Appendix IV.4 Potential distribution model of Monarch Butterflies

Background

The monarch butterfly or Danaus plexippus is a species of lepidoptera of the Nymphalidae family. Their reproduction cycle lasts 30 days and is composed by the states of egg, caterpillar, chrysalis and imago or adult.

Table 1. Reproduction cycle of Monarch Butterflies

Stage	Description
Egg	It lasts between 3 and 8 days and they show a flatten or spherical shape and ornamented surface. Eggs are laid on *Asclepias sp. leaves. (milkweed plants).*
Caterpillar or larva	It lasts between 7 and 17 days and they have chewing mouth parts which produce silk, and prolegs on the abdominal segments in addition to the actual thoracic legs. They eat the crust of their own egg and *Asclepias sp. leaves.*
Chrysalis or pupa	It lasts between 8 and 15 days and caterpillars grow inside silk cocoons to give place to another form called chrysalis. During this stage they stop eating.
Imago or adult	After emerging from the chrysalis, the butterfly is ready to reproduce, mate and lay eggs. Adults live approximately 5 weeks; however, it has been observed that monarchs born in the late summer might live for up to 8 months. The latter are the ones that migrate to Mexico to spend the winter.

Source: Galindo-Leal et al, 2000

The time needed to mature during their development is proportionally inversely related to the photo-period, duration of daylight hours, and temperature, that is, during spring and summer as there are more daylight hours during the day and temperature is higher, the lifespan of monarch butterflies is shorter; whereas their vital period extends in autumn and winter as daylight hours and temperatures decrease, so the length of stages in each life cycle varies in terms of weather and the region where individuals develop.

An adult lives approximately five to eight weeks; however, monarch butterflies born late summer may live for up to eight months and migrate to Mexico for the winter. (Galindo-Leal et al, 2000). Even if the monarch butterfly is distributed in several parts of the world, Canada, USA, Mexico, Cuba, Peru and Argentina, and it has also been registered in Australia and Hawaii, in North America a phenomenon occurs that does not take place in any other place: migration of monarch butterflies for more than 3000 km (Malcom, 1987).

Danaus plexippus are the only butterflies capable of traveling such long distances back and forth when migrating. Autumn migration begins late August and early September in the north of the USA and south of Canada, with daily journeys between 80 and 160 km/day. The flying capacity of the monarch butterfly is amazing. Butterflies have been observed in different places of North America flying between 600 and 1200 meters, rising into thermal currents and even entering clouds (GIBO, 1981).

North America hosts two well-defined populations of monarch butterfly: the eastern and western migratory population. The eastern population is located to the east of the Rocky mountains and migrates to the center of Mexico, while the western population hibernates in the Coast of California. Some butterflies in dispersion of the western population are likely to follow the mountains from California and go through Nevada and Arizona until reaching the hibernating sites of the eastern population in Mexico.

North America eastern population migrates in autumn towards to south for the winter concentrated in a little more than a dozen of mountainous sites of Mexico, discovered in 1975. Spring migration happens early March. With warm temperatures monarch butterflies become more active and some of them interrupt the diapause to start mating and eggs are deposited on their nutritious plants (Asclepias sp*), so their descendents continue migrating and progressively reach the northern limit of their distribution which reaches south Canada early or mid June to return during the following autumn. Recently, it has been documented that they use the gallery forests of rivers as corridors (Dingle, et al., 2005).*

In this document we intend to determine the potential distribution of monarch butterflies according to rain and temperature parameters. First, we considered using the distribution of *Asclepia sp* to generate models; however, the species used in Mexico are not known so it was impossible to use this environmental factor. Next, the methodology applied is described.

General methodology applied

In general terms, a potential distribution model of a species is a map representing the appropriateness and inappropriateness of the territory for the presence of a species at continuous scale which tends to adjust to the range 0-1 (0: incompatible; 1: ideal). If a point on the terrain has a value near 1 it means that descriptive values in that point are very similar to those existing in the current site of presence of the species, therefore, consequently and upon absence of other factors, that place might be considered compatible for their existence. The generic procedure to build a potential distribution model for a given species is summarized in the following table.

1. <u>Geographically locate the presence of the species</u> and, if possible, establish absence points.
2. <u>Define a group of descriptive variables</u> to be used as predictors to define an *environmental niche* for the species from the presence and absence data available and their geographic location. For each point of presence or absence the values of

independent variables corresponding to that geographic location are extracted. The group of presence/absence records, geographic coordinates, descriptive variable values composes what is called training sample.

3. Establish a statistical relationship between descriptive variables and dependent variables (presence/absence). This process consists essentially in generating an algorithm related to each combination of independent variable with the presence or absence of the species analyzed. This relationship is called statistical model. The feature is interpreted with the idea that the probability of a species present at a place depends on the values of descriptive variables; for example, a species may disappear as summer temperature values increase and rain values decrease.

4. Build the cartographic model or potential distribution model (MDP) from the statistical model. This procedure is carried out by labeling each point of the area of study with the corresponding P(i) value based on the values of independent variables at that point.

Next, the methodology applied is presented with further detail.

1. Geographic location of the presence of the species

Collecting records of *D. plexippus* obtained from Global Biodiversity Information Facility (GBIF, http://www.gbif.org/) and the National System on Biodiversity Information (SNIB, http://www.conabio.gob.mx/remib/doctos/snib.html) were used.

Information obtained was filtered and organized in a database according to migration periods reported in books. Records that deferred from the distribution pattern reported for the species, as well as records presenting extreme temperature and rain values were excluded; this was done by the Modeling/Bioclim-Domain module with which accumulated frequency curves that allowed recognizing records with extreme temperature and rain values were obtained.

The number of collecting records for *D. plexippus* was 1,094 non-duplicated data from a database of 3,095 observations. The largest amount of records was observed in the central region of Mexico, northeast US and southeast Canada.

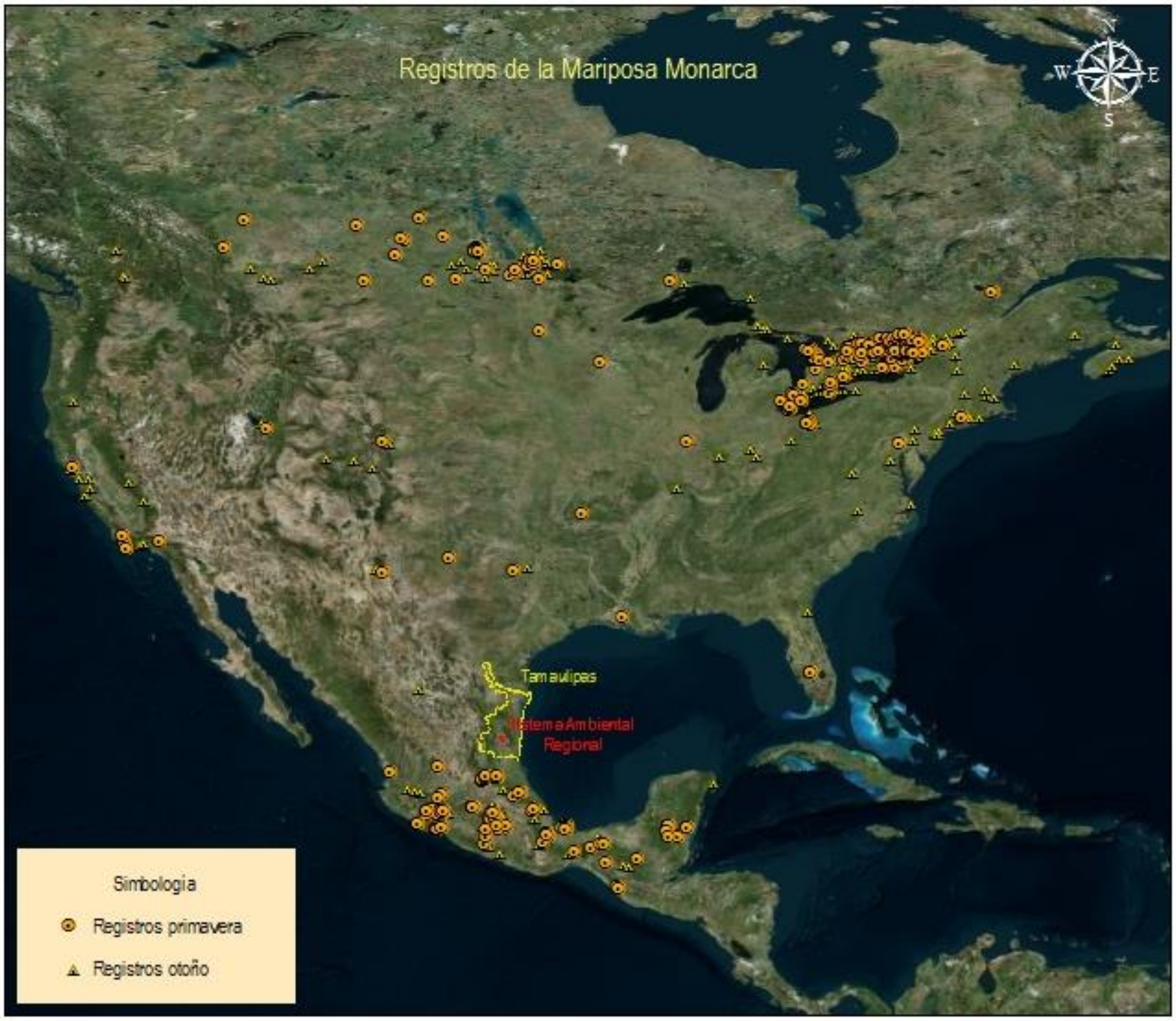

Figure 1. Distribution of records for Monarch Butterfly

2. Definition of a group of descriptive variables

Variables used to model the geographic distribution correspond to 19 bio-climatic variables with spatial resolution of 1 km^2, representing an annual trend (average annual temperature, annual rain), seasonality (annual record of temperature and rain) and extreme limits of environmental factors (minimum and maximum monthly temperatures, quarters with and without rain). Climate elements from which the 19 variables used by BIOCLIM were obtained, corresponding to monthly average precipitations, and monthly maximum and minimum temperatures, referred to a period encompassing 1950 through 2000 (Hijmans et al., 2005).

Table 2. Description of bio-climatic variables used in generation of potential geographic distribution models

Variable	Name	Description
BIO 1	Average annual temperature	The measurement of all average monthly temperatures. Every average monthly temperature is the average of maximum and minimum monthly temperatures.
BIO 2	Average day interval (Monthly average of max temp - min temp)	The average of all intervals of monthly day temperature. Every interval of monthly temperature is the difference between maximum and minimum monthly temperature every month.
BIO 3	Isothermality (P2/P7) (*100)	Average daily interval (parameter 2) divided by the annual interval of temperature.
BIO 4	Temperature seasonality (standard deviation *100)	Standard deviation of average monthly temperatures expressed as a percentage with respect to the average of said temperatures.
BIO 5	Max temperature of the warmest month	The highest of maximum monthly temperatures
BIO 6	Min temperature of the coldest month	The lowest of minimum monthly temperatures
BIO 7	Annual interval of temperature (P5-P6)	The difference between the maximum temperature of the warmest month and the temperature of the coldest month
BIO 8	Average temperature of the most humid quartile	After determining the most humid quartile, the average for this period of time is calculated
BIO 9	Average temperature of the driest quartile	After determining the driest quartile, the average for this period of time is calculated
BIO 10	Average temperature of the hottest quartile	After determining the hottest quartile, the average for this period of time is calculated
BIO 11	Average temperature of the coldest quartile	After determining the coldest quartile, the average for this period of time is calculated
BIO 12	Annual rain	The addition of all estimated monthly precipitations
BIO 13	Precipitation of the most humid month	It is the precipitation of the most humid month
BIO 14	Precipitation of the driest month	It is the precipitation of the driest month
BIO 15	Precipitation seasonality (variation coefficient)	The C.F. is the standard deviation of the average of monthly precipitations expressed as a percentage regarding the

Variable	Name	Description
		average of those months.
BIO 16	Precipitation of the most humid quartile	After determining the most humid quartile, the total precipitation for this period of time is calculated
BIO 17	Precipitations of the thickest quartile	After determining the driest quartile, the total precipitation is calculated
BIO 18	Precipitation of the hottest quartile	After determining the hottest quartile, the total precipitation for this period of time is calculated
BIO 19	Precipitation of the coldest quartile	After determining the coldest quartile, the total precipitation for this period of time is calculated

The exploratory analysis of 19 bio-climatic variables obtained for collecting records of monarch butterflies indicate that the environments where they are found show an average annual temperature of 8.11^{o}C and total average annual rain of 920 mm, which represents temperate and rainy climates. The spectrum of the value of bio-climatic variables shows rainy-temperate and tropical-rainy environments.

Table 3. Description of bio-climatic variables used in generation of potential geographic distribution models

Variable	Medium	Interval	Min	Max
Bio1	8.11	0.34	-1.41	28.45
Bio2	11.01	0.11	6.18	18.16
Bio3	31.56	0.81	21.49	74.65
Bio4	963.70	19.13	72.57	1391.90
Bio5	26.80	0.16	17.20	39.50
Bio6	-11.12	0.57	-26.00	17.90
Bio7	37.92	0.47	13.90	51.50
Bio8	16.21	0.37	-4.48	29.00
Bio9	-1.72	0.64	-17.58	28.45
Bio10	19.45	0.16	8.95	30.63
Bio11	-4.33	0.58	-17.58	26.02
Bio12	920.30	21.38	180.00	3892.00
Bio13	114.49	4.92	23.00	804.00

Variable	Medium	Interval	Min	Max
Bio14	48.01	1.20	0.00	94.00
Bio15	29.60	1.81	7.41	125.12
Bio16	320.72	12.88	59.00	1980.00
Bio17	154.46	3.73	1.00	313.00
Bio18	252.63	5.70	3.00	1070.00
Bio19	180.94	4.47	18.00	624.00

3. Establish a statistical relationship between descriptive variables and dependent variables (presence/absence).

The climatic affinity models prepared for *D. plexippus* considered an exploratory analysis of spring migration records as of autumn migration through the *Modeling* module present in DIVA-GIS. Two algorithms were used, *Bioclim* and *MaxEnt*, to determine the geographic distribution pattern of *D. plexipus* based on climatic variables described in Table 2 and 3.

BIOCLIM

The BIOCLIM procedure consists in identifying minimum and maximum variables of each environmental variable, to define a *"multidimensional environmental hub"* which allows estimating the climatic affinity of species, in this case of monarch butterflies.

Maximum and minimum values for each variable described in Table 3 are used to establish a *multidimensional environmental hub* or also called *core control*, with the purpose of evaluating the probability of presence/absence of monarch butterfly based on climatic affinity.

Records in the *multidimensional environmental hub* of 95% indicate that annual precipitation ranges between 500 and 1400 mm, average annual temperature between 2.5 and 23^{o}C, temperature of the hottest quartile between 16.5 and 26^{o}C and temperature of the coldest quartile presented a very wide variation with values between -14 to 20^{o}C

MaxEnt

Among the output options of MaxEnt, a jackknife test was chosen to identify variables that contribute to the model as much as possible. The selection of variables that were not correlated and used for the generation of distribution models was made with an Analysis of Main Components through the PAST statistics program (http://folk.uio.no/ohammer/past/), which allowed reducing the number of variables to less than half and reducing redundancy of environmental information.

4. Build the cartographic model or potential distribution model

For the generation of distribution models we used the DIVA-GIS program (http://www.diva-gis.org/), a geographic information system used for the analysis of databases from gene, herbal and zoology collection banks designed to determine genetic, ecologic and geographic patterns for the distribution of wild and domesticated species. This program obtains collecting records, values of temperature and precipitation existing in the continents except for the Antarctica and the oceans.

The use of BIOCLIM helped obtain a potential distribution model of monarch butterfly, in terms of minimum and maximum limits of variables related to rain and temperature.

The model generated by BIOCLIM assigns five categories that recognize the areas meeting the climatic conditions of the core control as presented in the following table:

Table 3. Categories of climatic affinity

Categories	Criteria
Inappropriate	Areas presenting values out of the core control or multidimensional environmental hub
Low	Areas within 0 - 2.5 and 97.5 - 100 percentiles
Medium	Areas within 2.5 - 5 and 95 - 97.5 percentiles;
High	Areas which values are within 5 - 10 and 90 - 95 interval
Very high	Areas located within 10 - 20 and 80 - 90 percentiles
Excellent	Areas located within 20 - 50 and 50 and 80 percentiles

The climatic affinity model estimated with BIOCLIM does not consider 2.5% of the lowest and highest values for each variable used in determining the categories of the *multidimensional environmental hub*, the group of data represents the limits of 2.5 - 97.5 percentiles

The model obtained indicated that for 1094 non-duplicated records and a hub of 0.05 percentiles, the distribution pattern shows a wide area of climatic affinity (class: medium, high, very high and excellent) at the central east and northeast of the United States, as well as the center and east of Mexico, over the Faja Volcánica Mexicana and the Sierra Madre Oriental respectively.

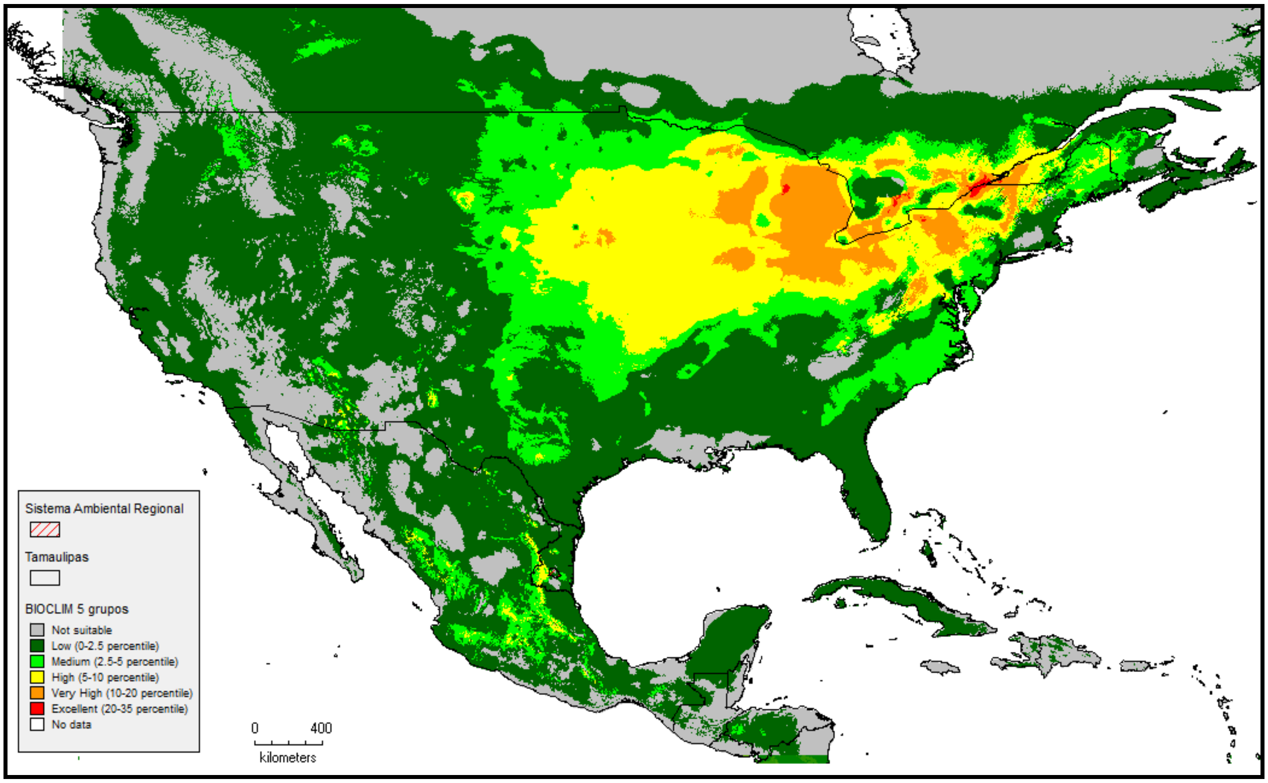

Figure 2. Climatic affinity model obtained with Bioclim

As for the Regional Environmental System (SAR) it was determined that it is located in an area of low climatic affinity (hub for a percentile of 0.025) for the records related to autumn and spring migration. In both models, for the SAR and the Project Area, inappropriate areas were found (gray areas) and of low climatic affinity (percentile 0-2.5).

The areas of greater climatic affinity are located to the east and west of the SA on the Sierra de Tamaulipas and the Sierra Madre Oriental, with high, very high and excellent climatic affinity categories. This is consistent with sites of very low variation of temperature and moderate rain.

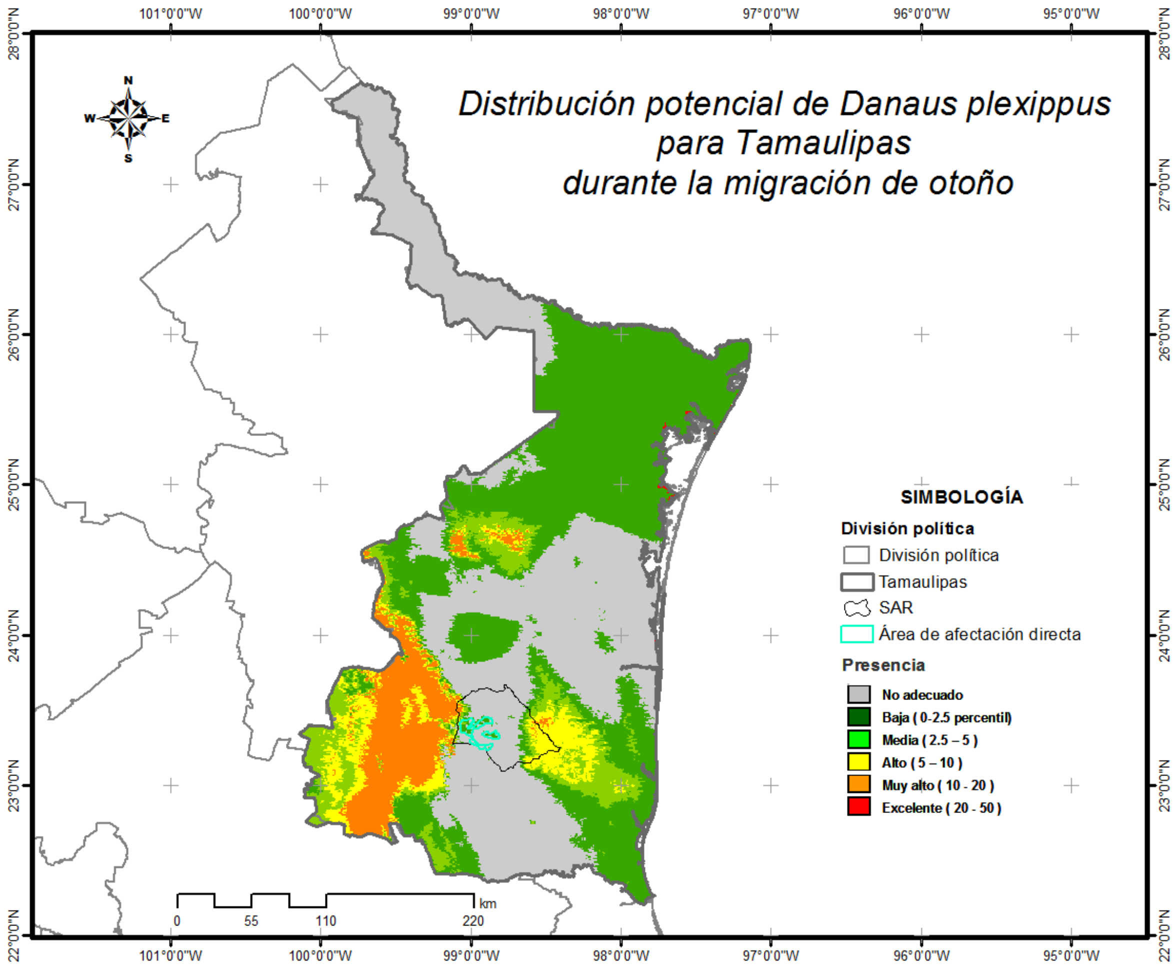

Figure 3. Models obtained for autumn migration with Bioclim for the State of Tamaulipas and the Environmental System

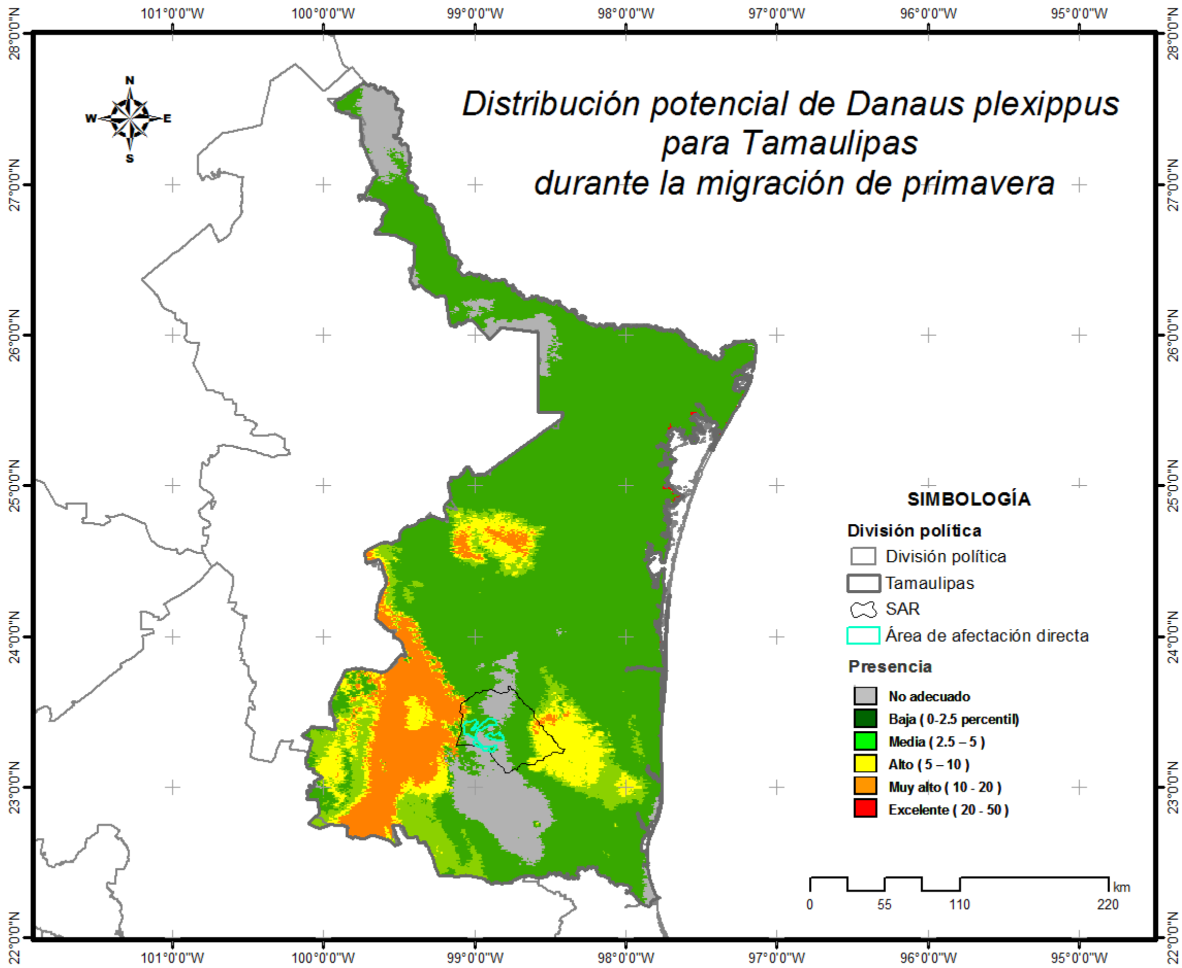

Figure 4. Models obtained for spring migration with Bioclim for the State of Tamaulipas and the Environmental System

In general, affinity models for the different migration periods are very similar excluding the south and north side of the SAR and establishing the east and west sides as sites of low climatic affinity. The difference in the extension of the low affinity area (green color) between spring and autumn models lies in the total number of records which was 540 and the second 1250 respectively.

MaxEnt

MaxEnt, a program based on a Maximum Entropy distribution for modeling the geographic distribution of species, starts by adjusting data from a uniform distribution which continues modifying until a distribution of maximum entropy. The model is based on adjusting the parameters of final distribution. This algorithm is better to "insert" among occurrence points than to predict non-observed areas.

The distribution pattern obtained by MaxEnt shows that the areas of higher adaptation are located in the center of Mexico, southeast and northeast of the United States and southeast of Canada. MaxEnt predicts very accurately between sampling points but does not have predicting capacity for zones with few collecting records. This fact was confirmed in the model obtained, which predicts that the areas with high adaptation values are the center of Mexico and southeast Canada. And this is consistent with the areas presenting a higher number of collecting records. MaxEnt did not distinguish intermediate areas of high adaptation between the records from north US and center of Mexico.

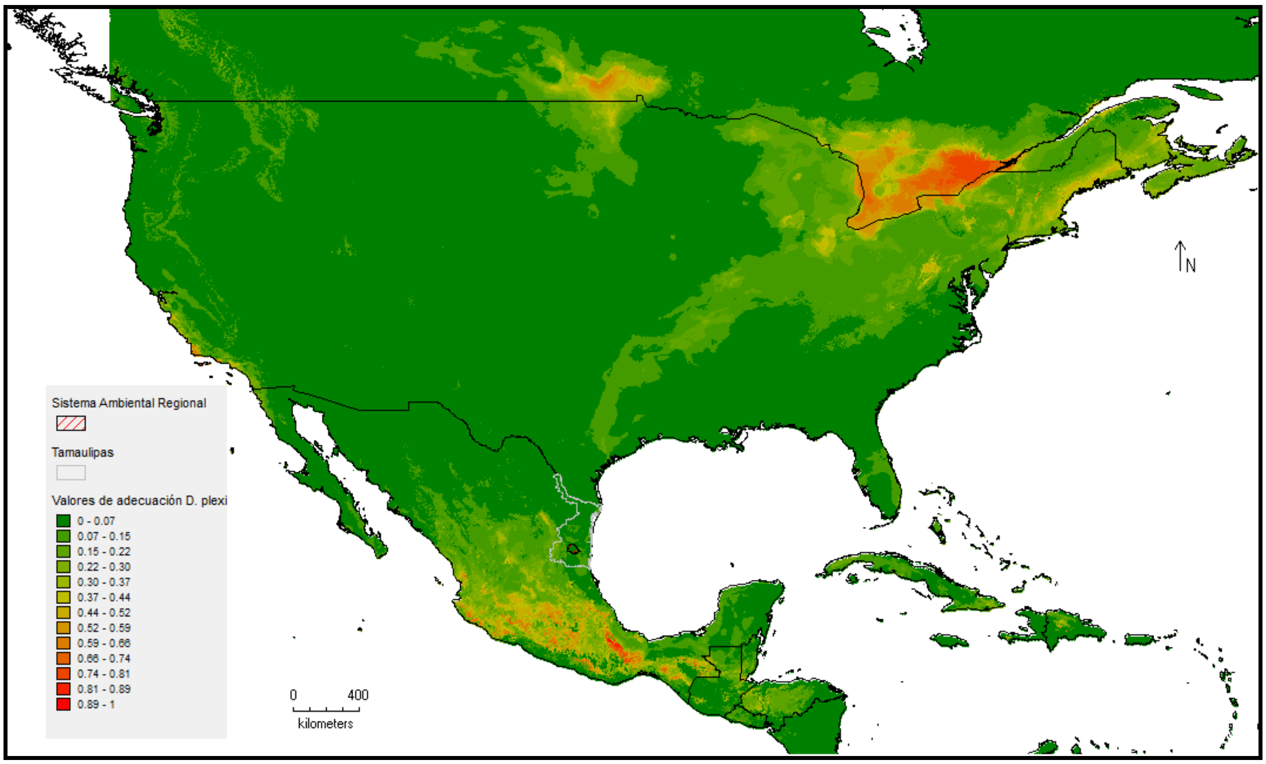

Figure 5. Potential distribution pattern of monarch butterfly obtained by MaxEnt

The environmental adaptation level according to the MaxEnt model for the Regional Environmental System was less than 5%.

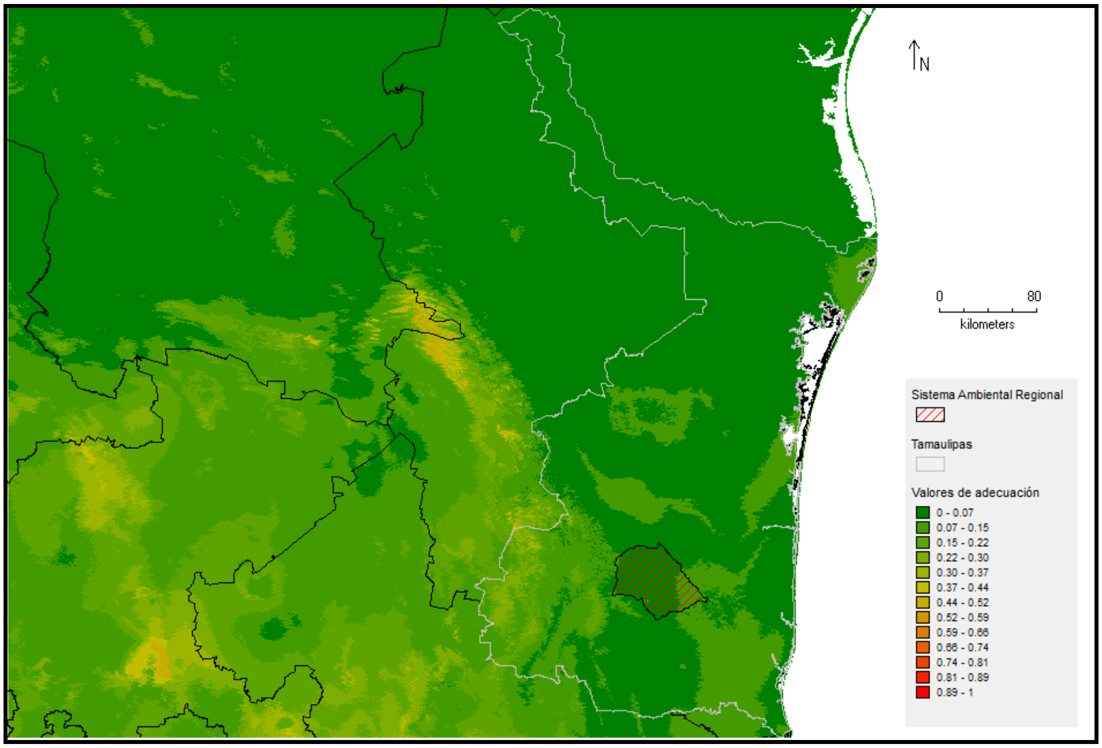

Figure 6. Potential distribution pattern of monarch butterfly obtained by MaxEnt in an approach for the State of Tamaulipas

In particular, it stands out for being located in an area of plateaus, with altitudes between 200 and 480 m, with average annual temperatures of 25°C and moderate rains that agree with the general pattern of the species; however, the prevailing condition of warm temperatures determines the low levels of climatic affinity and adaptations presented in models obtained by BIOCLIM and MaxEnt respectively. Considering the aforementioned, it is estimated that the incidence of butterflies around the plateaus area is minimum for it does not present ideal climatic conditions for their settlement, due to the tropical condition prevailing in the area.

In order to improve the models a higher number of records is required, especially in the areas presenting a certain degree of affinity, Sierra Madre Oriental and Sierra de Tamaulipas which represent favorable climatic conditions for *D. plexippus*. In order to fully eliminate if the plateaus belong to the migratory route of butterflies, information obtained through monitoring will be fundamental for it will enable obtaining data on the presence and abundance of butterflies in said area.

Literature consulted

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