapping zones (USGS Forest Service, 2022).
3. Downloaded and prepared respective datasets for the previous decade (2003 and 2008) and the recent decade (2013 and 2018) to compute monarch habitat suitability:
    a. X variable: Monarch overwintering sites (coordinates). Data cleaning process including elimination of sites with no-data (i.e., private properties or missing coordinates) or/and sites that have less than 10 butterfly counts. Thus, a total

of 276 of known presence occurrences (i.e., overwintering sites) were used, i.e., 60, 72, 77, and 67 site coordinates were used for year 2003, 2008, 2013, and 2018 respectively.

   b. Y variables: LC (13 land cover types), LST_day, LST_night, and precipitation.

4. Ran the Maxent species distribution model for the years 2003, 2008, 2013, and 2018 respectively.
5. Generated the deliverables:
   a. Four habitat suitability model maps that indicated predicted areas (pixel-based) where the habitat conditions were more/less suitable for the western monarchs based on the defined study area.
   b. Summary statistics of "model fit," i.e., area under the ROC (receiver operating characteristic) curve (AUC); values ranging from 0 to 1, where 1 is the best fit.
   c. Habitat suitability difference map (2018 vs. 2003).
6. Compared the four maps (2003, 2008, 2013, and 2018) to observe change over time, and the difference map to determine if the overwintering habitat suitability in the recent decade had decreased when compared to the previous decade.

Note that besides the above-mentioned deliverables generated to answer both research questions, additional charts, diagrams, and maps were also included to enhance analysis and visualization.

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