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Challenges for Monitoring the Extent and Land Use/Cover Changes in Monarch Butterflies' Migratory Habitat across the United States and Mexico

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Abstract: This paper presents a synopsis of the challenges and limitations presented by existing and emerging land use/land cover (LULC) digital data sets when used to analyze the extent, habitat quality, and LULC changes of the monarch (*Danaus plexippus*) migratory habitat across the United States of America (US) and Mexico. First, the characteristics, state of the knowledge, and issues related to this habitat are presented. Then, the characteristics of the existing and emerging LULC digital data sets with global or cross-border coverage are listed, followed by the data sets that cover only the US or Mexico. Later, we discuss the challenges for determining the extent, habitat quality, and LULC changes in the monarchs' migratory habitat when using these LULC data sets in conjunction with the current state of the knowledge of the monarchs' ecology, behavior, and foraging/roosting plants used during their migration. We point to approaches to address some of these challenges, which can be categorized into: (a) LULC data set characteristics and availability; (b) availability of ancillary land management information; (c) ability to construct accurate forage suitability indices for their migration habitat; and (d) level of knowledge of the ecological and behavioral patterns of the monarchs during their journey.

Keywords: Monarch butterflies; *Danaus plexippus*; migratory habitat; land use/cover

1. Introduction

Monarch butterflies (*Danaus plexippus*) are a unique species as a trinational cross-border migrant with eastern populations traveling over 4000 km from the Great Lakes in Southern Canada to overwintering sites in the Oyamel (*Abies religiosa*) forests of Central Mexico [1,2]. There is also a smaller population west of the Rocky Mountains that travels some 500 km to overwintering sites in the coast of Southern California and Northern Baja California in Mexico [2]. Renowned as providing large cultural ecosystem services, the monarch has become the state insect of seven states in the United States of America (US), the official insect of Quebec, Canada and the Monarch Butterfly Biosphere Reserve (MBBR) in Michoacán, Mexico was declared a UNESCO (United Nations Educational, Scientific and Cultural Organization) world heritage site in 2008. Stressing their importance, the White House included monarch butterflies in their pollinator conservation priority behind the honeybee [3].

The availability of nectar, roosting locations, and water sources along the monarchs' long migration are essential to their survival. When monarchs feed on nectar, they accumulate lipids, which serve as their energy stocks. During the fall migration, these are not only necessary for completing the migration but are also essential for surviving the overwintering period [4,5]. Most of the lipid accumulation in the fall is believed to occur throughout Texas and Mexico. This has been found by comparing monarch lipid levels during fall migration in Virginia to levels in overwintering colonies in Mexico over a four-year period (1998–2001). Lipid levels in Virginia were found to be, on average, 4% of those found in butterflies in overwintering sites [5].

The relationships among climate, microclimates, specific land use/land cover (LULC) types, and the abundance of monarchs are complex and difficult to predict. There is a diversity of dynamic environmental conditions along their extensive migration routes. For example, in the spring migration, climatic conditions in Texas have been linked to changes in the size of monarch breeding populations in Ohio and Illinois. Precipitation and temperature are suggested as the factors most closely related to these changes. Local agricultural land use with application of herbicides has recently been proven to be associated with reduced abundance of adult monarchs [6,7].

Several studies have linked monarchs' abundances in one region of their life cycle with environmental conditions or abundances in a different region. Early season warm temperatures in the northern breeding areas were negatively correlated to overwintering abundances the following year, but late season warming was positively correlated [8]. Breeding populations in the North–Central US were correlated with higher precipitation and cooler temperatures in Texas during the spring [6].

LULC digital data sets are important in modeling the extent, suitability, and spatial arrangement of the monarch butterfly habitat. Thematic LULC classifications serve as a proxy for identifying variations in the level of suitability for monarch activities such as foraging, roosting, and breeding. Changes in the natural range of plant species used by the monarchs alter their breeding grounds, distribution, and populations [9,10]. The United States Department of Agriculture's (USDA) National Resources Inventory (NRI) has been used to measure changes in foraging suitability for honey bees and native pollinators across the US [11]. The US Geological Survey's (USGS) National Land Cover Database (NLCD) has been used to characterize land cover found around roosting sites in Texas [12]. The USDA's Economic Research Service (ERS) Major Land Uses (MLU) database has been used to estimate monarch propagation and milkweed quantities in breeding habitat [13]. LULC change analysis can also reveal areas with disturbed vegetation which have shown to have better foraging suitability [14].

Recent studies have emphasized the importance of carrying out coordinated monarch habitat conservation and restoration actions over large areas requiring cooperation across national borders and several LULC classification systems [15–17]. More specifically, to identify and monitor migratory habitat, analyses must span the US and Mexico. However, studying LULC across borders poses several challenges. Between the US and Mexico, there are differences in digital data availability, original data sources, production methods, thematic classifications, resolution, and accuracy. This creates complications and limitations for cross-border analyses. In addition, the monarch's association with, and dependency on, specific LULC types varies both temporally and geographically. Hence, there is uncertainty on the influence of specific LULC types (e.g., urban areas, agriculture, or forests) on the monarch's migratory habitat quality [12,13]. For example, depending on the data resolution and granularity of the thematic classes, urban areas can contain varying levels of vegetative mosaics, some of which can support monarchs. Similarly, agriculture can consist of different crops, adjacent fence rows, and different ma nagement techniques, and forests could vary in density, fragmentation, species, and adjacency to other LULC types.

Changes in LULC and in land management practices (e.g., in crop lands) in the migratory routes of the monarchs have been hypothesized as an important contributor to the decline of their population [13,18–20]. Hence, to effectively monitor the conditions and changes in the monarch migratory habitat, digital LULC data sets would ideally have exceptionally high spatial and thematic resolution and be supplemented with ancillary data (e.g., land and crop management practices). Furthermore, the LULC thematic classes of national data sets would need to be homogenized to be compatible across national borders and be available for at least two dates to be able to conduct change detection analyses [11,21,22].

The purpose of this article is to present a synopsis of the characteristics and limitations of existing and emerging digital LULC data sets when used to determine the extent and LULC changes occurring in the monarchs' migratory habitat across the US and Mexico that might be affecting their population. This information is not currently available in a consolidated way to assist researchers, land managers, and the general public in quickly understanding the gaps in LULC data, information, and knowledge required to study this habitat and analyze its impacts on the monarch populations.

The rest of this paper is organized as follows. Section 2 presents a background on the characteristics, state of the knowledge, and issues related to the monarch migratory habitat. Section 3 summarizes the currently available LULC digital data sets, their characteristics, and limitations to support the study of the monarchs' migratory habitat. First, the data sets that have a global or US/Mexico cross-border extent are presented, then the data sets that cover the national extent of Mexico, followed by the data sets that cover the national extent of the US. Section 4 presents information about issues and challenges involved in creating cross-walks between the existing LULC data sets on both sides of the border. Section 5 presents recently released historical and frequently updated multiresolution data sets and free Cloud-based tools available for analyzing them. These data and tools offer opportunities for future studies of changes in the monarchs' migratory habitat. Section 6 presents a discussion of the challenges created by the current state of the knowledge and available LULC digital data sets when used to characterize and monitor the monarchs' migratory habitat and points to some alternatives to move forward the research agenda. Finally, the Section 7 summarizes some important points and suggests some strategies to advance the knowledge of the characteristics and LULC changes in the monarchs' migratory habitat.

2. Background on the Monarchs' Migratory Habitat

Monarch butterflies have three habitats: overwintering, breeding, and migration [4,5]. Overwintering habitat has been extensively studied [2,23–27]. The breeding habitat for the eastern migratory population of monarchs ranges from Texas to the Northeastern US, surrounding the Great Lakes and going into Canada. Reproduction primarily takes place in the US Midwest but can take place anywhere where milkweed (*Asclepias* spp.) is found. The increased use of herbicides and pesticides in agricultural fields in the US Midwest is responsible for the milkweed limitation hypothesis, which is one of the leading theories for explaining the monarch population decline [13,18–20].

Monarch migratory habitat has been studied in relation to migratory corridors, their extent, foraging vegetation, land management strategies, LULC, and the use of information from pollinator species such as honeybees as proxies for monarchs' habitat [4,11,12,14,16,28–30]. Some research attributes the declines in conducive migratory habitat as responsible for the declines in monarchs' population [29]; however, this finding is still debated [20,31]. Limited knowledge exists about the behavior of monarchs during migration and their relationship to different LULCs throughout their migration range [12,30].

East and West populations of monarchs have different geographic ranges and migration patterns. While the West population remains primarily in California and the Western US, the migratory extent of the Eastern population ranges from Canada, bordering the Great Lakes, to Central Mexico on the border between the states of Mexico and Michoacán, where the Monarch Butterfly Biosphere Reserve (MBBR) is located [2,5]. The exact extent of the migratory boundaries is difficult to delineate. Widely distributed roosting locations have been identified across the Eastern US, indicative of a multitude of major migratory corridors. However, these corridors converge upon two corridors in Texas, the Central Texas and Coastal Texas flyways [32]. It is believed these two routes converge once more at the Mexico/Texas border and form one migratory corridor through Mexico leading to the MBBR [33]. The migratory corridor beginning in Texas and through Mexico is considered the most crucial to the survival of the overwintering population [4,5].

Milkweed (*Asclepias* spp.) is most commonly associated with the monarch butterfly for breeding and foraging during their migration [13,18]. In efforts to restore nectar along migratory routes, the "Monarch Highway" was created in 2016. The US states of Minnesota, Iowa, Missouri, Kansas, Oklahoma, and Texas created a partnership to plant milkweed along Interstate 35. The White House also created a pollinator health task force in 2015 in efforts to understand the issues confronting native pollinators and "restore or enhance 7 million acres of land by 2020" [3]. Some non-native species of milkweed, such as *Vincetoxicum*, have been planted due to the White House pollinator initiative and are used by female monarchs to lay eggs but do not support caterpillars once they are born [29]. Several species, in addition to milkweed, have been identified as suitable for monarch foraging, among them [5,14,17,18,34]. The daisy family (asters, goldenrods, dahlias, marigolds, zinnias); dogbane; ironweed; coneflower (*Rudbeckia* spp.); goldenrod; fleabane; thistle; peony; lupine; vetch; wild yarrow; phlox'; clover; alfalfa; *Bidens uristosa*; and species of *Asteraceae* [5,14,16,17,34]. In Mexico, between 40 and 50 species have been identified as conducive to either foraging or roosting [35]. There are additional conducive species found in overwintering habitat [36]. Some butterflies also obtain nutrients, minerals, and salt from rotting fruit, tree sap, animal dung and urine, carrion, clay deposits, and mud puddles [34].

In an exploratory study to determine the best land cover for pollinators, the United States Department of Agriculture (USDA) derived forage suitability indices (FSI) for various land cover types in the US based on pollen and nectar availability [11]. These indices were derived from the National Resources Inventory data (NRI https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/) using the pollination services model [37]. The study indicates grassland, forest, pasture, rangeland, and rural roadsides as the highest conducive land covers to foraging. The lowest were barren land and open water. Agriculture was dependent on the crop and was broken up into four categories of conduciveness: (1) very low: corn, wheat, rice, barley, and sorghum; (2) low: soybeans, cotton, buts, and grapes; (3) medium: citrus, melons, potatoes, strawberries; and (4) high: sunflowers, berries.

The USDA FSI illustrates the complexities and limitations of using LULC data to identify suitability and quality of monarch migratory habitat. Wetland, shrubland, developed area, and perennial ice/snow were not included in the FSI results. Subcategories of forest and grassland were also not considered. The FSI is not species-specific and focuses on honeybees and other native pollinators. Further, the FSI does not consider land management practices, pesticide and herbicide application, parasites, diseases, or spatial contiguity and arrangement of different LULC types. Finally, the NRI data are produced at one sample point per parcel of land, resulting in very coarse spatial resolution.

Different LULC have been proposed as more conducive to migration habitat. Agricultural lands (especially corn and soy) historically contained milkweed, making this land cover conducive to breeding. However, the use of glycophosphate in fields has greatly reduced milkweed, making agricultural fields exceptionally poor breeding habitat [13]. However, modeling agricultural areas in Mexico is difficult because documentation of herbicide and pesticide use in Mexico is not reliable [38].

Roadsides also have been reported as having mixed conduciveness. While the USDA FSI has listed rural roadsides with a high FSI, it does not include urban roadsides, nor does it report roadside management practices. Roadsides with natural vegetation or supplemented nectar-producing flora, such as the milkweed corridor along the Interstate 35, are highly conducive to monarchs. However, planting non-native species, the usage of pesticides and herbicides, as well as mowing, decrease pollinator habitat suitability [28]. Monarchs experience vehicle mortality when crossing roads [39]; however, the mortality rates are negligible when compared to the benefits of natural vegetation on roadsides [28].

Developed areas and urban landscapes vary in their ability to support the monarchs' migration. Low levels of development disturb vegetation and can introduce grasslands, both of which are beneficial to nectar production for monarchs [40]. Urban parks, community gardens, and green architecture can create vegetative mosaics in developed areas, contributing to migration habitat [28,41]. However, as development increases, so do impermeable surfaces diminishing land cover that can support foraging and roosting [42]. Similar to roadsides, the use of pesticides and herbicides, suppression of native vegetation, and maintenance practices (e.g., mowing, trimming) reduce the foraging suitability for monarchs [14,28]. The conduciveness of urban parks is largely reliant on management practices. Urban areas have been studied in relation to bees, but very little has been done regarding monarchs [11].

Forests also appear to have mixed levels of migratory habitat conduciveness. The USDA has given forests a high FSI. Forests in Arkansas that are subject to prescribed burns have shown higher densities of monarchs [14]. Prescribed burns have increased nectar abundance in Oklahoma, Arkansas, Texas, the Western US, and Mexico [30]. Disturbed areas in general have been shown to increase the abundance of foraging through the production of flowering flora. These areas can include anthropogenic-induced grasslands and fields, prescribed burn areas, timber harvest locations, grazing, roadsides, including verges, and rights-of-way along fences and powerlines [14,30,43].

During migration, monarchs require roosting locations every night. Little research has been done on roosting habitat as it relates to land cover except for one study in Texas [12]. It indicates that 97% of roosting observations occurred in trees with no particular preference for a tree species. These trees were found within a 10 km radius of roosting locations, and more open water was found near roosting sites than in random locations. In Southern Texas, the land surrounding roosting locations was 67% cropland, and closer to Mexico, it was 61% grassland [12]. Roosting locations were found to be closer to deciduous forests and urban areas than in random locations; however, these findings are based on monarch roosting observation data, which tend to be more frequently reported near urban areas.

Finally, there is the issue of synchronicity of monarchs' presence and conditions in specific LULC types (e.g., fallow agricultural lands). Tracking the migration of the monarch butterfly has been facilitated by citizen science groups since 1975, with the majority of data collection beginning in 1993 [29,32]. Fifteen citizen science organizations have been identified that collect data on the monarch either nationally in the US or through regional and local efforts [30]. The information produced by these groups is only monarchs' presence data (i.e., where monarchs and monarch roosting locations have been sighted). The Monarch Larva Monitoring Project (MLMP) uses citizen science to document egg counts and larvae on milkweeds in the US [19]. These occurrence data sets have been used in several studies [5,9,12,20,31–33]. Citizen science data come with a number of issues and limitations. The data are frequently acquired through convenience sampling, and the collection methods are not standardized (e.g., collection locations, time and frequency of collection, and number of collection participants), making data aggregation and comparisons difficult and unreliable.

3. Land Use/Land Cover (LULC) Data Sets

As mentioned in the previous section, the migratory habitat of the monarch needs more study to better understand its extent, characteristics, association of monarch populations to different LULC extents, and LULC changes occurring in this habitat. LULC digital cartographic products capable of supporting these endeavors ideally would have the following characteristics. They would seamlessly span the large extent of the migratory habitat and be homogenous regarding their spatial resolution, accuracy, and thematic classes. Their spatial resolution would have to be fine enough to identify and enable the monitoring of changes in small areas of high habitat value in natural, urban, and agricultural/grasslands environments. While the most appropriate spatial resolution to achieve these tasks has not yet been determined, vegetation mapping in urban areas has been performed successfully with high-resolution data (submeter LIDAR Light Detection and Ranging data and 4 m satellite imagery) [44,45]. Using 4 m spatial resolution images has achieved overall accuracies of 87% in urban areas [45]. Quality Level 1 (QL1) LIDAR has been reported to be accurate up to 0.25 m spatial resolution in sample cases [12]. However, the USGS lists a Minimum Mapping Unit (MMU) of 1 m for these data [46].

When considering the data sets presented in this paper, it is important to remember the relationships and implications of the concepts of resolution and MMU [47]. In theory, the smallest possible feature that could be mapped would be equal to one pixel of the satellite image used to produce a cartographic product, such as a LULC map (e.g., 30 × 30 m for Landsat images). However, it is generally agreed that the smallest observable feature that can be reliably identified would need to be four contiguous pixels in size (i.e., 60 × 60 m for Landsat images) [48]. Further, it is important to remember the relationships between map scale, effective resolution, and MMU [49]. For example, a map scale of 1:250,000 has an effective resolution of 125 m and a MMU of 1.56 hectares.

The ideal thematic classes' granularity would be specific enough to identify and monitor LULC classes that are of high value or essential for the monarchs' survival during their migration. In addition, these thematic classes would be homogenous and comparable across the cross-border extent of the migratory habitat and be available for at least two different dates to allow for change detection. The complexity and difficulty of meeting these ideal characteristics are further compounded by the need for spatiotemporal information regarding the phenology of diverse plants that are essential for foraging during the monarchs' migration. The White House's Pollinator Research Action Plan lists phenology of pollinating plants as a key research gap [3]. Some work has been done but focuses on *Asclepias* in relation to monarch breeding grounds and climate change [6,9].

LULC data sets with these ideal characteristics do not currently exist. Hence, to analyze the migratory corridor across borders, two options are currently available: (1) using cross-border/global data sets; or (2) matching and combining (cross-walking) LULC data sets from each side of the US–Mexico border. Next, we present the LULC data sets that are available for each of these options.

3.1. Cross-Border/Global Data Sets

Table 1 lists cross-border/global LULC data sets that cover the extent of the monarch migratory corridor in North America. These data sets have the following limitations when used to study the monarchs' migratory habitat: (1) coarse spatial resolution for habitat analysis purposes; (2) different and coarse granularity of LULC thematic classes; (3) different sources and methodologies to obtain their LULC classifications; and (4) different or not-reported levels of accuracy.

Even with the best currently available spatial resolution with global coverage (30 m) or finest LULC thematic classification (22 classes), it is not possible to detect LULC types that have been identified as important for migratory habitat [14,28] such as grasslands on roadsides; numerous vegetation and garden patches in urban areas; small streams; and narrow corridors of disturbed forests.

Misclassification of LULCs that are habitat-conducive could lead to falsely quantifying the amount of foraging available and mislead studies about how LULC changes in migration habitat affect changes in the monarch population. Currently, the most applicable highest resolution data set released for multiple dates (2000 and 2010) and capable of changing detection is GlobeLand30 (GL30) [47]. While the FROM-GLC data set is produced at the same spatial and thematic resolution, its overall accuracy is lower, and it has not been tested specifically for Mexico [50–52].

Thematic classes' granularity is also a limitation in these data sets. Even the data sets with the largest number of thematic classes are limited in their ability to differentiate vegetation types and their subcategories that can be used to estimate densities of specific nectar-producing flora and create an accurate monarch forage suitability index. More thematic classes are necessary at finer spatial resolutions to account for different types of vegetation that are conducive for monarch migration habitat.

Table 1. Cross-border and global land use land cover (LULC) data sets covering the extent of monarch migration habitat.

Land Cover Data Set	Thematic Classes	Spatial Resolution	Temporal Availability	Data source and Original Purpose	Available at:
GlobeLand30 (GL30)	10	30 m	2000 2010	Data sources: Landsat TM/ETM+ and HJ-1, (China environmental disaster Alleviation Satellite). Also used ancillary datasets Purpose: Finer scale global land cover dataset for natural resources management, environmental studies, urban planning for sustainable development	www.globeland30.org Background information: http://www.globeland30.org/home/Enbackground.aspx.
Finer Resolution Observation and Monitoring of Global Land Cover (FROM-GLC)	10	30 m Working on 10 m resolution classification	2015 2017	Data source: Landsat TM/ETM+ Purpose: To provide higher resolution land use land cover across a global extent. General use for change detection and climate science.	http://data.ess.tsinghua.edu.cn/
North American Land Change Monitoring System (NALCMS)	19	250 m	2005 2010	Data source: Moderate Resolution Imaging Spectroradiometer (MODIS). Purpose: Moderate resolution cross border environmental concerns for climate change, carbon sequestration, biodiversity loss, and changes in ecosystem structure and function	https://catalog.data.gov/dataset/north-american-land-change-monitoring-system-nalcms-collection http://www.cec.org/tools-and-resources/north-american-environmental-atlas/north-american-land-change-monitoring-system
Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover. Aqua and Terra Product MCD12Q1	17	500 m	Annual 2001 2017	Data source: MODIS Purpose: To aid in the understanding of environmental systems around the globe.	https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/land-cover-and-phenology/MCD12Q1/
Land Cover-Climate Change Initiative (LC-CCI)	22	300 m	2000 2005 2010	Data source: Composite-MERIS FR/RR, AVHRR, SPOT-VGT, and PROBA-V Purpose: To develop a consistent land cover data set for scientists to perform climate modeling.	https://www.esa-landcover-cci.org/?q=taxonomy/term/5 https://www.esa-landcover-cci.org/?q=node/158
GlobCover	22	300 m	2 periods: December 2004–June 2006 January–December 2009	Data source: MERIS sensor on ENVISAT satellite. Purpose: To produce global composite land cover maps	http://due.esrin.esa.int/page_globcover.php
Sentinel-2 (Multispectral instrument)	Simulated natural color (*emerging land cover classification*)	10 m 20 m	2015-present every 10 days	Data source: European Sentinel satellite Purpose: Land cover, use and change detection mapping: https://sentinel.esa.int/web/sentinel/thematic-areas/land-monitoring/land-cover-use-and-change-detection-mapping	https://www.usgs.gov/centers/eros/science/usgs-eros-archive-sentinel-2?qt-science_center_objects=0#qt-science_center_objects
Land Cover-Climate Change Initiative (LC-CCI)	10	10 m	2017 (*Emerging data—not yet released*)	Data source: European Space Agency (ESA)—Earth Observation (EO) Purpose: Improving the understanding of the interaction between climate and land cover while increasing the spatial resolution of 1 order of magnitude (from 300 to 10–30 m) with respect to the LandCover_cci	http://cci.esa.int/HRLandcover http://2018mexicolandcover10m.esa.int/

Global and cross-border data sets are also not always the best for analyzing LULC changes across large geographic regions. Variations in ecoregions, bioclimatic variables, and topography create changing conditions that complicate and reduce the accuracy of classifications across the world [53–55]. No comprehensive accuracy assessments have been performed for any of the global and cross-border data sets listed in Table 1. Only some local, regional, or national accuracy assessments have been done, for example, for GlobeLand30 [52,54,56,57]. A recent publication lists 14 of these studies with a summary of their findings [58].

Data sets that exhibit potential future application include higher resolution releases of the North American Land Change Monitoring System (NALCMS) and the Land Cover–Climate Change Initiative (LC–CCI) data sets. As of 2017, the NALCMS has developed a 10 m spatial resolution LULC data set covering the extent of North America with 19 thematic classes. This resolution and level of thematic granularity could provide a greater ability to more accurately assess the changes in the monarch butterfly habitat. At this time, it is only available for year 2010, and hence, no change detection analyses can be performed. The European Space Agency (ESA) has plans to develop their Land Cover-Climate Change Initiative (LC–CCI) LULC data set with global coverage at 10 m spatial resolution. Their most recent LULC product is a prototype that covers the extent of Africa at 20 m spatial resolution with 10 thematic classes.

3.2. LULC Data Sets for Mexico

Table 2 presents the LULC data sets with national coverage in Mexico. The INEGI Series II through VI data sets [59] are the only authoritative comparable LULC data sets with national coverage available for Mexico. The INEGI Series offer an excellent thematic classes' granularity with a total of 176 LULC classes. Each of these data sets is at a scale of 1:250,000 and is provided in the Lambert Conical Conformal projection. INEGI has homogenized the LULC classes in these layers; hence, temporal changes can be evaluated.

The usefulness of the INEGI Series II to VI for analyzing current state and changes in the LULC conducive for monarchs' migratory habitat is limited by their coarse spatial resolution (scale 1:250,000). At this scale, it is not possible to identify small but important vegetative mosaics that contribute to foraging in the migration habitat (e.g., urban gardens and green areas; disturbed vegetation on the edges of forests and roads).

Table 2. Land use land cover (LULC) data sets from Mexico covering the extent of monarch migration habitat.

Land Cover Data Set	Thematic Classes	Spatial Resolution	Temporal Availability	Data Source and Original Purpose	Available at:
National Institute of Statistics and Geography (INEGI)	176	Scale 1:250,000 vector format.	Series II (1993), III (2002), IV (2008), V (2013), and VI (2017)	Data source: Landsat satellites. Purpose: Indicate the distribution of natural and induced vegetation, level of growth, location of water bodies, forestry, and agriculture.	https://www.inegi.org.mx/temas/mapas/usosuelo/
Monitoring Activity Data for the Mexican REDD+ program (MAD-Mex)	66	20 m, RapidEye Satellite (German) and 30 m Landsat	(*Emerging data set—not yet released*)	Data source: RapidEye and Landsat Purpose: To automate the production of land cover data sets for Mexico to study emissions, deforestation and forest degradation.	https://github.com/CONABIO/madmex-tutorials

As of December 2018, the Monitoring Activity Data for the Mexican REDD+ program (MAD-MEX) data sets have not been officially released. The MAD-MEX is a system to provide standardized annual land cover information by automatic satellite image classification for the Mexican territory (https://github.com/CONABIO/madmex-tutorials). MAD-MEX processes data from two satellites: Landsat (https://landsat.usgs.gov/) and RapidEye (https://www.planet.com/products/satellite-imagery/files/160625-RapidEye%20Image-Product-Specifications.pdf). The product contains 66 LULC thematic classes which could potentially help in identifying vegetation conducive to the monarchs' migration.

The INEGI LULC maps were used as training and validation data sets (242,170 samples), and the product has shown an overall accuracy of 71% [60].

3.3. LULC Data Sets in the US

Table 3 presents the LULC data sets with national coverage for the US. The National Land Cover Database (NLCD) is the authoritative LULC data set for the US and is produced at a spatial resolution of 30 m with 16 thematic classes. Its classes distinguish natural and introduced grasslands and levels of built infrastructure. Ancillary data sources such as the Cropland Data Layer (CDL) and the Landscape Fire and Resource Management Planning Tools Program (LANDFIRE) allow the identification of the extent of different types of disturbed areas that can be used to identify high-value migratory habitat.

Table 3. Land use land cover (LULC) data sets from the US covering the extent of monarch migration habitat.

Land Cover Data Set	Thematic Classes	Spatial Resolution	Temporal Availability	Data source and Original Purpose	Available at:
National Land Cover Database (NLCD) 2016	16	30 m	2001 2004 2006 2008 2011 2013 2016 (*Published April 2019*)	Data source: Landsat Purpose: Assessing ecosystem status and health, modeling nutrient and pesticide runoff, understanding spatial patterns of biodiversity, land use planning, deriving landscape pattern metrics, and developing land management policies.	https://www.mrlc.gov/national-land-cover-database-nlcd-2016
Cropland Data Layer (CDL)	(60+)	30 m (2008–2018); 56 m (2004–2007)	Every year	Data source: Composite—Landsat, IRS-P6 Resourcesat-1, ResourceSat-2, MODIS, DEIMOS-1, UK-DMC 2, and SENTINEL-2 Purpose: To provide acreage estimates to the Agricultural Statistics Board for major commodities and to produce digital, crop-specific, categorized georeferenced output products.	https://www.nass.usda.gov/Research_and_Science/Cropland/Release/index.php
Landscape Fire and Resource Management Planning Tools Program (LANDFIRE)—Vegetation Disturbance	8	30 m		Data source: Landsat Purpose: Provide landscape level geospatial products that show vegetation, disturbance from biological, chemical, development, fire, insect disease, mechanically added/removed, and windthrow.	https://www.landfire.gov/

4. Attempts to Cross-Walk the Data Sets

In addition to using one of the LULC data sets mentioned in previous sections, these data sets can be combined, or cross-walked. Cross-walking is the integration of multiple LULC data sets for the purpose of expanding their individual areal extent, increasing their temporal frequency, homogenizing their thematic classifications, or improving their accuracy. While cross-walks can be beneficial and have shown the ability to improve the accuracy of classifications, this process often reduces their spatial and thematic resolution [61,62]. A variety of methods have been used and compared for cross-walking LULC data sets [55]. However, all established methods require spatial overlap of the data sets to compare performance of the cross-walk results at each location [55,61–65]. Therefore, the national LULC data sets listed in Tables 2 and 3 cannot be assessed for how reliable any cross-walked classification system will be for monarch migration habitat.

Assessing the quality of the matching resulting from cross-walking different LULC data sets is difficult, particularly when there is no spatial overlap in their extent. Due to the geographic variation in vegetation, topography, and land management practices between Mexico and the US, the algorithms used to define thematic classes in both countries are not compatible. Using thematic classes from both sides of the border interchangeably adds inherent uncertainty to the thematic classification resulting from the cross-walking process. Additionally, not all thematic classifications have equivalent classes to match. For example, Mexico's national LULC data sets known as Series II, III, IV, V, and VI produced by the INEGI [59] include primary forest, secondary forest, and shrubland, while the US NLCD data set has the shrubland class, but it does not distinguish between forest cover successional stages. Methods to resolve these discrepancies exist for LULC data sets with overlapping extents, but this is not in the case for the US and Mexico's national data sets [55].

5. Collect Earth (CE), Collect Earth Online (CEO), Google Earth (GE), and Google Earth Engine (GEE)

Collect Earth (CE; http://www.openforis.org/tools/collect-earth.html), Collect Earth Online (CEO; http://www.openforis.org/tools/collect-earth-online.html), Google Earth (GE; https://www.google.com/earth/), and Google Earth Engine (GEE; https://earthengine.google.com/) are a set of Open-source tools that work together to provide access and analytical capabilities for a large collection of high resolution imagery from the Landsat (https://www.usgs.gov/land-resources/nli/landsat; 30 m resolution, 1972–present day), MODIS (https://modis.gsfc.nasa.gov/gallery/; 500 m resolution; since 1999), and Sentinel (https://sentinel.esa.int/web/sentinel/home; several sensors, 10 m resolution since 2014–2015) satellites, as well as other geospatial data sets of aerial photography and climate data. The data catalogue with details of data sets and their temporal and spatial availability can be accessed at https://developers.google.com/earth-engine/datasets/. An overview of the structure and functionality of these tools and the methodology used to carry out land monitoring through augmented visual interpretation are presented in [66]. Other publications [67,68] present how these tools can be used by scientists and non-experts to carry out land use change monitoring and analyses for species conservation.

The processing capabilities of these tools and the easy access to recent and frequently updated cross-border high-resolution images offer the potential to support innovative LULC change monitoring studies for the whole extent of monarchs' migratory habitat (e.g., https://sentinel.esa.int/web/sentinel/thematic-areas/land-monitoring/land-cover-use-and-change-detection-mapping). They can also provide a platform to integrate and analyze contributions from scientists and citizen volunteers [68] regarding presence and abundance of monarchs as well as plant species essential for their survival during their migration.

6. Discussion

Due to the characteristics of the currently available and emerging LULC data sets as well as the state of the knowledge of the monarchs' migratory habitat, the geographic extent of this habitat and the LULC changes within it that might be affecting the monarchs' population can only be measured and modeled at a coarse resolution and more appropriately at a regional level. The issues that create challenges and limitations to these assessments can be categorized into: (a) LULC data sets characteristics and temporal availability; (b) availability of ancillary land management information; (c) ability to construct accurate forage suitability indices based on knowledge of the phenology and abundance of plant species used by monarchs during their migration (e.g., https://www.usanpn.org/news/spring); and (d) level of knowledge of the ecological and behavioral patterns of the monarch during their journey. Improvement in these areas will increase our ability to understand, model, and predict the implications of LULC and its changes in the migration habitat and on monarchs' population changes. Despite limitations, analyses and modeling with current data must be carried out to assist in reducing uncertainties and creating approximations to support the design and execution of management and conservation actions. In what follows, we touch briefly on each of these challenges.

Currently available LULC data sets need improvement in spatial resolution, thematic classes' granularity, expanding their extent across borders, and to be available and homogenous for at least two dates to enable change detection analyses. The highest resolution currently available for cross-border analyses is 30 m (GlobeLand30). At this resolution, the intricacies of landscape mosaics that are conducive to foraging or roosting in the migratory habitat are not detectable (e.g., grassland along roadsides, streams, disturbed patches of forest, and vegetative corridors through urban areas). GlobeLand30's coarse thematic classes granularity (10 classes) does not distinguish between types of forests, shrublands, or grasslands. This limits the ability to estimate the density of nectar-producing flora associated with each land cover type. Data sets with higher thematic classes' granularity such as the INEGI Series or the NLCD are not cross-border. Trying to overlap these higher thematic granularity data sets with GlobeLand30 to refine its LULC classes propagates classification errors, and the resulting product is not reliable for better estimating migratory habitat. We have tested this approach over small areas with unsatisfactory results. Additionally, the thematic classifications of the US and Mexico national data sets are not homogeneous in resolution, number of classes, and accuracy across the border and hence cannot be compared or combined with other LULC data sets. Both thematic granularity and spatial resolution need to be homogenized in time and space to be able to perform LULC change detection analyses across the entire extent of monarch migratory habitat.

In addition to accurately and precisely knowing the type of LULC, land management practices can determine whether a specific LULC type is conducive to migratory habitat or not. This is most notable for pesticide and herbicide application, vegetation maintenance practices (e.g., forest fuel treatments, mowing), and creation of supplemented monarch foraging vegetation. Agriculture and grasslands are found to be some of the most conducive LULC types to foraging. However, herbicides can destroy naturally occurring nectar sources, and pesticides can weaken and kill monarchs directly. This brings into question the conduciveness of agricultural fields, pasture/rangeland, grasslands along roadsides or utility rights-of-way, and various vegetative corridors and mosaics through urban environments (e.g., parks, home gardens). This information is not well documented, especially throughout Mexico. Forest fuel treatments, such as prescribed burns and thinning, create disturbed areas that can create additional foraging for monarchs. Due to the spatial resolution and temporal lag between LULC data sets, it is not possible to detect where these practices are occurring. Mowing also can destroy conducive grassland habitat. Fallowing practices on pasture and rangeland can also determine the foraging habitat availability. Efforts to create supplemented foraging, such as the Interstate-35 milkweed corridor and the US National Park Service efforts to improve migratory pollinator corridors, need to be easily accessible in formats that can be input into geographic information systems (GIS) to better support the study and modeling of migratory habitat.

Many species of nectar producing flora that are conducive for the monarch habitat have been identified. However, it is difficult to assess the amount of foraging these plant species collectively supply over the extent of the monarchs' migration. While the USDA has created a foraging suitability index for native pollinators, it is more focused on the honeybee, specific to the US, and comes with a host of limitations. A monarch migration specific foraging suitability index has yet to be created. The Instituto de Ecología of the Universidad Nacional Autónoma de México (UNAM) (Ecology Institute in the National Autonomous University of Mexico) has been working on identifying monarch-conducive plant species and consolidating this information for easy access. Additionally, for each plant species, it is necessary to document information about its geographic extent, associated land cover type, density estimations, nectar production, monarch usage, effects of land management practices, and phenological behavior.

More and better monarch ecological and behavioral information can also improve habitat models through understanding of how they use their environment. Many questions have not yet been answered in the literature, including: How far are monarchs are willing to travel between foraging resources, roosting locations, and water sources? How does the spatial arrangement of migratory habitat (i.e., connectivity and fragmentation) influence migration success? Additionally, how do other environmental factors come into play: wind, temperature, solar radiation, elevation, slope, aspect, precipitation, and water accumulation?

In addition to the previously mentioned issues, monarchs' occurrence data created through sightings reports have largely been used to study their migration. Unfortunately, these data come with several limitations. They are occurrence data only. We do not know where monarchs are not present, only where sightings have been reported. The data that are available are collected through convenience sampling. The distribution of monarch occurrences closely resembles the distribution of human population centers and accessible areas along the migration route, which results in higher monarchs' occurrence densities associated with higher human population presence and accessibility. The collection methods are not consistent. The locations, time, frequency of sampling, and number of sampling participants are all variable. These factors vary not only temporally (from season to season) but also geographically and in relation to LULC. Due to the inconsistencies in how the data are produced, they can be at best used as a rough approximation to identify the migratory extent, as well as arrival and departure times from each location. They cannot be reliably used for estimating monarchs' population. Current efforts by the US Geological Survey (USGS) and other agencies (shortly to be published) are on the way to develop a continental level sampling strategy.

A potential alternative to overcoming some of the limitations discussed above is multiscale monitoring and modeling. This incorporates data sets at various spatial resolutions from local to landscape levels. Multiscale data set composites have been found useful for modeling the presence of butterflies, pollinator habitat, and pollen flow [69–71]. A study which characterized butterfly habitat found that while fine scale LIDAR (Light Detection and Ranging) data sets were better predictors of habitat than coarse scale vegetation data sets, creating a multiscale model with the use of both data sets provided the best performance [72]. An example that could be applicable to modeling monarch migration habitat in the US is using LANDFIRE vegetation land cover in combination with NatureServe's Ecological Systems data set of 144 vegetation types [73]. Determining areas where land cover classifications overlap or are in proximity to locally collected nectar producing flora could aid in improving predictions of the location of foraging areas for monarchs. This multiscale approach has been performed in urban areas where field measurements of vegetation have been combined with satellite imagery [45]. In the subtropical climate zone of the city of Nanjing in China, this approach has reported overall land cover accuracies of 87.71%, achieving higher accuracy than any single scale approach.

7. Conclusions

Assessing with a high degree of confidence the extent and changes occurring in the monarch butterflies' migration habitat and how they impact their population is currently difficult. There are no cross-border LULC data sets with enough spatial resolution, temporal frequency, and thematic classification granularity to determine with high accuracy and confidence the extent and spatial arrangement of this habitat. Land management information is not captured or disclosed at a level that differentiates conducive vs. non-conducive practices in known habitat conducive LULC types.

Information about foraging is not complete or consolidated enough to create a robust foraging suitability index that is applicable specifically to monarch migration habitat. The behavior of monarchs during migration is not clearly understood, and questions are unresolved about how they use their environment during their journey. These factors generate uncertainty in the knowledge about the monarchs' migratory habitat.

The challenges and limitations for determining the extent, suitability, and changes in the monarchs' migratory habitat can be categorized into: (a) LULC data sets characteristics and availability; (b) availability of ancillary land management information; (c) ability to construct accurate forage suitability indices based on knowledge of the phenology and abundance of plant species used by monarchs during their migration; and (d) level of knowledge of the ecological and behavioral patterns of the monarchs during their journey.

Multiscale, multiresolution monitoring and modeling of the monarchs' population and LULC changes in their migratory habitat can be performed in strategically chosen areas along their migratory routes to address the challenges mentioned above. Areas so far identified as critical (e.g., Texas) for which numerous data sets and on-the-ground resources exist can be used as pilot areas to move forward the monarchs' migratory habitat research agenda. The availability of recent and frequently updated data sets and analytical tools on the Cloud (such as those mentioned in Section 5 in this paper) promise to provide more and new resources to monitor the LULC changes in the monarchs' migratory habitat.

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