UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO
POSGRADO EN CIENCIAS BIOLÓGICAS
FACULTAD DE ESTUDIOS SUPERIORES IZTACALA
ECOLOGÍA

¿POLINIZACIÓN EN RIESGO? IMPACTOS DEL CAMBIO CLIMÁTICO GLOBAL EN LOS PATRONES DE DISTRIBUCIÓN DE LOS COLIBRÍES Y SUS PLANTAS ASOCIADAS EN MÉXICO

TESIS

(**POR ARTÍCULO CIENTÍFICO**)

Together forever? Hummingbird-plant relationships in the face of climate warming

QUE PARA OPTAR POR EL GRADO DE:

MAESTRA EN CIENCIAS BIOLÓGICAS

PRESENTA:

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LOS REYES IZTACALA, TLALNEPANTLA, ESTADO DE MÉXICO. 2022.

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ASUNTO: Oficio de Jurado

M. en C Ivonne Ramírez Wence
Directora General de Administración Escolar, UNAM
Presente

Me permito informar a usted que en la reunión ordinaria del Comité Académico del Posgrado en Ciencias Biológicas, celebrada el día **25 de abril de 2022** se aprobó el siguiente jurado para el examen de grado de **MAESTRA EN CIENCIAS BIOLÓGICAS** en el campo de conocimiento de **Ecología** de la alumna **REMOLINA FIGUEROA DANIELA** con número de cuenta **310120236** por la modalidad de graduación de **tesis por artículo científico** titulado: **"Together forever? Hummingbird-plant relationships in the face of climate warming.",** que es producto del proyecto realizado en la maestría que lleva por título: **"¿Polinización en riesgo? Impactos del cambio climático global sobre los patrones de distribución de los colibríes y sus plantas asociadas en México.",** ambos realizados bajo la dirección de la **DRA. MARÍA DEL CORO ARIZMENDI ARRIAGA,** quedando integrado de la siguiente manera:

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Vocal: **DRA. SILVANA MARTÉN RODRÍGUEZ**
Vocal: **DRA. LAURA EDITH NUÑEZ ROSAS**
Secretario: **DR. DAVID ALEXANDER PRIETO TORRES**

Sin otro particular, me es grato enviarle un cordial saludo.

ATENTAMENTE
"POR MI RAZA HABLARÁ EL ESPÍRITU"
Ciudad Universitaria, Cd. Mx., a 30 de mayo de 2022

COORDINADOR DEL PROGRAMA

DR. ADOLFO GERARDO NAVARRO SIGÜENZA

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RESUMEN

Identificar los riesgos de extinción de las especies e incluso el desacoplamiento de sus asociaciones ecológicas ante el cambio climático global es considerado un paso crítico para establecer estrategias de conservación biológica efectivas a largo plazo. En este estudio se evaluaron los efectos potenciales del cambio climático global (CCG) en los patrones de co-distribución de 12 especies endémicas de colibríes y 118 plantas asociadas a su alimentación. Utilizando el enfoque de modelos de nicho ecológico, se estimó el área de distribución potencial de las especies y el grado de coincidencia espacial colibrí-planta para el presente y el futuro (años 2040, 2060 y 2080). Además, se realizó un análisis de diversidad beta temporal (basado en el índice de Sorensen) para evaluar cambios en el ensamblaje de las comunidades a través del tiempo. Asimismo, para determinar el impacto potencial del CCG en la organización de las interacciones colibrí-planta, se calcularon dos métricas típicas para redes de co-ocurrencia animales-plantas: tamaño y sobrelapamiento de nicho. Los resultados obtenidos mostraron que, aun asumiendo que las especies sean capaces de dispersarse a nuevas áreas, el ~50% de las especies de colibríes y plantas analizadas van a experimentar reducciones en el área de distribución, así como desacoples en el área de co-distribución colibrí-planta debido a cambios en la idoneidad climática. Los análisis para calcular la beta temporal sugieren además que habrá un recambio importante de especies al comparar entre los sitios en el presente y el futuro, mientras que el análisis de redes predice cambios en el tamaño de red y el sobrelapamiento de nicho a futuro. Estos cambios podrían implicar la formación de nuevos ensamblajes como resultado del recambio de especies e incluso una tendencia no uniforme a la especialización/generalización de las redes colibrí-planta en México. Los resultados obtenidos muestran que ante escenarios de CCG no debemos esperar respuestas uniformes entre las especies ni regiones. Desde esta perspectiva, para poder alcanzar la protección a largo plazo de servicios ecosistémicos importantes como la polinización, se requieren de más estudios que incorporen análisis de co-distribución de las especies para ayudar a la toma de decisiones en conservación.

Palabras clave: cambio global, interacciones bióticas, modelos de nicho ecológico, redes de co-ocurrencia, redes de polinización.

ABSTRACT

The identification of species' extinction risk and understanding their ecological associations are considered critical steps for achieving long-term conservation of biodiversity in the face of global changes. We evaluated the potential impacts of global climate change (GCC) on the co-distribution patterns of 12 Mexican endemic hummingbirds and 118 plants associated with their habitat uses. Using an ecological niche modelling approach, we estimated the species' potential distribution areas and their degree of range overlap at present and under future scenarios (years 2040, 2060, and 2080). Moreover, we performed temporal beta diversity analyses (based on Sorensen's index) to assess changes in community assembly over time. To determine the potential GCC impacts on the organization of hummingbird-plant relationships, we calculated niche overlap and network size metrics. Our results showed that even if we assume that species can disperse to novel habitat areas, ~50% of both hummingbird and plant species will face range reductions due to changes in their climate-suitability areas, which in turn will result in increased mismatch for their co-distribution patterns. Additionally, temporal beta analyses suggested species turnover between future and present for sites, as well as changes in size and niche overlap values for hummingbird-plant co-occurrence networks. Such changes could lead to the formation of novel assemblages through species reshuffling, with a non-uniform specialization/generalization of networks. These results emphasize that we should not expect uniform or matched responses among species and regions into the future. Therefore, analyses of species' co-occurrence are needed to accomplish the long-term protection of important ecosystem services such as pollination.

Keywords: global change, biotic interactions, ecological niche modelling, co-occurrence networks, pollination networks.

INTRODUCCIÓN GENERAL

Las interacciones bióticas son consideradas un componente esencial de la biodiversidad debido a su importante rol en las dinámicas ecológicas de las comunidades (Roemer et al., 2002; Thompson, 2009; Simmons et al., 2018) y en el mantenimiento de propiedades clave (estabilidad, resiliencia y resistencia) de los ecosistemas (Bascompte & Jordano, 2013). En consecuencia, el rol que tienen las interacciones bióticas en mediar las respuestas del cambio climático ambiental es crucial para mantener las funciones de los ecosistemas (Tylianakis et al., 2008). Sin embargo, y a pesar de su importancia, son pocos los estudios relacionados con el entendimiento de cómo los agentes de cambio global pueden impactar los patrones de co-ocurrencia (i.e., sobrelape de los rangos de distribución) de las especies y el ensamblaje de las comunidades (incluidas las interacciones bióticas) (Pearson et al., 2019; Heinen et al., 2020).

Los efectos individuales y sinérgicos del cambio climático global (CCG) y de uso del suelo podrían intensificar el riesgo de extinción de las especies y, además, causar una reorganización de la biodiversidad en el planeta (Lovejoy & Hannah, 2004; Pecl et al., 2017; Ceballos & Ehrlich, 2018). En este sentido, se esperan cambios a gran escala en la composición de las comunidades que conllevarían a un proceso de homogeneización del paisaje y, consecuentemente, a la modificación de las interacciones bióticas (Blois et al., 2013; Jordano, 2016a) y el funcionamiento de los ecosistemas, así como de los servicios que estos proveen a la humanidad (Senapathi et al., 2015; Kovács-Hostyánszki et al., 2017). De hecho, la pérdida de interacciones ecológicas importantes, como es el caso de la polinización y la dispersión de semillas, podrían tener efectos perjudiciales en los ecosistemas ya que muchas especies no serían capaces de completar sus ciclos de vida sin la presencia de las especies con las que interactúan (Jordano, 2016a). Diversos estudios han documentado los declives y las múltiples amenazas que enfrentan los polinizadores (Vanbergen & Initiative, 2013; Potts et al., 2016; Kovács-Hostyánszki et al., 2017) y, por ello, hoy en día son un foco de interés internacional. De este modo, el estudiar los impactos del CCG y de uso de suelo en las interacciones bióticas es considerado una prioridad de investigación para lograr alcanzar efectivamente una conservación a largo plazo de la biodiversidad (García-Callejas et al., 2018, 2019; Pearson et al., 2019; Regolin et al., 2020).

Para abordar estos temas en los últimos años se han utilizado distintas metodologías que permiten explicar, entender y predecir la distribución espacio-temporal de la biodiversidad, como es el caso de los modelos de nicho ecológico y distribución de las especies (Peterson et al., 2011). Inclusive, su uso ha aumentado drásticamente, con más de 6,000 estudios en las últimas dos décadas (Araújo et al., 2019). Sin embargo, a pesar de este uso tan extendido, el estudio de los patrones de co-ocurrencia de las especies, el ensamblaje de las comunidades y las interacciones potenciales entre las especies ha sido poco explorado y, particularmente, al diseñar esfuerzos específicos de manejo (Palacio & Girini, 2018; Heinen et al., 2020; Ramírez-Ortiz et al., 2020). Esto representa un importante vacío de información ya que las asociaciones bióticas pueden ser tan relevantes como los cambios en la temperatura y la precipitación (Araújo & Luoto, 2007; Şekercioğlu et al., 2012; Atauchi et al., 2018; Luna et al., 2022).

Actualmente, un enfoque alternativo para lidiar con este problema es el uso de redes de co-ocurrencia, en donde las especies son los nodos y las co-ocurrencias entre ellas son los conectores. Estas son de gran ayuda para inferir interacciones potenciales entre las especies a gran escala y para entender la organización de las interacciones bióticas a través del tiempo y el espacio (Araújo et al., 2011; Corro et al., 2019; Antoniazzi et al., 2020). Por ejemplo, el tamaño de la red (número de especies en la red) y el sobrelapamiento de nicho (medida de similitud promedio en el patrón de interacción entre especies del mismo nivel trófico) son dos descriptores de la red que pueden ser útiles para evaluar lo anterior (Dormann et al., 2009). Por ello, está alternativa —que no está exenta de críticas (Blanchet et al., 2020)— representa un importante primer paso para aumentar nuestro conocimiento sobre el ensamblaje de especies ante el cambio global (Morueta-Holme et al., 2016).

Los colibríes (Aves:Trochilidae) son el modelo ideal para explorar las relaciones entre la distribución espacio-temporal de la biodiversidad y las interacciones bióticas ya que este grupo de aves nectarívoras desempeña un importante rol en el funcionamiento de los ecosistemas al polinizar cerca del 15% de las especies de plantas en América (Able, 2000; Buzato et al., 2000). Además, son considerados uno de los grupos más amenazados del mundo. Desafortunadamente, las predicciones realizadas sobre el riesgo de extinción para las especies de colibríes no son optimistas, ya que se esperan declives poblaciones e importantes reducciones en su hábitat como consecuencia de los cambios ambientales globales (Correa-Lima et al., 2019; Chávez-González et al., 2020; Infante et al., 2020; Prieto-Torres et al., 2021). Además, los patrones espacio-temporales de distribución de los colibríes podrían variar debido a la fenología de floración de las plantas que usan como fuente de néctar (Correa-Lima et al., 2019; Chávez-González et al., 2020; Infante et al., 2020a). De este modo, los cambios en la composición florística y en la coincidencia fenológica representan un reto para el establecimiento de las interacciones colibrí-planta en el futuro. Por ello, es importante evaluar la susceptibilidad de las interacciones ante el CCG, especialmente si consideramos que la reducción de estos polinizadores podría crear efectos en cascada, resultando en la pérdida de biodiversidad y en la degradación de los servicios ecosistémicos (Ollerton et al., 2011).

Los colibríes de México (tanto las especies amenazadas como las no amenazadas) no son la excepción para estos escenarios críticos en el futuro. Estudios recientes han demostrado que el calentamiento global podría tener un impacto negativo en las especies al disminuir sus abundancias y al aumentar su riesgo de extinción, inclusive favoreciendo la reorganización de las comunidades en el país en las décadas futuras (Lara-Rodríguez et al., 2012; Correa-Lima et al., 2019; Chávez-González et al., 2020; Prieto-Torres et al., 2021). Además, los resultados sugieren que la actual Red de Áreas Protegidas del país no es efectiva para salvaguardar a las especies, ni lo será en el futuro (Prieto-Torres et al., 2021). Sin embargo, un problema importante en ese estudio es que únicamente se consideraron variables climáticas al modelar la distribución de los colibríes ante escenarios de cambio climático, mientras que variables bióticas como los cambios en la composición florística o los patrones de co-ocurrencia de las especies no fueron evaluados. En consecuencia, el riesgo de extinción y los impactos predichos podrían ser aún más drásticos, especialmente para las especies endémicas y amenazadas. Por ello, es importante que futuros esfuerzos de conservación contemplen información biótica y abiótica para detectar cuáles especies son más resilientes y qué regiones son más estables ante la pérdida de biodiversidad (Pecl et al., 2017; Pearson et al., 2019; Mendoza-Ponce et al., 2020).

En este trabajo, se abordaron las siguientes preguntas de investigación: (1) ¿cómo el cambio climático global impactará el sobrelapamiento de nicho y el tamaño de las redes de co-ocurrencia de los colibríes endémicos de México y las plantas de las que se alimentan?; y (2) ¿la redistribución de aves y plantas, derivada del cambio climático global, causará el reemplazo no uniforme de especialistas por generalistas? Se asume que debido a que el cambio ambiental futuro potencialmente va a producir respuestas especie específicas— como cambios en la distribución y en los patrones de migración — habrá modificaciones no-uniformes en los patrones de co-ocurrencia de las especies que, en consecuencia, alterará las interacciones bióticas (McConkey & O’Farrill, 2015; García-Callejas et al., 2018, 2019). La obtención de esta información facilitará la toma decisiones que promuevan una protección efectiva de la biodiversidad, especialmente porque con el paso del tiempo las oportunidades para conservar a los colibríes y a otras comunidades de polinizadores están siendo drásticamente reducidas (Dicks et al., 2016; Potts et al., 2016).

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Together forever? Hummingbird-plant relationships in the face of climate warming

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Short title: Hummingbird-plant networks under climate change

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ABSTRACT

The identification of species' extinction risk and understanding their ecological associations are considered critical steps for achieving long-term conservation of biodiversity in the face of global changes. We evaluated the potential impacts of global climate change (GCC) on the co-distribution patterns of 12 Mexican endemic hummingbirds and 118 plants associated with their habitat uses. Using an ecological niche modelling approach, we estimated the species' potential distribution areas and their degree of range overlap at present and under future scenarios (2040's – 2080's). Moreover, we performed temporal beta diversity analyses (based on Sorensen's index) to assess changes in community assembly over time. To determine the potential GCC impacts on the organization of hummingbird-plant relationships, we calculated niche overlap and network size metrics. Our results showed that even if we assume that species can disperse to novel habitat areas, ~50% of both hummingbird and plant species will face range reductions due to changes in their climate-suitability areas, which in turn will result in increased mismatch for their co-distribution patterns. Additionally, temporal beta analyses suggested species turnover between future and present for sites, as well as changes in size and niche overlap values for hummingbird-plant co-occurrence networks. Such changes could lead to the formation of novel assemblages through species reshuffling, with a non-uniform specialization/generalization of networks. These results emphasize that we should not expect uniform or matched responses among species and regions into the future. Therefore, analyses of species' co-occurrence are needed to accomplish the long-term protection of important ecosystem services such as pollination.

Keywords: global changes, biotic interactions, ecological niche modelling, co-occurrence networks, pollination networks.

INTRODUCTION

Biotic interactions are considered an essential component of biodiversity because of their important role in maintaining communities' ecological dynamics (Roemer et al. 2002; Thompson 2009; Simmons et al. 2018) and key properties of ecosystems (i.e., stability, resilience, and resistance; Bascompte and Jordano 2013). Species interactions are therefore a crucial mediator of responses to global environmental change because they maintain ecosystem functions (Tylianakis et al. 2008). Species can only interact if they are simultaneously present, making understanding species' co-occurrence patterns (i.e., range overlap) a crucial first step toward understanding how global change drivers may impact the interactions between individual species and throughout the community assembly (including species interactions). However, there are still large literature gaps in this area (Pearson et al. 2019; Heinen et al. 2020).

Synergetic and individual effects of land conversion and global climate change (GCC) may intensify extinction risk and redistribute biodiversity (Pecl et al. 2017; Ceballos and Ehrlich 2018; Lovejoy and Hannah 2019). In this sense, large-scale compositional shifts are expected (i.e., some species will become locally extinct or replaced by newcomers) through landscape homogenization, as well as the modification (i.e., novel, altered or lost) of ecological interactions (Blois et al. 2013; Jordano 2016a), ecosystem functioning, and the services provided by them (Senapathi et al. 2015; Kovács-Hostyánszki et al. 2017). Loss of key ecological interactions (e.g., pollination, seed dispersal) may have detrimental impacts on ecosystems and even cause their collapse, mainly because many species cannot complete their life cycles without their interaction partners (Jordano 2016a). In fact, several studies have documented pollinator declines and the threats behind them (e.g., Vanbergen and Initiative 2013; Potts et al. 2016; Kovács-Hostyánszki et al. 2017), which has led to pollinators becoming the focus of current international concern. Hence, accounting for the complex interplay between climate and habitat change, and the organization of biotic interactions is considered a research priority in order to achieve long-term conservation targets (García-Callejas et al. 2018; Pearson et al. 2019; García-Callejas et al. 2019; Regolin et al. 2020).

To address these challenges, methodological frameworks such as ecological niche and species distribution models have been increasingly used to explain, understand, and predict the spatio-temporal distribution of biodiversity (see Peterson et al. 2011). Use of these methodologies has exploded over the past two decades, with more than 6,000 studies on biodiversity assessments in the past 20 years (see Araújo et al. 2019). However, despite the extensive use of tools that are well suited to describing species' co-occurrence patterns, community assembly and potential species interactions are often overlooked in the literature and when designing specific management efforts (Palacio and Girini 2018;

Ramírez-Ortiz et al. 2020; Heinen et al. 2020). This is an important information gap because changes in biotic associations can be as relevant as changes in temperature and precipitation, if not more so (Araújo and Luoto 2007; Şekercioğlu et al. 2012; Atauchi et al. 2018; Luna et al. 2022).

Currently, an approach to deal with this problem is the usage of co-occurrence networks, in which species are treated as nodes and their co-occurrences as links. These are helpful for inferring potential broad-scale interactions between species and for understanding the organization of biotic associations across time and space (Araújo et al. 2011; Corro et al. 2019; Antoniazzi et al. 2020). In fact, network size (i.e., number of species in the network) and niche overlap (i.e., mean similarity in interaction pattern between species of the same trophic level) are two network descriptors that could be suitable for evaluating the co-occurrence networks (Dormann et al. 2009). Although this approach has its limitations (e.g., difficulty to identify asymmetric interactions, temporal variation in interactions, coexistence in negative interactions, etc.; see Blanchet et al. 2020), it is an important first step to improve our knowledge of species assembly in the face of rapid global change (Morueta-Holme et al. 2016).

Hummingbirds (Aves: Trochilidae) are an ideal model to explore the relationships between the spatio-temporal distribution of biodiversity and biotic interactions. These specialized nectarivorous birds play an important role in ecosystem functioning by pollinating nearly 15% of the plant species in North and South America (Buzato et al. 2000; Able 2000). At the same time, they are considered one of the most threatened groups in the world (https://www.iucnredlist.org/). Predictions of extinction risk in hummingbirds are not optimistic, since population declines and important habitat reductions are expected as a consequence of global environmental changes (e.g., Correa-Lima et al. 2019; Infante et al. 2020; Chávez-González et al. 2020; Prieto-Torres et al. 2021). Moreover, the spatio-temporal distribution patterns of hummingbirds could also vary due to the flowering phenology of the plants they use as nectar resources (Correa-Lima et al. 2019; Infante et al. 2020a; Chávez-González et al. 2020). Such changes in floristic composition and phenological overlap represent further challenges for plant–hummingbird interactions in the future. Given that a reduction in these pollinators could create a feedback loop with biodiversity loss and degradation of ecosystem services (e.g., Ollerton et al. 2011), it is imperative to evaluate the susceptibility of these interactions to GCC.

The hummingbird species of Mexico are no exception to these future critical-reduction scenarios, including both currently threatened and non-threatened species. Recent studies have shown that climate warming could have a serious negative impact on individual species by decreasing their abundance, increasing their extinction risk, and even reorganizing entire communities throughout the country in the coming decades (e.g., Lara-Rodríguez et al. 2012; Correa-Lima et al. 2019; Chávez-

González et al. 2020; Prieto-Torres et al. 2021). More importantly, results reinforce the idea that current Protected Areas (PAs) are not effective for safeguarding these species at present, nor will they be into the future (see Prieto-Torres et al. 2021). However, an important drawback of that study is that only climate-suitability effects were considered when modelling the hummingbirds' distribution under future GCC scenarios. Biotic effects, such as changes in the floristic composition or in hummingbird-plant co-occurrence patterns were not evaluated. So, the impacts and extinction risks may be even more drastic, especially for globally threatened and endemic species. Therefore, future conservation efforts should consider both biotic and abiotic information to detect which species are most resilient and which regions are most resilient to biodiversity loss (see Pecl et al. 2017; Pearson et al. 2019; Mendoza-Ponce et al. 2020).

In this work, we sought to answer the following questions: (1) how could predicted GCC impact niche overlap and the size of co-occurrence networks of Mexican endemic hummingbirds and the plants they pollinate? and (2) does climate-driven redistribution of birds and plants indicate the uneven replacement of specialists by generalists across the region? We assumed that because future environmental change will potentially produce species-specific responses —such as distributional shifts (e.g., elevational ranges and local abundance) and migration patterns— it may lead to uneven modifications of the species co-occurrence patterns and, consequently, alter the interspecific dynamics that controls interactions (McConkey and O'Farrill 2015; García-Callejas et al. 2018, 2019). An understanding of this information will help to identify patterns of species response to GCC that can support rational biodiversity protection. This is especially critical because the conservation possibilities for hummingbirds and other pollinator communities will drastically decrease over time (see Dicks et al. 2016; Potts et al. 2016).

METHODS

Species selection and historical records

Species selection was based on the diversity within the interaction networks of

12 hummingbird species that are endemic to Mexico (Arizmendi and Berlanga 2014) and the availability of biological information and occurrence data of the plants pollinated by them. The plant list was compiled from two sources: a) specialized literature (see Appendix S1); and b) the taxonomic identification of specimens that were recorded as nectar resources and photographed in online databases (i.e., SNIB [https://www.snib.mx/], eBird [https://ebird.org/explore] and *i*Naturalista [https://www.naturalista.mx]). In sum, occurrence records for 118 plant species were assembled,

excluding plants that are exotic in Mexico. All hummingbird species' names followed Chesser et al. (2020) and plant names followed the *Linear Angiosperm Phylogeny Group* taxonomy (APG IV 2016).

For each species, occurrence records were obtained from different scientific collections and online collaborative public databases (Global Biodiversity Information Facility [GBIF; https://www.gbif.org/], EncicloVida, eBird, SiB-Colombia [https://sibcolombia.net/]). The information from GBIF was downloaded directly using the "*rgbif*" library of R software (Chamberlain et al. 2021). Then, to avoid uncertainties related to geocoding errors that affect model performance (Beck et al. 2014; Perez-Navarro et al. 2021), a data cleaning process was performed by species. This process consisted of four steps: (a) the removal of records without latitude–longitude coordinates or that had data transcription errors (e.g., reversed latitude and longitude fields); (b) the exclusion of records that did not have data for the bioclimatic variables used; (c) data falling outside the year interval from 1970 to 2021; and (d) eliminating occurrences that were repeated among sources and retaining only information corresponding to unique localities within a vicinity of ~5 km^2 (i.e., same to spatial resolution of bioclimate variables). Also, for records from 2001 to 2020, an outlier exclusion procedure was performed in the environmental space by removing points that fell outside the interquartile range of three environmental variables (annual mean temperature, annual precipitation, and precipitation seasonality) for occurrences from years 1970 to 2000 (e.g., Robertson et al. 2016; Prieto-Torres et al. 2020). Additionally, to avoid biases derived from spatial autocorrelation in areas that were heavily represented in the data, we only retained localities that were farther from each other than the mean distance between occurrence records for each species. All data were transformed to decimal degrees based on the WGS84 datum. Species with unbiased distributions (i.e., with a good geographic representation of their known geographic distribution) and with a minimum of 10 records were selected. After all of these steps, there was a total of 71,285 unique occurrence records for all hummingbird and plant species (see Supplementary Information Appendix S2).

Ecological niche modeling and validation

The maximum entropy algorithm implemented in MaxEnt ver. 3.4.3 (Phillips et al. 2017) was used to model climatic suitability for the potential distributional areas per species. This algorithm estimates the probability of suitability, ranging from 0 [unsuitable] to 1 [perfectly adequate], for each pixel given a sample of the background, following the idea that the expected value for each feature (i.e., climatic variables) must be equal to the empirical average value of presence points of the species (Phillips et al. 2006; Elith et al. 2006, 2011). This algorithm was selected for its good performance using presence-only data (Elith et al. 2011) and because it allows a calibration protocol to assess model complexity by selecting the best modelling parameters (see Muscarella et al. 2014; Cobos et al. 2019).

To characterize the species' ecological niches, environmental data from WorldClim 2.1 (at ~5 km^2 cell size resolution; Fick and Hijmans 2017) was used. Four bioclimatic variables were excluded (bio 8, bio 9, bio 18 and bio 19) because they showed spatial anomalies in the form of odd discontinuities between neighboring pixels (see Escobar et al. 2014). Further, to avoid the overfitting and overestimation of model accuracy that can occur with an overly dimensional environmental space and collinearity among variables, two approaches were applied: (1) selection of a subset of uncorrelated variables based on a Pearson's correlation coefficient ($r < 0.8$) and Variance Inflation Factor (VIF <10); and 2) derivation of a set of four variables that explained up to 95% of the total variance using a Principal Component Analysis (PCA; see Hanspach et al. 2011). PCA was performed using the statistical software R 3.4.1 (R-Core Team, 2018) and the packages "*usdm*" (Naimi, 2015) and "*ENMGadgets*" (Barve and Barve, 2016). In addition, given that dispersal plays a crucial role in the distribution of the organisms and must be considered in the development of such models (Barve et al. 2011), an area for model calibration, known as "M", was created (Soberón and Peterson 2005). For each species, this area was defined by intersecting the occurrence records with the Terrestrial Ecoregions (Dinerstein et al. 2017) and the Biogeographical Provinces of the Neotropics (Morrone 2014).

For all cases, models were generated using a randomly selected subset of 75% of the records as training data and the remaining 25% for model evaluation (testing data). To reduce model overfitting, models were first calibrated by creating 570 candidate models (per species), with parameterizations resulting from the combinations of 19 regularization multipliers (β: 0.5–8.0); 15 feature classes (i.e., combinations of linear, quadratic, product, and threshold responses); and the two distinct sets of variables (un-correlated *vs.* Principal Component Analysis). The selected model parameterizations were the ones that resulted in significant models (partial ROC with $E = 5\%$, 500 iterations, and 50% of data for bootstrapping; see Peterson et al. 2008), omission rates lower than a previously defined error rate ($E = 5\%$; Anderson et al. 2003), and the lowest Akaike Information Criterion value for each species (AICc; Muscarella et al. 2014; Merow et al. 2014), in that order. The chosen predictors and parameter settings were used to create final models with 10 replicates by bootstrap, *cloglog* outputs (Phillips et al. 2017), and transferred to present and future global environmental scenarios (see below). Final model projections were created allowing "unconstrained extrapolation" and "extrapolation by clamping" in Maxent (Elith et al. 2011; Merow et al. 2014). All modeling processes were performed using the '*kuenm'* R package (Cobos et al. 2019).

After all models were generated, the distribution maps for each species under each climate scenario (current *vs*. future [see below]) were created. To do that, median values across replicates were calculated to summarize model predictions (Campbell et al. 2015). Then, the logistic values of suitability were converted from each model into a presence-absence map by setting a decision threshold equal to the tenth percentile training presence, which reduce commission errors (areas of over-prediction; see Liu et al. 2013). For all plant species, models were calibrated using the available data for their entire current range, and then cropped to the approximate geographic extent of Mexico.

Future climate change and dispersal scenarios

The potential distribution areas for individual species and hummingbird-plant assemblages were predicted for the years 2040, 2060 and 2080. Variables for future climate projections were based on the Coupled Model Intercomparison Project 6 (CMIP6; Stoerk et al. 2018). From the CMIP6, five general circulation models (CanESM5, MIROC6, BCC-CSM2-MR, CNRM-CM6-1, and IPSL-CM6A-LR) and an intermediate Shared Socio-economic Pathway scenario (i.e., SSP3 7.0) that assumes a high greenhouse gas emission and low climate change mitigation policies (Riahi et al. 2017) were selected. These general circulation models were selected based on: (1) the demonstrated improvements in the estimation of zonal-mean atmospheric fields, equatorial ocean subsurface fields, precipitation values and the simulation of El Niño-Southern Oscillation in the Americas (e.g., Boucher et al. 2020), and (2) the results obtained from GCM compareR's web application (Fajardo et al. 2020) adopting the "storyline" approach (Shepherd et al. 2018) in which GCM projections are classified into narratives that represent specific future climate conditions (Zappa & Shepherd, 2017): a) high temperature and low precipitation compared to the ensemble projection (CanESM5), b) low temperature and high precipitation compared to the ensemble projection (MIROC6) and, c) temperature and precipitations close to the average ensemble projection (CNRM-CM6-1, BCC-CMS2-MR, and IPSL-CM6A-LR).

For each species, the future (years 2040, 2060 and 2080) geographic distribution was obtained by manually overlaying the binary projections from the five global climate models, allotting "presence" to a pixel were most of the predictive models coincided (i.e., suitable in three or more general circulation models). Then, loss and gain of suitable habitats were calculated by comparing the geographic projections of niche models in current and future scenarios. The comparisons were categorized as follows: a) when current and future areas were suitable, these were defined as stable suitable areas; b) when current was suitable and future not suitable, loss of suitable areas was defined; and c) when current was not suitable and future was suitable, gains of suitable areas were identified. These areas of stability, gain and loss were calculated (in km^2) for all species under two different dispersion scenarios: “contiguous dispersion” *vs.* “non-dispersion”. In the contiguous dispersion scenario, it is assumed that species will be able to disperse through suitable conditions within “M”. In the non-dispersion scenario, species are assumed to be unable to disperse at all (i.e., only cells that are occupied in the present can be occupied in the future). The “non-dispersion” scenario only allows for decreases in distributional range in response to GCC; therefore, it is the most “unfavorable” for the species (see Peterson et al. 2002; Prieto-Torres et al. 2021). All ecological niche modelling processing was performed using the “*maptools*” (Bivand et al. 2016), “*raster*” (Hijmans 2015) and “*LetsR*” (Vilela and Villalobos 2016) R packages.

Model uncertainty

The Mobility-Oriented Parity was implemented using the “*ntbox*” R package (Osorio-Olvera et al. 2020) to measure the risk of strict extrapolation into future species’ models resulting from projections to non-analogous conditions. The MOP consists of measuring the similarity between the closest 10% of the environmental conditions of the calibration area to each environmental condition in the area of transference (see Owens et al. 2013; Alkishe et al. 2017). Areas of projection with values of similarity of zero indicate higher uncertainty, as suitability in those regions derive from model extrapolation only, and caution is required when interpreting the likelihood of species presence in such areas (Alkishe et al. 2017). Binary maps of MOP results were generated considering only areas with zero similarity as strict extrapolation areas.

Spatio-temporal patterns of species co-distribution

The hummingbird-plant co-occurrence richness maps for each climate and dispersal scenario were created. To do this, the areas of high/low expected hummingbird-plant richness were identified employing a color gradient of four equal intervals. Then, using “*tempbetagrid*” functions for R (kindly provided by José Hidasi-Neto; available at: http://rfunctions.blogspot.com/), the temporal beta diversities between the present and future scenarios of each cell (i.e., species turnover from present to future) were calculated. Subsequently, to assess the potential modification in co-occurrence patterns across time, the geographic patterns between endemic hummingbirds and the plants they feed on were compared, considering only the species that are known to interact in the present. This allows the identification of potential disruptions of important ecological associations between taxa under future climate scenarios.

Ecological co-occurrence networks

To analyze the impacts of GCC on the structure of hummingbird-plant co-occurrence networks in Mexico, we built presence-absence matrices (PAMs) of co-occurrences between endemic hummingbirds and the plants they use as nectar resources for each of the biogeographical provinces identified across the country (Morrone 2014) based on information gathered from specialized literature and online databases. To avoid statistical problems due to low sample size, all provinces where less than three hummingbird species and three plant species occurred in the current scenario were eliminated from the analyses. This resulted in comparisons in eight biogeographical provinces: Costa del Pacífico, Depresión del Balsas, Eje Volcánico, Golfo de México, Oaxaca, Sierra Madre del Sur, Sierra Madre Occidental, and Sierra Madre Oriental (Fig. 1).

In sum, we built 56 binary co-occurrence networks for current and future scenarios ($A = i \times j$), where hummingbirds (i) were represented as rows and plants (j) as columns. All interactions between the i hummingbird species and the j plant species were defined by $A_{ij} = 1$, while the interactions that did not occur were coded as zero. Then, using the package *bipartite* implemented in R (Dormann et al. 2021), two network descriptors (network size and niche overlap) for each hummingbird-plant co-occurrence network per province and climate scenario were calculated. Network size was calculated by multiplying the number of hummingbird species (i.e., rows) by number of plant species (i.e., columns). Higher network size values indicate more species-rich networks. Niche overlap, based on Horn's similarity index, estimates the degree of similarity among potential hummingbird-plant interactions; high values indicate high similarity between species trophic niches (i.e., low trophic specialization; see Dormann et al. 2009). Finally, Generalized Linear Models (GLMs) using Gaussian distribution were fit to test whether the percentage of change in the network size and niche overlap values differed among climate and dispersal scenarios. When significant differences were observed, contrast analyses were performed using the "*RT4Bio*" R package (Tylianakis et al. 2008; Reis Jr R et al. 2015).

RESULTS

Model statistics

All models were statistically significant, meeting AIC criteria, exhibiting significant values for the partial ROC test (mean AUC ratio of 1.50; $P < 0.05$) and low omission error values (average 3.42 ± 4.20%) for the 10% training presence threshold. Based on these performance estimates, our models were better than random and had good discrimination capacity in recovering the ecological niches for each species. For performance values and parameter settings chosen for each species see Supporting Information Appendix S2.

Current species richness and co-distribution patterns in Mexico

Overall, the number of hummingbirds per site varied from 1 to 6 species (mean values of 1.86 ± 1.09 spp.), and plant species richness varied from 1 to 72 species (mean 18.72 ± 15.88 spp.). For both hummingbirds and plants, current hotspots (i.e., sites whose species richness exceeded half of the maximum values observed) are located mainly in the states of Oaxaca, Guerrero, and Chiapas (Fig. 1). Hummingbird species were associated with between six (*Pampa excellens*) and 42 plant species (for *Phaeoptila sordida*), with an average of 13 ± 10.33 plant species per hummingbird. Plant species interacted with an average of 1.32 ± 0.74 hummingbird species. Our distributional model estimates showed hummingbird-plant spatial coincidence values averaging 62.1 % ± 28.9 % km^2 under the current scenario, ranging from 44.3 ± 38.5% (*Basilinna xantusii*) to 84.3 ± 12.9% (*P. excellens*). The hummingbird-plant network analysis showed values, on average, of 0.32 ± 0.10 and 397.13 ± 331.04 for the niche overlap and network size, respectively.

Impacts of future climate change on species range patterns

Our results suggest that GCC will potentially lead to an important modification in both individual species' ranges and overall species richness patterns for Mexican endemic hummingbirds and their associated plants in the future (see Appendix S3). In general, the future scenarios were similar in their qualitative predictive patterns, although the pessimistic and unfavorable scenarios (i.e., SSP3 7.0 and non-dispersal ability) predicted larger decreases. When assuming a contiguous dispersion scenario, GCC could produce a range expansion for 50% of hummingbird species (on average from 33.84 ± 23.47% [2040's] to 83.80 ± 65.58% [2080's]) and 45.76% of plants (25.47 ± 29.27% [2040's] to 70.54 ± 87.95% [2080's]). Under the non-dispersion scenario, range reductions were the most plausible response for both hummingbird species (on average from -11.83 ± 11.79% [2040's] to -32.95 ± 26.99 % [2080´s]) and plants (from -17.6 ± 16.42% [2040's] to -23.73 ± 23.49% [2080's]). These unfavorable scenarios predict that GCC will lead to large reductions (>10%) of the climate suitability areas for 83.3% of the hummingbirds and 79.6% of the plants in the future. This general reduction in the species' distributional ranges is related to changes in climate-suitability (on average 0.07 [2040's] – 0.14 [2080's]) that are currently available. MOP results indicated that strict extrapolative areas occur mostly beyond the potential distributional areas predicted by models in the future climates across Mexico (on average <5% of predicted suitable areas match future novel conditions).

These individual modifications of the species' distributional ranges could thus lead to changes in the spatial patterns of the assemblages across the country (Fig. 2). Overall, the temporal beta diversity values ranged from 0.09 (non-dispersion scenarios) to 0.15 (dispersion scenarios). On average, richness patterns tended to decrease for both hummingbirds (from -10.46% [dispersion assumption] to -13.77% [non-dispersion assumption]) and plants (from -2.80% [dispersion] to -14.28% [non-dispersion]) in the future (see Appendix S3). Similarly, hotspot areas were also predicted to decrease in size for hummingbirds (ranging from 19.6% [2040's dispersion scenario] to 72.6% [2080´s non-dispersion scenario]) and plants (from 6.8% [2040's dispersion scenario] to 44.6% [2080´s non-dispersion scenario]). Furthermore, these hotspots areas for taxa were predicted to have less overlap in the future scenarios (from 24.2% [2040's dispersion scenario] to 12.4% [2080´s non-dispersion scenario]) than at present (27.3%).

Hummingbird-plant co-occurrence networks

The average number of plant species associated with each hummingbird species (13 ± 10.33 spp.) and hummingbird species associated with each plant species (1.32 ± 0.74 spp.) was predicted to remain similar in the future scenarios. However, the hummingbird *Eupherusa cyanophrys* will no longer share distribution with the plant *Justicia aurea* by the 2080's, even under the favorable dispersion scenarios. Moreover, reductions of 5.92% [dispersion scenario] to 6.8% [non-dispersion scenario] in the area of co-occurrence between hummingbirds' and plants' geographic was also predicted. Two hummingbird species —*Eupherusa ridgwayi* and *Pampa excellens*– are expected to be the most strongly affected, with reductions of >18% of the spatial coincidence with their associated plants under wither dispersion scenario. On the contrary, *Selasphorus heloisa* will potentially increase (on average >4%) the proportional area of co-occurrence with its associated plants.

We observed differences between the current and future scenarios when analyzing the percentage change in niche overlap and network size (Fig. 3; GLM: all P-values < 0.05). The hummingbird-plant co-occurrence network analyses for the future showed an increase in size values under both dispersion scenarios (410.4 ± 368.7 [non-dispersion scenario] and 604 ± 308.06 [dispersion scenario]). On the contrary, niche overlap values did not change on the non-dispersion scenarios (Horn's index: 0.32 ± 0.1) but decreased (Horn´s index: 0.27 ± 0.07) under the dispersion scenario. Overall, the following patterns emerged from our projections: 1) changes in network size will be largest in the year 2040 under the dispersion scenarios (F = 2.9739, $P = 0.02$); 2) changes to niche overlap were higher under all future scenarios that assumed dispersion (F = 4.2019, $P < 0.01$); and 3) the provinces most affected by this change will be Oaxaca (for both niche overlap [21.8% of change observed] and size network [147.0% of change]), Sierra Madre del Sur (niche overlap [20.6% of change] and size network [32.6% of change]), and Sierra Madre Oriental (for network size [111.9% of change]) (Table 1).

DISCUSSION

Several studies have investigated the potential impacts of climate variations on animal–plant networks, mainly for insects and host species or plants (see Schweiger et al. 2008; Gorostiague et al. 2018). Fewer studies have dealt with changes in interspecific relationships among vertebrates, with the exception of carnivorous mammals and pollinator-bats (e.g., Pandey and Papeş 2018; Scully et al. 2018; Corro et al. 2021). Although there is still debate about the link between co-occurrence data and species' interactions (see Jordano 2016b; Blanchet et al. 2020; Chávez-González et al. 2020), it is a truism of ecology that species must co-occur to directly interact. From this perspective, we have shown that changes in the co-occurrence networks will probably have variable effects depending on the species, but for hummingbirds and their plants, important negative effects seem likely in the future. Our results show that endemic hummingbirds and plants are likely to undergo changes that are not uniform and differ among group of species across Mexico in the future.

These results are in agreement with other studies in Mexico, suggesting that the estimated patterns of change for biota are attributed to the expected increase in the average temperature and decrease in annual precipitation (see Cuervo-Robayo et al. 2020). This is of major concern, since range reductions will probably affect the physiological responses and activity patterns of individual species and population dynamics, increasing the species' vulnerability to global extinction (Tylianakis et al. 2008; Sonne et al. 2022), especially if species are not capable of quickly adapting to new environmental conditions. In fact, although upslope shifts have been predicted for hummingbird and plant species in the future (Le Roux and McGeoch 2008; Buermann et al. 2011; Crimmins et al. 2011; Graham et al. 2017; Correa-Lima et al. 2019), many studies reported declines in wing-loading capacity and flight-limited performance traits for hummingbirds at higher altitudes along elevational gradients (Altshuler et al. 2004; Correa-Lima et al. 2019). From this perspective, more studies analyzing the ability of these taxa to rapidly adapt or move into new areas are encouraged (see de Matos Sousa et al. 2021).

On the other hand, climate-driven range shifts may cause modifications in the co-occurrence patterns of taxa and on communities' structure through species' reshuffling (see Lovejoy and Hannah 2019; Sonne et al. 2022). The spatial mismatches between taxa observed here suggest potential changes in the availability of mutualist partners that could lead to decoupling of the pollination interaction, with detrimental effects for ecosystems functioning (Stenseth et al. 2002; Visser and Both 2005; Hegland et al. 2009; Correa-Lima et al. 2019). For example, it is well known that the flowering times of early-flowering plants appear to be changing more quickly in response to warming temperatures, while late-flowering plants are more susceptible to frost at high elevations (e.g., Phillips et al. 2018; Descamps et al. 2021; Powers et al. 2022). The consequent reduction in floral resources for pollinators could have detrimental impacts on ecosystems because many species will not be able to complete their life cycles in the future (Scaven and Rafferty 2013; Takkis et al. 2018). In the case of highly specialized hummingbird-plant relationships, it is unlikely that other animals would take over pollination if hummingbirds were absent (Linhart and Feinsinger 1980), such changes could favor an increase of the co-extinction risk for species (see Sonne et al. 2022). Nonetheless, hummingbird-plant networks are known to be highly dynamic, with species turnover and rewiring (not evaluated here) acting as the primary drivers of spatio-temporal changes in the composition of interactions. It is therefore possible that network plasticity could mitigate the effects of GCC scenarios on plant reproduction and hummingbirds' food resources (Poisot et al. 2012; CaraDonna et al. 2017; Correa-Lima et al. 2019; Chávez-González et al. 2020). However, this issue remains poorly studied.

Here, predicted species turnover patterns and changes of network size/niche overlap values suggest that several species will probably not be able to colonize novel areas in the future. As results showed, the species turnover patterns could promote forming new assemblages changing not only the identity of species in the network, but also network properties such as nestedness and specialization (see Dormann et al. 2009). This is relevant because small-range species are typically habitat specialists (Sonne et al. 2016), so they may not be able to colonize new areas or persist in novel conditions in the near future (Broennimann et al. 2006). Sonne and coworkers (2022) assessed hummingbird-plant communities' vulnerability to climate change across America and found that communities in North America experienced lower rates of climate-driven extinctions compared with coextinction and colonization. In these communities climate-driven extinction impacted species in the network's periphery, instead of core (generalist) species (Sonne et al. 2022). For these cases, generalist species could play an important role in community-level resilience to GCC due to their ability to connect to many mutualistic partners distributed throughout the network (Sonne et al. 2022). This scenario could be especially true for endemic Mexican hummingbird species, which belong principally to Emerald (61.54%) and Bee (23.08%) clades (McGuire et al. 2014). These hummingbirds are mostly ecologically generalists with straight beaks of medium length and small to intermediate body sizes (Rodríguez-Flores et al. 2019), characteristics that in GCC scenarios may facilitate the interaction with a great array of floral morphologies, integrating new floral resources to the network and diminishing hummingbird extinction probability. However, floral visitation does not guarantee pollination, and the effect of interaction turnover and/or rewiring on plant reproduction must be considered.

Past and contemporary climate play an important role in determining specialization on mutualistic systems (Dalsgaard et al. 2011). Temperate hummingbird-plant networks were less specialized than tropical networks (measured with network-level contemporary specialization, Blüthgen et al. 2006) and this pattern was tightly linked to species-poor networks, low contemporary precipitation and high Quaternary climate-change velocity. This climatic scenario favored low biotic specialization and local adaptations in North America hummingbird-plant communities (Dalsgaard et al. 2011). The factors that influence a species' potential to establish and survive in new areas is difficult to predict, such that these results should be interpreted with caution, but there is evidence that new assemblages could form in locations that are currently at the extreme ends of the environmental gradient, such as dry regions and high elevation zones (Graham et al. 2017).

Whether GCC will affect ecosystem functioning depends on how interactions among species are affected (Hegland et al. 2009). It is important to highlight that communities where niche overlap and competition are high tend to be more unstable and less resilient to change (Pastore et al. 2021; Sonne et al. 2022), although colonization by generalist species could compensate for local extinctions to some extent. From this perspective, special attention must be paid to the provinces of Oaxaca, Sierra Madre del Sur, and Sierra Madre Oriental (Table 1). According to our results, they are also expected to be the most affected provinces in the future by GCC. However, these sites are considered hotspot areas for both hummingbird and plant species, at the same time as being high-priority conservation areas for hummingbirds under climate and land-use changes (see Prieto-Torres et al. 2021). We therefore argue that it is important to include relevant biotic interactions in the prediction of GGC impacts fin order to increase the accuracy of model forecasts. We also recommend additional fieldwork to test the projections based on our results to obtain reliable knowledge of both species and assemblage responses to future environmental scenarios.

Although this study is a first approach for understanding hummingbird-plant co-occurrence patterns in the face of global changes, it includes only a small subset of co-occurrence networks, since only endemic hummingbird species where studied. Future research incorporating all Mexican hummingbirds and their associated plants are needed, especially focused to quantify the intensity of the interaction and include ecological information as morphology (body size, beak length and curvature, corolla length and curvature) and hummingbird and floral abundances. Also, further analyses incorporating other factors that influence species co-occurrences at fine scales, such as land-use change, are critical because circumstantial evidence suggests that hummingbird-pollinator losses due to deforestation intensification are already happening (Infante et al. 2020b).

In sum, the main lesson from this study is that it is not just more land that is needed to guarantee the medium and long-term conservation of biodiversity and important ecosystem services like pollination. Understanding species' extinction risk and breakdowns in their ecological associations are critical for forming management strategies and conservation plans. It is therefore imperative that policy-makers promote new policies, and our results constitute a valuable guide for using scientific evidence of which species and areas require attention to achieve more efficient conservation planning in Mexico for these highly vulnerable and specialized taxa but, especially, to accomplish the long-term protection of important ecosystem services such as pollination.

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TABLES

Table 1 Summary of niche overlap and network size metrics for the hummingbird-plant co-occurrence patterns across eight Mexican biogeographical provinces under future climate scenarios (years 2040, 2060, and 2080) based on intermediate Shared Socio-economic Pathway scenario (i.e., SSP3 7.0) and two dispersion assumptions.

	Costa del Pacífico	**Depresión del Balsas**	**Eje Volcánico**	**Golfo de México**	**Oaxaca**	**Sierra Madre del Sur**	**Sierra Madre Occidental**	**Sierra Madre Oriental**
Niche overlap								
Current	0.19	0.28	0.28	0.36	0.54	0.24	0.30	0.36
Dispersion scenario								
2040’s	0.17	0.23	0.23	0.35	0.33	0.17	0.31	0.30
2060’s	0.17	0.24	0.30	0.35	0.33	0.17	0.32	0.31
2080’s	0.17	0.24	0.22	0.35	0.32	0.17	0.32	0.31
Non-dispersion scenario								
2040’s	0.19	0.28	0.30	0.35	0.51	0.22	0.32	0.36
2060’s	0.19	0.29	0.30	0.35	0.51	0.22	0.32	0.35
2080’s	0.19	0.29	0.30	0.35	0.51	0.22	0.32	0.35
Network size								
Current	950	574	378	111	111	765	180	108
Dispersion scenario								
2040’s	1,177	783	744	248	380	1,210	164	345
2060’s	1,155	774	468	99	380	1,210	160	350
2080’s	1,166	765	744	99	375	1,199	160	345
Non-dispersion scenario								
2040’s	940	539	468	99	171	828	152	108
2060’s	920	532	474	99	171	819	152	105
2080’s	920	532	480	99	168	819	152	102

FIGURES

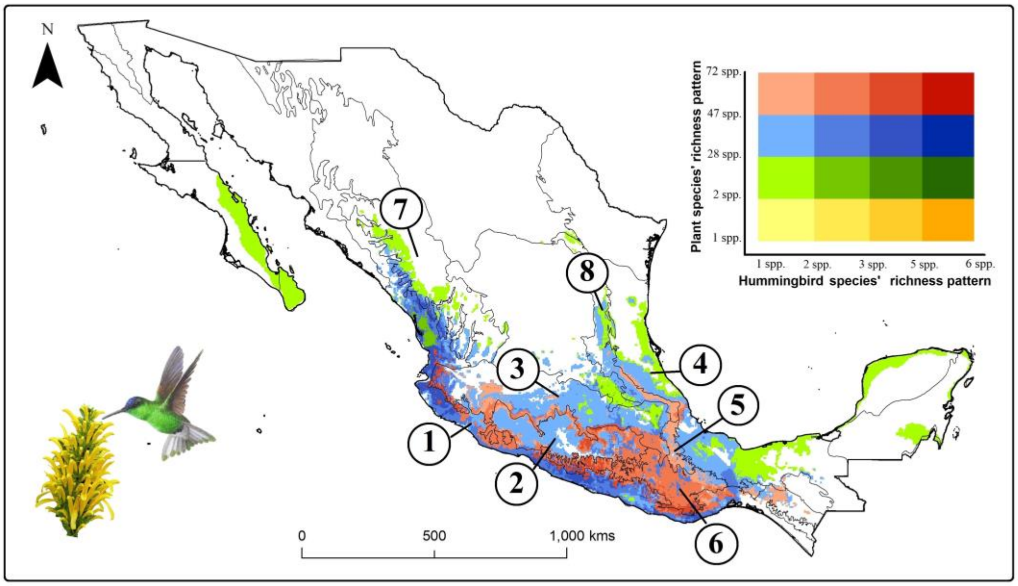

Figure 1 Map of the current endemic hummingbird-plant richness co-occurrence patterns across Mexico. The color gradient represents species richness patterns, with areas in red showing overlap of the maximum richness values for both hummingbird and plant species. Numbers in the map correspond to biogeographical provinces considered in this study: (1) Costa del Pacífico; (2) Depresión del Balsas; (3) Eje Volcánico; (4) Golfo de México; (5) Oaxaca; (6) Sierra Madre del Sur; (7) Sierra Madre Occidental; and (8) Sierra Madre Oriental. The picture in the map depicts the interaction between the hummingbird *Eupherusa cyanophry*s and the plant *Justicia aurea* (Source: Arizmendi and Berlanga 2014).

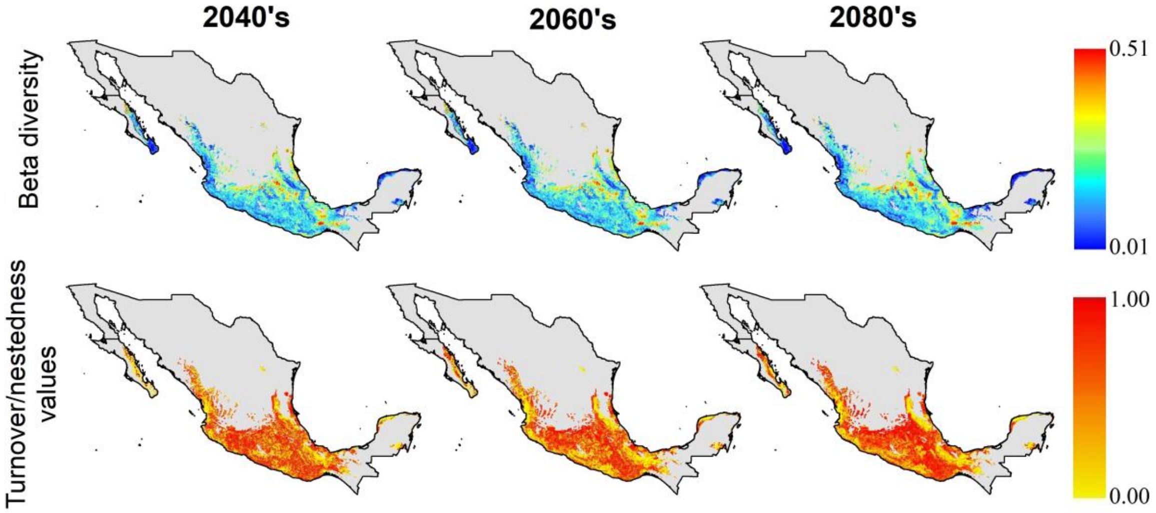

Figure 2 Spatio-temporal patterns for beta diversities of Mexican endemic hummingbird and plant species projected onto future climate scenarios (years 2040, 2060, and 2080) under an intermediate Shared Socio-economic Pathway scenario (i.e., SSP3 7.0) and assumption of dispersion for taxa. Maps of temporal beta diversity show the dissimilarity/similarity values for communities between the current and future scenarios within each cell; maps of turnover/nestedness indicate whether estimated temporal beta diversity values are more related to changes in species composition or to species losses/gains.

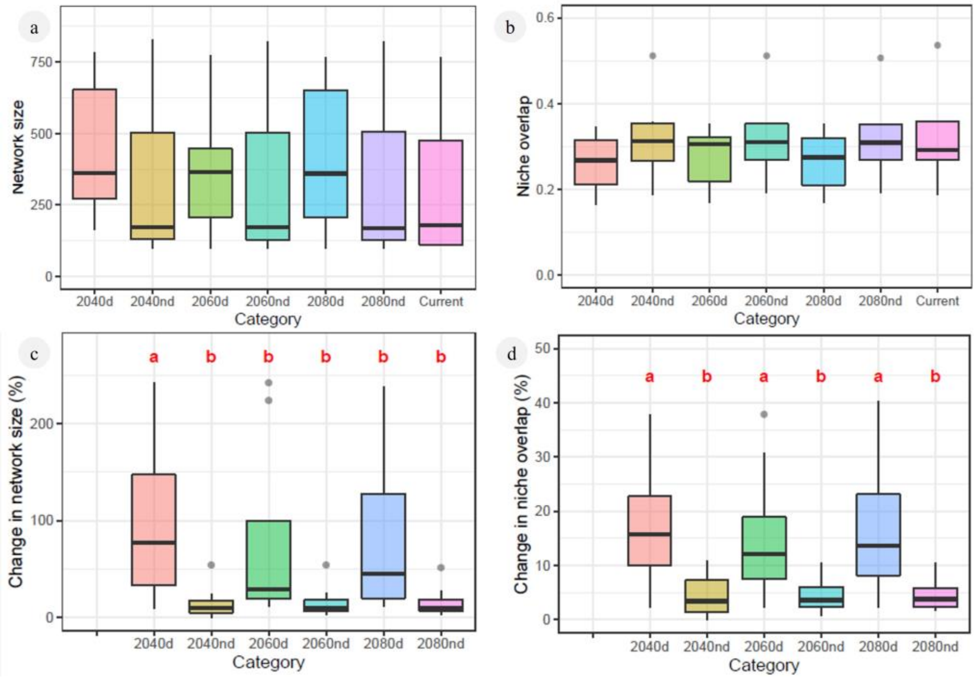

Figure 3 Summary of patterns of change observed in network size (a,c) and niche overlap (b,d) in the hummingbird-plant co-occurrence network under future climates, considering an intermediate Shared Socio-economic Pathway scenario (i.e., SSP3 7.0) and two assumptions of dispersion for taxa: contiguous dispersion (d) *vs.* non-dispersion scenarios (nd). Red letters indicate statistical differences (GLM: all P-values <0.05) between scenarios.

SUPPORTING INFORMATION

Appendix S1. Reference list of specialized literature consulted in this study to compile the list of plant species used as nectar resources by Mexican endemic hummingbirds.

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Appendix S2. List of the 12 endemic hummingbird species and their 118 associated plant species considered in this study. For each species, we provide the following information: GBIF doi, number of occurrences, bioclimatic variables set, parameter settings (feature classes and regularization multiplier values) used for modelling, and model performance values (partial ROC, Akaike Information Criterion and omission rate).

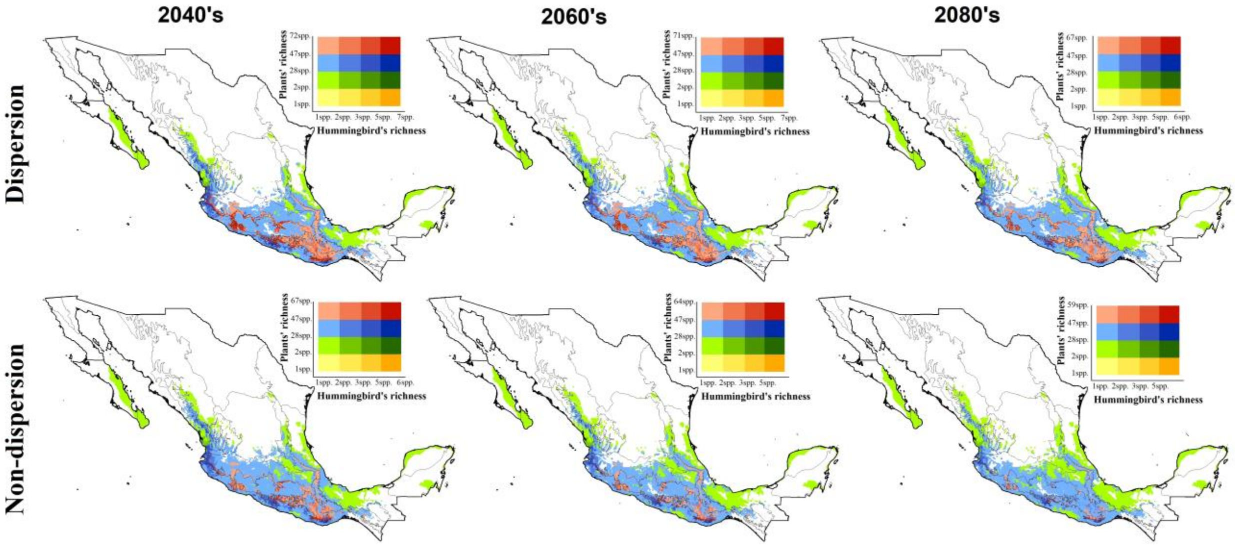
Species	**GBIF's access numbers (Doi)**	**Environmental variables used for models**	**Number of unique presence records into 5km^2**	**Feature**	**Regularizator multiple**	**ROC-Partial values**	**AICc**	**% Omission testing data**
Hummingbirds								
Basilinna xantusii (Lawrence, 1860)	GBIF.org (29 October 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.zgwev9	PC1, PC2, PC3, PC4	36	lq	0.8	1.87	371.78	0.0
Calothorax pulcher Gould, 1859	GBIF.org (08 November 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.kndz8m	Bio 2, Bio 3, Bio 4, Bio 6, Bio 13, Bio 14	34	lq	3.5	1.68	470.29	3.5
Lophornis brachylophus R.T.Moore, 1949	GBIF.org (29 October 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.dst5fk	PC1, PC2, PC3, PC4	10	l	1.6	1.97	320.84	10.0
Phaethornis mexicanus Hartert, 1897	GBIF.org (29 October 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.kzvfeb	Bio 2, Bio 3, Bio 5, Bio 12, Bio 15, Bio 17	67	pth	6	1.60	926.95	0.0
Doricha eliza (Lesson & Delattre, 1839)	GBIF.org (29 October 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.axuxmz	Bio 2, Bio 3, Bio 4, Bio 5, Bio 12, Bio 15	53	lqt	1.8	1.94	573.83	0.0
Eupherusa cyanophrys J.S.Rowley & Orr, 1964	GBIF.org (12 November 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.2mjazp	Bio 2, Bio 4, Bio 6, Bio 14, Bio 15, Bio 16	29	lth	3.5	1.85	312.92	0.0
Eupherusa poliocerca Elliot, 1871	GBIF.org (12 November 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.sjx7up	PC1, PC2, PC3, PC4	27	t	2	1.62	332.96	0.0
Cynanthus auriceps (Gould, 1852)	GBIF.org (14 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.ahtkn4	Bio 2, Bio 3, Bio 4, Bio 5, Bio 12, Bio 14, Bio 15	213	lpt	1.8	1.62	2856.09	3.0
Eupherusa ridgwayi Nelson, 1900	GBIF.org (14 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.4s5x5r	Bio 3, Bio 4, Bio 7, Bio 10, Bio 12, Bio 17	15	lp	0.8	1.94	178.85	0.0
Pampa excellens (Wetmore, 1941)	GBIF.org (14 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.r8fhke	Bio 3, Bio 7, Bio 11, Bio 15, Bio 16	22	lqp	1	1.80	257.12	0.0
Phaeoptila sordida (Gould, 1859)	GBIF.org (14 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.g8bav6	Bio 2, Bio 3, Bio 6, Bio 13, Bio 14, Bio 15	157	lq	0.4	1.60	2030.60	3.0
Selasphorus heloisa (Lesson & Delattre, 1839)	GBIF.org (14 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.kxvqq8	PC1, PC2, PC3, PC4	196	lqp	0.8	1.46	2835.01	3.0
Plants								
Bomarea edulis Herb.	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.6b34je	PC1, PC2, PC3, PC4	629	lqt	5	1.15	11963.3	4.2
Tigridia orthantha (Lemaire) Ravenna	GBIF.org (02 March 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.pz4bym	Bio 03, Bio 06, Bio 07, Bio 13, Bio 15	34	qp	1	1.82	361.6279	0.0
Agave marmorata Roezl	GBIF.org (22 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.kdasap	PC1, PC2, PC3, PC4	22	qpt	0.4	1.74	256.5038	0.0
Bessera tenuiflora J.F.Macbr.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.77e4zj	PC1, PC2, PC3, PC4	30	lp	0.6	1.87	310.0776	0.0
Heliconia spissa Griggs	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.7bmvw3	Bio 02, Bio 04, Bio 05, Bio 14, Bio 15, Bio 16	55	lqt	1.6	1.4	803.0821	10.0
Heliconia latispatha Benth.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.8nzgus	Bio 01, Bio 02, Bio 03, Bio 13, Bio 14, Bio 15	575	lqpt	1.4	1.14	9998.005	4.6
Heliconia collinsiana Griggs	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.upgt5a	Bio 01, Bio 02, Bio 03, Bio 13, Bio 14, Bio 15	119	lqpt	1.8	1.32	1761.024	4.5
Heliconia schiedeana Klotzsch	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.22pjwe	Bio 01, Bio 03, Bio 07, Bio 14, Bio 15, Bio 16	103	qp	1.2	1.43	1439.39	0.0
Canna indica L.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.t6n799	Bio 02, Bio 03, Bio 05, Bio 13, Bio 14, Bio 15	957	lqpt	1	1.23	18603.14	4.4
Costus pictus D. Don	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.umhgg4	PC1, PC2, PC3, PC4	134	lpq	1.2	1.24	2080.798	4.0
Tillandsia limbata Schltdl.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.azuzxw	PC1, PC2, PC3, PC4	64	t	1.2	1.22	911.235	0.0
Caesalpinia pulcherrima (L.) Sw.	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.bb33d5	Bio 01, Bio 02, Bio 03, Bio 10, Bio 13, Bio 14, Bio 15	1021	pt	1	1.25	19730.36	4.7
Calliandra peninsularis Rose	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.w7zp7a	PC1, PC2, PC3, PC3	16	l	0.6	1.98	153.9511	0.0

Chloroleucon mangense Britton & Rose	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.kmvjse	PC1, PC2, PC3, PC4	365	lq	4.5	1.2	6356.979	4.4
Erythrina flabelliformis Kearney	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.8nkhpf	Bio 02, Bio 03, Bio 10, Bio 13, Bio 14, Bio 15, Bio 17	164	qp	0.6	1.35	2476.774	3.2
Erythrina americana Mill.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.a52yzg	Bio 02, Bio 03, Bio 04, Bio 05, Bio 14, Bio 15, Bio 16	234	lq	0.6	1.24	3739.804	2.3
Erythrina folkersii Krukoff & Moldenke	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.gmuk67	Bio 02, Bio 03, Bio 06, Bio 13, Bio 14, Bio 15	60	t	1.6	1.43	876.1323	9.1
Erythrina berteroana Urb.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.rkjnwn	Bio 02, Bio 03, Bio 05, Bio 13, Bio 14, Bio 15	198	t	1.4	1.21	3196.6	2.7
Hesperalbizia occidentalis (Brandegee) Barneby & J.W.Grimes	GBIF.org (02 March 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.pbuh5f	Bio 02, Bio 03, Bio 05, Bio 14, Bio 15, Bio 16	192	qp	0.8	1.5	2816.215	2.8
Parkinsonia praecox (Ruiz & Pav.) Hawkins	GBIF.org (21 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.cq68w3	Bio 01, Bio 02, Bio 03, Bio 13, Bio 14, Bio 15	358	qp	1.4	1.61	6304.847	3.0
Phaseolus coccineus L.	GBIF.org (02 March 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.z4a9gh	Bio 01, Bio 02, Bio 03, Bio 04, Bio 14, Bio 15, Bio 16	895	lqpt	0.8	1.49	14136.28	4.8
Sphinga platyloba (Bertero ex DC.) Barneby & J.W.Grimes	GBIF.org (02 March 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.j6m884	Bio 03, Bio 04, Bio 05, Bio 06, Bio 13, Bio 14	138	p	0.6	1.54	1931.204	3.8
Zapoteca formosa (Kunth) H.M.Hern.	GBIF.org (02 March 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.cb2y9j	Bio 02, Bio 03, Bio 04, Bio 05, Bio 13, Bio 14, Bio 15	673	t	1.4	1.55	11800.75	4.8
Rubus adenotrichus Schltdl.	GBIF.org (02 March 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.j8sz3a	Bio 02, Bio 03, Bio 05, Bio 15, Bio 16, Bio 17	146	lqp	0.6	1.48	2110.058	3.6
Clusia salvinii Donn.Sm.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.f5fu38	PC1, PC2, PC3, PC4	218	lqp	0.6	1.4	3474.97	4.9
Cnidoscolus rostratus Lundell	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.k55bsd	Bio 03, Bio 04, Bio 06, Bio 07, Bio 13, Bio 15	25	pt	1	1.79	329.3044	0.0
Cnidoscolus multilobus (Pax) I. M. Johnst.	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.2a3eph	PC1, PC2, PC3, PC4	160	lqpt	1	1.3	2494.469	3.3
Croton suberosus Kunth	GBIF.org (02 March 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.ckvnvy	Bio 02, Bio 03, Bio 04, Bio 05, Bio 14, Bio 15, Bio 16	87	t	2.5	1.36	1168.13	0.0
Euphorbia cymbifera (Schltdl.) V.W.Steinm.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.byar4q	PC1, PC2, PC3, PC4	25	qp	1	1.7	271.8201	20.0
Euphorbia calcarata (Schltd.) V.W.Steinm.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.v2fmp9	Bio 03, Bio 04, Bio 05, Bio 07, Bio 12, Bio 15	49	lq	0.6	1.61	692.3963	0.0
Combretum farinosum Kunth	GBIF.org (02 March 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.hmqha8	Bio 02, Bio 03, Bio 04, Bio 10, Bio 14, Bio 15, Bio 16	337	lt	1	1.52	5083.857	1.6
Combretum fruticosum Stuntz	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.4ekghu	Bio 02, Bio 03, Bio 05, Bio 13, Bio 14, Bio 15	772	lp	0.4	1.17	15103.7	4.8
Cuphea appendiculata Benth.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.x2rqdn	PC1, PC2, PC3, PC4	198	lq	8	1.31	3041.966	2.7
Cuphea jorullensis Kunth	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.gvvhqp	PC1, PC2, PC3, PC4	90	pt	1.4	1.58	1231.59	5.9
Fuchsia arborescens Sims	GBIF.org (01 January 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.tbgr95	Bio 01, Bio 02, Bio 03, Bio 15, Bio 16	150	lpt	3	1.36	2145.924	7.1
Fuchsia encliandra Steud.	GBIF.org (01 January 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.bj7kkf	Bio 01, Bio 02, Bio 03, Bio 13, Bio 14, Bio 15	136	lq	5	1.43	1995.863	7.7
Fuchsia hybrida Hort.	GBIF.org (01 January 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.fqta6g	Bio 01, Bio 02, Bio 03, Bio 14, Bio 15, Bio 16	66	lq	0.4	1.86	1104.72	0.0
Fuchsia microphylla Kunth	GBIF.org (01 January 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.xzezup	PC1, PC2, PC3, PC4	396	t	6	1.19	6000.468	4.1
Fuchsia parviflora Lindl.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.grzwve	PC1, PC2, PC3, PC4	127	pt	2.5	1.61	1824.347	4.2
Paullinia sessiliflora Radlk.	GBIF.org (02 March 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.g9bjew	Bio 03, Bio 04, Bio 05, Bio 14, Bio 16	59	lqp	0.6	1.5	922.1073	0.0
Guarea glabra Vahl	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.n4uhjy	Bio 02, Bio 04, Bio 13, Bio 14, Bio 15	737	lqpt	3	1.21	13247.78	4.3
Ceiba aesculifolia (Kunth) Briteen & Baker f.	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.efuk5q	PC1, PC2, PC3, PC4	490	lqp	0.8	1.26	7873.903	4.3
Chiranthodendron pentadactylon Larreat	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.dvb2ez	Bio 02, Bio 03, Bio 05, Bio 13, Bio 14, Bio 15	94	qpt	3.5	1.7	1229.229	0.0
Helicteres guazumifolia Kunth	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.dyuthp	PC1, PC2, PC3, PC4	560	t	2.5	1.15	10749.43	3.8
Hibiscus uncinellus Moc. & Sessé ex DC.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.3f7gzn	Bio 03, Bio 06, Bio 07, Bio 13, Bio 15	159	lqt	1.8	1.57	2288.66	3.3
Malvaviscus arboreus Cav	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.c7u72p	Bio 02, Bio 03, Bio 05, Bio 13, Bio 14, Bio 15	2356	lqt	2.5	1.3	4534342	5.0
Physodium adenodes (Goldberg) Fryxell	GBIF.org (02 March 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.dnhhd4	Bio 02, Bio 03, Bio 05, bid 013, Bio 14, Bio 15, Bio 17	62	lq	0.6	1.37	897.0004	0.0
Pseudobombax ellipticum (Kunth) Dugand	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.smg67v	Bio 02, Bio 04, Bio 05, Bio 14, Bio 15, Bio 16	384	lqp	1.2	1.22	6242.061	4.2
Triumfetta speciosa Seem.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.p3qhhp	PC1, PC2, PC3, PC4	164	lt	1.4	1.3	2455.246	3.2
Psittacanthus auriculatus (Oliv.) Eichler	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.tfvqae	Bio 02, Bio 04, Bio 11, Bio 13, Bio 15	27	lpt	1.4	1.9	340.3224	0.0
Psittacanthus ramiflorus G. Don	GBIF.org (01 January 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.6gzzk5	Bio 01, Bio 02, Bio 03, Bio 14, Bio 16, Bio 17	102	p	0.4	1.18	1544.255	10.5
Psittacanthus calyculatus G. Don	GBIF.org (01 January 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.7fsbn5	Bio 02, Bio 03, Bio 04, Bio 05, Bio 13, Bio 14, Bio 15	490	qt	3	1.35	8201.97	4.3
Mirabilis jalapa L.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.safnsy	Bio 01, Bio 02, Bio 03, Bio 13, Bio 14, Bio 15	1512	lpt	1.6	1.23	29885.31	4.9
Cephalocereus columna-trajani (Karw.) K. Schum	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.vwuzaf	PC1, PC2, PC3, PC4	10	lqp	0.4	1.95	119.4221	0.0

Escontria chiotilla Rose	GBIF.org (28 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.sb7qgm	Bio 02, Bio 03, Bio 13, Bio 14, Bio 15	53	qt	1	1.55	621.5191	10.0
Marginatocereus marginatus (DC.) Backeb.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.xr5twn	PC1, PC2, PC3, PC4	99	lqp	0.4	1.57	1363.015	0.0
Myrtillocactus schenckii Britton & Rose	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.rcx2s7	PC1, PC2, PC3, PC4	13	qt	5.5	1.92	166.7983	0.0
Myrtillocactus geometrizans Console	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.svuqj6	Bio 02, Bio 03, Bio 04, Bio 06, Bio 14, Bio 15, Bio 16	389	t	8	1.48	5688.786	4.1
Neobuxbaumia tetetzo (F.A.C. Weber ex K. Schum.) Backeb	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.qdskh2	PC1, PC2, PC3, PC4	16	lqp	0.6	1.9	188.3034	0.0
Neobuxbaumia scoparia (Poselg.) Backeb.	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.dxjke9	PC1, PC2, PC3, PC4	16	q	0.4	1.84	181.1308	0.0
Nopalea dejecta Salm-Dyck	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.wph6mf	Bio 02, Bio 03, Bio 05, Bio 14, Bio 15, Bio 16	100	qp	0.4	1.36	1494.783	0.0
Opuntia excelsa Sanchez-Mej.	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.25223a	Bio 02, Bio 03, Bio 04, Bio 05, Bio 13, Bio 15	22	t	1.2	1.61	299.7294	0.0
Opuntia pilifera F.A.C. Weber	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.d6hm2v	Bio 03, Bio 06, Bio 07, Bio 14, Bio 15, Bio 16	65	lq	0.4	1.56	828.7429	8.3
Opuntia hyptiacantha F. A. C. Weber	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.baajf4	PC1, PC2, PC3, PC4	179	lp	0.4	1.45	2590.022	2.9
Pachycereus weberi (J.M. Coult.) Backeb.	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.kpuchw	PC1, PC2, PC3, PC4	40	lqp	0.6	1.67	421.3055	12.5
Pachycereus hollianus (F.A.C. Weber) Buxb.	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.3rzmuk	Bio 03, Bio 07, Bio 15, Bio 16	14	q	0.4	1.97	147.9136	0.0
Pilosocereus chrysacanthus (F.A.C. Weber) Byles & G.D. Rowley	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.uybd74	Bio 02, Bio 03, Bio 06, Bio 07, Bio 13, Bio 15	36	lp	0.4	1.54	386.109	14.3
Polaskia chichipe (Rol.-Goss.) Backeb.	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.zreqha	Bio 03, Bio 06, Bio 07, Bio 13, Bio 14, Bio 16	14	lp	0.8	1.97	130.8938	0.0
Stenocereus pruinosus (Otto) Buxb.	GBIF.org (28 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.n7qm3v	PC1, PC2, PC3, PC4	113	lpt	2	1.59	1636.869	4.8
Stenocereus stellatus (Pfeiff.) Riccob.	GBIF.org (28 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.v8r3zu	PC1, PC2, PC3, PC4	40	lq	0.4	1.78	461.9097	0.0
Stenocereus griseus (Haw.) Buxb	GBIF.org (28 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.tynctr	Bio 02, Bio 03, Bio 05, Bio 12, Bio 14, Bio 15	56	t	1.6	1.78	829.2492	0.0
Fouquieria splendens Engelm.	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.7r7axs	Bio 01, Bio 02, Bio 03, Bio 13, Bio 14, Bio 15	1454	t	3	1.36	23895.97	4.8
Fouquieria diguetti (Tiegh.) I.M.Johnst.	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.9djj25	Bio 03, Bio 05, Bio 06, Bio 14, Bio 15, Bio 17	164	lpt	0.4	1.54	2157.395	3.2
Fouquieria formosa Kunth	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.g38ye8	Bio 02, Bio 03, Bio 04, Bio 06, Bio 13, Bio 14, Bio 15	108	pt	1.6	1.68	1350.694	0.0
Clethra mexicana DC.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.4vm2js	Bio 02, Bio 03, Bio 04, Bio 05, Bio 14, Bio 15, Bio 16	555	qpt	2	1.41	8931.205	4.8
Arbutus xalapensis Kunth	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.q2489g	PC1, PC2, PC3, PC4	1016	lqpt	1.2	1.43	16027.04	4.7
Bouvardia ternifolia Schltdl.	GBIF.org (21 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.hnzfrv	Bio 01, Bio 02, Bio 03, Bio 14, Bio 15, Bio 16	1162	lqpt	1	1.46	18472.48	3.2
Crusea coccinea DC	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.suguyu	PC1, PC2, PC3, PC4	172	p	4.5	1.3	2781.794	3.1
Ernodea littoralis Sw.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.t568xg	Bio 03, Bio 04, Bio 05, Bio 10, Bio 15	27	qt	1.4	1.74	291.3148	0.0
Faramea occidentalis (L.) A. Rich.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.5y9rds	Bio 02, Bio 03, Bio 04, Bio 05, Bio 13, Bio 14, Bio 15	623	qp	1	1.22	11844.96	4.3
Hamelia rostrata Bartl. Ex DC.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.acx6ee	PC1, PC2, PC3, PC4	128	qpt	1.6	1.41	1918.384	4.2
Hamelia patens Jacq.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.v4vq7b	Bio 01, Bio 02, Bio 03, Bio 13, Bio 14, Bio 15	2365	lqp	0.4	1.1	46740.11	4.5
Palicourea padifolia (Roem. & Schult.) C.M.Taylor & Lorence	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.unphxj	Bio 02, Bio 03, Bio 05, Bio 13, Bio 14, Bio 15	404	lq	0.8	1.29	6034.548	3.9
Sommera grandis Standl.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.krjmpp	PC1, PC2, PC3, PC4	48	p	0.4	1.43	707.7721	0.0
Cordia seleriana Fernald	GBIF.org (02 March 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.wbyxc2	PC1, PC2, PC3, PC4	65	lqp	6	1.68	824.6397	0.0
Cordia sebestena L.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.ywcqq4	PC1, PC2, PC3, PC4	150	qt	2.5	1.39	2321.725	3.6
Ipomoea hederifolia L.	GBIF.org (21 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.5zym49	Bio 02, Bio 03, Bio 05, Bio 13, Bio 14, Bio 15	1113	lqp	0.4	1.19	27186.19	4.8
Ipomoea pauciflora Mart. & Gal	GBIF.org (21 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.x8kc3k	Bio 02, Bio 03, Bio 04, Bio 05, Bio 15, Bio 16, Bio 17	200	lqt	3	1.33	2975.038	2.6
Ipomoea cholulensis Kunth	GBIF.org (21 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.v2a2rj	Bio 02, Bio 03, Bio 05, Bio 14, Bio 15, Bio 16	121	lqt	0.4	1.14	1914.681	4.3
Ipomoea neei (Spreng.) O´Donell	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.7jh2hh	Bio 02, Bio 03, Bio 05, Bio 13, Bio 14, Bio 15	114	qt	2.5	1.28	1808.415	4.5
Ipomoea stans Cav.	GBIF.org (21 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.99gm46	Bio 01, Bio 02, Bio 03, Bio 04, Bio 12, Bio 14, Bio 15	202	pt	1.4	1.52	2892.645	2.6
Ipomoea wolcottiana Rose	GBIF.org (21 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.ddsqj8	Bio 02, Bio 03, Bio 04, Bio 05, Bio 12, Bio 14, Bio 15	81	lqt	0.4	1.42	1191.084	0.0
Juanulloa mexicana Miers	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.ce9ekx	Bio 01, Bio 02, Bio 04, Bio 14, Bio 15, Bio 16	123	lqp	0.4	1.33	1887.593	4.3
Solanum tridynamum Dunal	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.4ab5dq	Bio 02, Bio 03, Bio 05, Bio 13, Bio 14, Bio 15	378	p	0.8	1.41	5980.803	4.2

Moussonia deppeana Klotzsch ex Hanst.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.5be6cx	PC1, PC2, PC3, PC4	283	lqp	0.4	1.69	4080.336	3.8
Penstemon kunthii G. Don	GBIF.org (16 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.yp7wcd	Bio 01, Bio 02, Bio 03, Bio 13, Bio 14, Bio 15	123	lq	0.6	1.39	1816.945	4.3
Buddleja sessiliflora Kunth	GBIF.org (02 March 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.byhx2x	Bio 03, Bio 03, Bio 06, Bio 13, Bio 14, Bio 15	480	qpt	4.5	1.38	7730.543	4.4
Dicliptera sexangularis Juss.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.pdt4vz	Bio 02, Bio 04, Bio 10, Bio 13, Bio 14, Bio 15	195	lqpt	1.8	1.52	3020.401	2.8
Justicia mexicana (Seem.) Rose	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.zv2jkj	Bio 02, Bio 03, Bio 04, Bio 06, Bio 13, Bio 14, Bio 15	60	qp	0.4	1.46	836.172	0.0
Justicia candicans (Nees) L.D.Benson	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.fv4645	PC1, PC2, PC3, PC4	320	pt	1.6	1.36	5106.439	5.0
Justicia aurea Schltdl.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.xpc96j	Bio 01, Bio 02, Bio 03, Bio 13, Bio 14, Bio 15	246	lqpt	2.5	1.37	3812.359	4.3
Louteridium mexicanum (Baill.) Standl.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.9ze33t	Bio 03, Bio 05, Bio 07, Bio 13, Bio 14, Bio 15	54	lqt	2	1.71	730.4835	0.0
Adenocalymma inundatum Mart. Ex DC.	GBIF.org (02 March 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.bcc77j	Bio 02, Bio 03, Bio 05, Bio 13, Bio 14, Bio 15	183	qpt	2.5	1.19	3314.656	2.9
Astianthus viminalis Baill.	GBIF.org (02 March 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.g2ym92	Bio 03, Bio 04, Bio 05, Bio 14, Bio 15, Bio 16	139	lt	1.6	1.52	1945.843	3.8
Tabebuia rosea DC.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.ux4ax8	Bio 02, Bio 03, Bio 15, Bio 05, Bio 13, Bio 14, Bio 15	720	lqp	0.4	1.27	13791.15	4.4
Lantana camara L.	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.ku7qf6	PC1, PC2, PC3, PC4	4374	lqpt	0.4	1.25	87869.02	4.5
Lepechinia hastata (A. Gray) Epling	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.hrzj6m	Bio 02, Bio 03, Bio 13, Bio 14	12	lt	1.4	1.99	90.48088	0.0
Salvia elegans Vahl	GBIF.org (17 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.wezdfm	Bio 02, Bio 03, Bio 04, Bio 06, Bio 13, Bio 14, Bio 15	373	qp	1	1.49	5357.501	4.3
Salvia fulgens Cav.	GBIF.org (21 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.t9xtb9	Bio 02, Bio 03, Bio 04, Bio 06, Bio 12, Bio 14, Bio 15	128	p	1.8	1.49	1674.95	12.5
Salvia mocinoi Benth	GBIF.org (17 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.bmrhh6	Bio 02, Bio 03, Bio 05, Bio 13, Bio 14, Bio 15	248	qp	1	1.57	3723.867	0.0
Salvia mexicana L.	GBIF.org (21 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.tc3bjd	Bio 02, Bio 03, Bio 04, Bio 06, Bio 12, Bio 14, Bio 15	461	lt	1.2	1.61	6717.414	3.5
Salvia cacaliifolia Benth	GBIF.org (21 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.8etwhj	Bio 01, Bio 02, Bio 03, Bio 13, Bio 15	28	q	0.4	1.68	402.7137	0.0
Salvia urica Epling	GBIF.org (21 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.yvypbd	Bio 03, Bio 07, Bio 13, Bio 14, Bio 15	53	qt	0.6	1.53	871.4978	0.0
Salvia gesneriiflora Lindl. & Paxton	GBIF.org (21 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.ht7fzy	Bio 02, Bio 03, Bio 04, Bio 06, Bio 12, Bio 14, Bio 15	102	q	0.4	1.69	1282.675	0.0
Stachys coccinea Ortega	GBIF.org (29 December 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.kf2jvm	Bio 01, Bio 02, Bio 12, Bio 14, Bio 15	567	lq	0.8	1.21	9346.127	4.7
Vitex mollis Kunth	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.q5bqay	Bio 02, Bio 03, Bio 05, Bio 12, Bio 14, Bio 15, Bio 17	330	t	1.4	1.43	4932.643	4.8
Lobelia laxiflora Kunth	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.q2xeub	PC1, PC2, PC3, PC4	943	l	0.6	1.25	15446.82	4.5
Vernonia cordata Kunth	GBIF.org (09 February 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.6zpm79	PC1, PC2, PC3, PC4	114	lqpt	2	1.58	1666.748	4.5

Appendix S3. Maps for the future (years 2040, 2060 and 2080) hummingbird-plant richness co-occurrence patterns across Mexico under an intermediate Shared Socio-economic Pathway scenario (i.e., SSP3 7.0) and two assumptions of dispersion for taxa. The color gradient represents species richness patterns for both taxa, with areas in red showing the overlap of the maximum richness values for both hummingbird and plant species for each climate scenario.



DISCUSIÓN GENERAL Y CONCLUSIONES

Diversos estudios han investigado los impactos potenciales de las variaciones climáticas en redes animal-planta, especialmente para insectos y huéspedes/plantas (Schweiger et al., 2008; Gorostiague et al., 2018). Sin embargo, pocos estudios han abordado cambios en las relaciones interespecíficas en vertebrados, con la excepción de mamíferos carnívoros o murciélagos polinizadores (Pandey & Papeş, 2018; Scully et al., 2018; Corro et al., 2021). Aunque los cambios en las redes de co-ocurrencia en el futuro probablemente tengan efectos variables en las especies, en el caso de los colibríes y las plantas asociadas a su alimentación se esperan efectos negativos. De hecho, los resultados sugieren cambios no uniformes en los patrones de distribución de los colibríes y las plantas en México en el futuro. A pesar de la polémica en torno a la relación entre los datos de co-ocurrencia y las interacciones bióticas (Jordano, 2016b; Blanchet et al., 2020; Chávez-González et al., 2020), es un hecho que las especies deben co-ocurrir para interactuar directamente. De este modo, para poder alcanzar la protección a largo plazo de servicios ecosistémicos importantes, como la polinización, es necesario incorporar análisis de co-ocurrencia de las especies.

Los resultados obtenidos concuerdan con otros estudios realizados en México, en donde se sugiere que los patrones estimados de cambio en la biota se atribuyen a un aumento en la temperatura promedio y al decremento en la precipitación anual (ver Cuervo-Robayo et al., 2020). Esto es de gran relevancia debido a que las reducciones en los rangos de distribución de las especies podrían afectar sus respuestas fisiológicas y sus patrones de actividad, modificando sus dinámicas poblaciones e inclusive aumentando su riesgo de extinción (Tylianakis et al., 2008; Sonne et al., 2022), especialmente si no son capaces de adaptarse rápidamente a las nuevas condiciones ambientales. A pesar de que se han pronosticado migraciones altitudinales para plantas y colibríes en el futuro, algunos estudios reportan disminuciones en la capacidad y rendimiento del vuelo de los colibríes a mayores altitudes (Altshuler et al., 2004; Correa-Lima et al., 2019). Por ello, se requieren más estudios que analicen la capacidad de estos organismos de adaptarse o dispersarse a otras áreas (de Matos Sousa et al., 2021).

Por otro lado, los cambios de distribución derivados del cambio climático en el futuro podrían causar modificaciones en los patrones de co-ocurrencia de las especies y en la estructura de las comunidades (Lovejoy & Hannah, 2004; Sonne et al., 2022). En efecto, la disminución registrada en el grado de coincidencia espacial de las especies podría implicar cambios potenciales en la disponibilidad de mutualistas interactuantes que deriven, a su vez, en un desacoplamiento de la interacción de polinización con efectos perjudiciales para el funcionamiento de los ecosistemas (Stenseth et al., 2002; Visser & Both, 2005; Hegland et al., 2009; Correa-Lima et al., 2019). Por ejemplo, se sabe que los tiempos de floración de plantas con floración temprana están cambiando en respuesta al aumento de temperatura, mientras que las plantas con floración tardía son más susceptibles a congelarse en zonas de elevaciones altas (Phillips et al., 2018; Descamps et al., 2021; Powers et al., 2022). En consecuencia, se espera una reducción de los recursos florales para los polinizadores favoreciendo que las especies no sean capaces de completar sus ciclos de vida en el futuro (Scaven & Rafferty, 2013; Takkis et al., 2018). Lo anterior será de gran relevancia particularmente para aquellas interacciones especialistas colibrí-planta en donde es poco probable que otros animales lleven a cabo la polinización (Linhart & Feinsinger, 1980), favoreciendo el aumento en el riesgo de co-extinción de las especies (Sonne et al., 2022). No obstante, dado que las redes colibrí-planta son muy dinámicas—con el recambio de especies actuando como el principal motor de cambios espacio-temporales en la formación de las interacciones–– es posible que la plasticidad que presentan pueda mitigar los efectos en la reproducción de las plantas y en los recursos alimenticios de los colibríes ante escenarios climáticos futuros (Poisot et al., 2012; CaraDonna et al., 2017; Correa-Lima et al., 2019; Chávez-González et al., 2020).

El recambio de especies predicho en el futuro, junto con los cambios en el tamaño de la red y el sobrelapamiento de nicho, sugiere que muchas especies no serán capaces de colonizar nuevas áreas en el futuro. De hecho, este patrón de recambio en el futuro podría promover la formación de nuevos ensamblajes, cambiando la identidad de las especies en la red e inclusive propiedades de la red como el anidamiento y la especialización (Dormann et al., 2009). Esto es importante dado que las especies con distribución restringida son típicamente especialistas de hábitat (Sonne et al., 2016), por lo que podrían ser incapaces de colonizar nuevas áreas o persistir ante condiciones climáticas nuevas en el futuro (Broennimann et al., 2006). De hecho, Sonne y colaboradores (2022) evaluaron la vulnerabilidad de las comunidades de colibríes y plantas ante el cambio climático en América y encontraron que las comunidades en Norteamérica experimentarán menores tasas de extinción derivadas por los cambios climáticos comparadas con las tasas de co-extinción y de colonización. En estas comunidades la extinción causada por efectos climáticos impactará a las especies de la periferia de las redes, en lugar de las especies (generalistas) centrales (Sonne et al., 2022). En estos casos, las especies generalistas podrían desempeñar un rol importante en la resiliencia de las comunidades ante el CCG debido a su habilidad para conectarse con muchas especies dentro de la red (Sonne et al., 2022). Este escenario puede ser especialmente cierto para las especies de colibríes endémicas de México, que pertenecen principalmente a los clados de las Esmeraldas (61.54%) y de las Abejas (23.08%) (McGuire et al., 2014). Estos colibríes son generalistas en su mayoría, con picos rectos de longitud media y tamaños corporales de pequeño a medianos (Rodríguez-Flores et al., 2019). Estas características pueden facilitar la interacción con una gran variedad de morfologías florales, permitiéndoles integrar nuevos recursos florales a su dieta y disminuyendo el riesgo de extinción de los colibríes ante escenarios de CCG. No obstante, la visita a las flores no garantiza que haya polinización y el efecto del recambio de especies y/o el "rewiring" (capacidad de las especies de formar interacciones con otras especies en la comunidad) debe ser evaluado.

Los climas actuales y pasados juegan un importante rol en determinar la especialización de los sistemas mutualistas (Dalsgaard et al., 2011). Por ejemplo, se sabe que las redes colibrí-planta de climas templados eran menos especializadas que las redes de climas tropicales (medido con especialización a nivel de la red, Blüthgen et al., 2006) y que este patrón estaba estrechamente relacionado con redes pobres en especies, una baja precipitación contemporánea y una alta velocidad de cambio climático en el Cuaternario. Este escenario climático favoreció una baja especialización biótica y adaptaciones locales en las comunidades colibrí-planta en Norteamérica. Por otro lado, los factores que influyen en el potencial de una especie para establecerse y sobrevivir son difíciles de predecir —por lo cual deben tomarse con cautela. Sin embargo, existe evidencia de que los nuevos ensamblajes se formarán en localidades que se ubican actualmente en los rangos extremos del gradiente ambiental, como regiones áridas y zonas de alta elevación (Graham et al., 2017).

Los efectos que el CCG tenga sobre el funcionamiento de los ecosistemas dependerá de la forma en que las interacciones de las especies sean afectadas (Hegland et al., 2009). En este sentido, y a pesar de que la colonización de las especies generalistas pueda compensar hasta cierto punto las extinciones locales, es importante resaltar que las comunidades tienden a ser más inestables y menos resilientes al cambio cuando el sobrelapamiento de nicho y por ende, la competencia, son altos (Pastore et al., 2021; Sonne et al., 2022). Desde esta perspectiva, debe otorgarse especial atención a las provincias de Oaxaca, Sierra Madre del Sur y Sierra Madre Oriental ya que, de acuerdo con los resultados, serán las provincias más afectadas por el CCG. Además, son zonas de alta riqueza para las especies de colibríes y sus plantas, además de ser consideradas prioritarias para la conservación de los colibríes ante los escenarios de cambio climático y cambio de uso de suelo (Prieto-Torres et al., 2021). De este modo, se resalta la importancia de incluir interacciones bióticas relevantes en la predicción de los efectos del CCG para aumentar la veracidad de las predicciones en los modelos. También, se recomienda realizar trabajo de campo para probar las predicciones realizadas y obtener información confiable sobre las respuestas de las especies y las comunidades ante escenarios de cambio en el futuro.

El presente estudio representa un primer acercamiento al estudio de las redes de co-ocurrencia de los colibríes y sus plantas asociadas, sin embargo, es importante resaltar que los resultados descritos anteriormente representan sólo una parte de la red ya que sólo las especies endémicas de colibríes fueron contempladas. Por ello, se impulsa a realizar futuros estudios contemplando a todas las especies de colibríes con distribución en México y sus plantas asociadas, cuantificando la intensidad de las interacciones e incluyendo información ecológica como la morfología (tamaño, longitud y curvatura del pico, largo y curvatura de la corola) y las abundancias de colibríes y plantas. Asimismo, es necesario incorporar otros factores que influyen en la co-ocurrencia de las especies a fina escala, tales como el cambio de uso de suelo que actualmente es uno de los factores que más repercute en el declive de las poblaciones de estos importantes polinizadores (Infante et al., 2020b).

En conclusión, el entendimiento del riesgo de extinción de las especies y la potencial ruptura de sus asociaciones ecológicas ante el CCG es un paso crítico para establecer estrategias de manejo y planes de conservación. Los resultados aquí obtenidos demuestran que para garantizar la conservación a mediano y largo plazo de la biodiversidad y de servicios ecosistémicos importantes, como la polinización, se necesita más que sólo aumentar la extensión de tierra protegida. Es necesario que los tomadores de decisiones promuevan nuevas políticas de conservación, incorporando la protección de distintos niveles de la biodiversidad y no únicamente de las especies individuales. Desde esta perspectiva, el presente estudio representa evidencia científica útil que puede ser utilizada para una planeación eficiente de la protección y conservación de los colibríes y sus asociaciones ecológicas en el futuro.

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