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CONSECUENCIAS DEL CAMBIO CLIMÁTICO EN LOS PATRONES DE DISTRIBUCIÓN DE ÁRBOLES REQUERIDOS POR *Amazona finschi* (PSITTACIDAE): IMPLICACIONES PARA LA CONSERVACIÓN

TESIS

Que presenta

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RESUMEN

El cambio climático global (CCG) y los cambios en el uso de la tierra son las causas más importantes del actual deterioro de la biodiversidad. Si bien existe mucha información que mide los efectos del CCG en las especies, aún no se comprende por completo cómo esta inestabilidad global puede afectar las interacciones entre especies, en particular sobre los ecosistemas que ya son vulnerables. En este estudio se estimó la distribución potencial bajo modelos climáticos actuales y futuros (años 2050 y 2070), para el loro Amazona corona lila (*Amazon finschi*), una especie que se encuentra en peligro de extinción, y de ocho árboles leñosos asociados a su uso del hábitat, con el fin de responder: (1) ¿qué impacto podría tener el CCG previsto y la pérdida de hábitat en los patrones individuales y de co-distribución de las especies? ; y (2) ¿en qué medida la red de Áreas Protegidas (AP) existente ayudará a salvaguardar a los loros, sus especies anfitrionas y otras interacciones biológicas? Las diferentes proyecciones indican consistentemente que todas las especies tenderían a reducir sus rangos de distribución en los climas futuros. Desafortunadamente, los efectos son muy exacerbados (incluso dentro de las AP) cuando se combinan tanto el CCG como la pérdida de hábitat: más del 50% de la distribución restante de las especies y de los sitios de mayor riqueza vegetal podrían perderse en un futuro próximo. Se observa que tanto los rangos individuales de distribución de los árboles leñosos como la riqueza de especies de plantas albergan una alta proporción de las áreas de distribución de *A. finschi*. Sin embargo, esta congruencia espacial podría reducirse a futuro promoviendo posibles disrupciones de las asociaciones ecológicas entre taxones. Estos resultados proporcionan evidencia novedosa sobre qué áreas los tomadores de decisiones en México deberán enfocar esfuerzos de conservación para lograr la protección a largo plazo de esta especie endémica y altamente vulnerable.

Palabras clave: loro, patrones de biodiversidad, modelado de nichos ecológicos, áreas protegidas, bosques tropicales.

ABSTRACT

Today global climate (GCC) and land-use changes are the most significant causes of biodiversity decline and habitat reduction. Although information measuring these global drivers, we lack a full understanding on how it may impact the community assemblies (particularly species interactions) across ecosystems. Herein, we assessed the potential distribution of eight key woody-trees associated to the habitat of the Endangered Lilac-crowned Amazon (*Amazon finschi*) under current and future climates models (2050's and 2070's) and, to answer the questions: (1) how the predicted GCC and habitat loss could impact both individual species and their co-distribution patterns; and (2) how effective would be the existing Protected Areas (PAs) network be safeguarding both parrot-plants species and their biological interactions. Our projections were consistent in the identity of the species that are most vulnerable to GCC: all of species tended to reduce their distributional ranges in the future climates. Unfortunately, the effects were strongly exacerbated (even within existing Mexican PAs) when both GCC and habitat loss were combined: more than 50% of the remaining species' distribution and sites of highest plant richness could be lost in the future. Currently, both individual species ranges and richness of plants, shelter a high proportion (ca. 50%) of the *A. finschi*'s distribution. But this spatial congruence could be reduced in the future, likely promoting the disruptions of ecological associations between taxa. We provided novel evidence for decision-makers to enhance conservation efforts to attain the long-term protection of this endangered and Mexican endemic parrot.

INTRODUCCIÓN GENERAL

El cambio climático es uno de los problemas más grandes que enfrenta actualmente el mundo, el cual es atribuido a la alta acumulación de gases de efecto invernadero (GEI) en la atmósfera, derivado de las actividades antropogénicas, provocando un aumento de la temperatura global (Christensen *et al.*, 2007; Quiñones *et al.*, 2018). El Panel Intergubernamental de Cambio Climático (IPCC http://www.ipcc.ch/) define a este proceso como *"un cambio de clima atribuido directa o indirectamente a la actividad humana que altera la composición de la atmósfera mundial y que se suma a la variabilidad natural del clima observada durante períodos de tiempo comparables"* (IPCC, 2002). Durante el siglo XX la temperatura media global de la superficie aumentó aproximadamente 0.6 °C, lo que ha motivado a esta organización ha predecir que, de continuar la tendencia al alza en los siguientes cien años, la temperatura podría incrementar entre 1.1 y 6.4°C (IPCC, 2001; 2007; 2014). Esto evidencia la responsabilidad de las acciones humanas como una de las causas más importante del decremento de las poblaciones silvestres y la subsecuente extinción de especies (Root *et al.*, 2003; Opdam y Wascher, 2004; Scharlemann *et al.*, 2004; Lovejoy y Hannah, 2019) debido a la conversión de hábitats naturales a otros usos del suelo como la agricultura, las actividades de extracción (maderable o mineral), así como la formalización de la industria y asentamientos humanos (Foley *et al.*, 2005).

Es de especial importancia estudiar los efectos del cambio climático sobre la biodiversidad ya que se ha demostrado que impacta directa e indirectamente, tanto a poblaciones como ecosistemas (Mooney *et al.*, 2001; Parmesan, 2006; IPCC 2007, Janetos *et al.*, 2008). Estos cambios en el clima pueden modificar a diversas escalas espacio-temporales la configuración de los tipos de vegetación, los componentes presentes en un ecosistema e incluso sus interacciones, así como los patrones de migración, el tamaño y distribución de las poblaciones (Peterson *et al.*, 2002, Crick, 2004; Lemoine *et al.*, 2007, Ballesteros-Barrera, 2008, Huang y Geiger, 2008; Ledig *et al.*, 2010; Sáenz-Romero *et al.*, 2010, 2020). En general, una especie dependiendo de su capacidad de respuesta a los cambios, puede verse beneficiada o no por las modificaciones en el clima. De hecho, algunas especies serían incapaces de sobrevivir en los nuevos climas (aumentando su riesgo extinción), mientras que otras podrían modificar sus áreas de distribución (desplazamiento) o adaptarse a las nuevas condiciones (Peterson *et al.*, 2002; Vié et al., 2009; Jiménez *et al.*, 2010; Prieto-Torres *et al.*, 2016). Por lo tanto, analizar los

efectos del cambio climático en la distribución de las especies es esencial para las prácticas de conservación (Rebelo *et al*., 2010; Sáenz-Romero *et al*., 2010).

Una herramienta de investigación para determinar el impacto de la modificación de los patrones climáticos sobre la biodiversidad son los modelos de distribución espacial, considerando las condiciones climáticas actuales, del pasado y futuro (Mateo *et al*., 2011). Dichos modelos se basan en procedimientos estadísticos y cartográficos que, partiendo de datos de presencia, permiten inferir zonas potencialmente idóneas en función de sus características ambientales, geológicas, topográficas o climáticas. En estos modelos se estima y/o predice el área con aptitudes ambientales para la distribución potencial de un taxa para el tiempo en que el clima ha sido proyectado (Guisan y Zimmermann, 2000; Elith *et al*., 2006; Mateo *et al*., 2011). Por ello, son ampliamente utilizados en estudios del efecto potencial del cambio climático, la identificación de áreas prioritarias de conservación y el desarrollo de estrategias de protección para las especies, por mencionar algunos (Araujo *et al*., 2019; Prieto-Torres *et al.,* 2020). Sin embargo, a pesar de su uso extensivo, los patrones de distribución conjunta de especies a menudo se pasan por alto en la literatura (Atauchi *et al*., 2018; Heinen *et al*., 2020). Esta es una brecha importante de información porque la pérdida de interacciones de especies clave para, por ejemplo, la dispersión de semillas, tendrá impactos perjudiciales para los ecosistemas y las especies que dependen de ellos (Jordano, 2016). Por lo tanto, se necesita más investigación sobre estas ideas (Hegland *et al.*, 2009).

Los bosques tropicales secos (BST) dominados por árboles de hoja caduca, con temperatura media anual mayor a los 25°C y precipitación anual entre los 700 y 1600 milímetros (Banda, *et al*., 2016) albergan niveles importantes de riqueza de especies y endemismos. Sin embargo, son ecosistemas amenazados globalmente, por lo que son considerados en estado crítico de conservación (Miles *et al*., 2006; Ceballos *et al*., 2010). Actualmente estos bosques han sufrido grandes daños debido a su conversión generalizada a tierras de cultivo, acompañada por el pastoreo incontrolado de ganado e incendios (Miles *et al*., 2006; Ibarra-Montoya *et al*., 2011; Sánchez-Azofeifa *et al*., 2011; Prieto-Torres *et al*., 2016, 2018). En México se estima que anualmente se deforestan alrededor de 300,000 ha y se ha perdido el 73% de la vegetación original de BST, siendo uno de los ecosistemas que está desapareciendo más rápidamente (Trejo y Dirzo, 2000; Balvanera *et al*., 2000). Lo que impacta de manera directa a las especies de

mamíferos y aves que dependen de este tipo de vegetación (Dirzo y Raven 2003; Jordano *et al*., 2009).

Un ave endémica de México que se caracteriza por habitar los BST del país es *Amazona finschi* comúnmente denominado como loro corona lila, la cual anteriormente se distribuía desde el sur de Sonora y suroeste de Chihuahua hasta Oaxaca (Forshaw, 1989, Howell y Webb, 1995). Marín-Togo *et al.,* (2012) consideran que las poblaciones de *A. finschi* están declinando en paralelo con la perdida acelerada de su hábitat de anidación, ya que la distribución actual a lo largo de la costa del Pacífico de México muestra una reducción de 72.6% respecto de la distribución original estimada, siendo catalogada como "en peligro de extinción", por la Norma Oficial Mexicana NOM- 059 (SEMARNAT, 2010), y la Unión Internacional para la Conservación de la Naturaleza. Para el loro corona lila se han estudiado sus relaciones bióticas (recursos de cavidades, alimentación, etc.) para determinar la presencia de poblaciones viables (Monterrubio-Rico *et al.,* 2009; Renton *et al*., 2018). Sin embargo, los impactos potenciales de la conversión del paisaje y el calentamiento global en los patrones geográficos de las interacciones y de co-distribución (porque las especies deben coexistir para interactuar directamente) del loro-árbol no han sido evaluados en escala espacial.

Con base a lo antes expuesto, en el presente trabajo se tiene como objetivo evaluar cómo el cambio climático global previsto y la pérdida de hábitat podrían afectar tanto a las especies a nivel individual como a los patrones de co-distribución del loro corona lila y ocho árboles leñosos que requiere en su uso de hábitat y determinar la importancia de la red de Áreas Protegidas (AP) existente para salvaguardar a la especie de loro y sus plantas e interacciones biológicas. Esto ayudará a delimitar áreas con la mayor probabilidad de mantener los ensambles de especies, así como la preservación de la interacción entre el loro y las especies arbóreas que requiere para asegurar su supervivencia.

PRESENTACIÓN DEL ARTÍCULO

Predicting parrot-woody tree co-distribution patterns in the face of global changes: The case of Lilac-crowned Amazon for Neotropical dry forests

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Abstract. –

Today global climate (GCC) and land-use changes are the most significant causes of biodiversity decline and habitat reduction. Although information measuring these global drivers, we lack a full understanding on how it may impact the community assemblies (particularly species interactions) across ecosystems. Herein, we assessed the potential distribution of eight key woody-trees associated to the habitat of the Endangered Lilac-crowned Amazon (*Amazon finschi*) under current and future climates models (2050's and 2070's) and, to answer the questions: (1) how the predicted GCC and habitat loss could impact both individual species and their co-distribution patterns; and (2) how effective would be the existing Protected Areas (PAs) network be safeguarding both parrot-plants species and their biological interactions. Our projections were consistent in the identity of the species that are most vulnerable to GCC: all of species tended to reduce their distributional ranges in the future climates. Unfortunately, the effects were strongly exacerbated (even within existing Mexican PAs) when both GCC and habitat loss were combined: more than 50% of the remaining species' distribution and sites of highest plant richness could be lost in the future. Currently, both individual species ranges and richness of plants, shelter a high proportion (ca. 50%) of the *A. finschi*'s distribution. But this spatial congruence could be reduced in the future, likely promoting the disruptions of ecological associations between taxa. We provided novel evidence for decision-makers to enhance conservation efforts to attain the long-term protection of this endangered and Mexican endemic parrot.

Keywords: *Amazona finschi*, biodiversity patterns, ecological niche modelling, protected areas, species range shifts, Tropical forests.

INTRODUCTION

Now a days, the global climate change (GCC) is one of the biggest concerns we face. In fact, GCC is globally recognized amongst the most important drivers of biodiversity crisis due to alteration in temperature and precipitation patterns which modify the species distribution patterns, forcing species to re-accommodate its current distributional ranges (Lovejoy & Hannah, 2019). During the late 20th and early 21st centuries, the global average temperature has increased by 0.6 °C (IPCC; 2014) and future estimations for the coming decades are not optimistic (Pörtner *et al.*, 2021). Likewise, it is well-known that there is strong synergy between the agricultural activities and GCC, generating in many cases local or even global extinctions (Ceballos & Ehrlich, 2018). This has a deep and strong impact not only for biodiversity but also on ecosystem services and, consequently, on human well-being (Diaz *et al*., 2018). Therefore, there is a growing interest in understanding the combined effects of these global drivers on the spatio-temporal distribution patterns of biodiversity. This information is priceless to enable the implementation of accurate mitigation policies and practices for conservation (Rebelo *et al*., 2010; IPBES, 2019).

Ecological niche and species distribution models are some of methodological frameworks for assessing the potential effects of global changes on a wide range of biological entities (species, both aquatic and terrestrial) and at distinct geographic scales (Araujo *et al*., 2019). These approaches use statistical methods by relating geo-referenced occurrence data and environmental variables to project the Grinnellian niches (Rödder & Engler, 2011) and predict habitat suitability of species (see Peterson *et al*. [2011] for a detailed explanation). The use of these models has been a useful to define core areas of species diversity (Stats *et al*., 2020), evaluating both evolutionary and ecological hypotheses (Esparza-Orozco *et al*., 2020; Cornejo-Paramo *et al.,* 2020), as well as developing conservation strategies (Prieto-Torres *et al.,* 2021a). However, despite its extensive use, species' co-distribution patterns are often overlooked in the literature (Atauchi *et al.,* 2018; Heinen *et al*., 2020). This is an important information gap because loss of key species interactions (e.g., seed dispersal) may have detrimental impacts for the ecosystems and the species depending upon it (Jordano, 2016). Therefore, more research is urgently needed to mitigate the loss of yet more species (Hegland *et al*., 2009).

Neotropical dry forests (NDF) are considered among the highest diversity ecosystems, with higher biodiversity loss per individual and the synergetic effects of land conversion (Miles *et al*., 2006; Portillo-Quintero & Sanchez-Azofeifa, 2010; Banda *et al.*, 2016; Siyum, 2020) and GCC (e.g., Collevatti *et al*., 2013; Prieto-Torres *et al.,* 2016; 2021a). New evidence indicates that NDF distribution and survival for its inhabiting species could be strongly affected by these anthropogenic threats. Among the most recent findings, it has been proposed that the distribution ranges of over 50% bird species are expected to decrease as compared to current distributions, with uneven structural reorganization of assemblages (from the taxonomic to functional levels) and even the extinction of specialist species (Prieto-Torres *et al*., 2016, 2020, 2021b). The outcome of these range shifts may lead to significant changes in beta diversity (i.e., biodiversity turnover) and alter the ecosystem functions (e.g., Clavel *et al*., 2011). Such scenarios could represent further challenges for the long-term conservation of NDF biota. Mexican dry forests are, sadly, particularly vulnerable to these critical scenarios (Prieto-Torres *et al*., 2016; Allen *et al*., 2017; Manchego *et al.,* 2017).

Despite the increasing knowledge in ecological, biogeographical and conservation of Mexican dry forests biota over the past 20 years, many biodiversity trends and mechanisms in the face of future global changes remain poorly understood (e.g., Prieto-Torres *et al*., 2020, 2021a). In fact, an important drawback of most studies (at local and regional scales) is that frequently only abiotic effects are considered. This latter is critical because, for example, areas predicted to be climatically suitable but where essential resources (nesting sites, feeding, etc.) are lost may be in fact an unsuitable habitat for many animals such as mammals and birds (Brooks *et al*., 1997; Dirzo & Raven 2003; Jordano *et al*., 2009; Renton *et al*., 2018). From this perspective, the impact and extinction risks may be even more drastic than the predictions obtained in previous studies. Therefore, more integrative studies considering both environmental and biotic data are needed to evaluate the susceptibility of these interactions' level and the magnitude of global changes threats on NDF's biodiversity (Gillespie & Walter, 2001; de la Parra-Martinez, 2011; Renton *et al.* 2018). This latter is particularly important for endemic species and/or on those that are heavily threatened (see Prieto-Torres *et al.* 2020, 2021b).

The Lilac-crowned Amazon, *Amazona finschi* (Sclater, 1864), is a Mexican endemic bird species inhabiting mainly in the NDF from southwestern Sonora to northwestern Oaxaca.

Population size has been estimated <10,000 [4,700–6,700 mature] individuals, confined to an already severely fragmented habitat, thus declining area extent and quality due to anthropogenic activities (Renton *et al*., 2003; Monterrubio-Rico *et al*., 2009; Marin-Togo *et al*., 2012). In fact, previous studies suggest an important and rapid populations declination for this species (Marin-Togo *et al*., 2012). It is thus listed as an Endangered species according to national and international checklists (SEMARNAT, 2010; BirdLife International, 2020). There is literature about the Lilac-crowned Amazon and its important biotic relationships (e.g., tree phenology, cavity resources, feeding, etc.) to determine the presence of current viable populations (e.g., Monterrubio-Rico *et al*., 2009; Sanchez-Barradas *et al*., 2017; Renton *et al*., 2018). However, the potential impacts of landscape conversion and global warming into the co-distribution pattern and interactions (because species must co-occur to directly interact) of parrot-woody tree are not well-evaluated.

In this paper, we intend to: (a) assess how predicted GCC and habitat loss could impact both individual species and the co- distribution patterns of Lilac-crowned Amazon and eight woody-trees species associated to its habitat use; and (b) determine the importance of the existing Protected Areas (PAs) network to safeguard both parrot-plants species and their biological interactions. Based on this information, we provide new and more accurate evidence thorough integrative background to propose priority actions and conservation guidance for long-term conservation of this highly vulnerable and Mexican endemic parrot species.

METHODS

Species list and occurrence data

We focused our analyses on Lilac-crowned Amazon and eight woody plant species, including: *Aralia excelsa*, *Astronium graveolens*, *Brosimum alicastrum*, *Caesalpinia eriostachys, Erythrina lanata, Jatropha sympetala*, *J. malacophylla,* and *Piranhea mexicana.* These trees have distinct geographical distributions patterns (e.g., endemics to Mexico, or with different range extent across Neotropics, etc.; Table 1), but they are all considered as key for feeding (in both dry and rainy seasons) and nesting across the geographical and ecological distribution of Lilac-crowned Amazon populations (Renton & Salinas-Melgoza, 1999; Marsden *et al*.,

2001; Renton, 2001; Renton & Iñigo, 2003; Brightsmith, 2005; Ortega-Rodriguez & Monterrubio-Rico, 2008; Monterrubio-Rico *et al*., 2009).

Occurrence records for each species were pulled from different resources: (a) collaborative public online databases (Global Biodiversity Information Facility [GBIF; https://www.gbif.org/], Encliclovida [https://enciclovida.mx/]); (b) the National herbarium of Mexico (MEXU); (c) the specialized literature (e.g., Renton et al., 2003; Navarro-Sigüenza et al., 2018), and (d) fieldwork to identify nesting sites across Michoacan (2001-2005) and Sinaloa (2014-2020) states. The Information from GBIF was directly downloaded using the "*rgbif*" library to R software (Chamberlain *et al*., 2019). Access numbers for downloaded GBIF records are detailed in Table 1. All data were transformed into decimal degrees, based on the WGS84 datum.

Occurrence data was later filtered and cleaned (i.e., replicated records from multiple sources, data lacking location and year of collection information were removed) to identify imprecise occurrences that could negatively affect the model performance (Roubicek et al., 2010; Boria et al., 2014). We also removed occurrence points located within cities, since these occurrences may not accurately reflect the species habitat requirements. Here, we used data from years 1970 to 2021, hoping to best reflect the latest year patterns. However, for those records from 2001 to 2020 (i.e., without the same temporality of climatic layers), we performed an outlier exclusion procedure in the environmental space by removing points that fell outside the interquartile range of three environmental variables (annual mean temperature [bio 1], annual precipitation [bio 12], and precipitation seasonality [bio 15] for occurrences from 1970 to 2000 (Robertson et al., 2016, Prieto-Torres et at., 2020). Then, we removed spatially duplicates points nearer than ca. 5km² (i.e., the cell size resolution used for predictor variables). After these steps, we retained 3,199 unique occurrence records for all the species (Table 1).

Environmental input data: Current and future scenarios

To characterize the environmental niche of species, we selected predictors variables (with a 2.5 minutes of resolution) from Worldclim Project 2.1 (Fick & Hijmans, 2017). We excluded the four variables (bio 8, bio 9, bio 18 and bio 19) that combine temperature and precipitation, owing to known artefacts (Escobar *et al*., 2014). To reduce dimensionality and collinearity of

environmental layers, we applied four approaches to select environmental subsets: (1) the variables with the most important percentage of contribution into the model from exploratory analyzes in Maxent; (2) the variables with the AUC Jackknife values greater than 0.8; (3) correlation under a Variance Inflation Factor (VIF; Montgomery & Peck, 1992) criterion using the "*usdm*" R package (Naimi, 2015); (4) a set of four variables (explaining up to 95% of the total variance) derived from a Principal Component Analysis (Hanspach *et al*., 2011), as implemented in the "*ntbox*" R package (Osorio-Olvera *et al*., 2020). We selected the best approach for model building based on the statistics estimated in the "*kuenm*" R package (Cobos *et al*., 2019). Detailed information about the variables set used for each species is shows in Table 1.

For models based on future climate projections (2041-2060 [hereafter 2050] and 2061-2080 [hereafter 2070], we used climate data from the Coupled Model Intercomparison Project 6 (CMIP6; Stoerk *et al*., 2018) available at the Worldclim web portal. To do this, we selected two global climate models (Beijing Climate Center Climate System Model [BCC-CSM] and Interdisciplinary Climate Research Model [MIROC6]) based on the results (temperature and precipitations close to the average ensemble projection) obtained from GCM compareR´s web application (Fajardo *et al*., 2020). All projections were performed using two Shared Socio-economic Pathways scenarios: SSP2-4.5 and SSP5-8.5. Overall, despite that both SSP scenarios assume an increasing human population, the SSP5-8.5 scenario represents higher predicted greenhouse emissions in absence of climate change mitigation policies (Riahi *et al*., 2017), and so the results under this scenario may be interpreted as "pessimistic".

Ecological niche and species distribution models

For each species, we modelled the potential distribution using MaxEnt 3.4.3 (Phillips *et al*., 2017). This algorithm estimates the probability of suitability (ranging from zero [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 (Elith *et al*., 2006, 2011; Phillips *et al.*, 2006). Here, we opted to use MaxEnt over other available methods because it has been referred as a good performance method for presence-only data (Elith *et al*., 2011) —as our study.

Because dispersal plays a crucial role in the distributions of organisms and must be considered in the development of such models (Barve *et al.,* 2011), we created an area for model calibration (or "M"; see Soberón & Peterson, 2005) that attempts to reflects the accessible area (e.g., including dispersal barriers) for each species. We established "M" (a mask or GIS polygon) based on the intersection of occurrence records with the Terrestrial Ecoregions (Dinerstein *et al.*, 2017) and the Biogeographical Provinces of the Neotropics (Morrone, 2014). These masks, in turn, were later used to cut out the environmental variables that were previously selected for the species.

The models were generated using the "*kuenm*" R package (Cobos *et al*., 2019) to perform a calibration protocol assessing model complexity (Merow *et al*., 2014). To do this, we created 1,008 candidate models by combining four distinct sets of environmental predictors (see above), 18 regularization multiplier values (RM: 0.4, 0.5, 0.6, 0.7, 0.8, 1.1, 1.4, 1.7, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 6.0, 7.0, 8.0) and 14 feature classes (i.e., combinations of linear [l], quadratic [q], product [p], and threshold [h]). We used 25% random subsets of occurrence data for model evaluation (i.e., model testing and selection of best models). After model calibration, we created models with the selected parameter values, 500 iterations with 10 bootstrap replicates, and *cloglog* output (Phillips *et al*., 2017). The best models were chosen based on omission errors of less than 5% (Anderson *et al*., 2003), the partial ROC test (Peterson *et al*., 2008) and the corrected Akaike Information Criterion (AICc; Merow *et al*., 2014; Muscarella *et al*., 2014). All models were run allowing "unconstrained extrapolation" and "extrapolation by clamping" in Maxent projections, which allowed us to identify potentially novel conditions that could be considered suitable for each species in the future scenarios (Elith *et al*., 2011; Merow *et al*., 2014). For all plant species, models were calibrated using the available data for their entire current range, and the cropped to the approximate geographic extent of northwestern Mexico (i.e., known distribution of Lilac-crowned Amazon, Fig. 1).

To generate the potential distribution maps for each species under each climate scenario, we calculated median values across replicates to summarize model predictions (Campbell *et al*., 2015). Then, we created binary maps (presence-absence) using a cutoff threshold under the rule of the "tenth percentile training presence". This threshold omits the 10% of records with the lower values, assuming that they are not representative sites for the

species, and thus seeking to exclude outliers and minimize false-positive rate (Escalante *et al*., 2013; Liu *et al*., 2013). For each species, the future geographic distribution (for 2050 and 2070 years) was manually obtained for the species through consensus of binary projections from both global climate models (i.e., suitable in two models equal to presence). We obtained five consensus maps for the modeled forecast for each species (current, 2050 SSP2-4.5, 2050 SSP5-8.5, 2070 SSP2-4.5, and 2070 SSP5-8.5). Finally, we used the "*ntbox*" R package (Osorio-Olvera *et al*., 2020) to perform Mobility-Oriented Parity test (MOP; Owens *et al*., 2013) to identify sites with a higher degree of environmental dissimilarity and offer a view of the reliability of our model transfers (i.e., determine areas where strict extrapolation occurs; Owens *et al*., 2013; Alkishe *et al*., 2017).

Spatial analyses and summary metrics.

Loss and gain of suitable habitats under GCC were calculated by subtracting future from current potential distributions. This comparation allowed to identify areas of climatic stability (when both current and future areas are suitable). If loss of suitable areas was predicted in future-projected models, we proceeded to calculate the differences between current and future bioclimate variables values (Atauchi *et al*., 2020), and elevational shifts in species range using a digital elevation model (at ~5 km^2 cell size resolution; USGS, 2001). For areas of stability, gain and loss were calculated (in km^2) for all species under two different dispersion scenarios: "contiguous dispersion" (all cells within "M" having suitable conditions in the future could be considered as species range) *vs.* "non-dispersion" (only those cells that are currently occupied could be occupied in the future). Because the non-dispersion scenario allows only negative responses (decreases in distributional range) to GCC, it must be considered the most "unfavorable" for the species (Peterson *et al*., 2002; Atauchi *et al.,* 2020; Prieto-Torres *et al*., 2021a).

To evaluate the impacts of current habitat loss, such as areas modified by humans, into the species models under both current and future scenarios, we used the 2017 land cover and vegetation map generated by the Mexican *Instituto Nacional de Estadistica y Geografia* (INEGI, 2017). This map was later reclassified into two categories (intact vegetation *vs.* human-modified areas) discriminating pixels with more than 50% cover loss and extremely disturbed landscapes (urban areas, deforested areas, farming areas, and pastureland for cattle

ranching). We then calculated the percentages of the species' distribution (current, 2050's and 2070's) covered by human modified landscapes.

Assessment of potential modification into co-distribution patterns across time was based on two approaches: (a) comparing the geographic patterns between Lilac-crowned Amazon and each of woody-plant species; and (b) comparing the geographical range of Lilac-crowned Amazon with the potential species richness of plants (obtained by adding all binary maps of species) in intact natural forest areas. From this perspective, we are able to identify potential brakes (such as possible disruptions of important ecological associations between taxa) among species under future climate scenarios. All these analyses were performed based two-dispersal assumptions for the 2050' and 2070's.

Protected Areas network and long-term conservation areas

We estimated the importance of the existing Mexican PAs network for the species by calculating the proportion of potential distributional areas within current Mexican PAs. We overlapped the raster of current PAs with each species' distribution and the sites of highest plant richness (i.e., sites whose species richness exceeded half of the maximum values observed) for each climate scenario (current *vs.* future). PAs' boundaries were obtained from a shapefile downloaded from the Mexican *Comisión Nacional de Áreas Naturales Protegidas* (CONANP; available on: http://sig.conanp.gob.mx/website/pagsig/info_shape.htm), selecting both terrestrial official PAs and voluntary conservation areas. Then, we determined key regions for *A. finschi*'s long-term conservation based on the consensus of highest plant richness maps and the current suitable climate-areas of Lilac-crowned Amazon. In this respect, the consensus areas that did not match the already-established PAs and human-modified landscapes correspond to "priority conservation sites". These sites must, thus, be protected because they represent areas predicted to be suitable but also where essential resources could persist in face of global changes (e.g., Prieto-Torres *et al*., 2021b).

RESULTS

Species models and current parrot-woody plant co-distribution patterns

Our maxent models exhibited highly significant values for the partial ROC test (range = 1.16 – 1.87, $P < 0.05$) and low omission errors (on average $2.2 \pm 0.1\%$), indicating that final models

were statistically better than random expectations. Parameter settings and performance values for each model are detailed in Table 1. Based on these performance estimates, we consider our models to be accurate, having discriminating capacity for the recovery of ecological niches for each species.

The current predicted distribution area for Lilac-crowned Amazon in Mexico was of 74,175 km^2, showing a mean elevational range of 366.88 ± 268.22 m a.s.l., located mainly across Pacific coast from southern Sinaloa state to southeastern Oaxaca (Fig. 1). Parrot predicted model showed an important degree of overlap (21.3%) between highly human-modified areas and the estimated species ranges. Unfortunately, already-established Mexican PAs cover only less than 7% of the current distribution areas for Lilac-crowned Amazon (Table 2).

Plant species possess spatial distributional areas ranging from 540 km^2 (*Jatropha sympetala*) to 206,500 km^2 (*Brosimum alicastrum*), through an elevational range of 777.45 ± 63.2 m a.s.l. Plant species' predicted distribution overlap by 28.3% to highly human-modified areas, being *J. sympetala* (53.3%) and *Aralia excelsa* (29.8%) the species with the highest proportion of suitable areas affected. Furthermore, 30.0% of current distribution sites of highest plant richness overlapped with these highly human-modified areas (Fig. 1). Models further displayed a mean of $2.0 \pm 9.0\%$ overlap to current PAs area per individual species range and 6% for those sites of highest plant richness (Table 2).

Finally, based on distributional range of plant species within intact NDF areas, we observed that each plant species ranges coincided on average with the 47.6% of Lilac-crowned Amazon's distribution (Table 3). Besides, the number of potential plant richness species per site estimated across *A. finschi*'s distribution was of 3.9 ± 1.65 spp. Regions with the highest plants' species richness for Lilac-crowned Amazon corresponded to Guerrero, Jalisco, Oaxaca, and Michoacán states (Fig 1).

Impacts of future climate change

The species distribution projections under both climate changes and dispersion scenarios indicated that individual and overall species richness patterns (for plant cases) may be significantly modified in the future. Overall, future scenarios are similar in their predictive qualitative patterns, although the pessimistic and unfavorable scenarios, such as SSP5.85 and

not-dispersal ability, predict larger species potential area decreases (Fig. 2; Table 2; Appendix S1). According to resulting model predictions: (i) all species tended to reduce their distributional ranges for years 2050 and 2070 (independently of SSP and dispersal scenarios); (ii) plants species will possess, on average and independently of SSP/dispersal scenarios, less than 50% of their distribution within the future Lilac-crowned Amazon distributional ranges (Table 3); (iii) such changes in bird and plants are related to modifications in climate-suitability due to mean annual temperature tended to increase (by more than 2.0 °C) and annual precipitation values decreased (~100 mm). MOP analysis indicated that, regardless of the dispersion assumption, areas where strict extrapolation occurs outside the potential distributional areas predicted by models in the future climates across the study areas.

There was a variable number of potential plant richness species per site within the future geographical range of climate suitable areas estimated for *A. finschi*: SSP2-45 dispersion: 3.8 ± 0.99 spp. [2050's] and 3.5 ± 0.6 spp. [2070's]; SSP5-85 dispersion: 4.1 ± 1.04 spp. [2050's] and 3.0 ± 0.5 spp. [2070's]; SSP2-45 non-dispersion: 3.2 ± 1.2 spp. [2050's] and 2.7 ± 0.8 spp. [2070's]; SSP5-85 non-dispersion: 3.3 ± 1.2 spp. [2050's] and 2.0 ± 0.6 spp. [2070's]. In addition, we observed a reduction, on average of 15.4% [dispersion scenario] and 52.5% [non-dispersion scenario], in the number of sites with highest species richness of plants (red grids in Figs. 1 and 2). In fact, sites with highest species richness will occupy higher elevation zones (independently to dispersal scenarios; see Table 2) above the current average distribution. Besides, we observed that the remnant climate suitable ranges for plant species involved, on average, the 39.4-50.6% and 33.69-44.52% of Lilac-crowned Amazon's distribution in future for 2050 and 2070, respectively (Table 3).

Combined effects of climate change and current habitat loss
We observed that the combined effects of GCC and current human-modified areas would reduce species distribution by an average of ~55% [2050's] and ~76% [2070's] independently to dispersal scenarios (Table 2). Overall, with in both dispersion scenarios, Lilac-crowned Amazon showed important reductions (>60%) of potential intact distribution areas in the future. Also, most plant species future ranges overlapped with the currently highly human-modified areas (i.e., likely unsuitable for the species). This fact is particularly important for five of the eight species (*A. excelsa, B. alicastrum, E. lanata, J. malacophylla* and *P.*

mexicana), for which more than 60% of their remnant distribution in the future fell within these human-modified areas. Furthermore, on average ~35.5% of remnant sites of highest plant richness in the future overlapped within current highly human-modified areas.

Protected Areas network and long-term conservation areas

Our models predicted a reduction (on average 3.59% [dispersion scenario] – 3.25% [non-dispersion scenario]) in suitable areas for both parrot and plants species within the limits of several PAs in the future (Table 2). Likewise, the existing Mexican PAs had on average and regardless of the dispersion scenarios, only 3.42% overlap with the potential hotspot areas identified for the future (Fig. 3). The consensus of the suitable climate-areas for highest plant richness maps and the current suitable areas of Lilac-crowned Amazon showed low (i.e., 11,375 km^2) overlap values. Approximately 63.1% (i.e., 7,175 km^2) of the area of these long-term climate-resilient sites overlapped within current highly human-modified areas, while only ~3% (i.e., 325 km^2) were including within existing PAs. These priority conservation and highly-climate resilient sites (i.e., 3,875 km^2) cover mostly wide Guerrero (31.8%), Jalisco (28.6%), Colima (14.7%), and Oaxaca (13.4%). In addition, it was observed that the environmental conditions will continue to be adequate for the tree species within the Chamela-Cuixmala´s PAs. Thus, it can be inferred that the conservation of these areas is of vital importance to maintain high richness of species.

DISCUSSION

Our study represents an important first step to glimpse the possible effects of GCC combined with land uses practices for the distribution and habitat quality (including key species interactions) for a Mexican endemic and, most importantly, endangered bird species. In fact, these results indicated that *A. finschi* and its associated plants are likely to undergo spatio-temporal non-uniform changes across Mexico in the future. The increase in discontinuity, reduction and spatial displacement of distribution areas, suggest bleak scenarios for most analyzed species, which could increase their extinction vulnerability. Furthermore, these results predicted potential changes on the availability of mutualist partners that, as suggested by Correa-Lima et al. (2019), could lead to a decoupling in the interaction and having detrimental effects for ecosystems functioning. Because *A. finschi* request these eight woody-

plants for feeding and nesting in the NDF, to loss any of them could exerts ecologic and physiological pressure on the parrot (Renton & Salinas-Melgoza, 2004). In this respect, current and future conservation policy and decision-making must focus, not only on providing new sites where the species are protected individually, but also where species interaction may occur.

Although distribution models indicate that central Pacific region (mainly across coastal areas from Jalisco to Oaxaca states) constitute the regions with the most suitable conditions for Lilac-crowned Amazon, the current distribution of this species across the southern sites (Guerrero and Oaxaca) is limited by other important biotic (competition) and anthropogenic factors (Ríos-Muñoz and Navarro-Sigüenza, 2009). Common knowledge indicates w that this species has been practically extirpated due to human activities through cattle ranching and urban settlements expansion, that remove the natural vegetation and reduce available habitat (including potential resources) for this and others bird species (Renton & Iñigo, 2003; Ríos-Muñoz and Navarro-Sigüenza, 2009; Sierra-Morales et al., 2015). Besides, this reduction in available habitat will also be due to *A. autumnalis* presence, a competing species with the same-food guild, nesting and reproductive success (Gómez de Silva et al., 2005b; Navarro-Sigüenza et al., 2014).

From this perspective, areas predicted to be climatically suitable —even in the future— but where essential *A. finschi*'s resources are lost (e.g., nesting sites) may in fact be unsuitable for inhabiting this specialized parrot (Ortega-Rodríguez & Monterrubio-Rico, 2008). Although many parrot species are being increasingly forced to live and breed in fragmented or modified landscapes, several studies (de la Parra-Martínez et al., 2015; Flores et al., 2020; Martens and Woog, 2017) highlight the importance of large and old trees with suitable nest cavities as a key habitat requirement for reproduction and, therefore, survival of this species. Further research to assess the susceptibility of species and their interactions to environmental changes must be considered a top-priority endeavor, were monitoring programs would essential, especially for the species and areas predicted to suffer the most.

Additionally, variable models indicate precipitation seasonality (Bio 15 and Bio 16, Table 1) as limiting factor for distribution and breeding season of the Lilac-crowned Amazon (Monterrubio-Rico et al., 2015). In fact, such as amount of precipitation may affect the reproductive success due its influence on phenology of plant resources and availability of food

(Renton 2001; 2002; Renton & Iñigo-Elias, 2003; Renton & Melgoza, 2004; Renton, 2009; de la Parra-Martínez, 2011). This is a critical point to take in account due to recent studies have indicated a spatially heterogeneous decrease in annual precipitation across Mexico over the last one hundred years (Cuervo-Robayo et al., 2020). Adding this to future climate models, the species will most likely be pushed to higher elevations where humidity will be key on limiting the biota (Buernmann et al., 2011). Furthermore, observation record of bird's nests has been documented above 600 m a.s.l. (Renton, 2001; Ortega-Rodríguez & Monterrubio-Rico, 2008), out of to mean elevational range previously known for the species. Unfortunately, if low-elevation species —such *A. finschi* and their associated plants— are not capable to quickly adapt to new environments (especially at higher elevations) population sizes are expected to decrease, and their future survival may be more seriously threatened; adaptability of this species needs to be further (Ortega-Rodríguez & Monterrubio-Rico, 2008). More research analyzing these points are needed.

Finally, it is important to note that a decline in Lilac-crowned Amazon population size could also affect NDF dynamics (maintaining tree diversity) due to its role as canopy seed predator (Renton, 2001; Dirzo & Raven, 2003). So that, the potential extinction of *A. finschi* could have a cascading effect harming interspecific relationships (Manson et al., 2009) and, consequently, the ecological integrity and regeneration of NDF at its the northernmost limit of its range (Hardwick et al., 2004; Sueli, 2016). However, although our results are alarming, these should be taken with caution given the risk of predicting the adaptive potential of species to future conditions, since adaptive potential is in fact influenced by many additional factors that we do not evaluate here, such as reproductive rate, physiological capacity and habitat requirements (Peterson et al., 2002; Ortega-Rodríguez & Monterrubio-Rico, 2008).

Conservation implications

Despite the increasing conservation efforts for Psittacine in Mexico, here we document important gaps potentially affecting long-term protection of Lilac-crowned Amazon. Firstly, those (important) efforts have aimed to mainly at reduce habitat destruction, making artificial nests, nest surveillance, relocation of individuals and captive breeding (Enkerlin, 2000a), as well establishing refuges or conservation areas (Íñigo-Elías, 2000a). However, these immediate actions to preserve land or individuals, although important, will not suffice for

long-term conservation of *A. finschi.* Future management actions should focus too on maintaining suitable habitats in unprotected areas, mitigation of GCC and land-used impacts. Secondly, as our results indicate, the proportion of species' range contained within PAs will substantially decrease in the future, and most priority areas, of highly resilience to GCC and land use change are, in fact. located outside the current PAs (Table 2). This reinforces the idea that current PAs are ineffective and insufficient for safeguarding the biodiversity for the future. This picture is expected considering that NDF shows currently low proportion of surface (<10%) and a woefully inadequate representativeness of biota within PAs (Banda et al., 2016; Prieto-Torres et al., 2018). Future efforts to maximize the performance of the PA network and species protection must be reviewed.

From this perspective, the priority conservation areas found here for conservation of the Lilac-crowned Amazon (Fig. 3). Areas in Colima, Jalisco, and Oaxaca states are identified as "safe places" (i.e., sites with high species resources where human induced changes in the near future are not expected) for conservation of the Lilac-crowned Amazon and, therefore, the necessary resources and efforts should be directed for their long-term maintenance and preservation. An alternative towards that goal is the establishment of natural biological corridors and ecotourism programs that involve local population and thereby aid towards reducing species extraction. Besides, this approach could be applied to study the conservation status for other parrots' species in Mexico, especially considering that more than 86% of these taxa display important range reduction (>80-86%) of original ranges at national scales (Ríos-Muñoz & Navarro-Sigüenza 2009). We hope that these findings will trigger the interest of conservationists and policymakers and motivate them to delve more deeply into conservation of this Mexican endemic parrots.

CONCLUSIONS

In the near future, combined impact of drastic climate and land-use changes would strongly diminish conservation opportunities for Lilac-crowned Amazon in Mexico. We argue that analyzing individual drivers of global changes could promote inaccurate long-term policies in biodiversity, especially for those endemic and endangered species, like *A. finschi.* Besides, we do not expect a uniform response among species for the future. These results indicate that to reach an efficient conservation planning for these species, land is not the only solution, but

further comprehension of species' extinction risk and breakdown of its ecological associations is a critical step to facilitate and empower future management strategies and conservation plans. Here, we identified important opportunities to improve the level of long-term protection by placing PAs strategically into "safe places" with political will.

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TABLES

Table 1. List of species considered in this study. For each species, we included the information about taxonomy, GBIF's doi, and the parameters used in modelling (i.e., number of occurrences, bioclimatic variables set, feature [l = linear, q = quadratic, p = product, and t = threshold], and regularization multiplier [RM] values), as well as the performance values obtained to partial receiver operating characteristic [ROC-partial test] and omission error in the models

| Family	Species	GBIF's doi	Number of presences	Environmental variables	Feature	RM	ROC-partial	% Omission
Psittacidae	*Amazona finschi*	10.15468/dl.2nytzy	298	Bio 04, Bio 05, Bio 06, Bio 10, Bio 15, Bio 16, DEM	lqt	2.0	1.66	4.0
Anacardiaceae	*Astronium graveolens*	10.15468/dl.35tsh3	1,108	PC01, PC02, PC03, PC04	qp	1.4	1.16	5.0
Araliaceae	*Aralia excelsa*	10.15468/dl.skgqrr	79	Bio 07, Bio 13, Bio 14, Bio 17	lt	3.5	1.39	0.0
Euphorbiaceae	*Jatropha malacophylla*	10.15468/dl.kjkggu	63	PC01, PC02, PC03, PC04	p	1.0	1.32	0.0
Euphorbiaceae	*Jatropha sympetala*	10.15468/dl.27bz33	81	Bio 06, Bio 11, Bio 12, Bio 14, DEM	t	1.0	1.87	0.0
Fabaceae	*Caesalpinia eriostachys*	10.15468/dl.cc9nb4	159	PC01, PC02, PC03, PC04	lqp	0.4	1.48	3.0
Fabaceae	*Erythrina lanata*	10.15468/dl.wb94zn	221	PC01, PC02, PC03, PC04	pt	2.0	1.54	4.0
Moraceae	*Brosimum alicastrum*	10.15468/dl.6wndyc	1,158	PC01, PC02, PC03, PC04	lqp	0.4	1.36	4.0
Picrodendraceae	*Piranhea mexicana*	10.15468/dl.evzrvs	32	Bio 03, Bio 05, Bio 14, DEM	q	0.6	1.86	0.0

Table 2. Current and projected future distribution of Lilac-crowned Amazon (*Amazona finschi*) and eight woody-trees associated to its habitat-use. Results are shown based on current and two future climate scenarios (SSP2 4.5 y SSP5 8.5) for years 2050 and 2070 considering the consensus map from the two global climate models used (BCC-CSM and MIROC6).

|	Potential distribution area (km^2)	Prop. of loss/new areas by GCC	Impacts by GCC + habitat loss	Distribution within PAs	Mean elevation (m. a.s.l.)
CURRENT					
A. finschi	74,175	-	-	6.17%	366.88 ± 268.22
Woody-plants	117,525 ± 83,142	-	-	2.0 ± 9.0%	777.45 ± 63.2
SSP2 4.5					
2050'S DISPERSION					
A. finschi	32,750	-55.8 / 0.6	-60.1%	2.7	473.3 ± 245.6
Woody-plants	97,693.8 ± 70,496.2	-23.0 / 8.38	-43.1%	2.8 ± 7.5%	
2050'S NON-DISPERSION					
A. finschi	32,300	-56.5 / -	-60.3%	2.7 %	469.8 ± 243.7
Woody-plants	88,075 ± 65,031.24	-31.3 / -	-47.9%	2.9 ± 7.6%	
2070'S DISPERSION					
A. finschi	8,725	-88.24 / 0.03	-88.9%	1.31 %	596.97 ± 199.31
Woody-plants	69,740 ± 49,296.87	-40.0 / 9.1	-55.7%	5.1 ± 7.9%	
2070'S NON-DISPERSION					
A. finschi	8,700	-88.27 / -	-88.9%	1.31 %	597.89 ± 198.86
Woody-plants	60,681.3 ± 45,793.7	-49.4 / -	-52.8%	5.3 ± 8.0%	
SSP5 8.5					
2050'S DISPERSION					
A. finschi	26,925	-63.7 / 0.77	-67.2%	2.08 %	439.60 ± 248.45
Woody-plants	83,350 ± 63,222.3	-27.7 / 7.1	-47.5%	3.1 ± 7.8%	
2050'S NON-DISPERSION					
A. finschi	26,350	-64.48 / -	-67.1%	2.08 %	439.25 ± 247.76
Woody-plants	81,209,4 ± 59,336.8	-34.8 / -	-43.9%	3.3 ± 8.0%	
2070'S DISPERSION					
A. finschi	2,350	-96.83 / -	-96.9%	0.57 %	816.36 ± 87.10
Woody-plants	54,978.2 ± 46,100.7	-49.7 / 6.8	-61.5%	3.7 ± 5.8%	
2070'S NON-DISPERSION					
A. finschi	2,350	-96.83 / -	-96.9%	0.57 %	816.36 ± 87.10
Woody-plants	47,528.1 ± 40,732.8	-56.43 / -	-63.6%	4.1 ± 5.8%	

Table 3. Summary of overlapping values for distribution areas of Lilac-crowned Amazon (*Amazona finschi*) and its associated woody-plants under global change climate and land-used scenarios. Values of overlapping areas are shows in extent (km^2) and proportion (%) corresponding to *A. finshi*'s distribution.

| Species	Climate and dispersion scenarios				
	Current	2050/SSP245	2070/SSP245	2050/SSP585	2070/SSP585
DISPERSION					
Aralia excelsa	24,650 (33.2%)	7,225 (22.1%)	975 (11.1%)	6,975 (25.91%)	0 (0.00%)
Caesalpinia eriostachys	34,375 (46.3%)	8,650 (26.4%)	275 (3.15%)	7,675 (28.51%)	100 (4.26%)
Erythrina lanata	69,350 (93.5%)	31,700 (96.8%)	8,500 (97.4%)	26,250 (97.49%)	2,350 (100.00%)
Jatropha malacophylla	49,325 (66.5%)	18,675 (57.0%)	4,325 (49.57%)	15,000 (55.71%)	225 (9.57%)
Jatropha sympetala	8,100 (10.9%)	1,525 (4.6%)	0 (0.00%)	1,925 (7.15%)	0 (0.00%)
Piranhea mexicana	19,475 (26.3%)	1,600 (4.9%)	0 (0.00%)	1,475 (5.48%)	0 (0.00%)
Astronium graveolens	42,875 (57.8%)	25,900 (79.1%)	8,350 (95.7%)	23,050 (85.61%)	2,125 (90.43%)
Brosimum alicastrum	34,375 (46.3%)	32,300 (98.6%)	8,650 (99.14%)	26,550 (98.61%)	2,350 (100.00%)
Mean values	**47.61%**	**49.69%**	**44.52%**	**50.56%**	**38.03%**
NON-DISPERSION					
Aralia excelsa	-	6,750 (20.9%)	950 (10.9%)	6,550 (24.9%)	0 (0.00%)
Caesalpinia eriostachys	-	8,100 (25.1%)	225 (2.6%)	7,025 (26.7)	50 (2.1%)
Erythrina lanata	-	31,125 (96.4%)	8,425 (96.9%)	25,650 (97.3%)	2,200 (93.6%)
Jatropha malacophylla	-	14,925 (46.2%)	3,675 (42.2%)	11,575 (43.9%)	200 (8.5%)
Jatropha sympetala	-	1,025 (3.2%)	0 (0.00%)	1,325 (5.0%)	0 (0.00%)
Piranhea mexicana	-	1,600 (4.9%)	0 (0.00%)	1,475 (5.6%)	0 (0.00%)
Astronium graveolens	-	25,100 (77.8%)	8,325 (95.7%)	22,075 (83.8%)	2,100 (89.4%)
Brosimum alicastrum	-	13,150 (40.7%)	1,850 (21.3%)	11,800 (44.8%)	175 (7.5%)
Mean values	-	**39.39%**	**33.69%**	**41.50%**	**25.13%**

FIGURE CAPTIONS
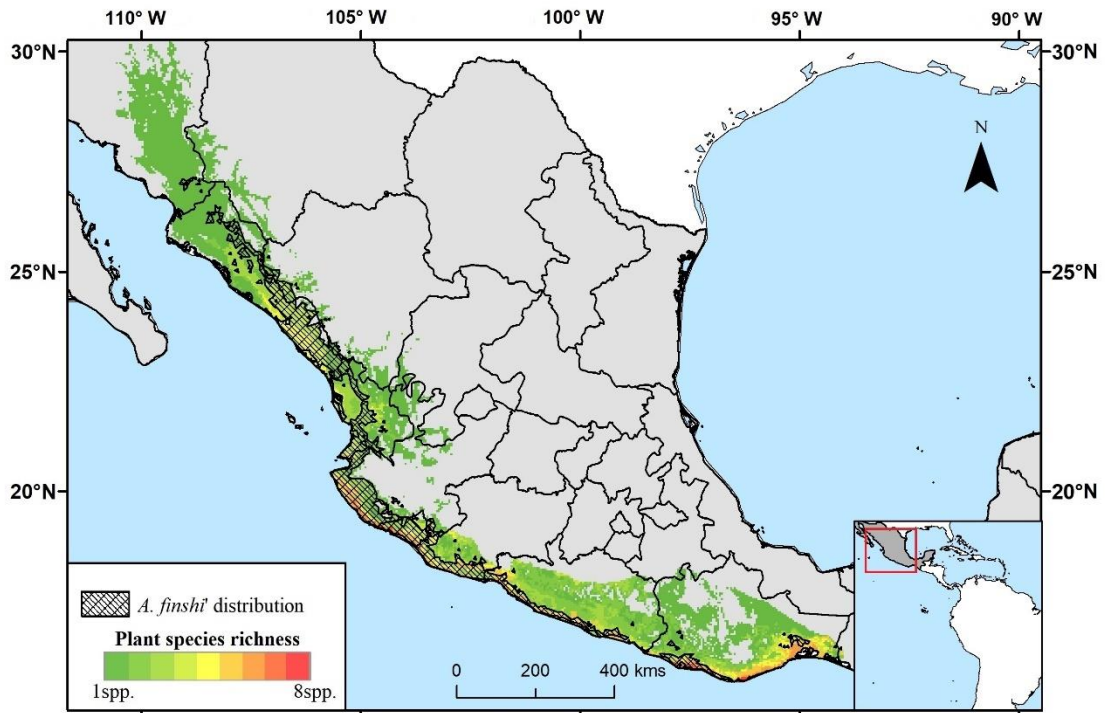
Figure 1. Map showing the current co-distribution patterns between the Lilac-crowned Amazon (*Amazona finschi*) and eight woody-trees associated to its habitat-use.
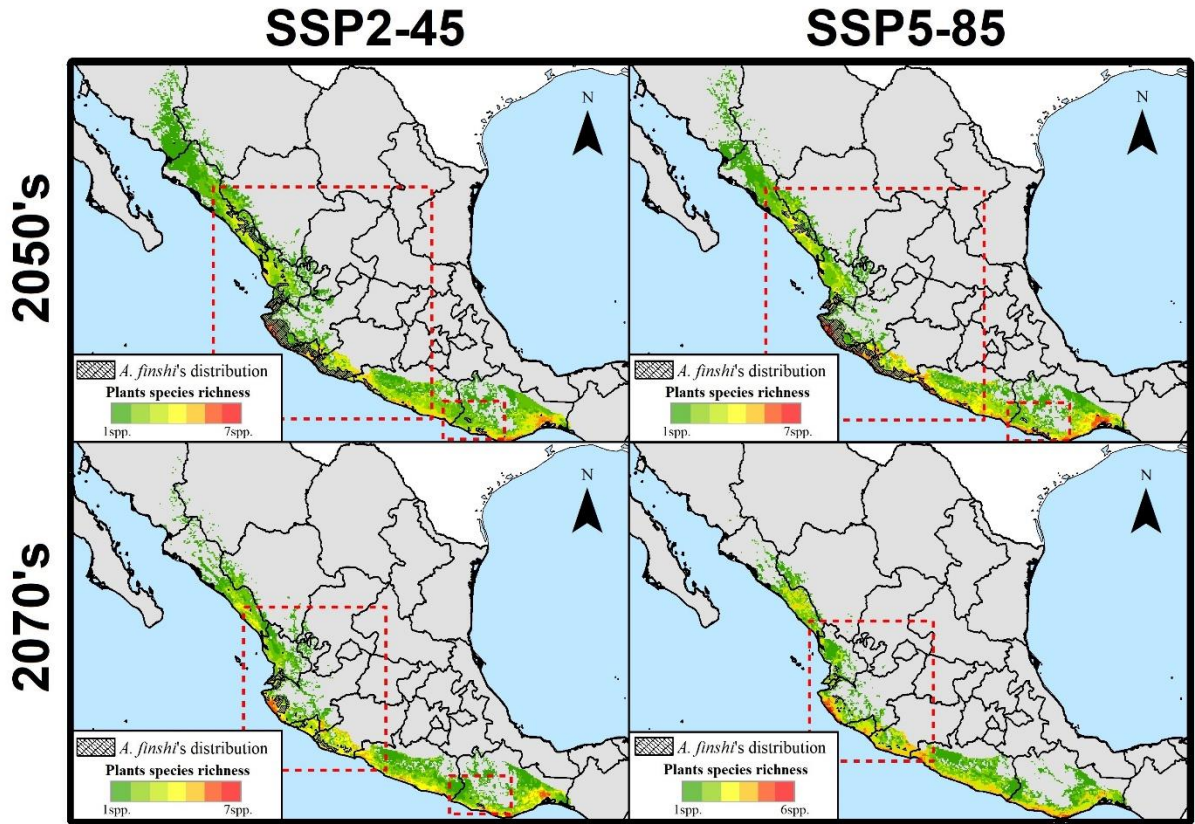
Figure 2. Species co-distribution patterns for Lilac-crowned Amazon (*Amazona finschi*) and the eight woody-trees associated to its habitat-use projected under two Shared Socio-economic Pathways scenarios (SSP2-4.5 and SSP5-8.5) for years 2050 and 2070 and considering the contiguous dispersion ability of species. Appendix S1 shows the maps of species richness patterns projected to future climate conditions considering the not-dispersion ability of species.
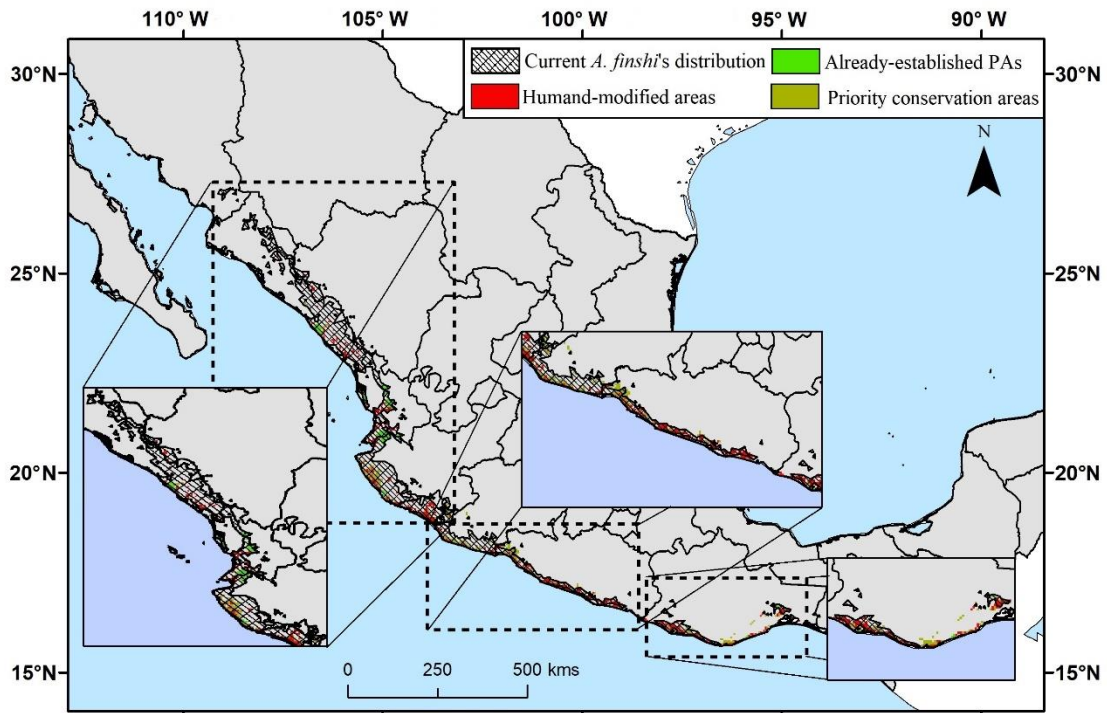
Figure 3. Priority conservation areas identified for the long-term protection of the Lilac-crowned Amazon (*Amazona finschi*) and the eight woody-trees associated to its habitat-use.

SUPPORTING INFORMATION

Appendix S1. Species co-distribution patterns for Lilac-crowned Amazon (*Amazona finschi*) and the eight woody-trees associated to its habitat-use projected under two Shared Socio-economic Pathways scenarios (SSP2-4.5 and SSP5-8.5) for years 2050 and 2070 and considering the non-dispersion ability of species.
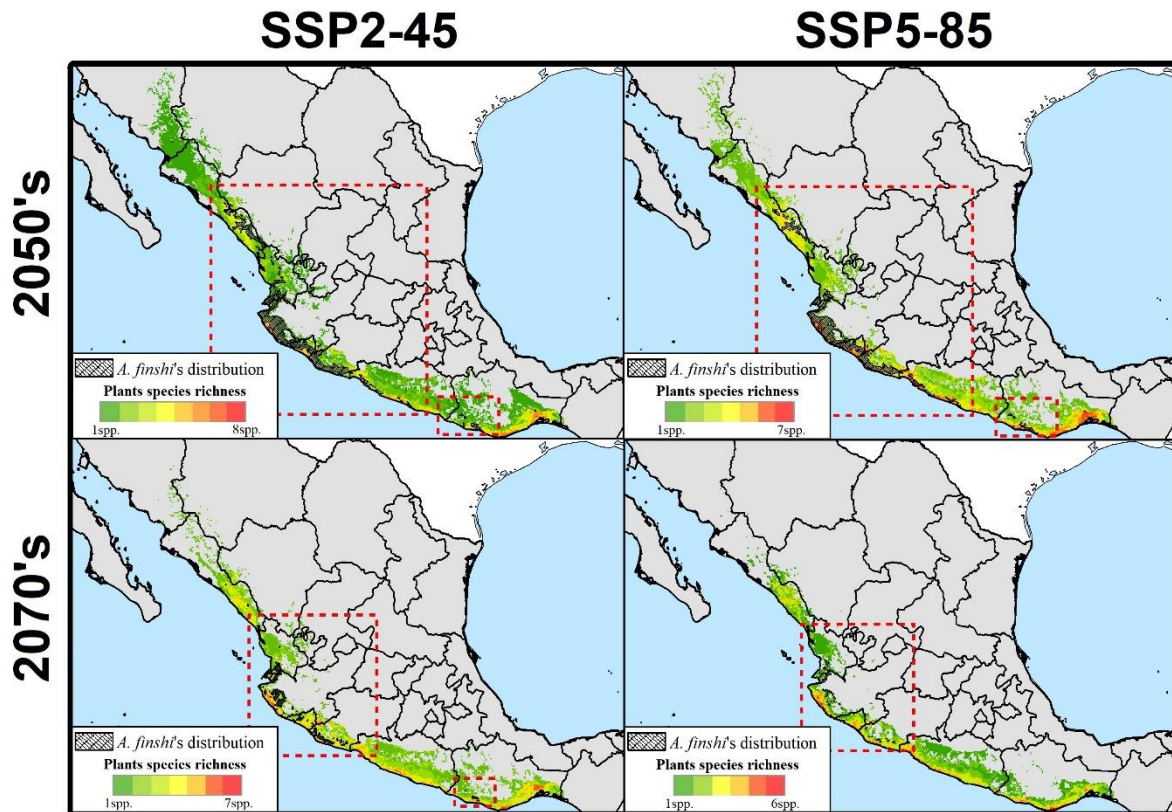
DISCUSIÓN GENERAL

Este estudio representa un importante paso para predecir los posibles efectos del CCG y las actuales prácticas de uso del suelo sobre la distribución y disponibilidad de hábitat (incluidas las interacciones entre especies) para una especie endémica y en peligro de extinción en México. De hecho, los resultados indicaron que es probable que *A. finschi* y sus plantas asociadas sufran cambios espacio-temporales no uniformes en el futuro. El aumento en el desfase entre las áreas de distribución y la reducción de estas sugiere escenarios sombríos para la mayoría de las especies, lo que podrá causar un aumento en sus grados de vulnerabilidad a extinción. Además, estos resultados predicen cambios potenciales en la disponibilidad de socios mutualistas que, como Correa-Lima y col. (2019) sugieren, podrían conducir al desacoplamiento de la interacción e incluso a efectos perjudiciales para el funcionamiento de los ecosistemas. Debido a que *A. finschi* requiere estas ocho plantas leñosas para alimentarse y anidar en el BST, la pérdida de cualquiera de ellas podría ejercer presión fisiológica sobre el loro (Renton y Salinas-Melgoza, 2004). En este sentido, las políticas de conservación y la toma de decisiones, actuales y futuras, deben centrarse no solo en la necesidad de nuevos sitios donde las especies se protejan por separado, sino también donde las interacciones entre especies sean posibles de ocurrir.

Es importante señalar que los modelos de distribución mostraron que la región del Pacífico central (principalmente a lo largo de las costas desde los estados de Jalisco hasta Oaxaca) involucra los sitios con las condiciones más adecuadas para esta especie de loro. Sin embargo, se sabe que la distribución del loro corona lila en los sitios más sureños (Guerrero y Oaxaca) está limitada por factores antropogénicos y bióticos (Ríos-Muñoz y Navarro-Sigüenza, 2009). Esta especie ha sido prácticamente extirpada debido a las actividades humanas (expansión de la ganadería y asentamientos urbanos) que eliminan la vegetación y reducen el hábitat disponible (incluyendo recursos potenciales) para esta y otras especies de aves (Renton y Iñigo, 2003; Ríos-Muñoz y Navarro-Sigüenza, 2009; Sierra-Morales *et al.*, 2015). Además, en estas áreas de alta diversidad de aves se encuentran otras especies con el mismo gremio alimentario, como es el caso de *A. autumnalis*, que impactan negativamente en el éxito reproductivo y de anidación debido a la competencia por recursos entre ellas (Gómez de Silva *et al.*, 2005b; Navarro-Sigüenza *et al.*, 2014).

Desde esta perspectiva, las áreas que se prevén sean climáticamente adecuadas, incluso en el futuro, pero donde se pierden los recursos esenciales de *A. finschi* (ej. los sitios de anidación) pueden ser, de hecho, un hábitat inadecuado para este loro especializado (Ortega-Rodríguez y Monterrubio-Rico, 2008). Aunque muchas especies de loros se ven cada vez más obligadas a vivir y reproducirse en paisajes fragmentados o modificados, varios estudios (de la Parra-Martínez *et al.*, 2015; Martens y Woog, 2017; Flores *et al*., 2020) destacan la importancia de árboles grandes y viejos con cavidades adecuadas para los nidos como requisito clave del hábitat para la reproducción y, por lo tanto, para la supervivencia de esta especie. En este sentido, la investigación para comprender la susceptibilidad de sus interacciones a los cambios ambientales debe considerarse un tema de máxima prioridad en investigación. Para ello, la implementación de programas de seguimiento es fundamental, especialmente para las especies y zonas que se prevé que sufran las disminuciones más drásticas.

Por otro lado, los resultados confirmaron la idea de que la estacionalidad de las precipitaciones (Bio 15 y Bio 16; Cuadro 1) debe ser considerada como un factor limitante para la distribución y época reproductiva de la amazona corona lila (Renton y Melgoza, 2004). De hecho, la cantidad de precipitación puede afectar el éxito reproductivo debido a que la precipitación en el sitio influye en la fenología de los recursos vegetales y la disponibilidad de alimento (Renton 2001; 2002; Renton y Iñigo-Elias, 2003; Renton y Melgoza, 2004; Renton, 2009; de la Parra -Martínez, 2011). Este es un punto crítico para tener en cuenta debido a que estudios recientes muestran una disminución espacialmente heterogénea en la precipitación anual en todo México durante los últimos cien años (Cuervo-Robayo *et al*., 2020). Por lo tanto, bajo climas futuros, es probable que las especies sean empujadas hacia elevaciones más altas donde la humedad futura será un factor limitante clave para la biota (Buernmann *et al.,* 2011). De hecho, con mayor frecuencia se observan registros de nidos del loro por encima del rango medio altitudinal reportado para la especie (600 m.s.n.m.; Renton, 2001; Ortega-Rodríguez y Monterrubio-Rico, 2008). Sin embargo, es importante tener en cuenta que si las especies de elevaciones bajas, como *A. finschi* y sus plantas asociadas, no pueden adaptarse rápidamente a nuevos entornos (especialmente en elevaciones más altas), se espera que el tamaño de la población disminuya y su la supervivencia futura puede verse amenazada (Ortega *et al*., 2019). Se necesitan más investigaciones que analicen la capacidad de estos taxones para adaptarse rápidamente o trasladarse a nuevas áreas y condiciones ambientales.

Finalmente, debido a su papel como depredador de semillas del dosel (Renton, 2001; Dirzo y Raven, 2003), la disminución de la población del loro corona lila también podría influir en la dinámica del BST (mantener la diversidad de árboles). En este sentido, la posible extinción de *A. finschi* podría producir un evento en cascada que perjudique las relaciones interespecíficas (Manson *et al.,* 2009) y, en consecuencia, la integridad ecológica y la regeneración del BST en el límite más septentrional de su área de distribución (Hardwick *et al*., 2004; Sueli, 2016). Sin embargo, los resultados acá mostrados deben tomarse con cautela porque el potencial de adaptación de las especies a las condiciones futuras es muy difícil de predecir, ya que su potencial de adaptación está influenciado por muchos factores adicionales —que no fueron evaluados aquí— como las tasas reproductivas, la capacidad fisiológica y requerimientos de hábitat (Peterson *et al*., 2002; Ortega *et al*., 2019).

Implicaciones para la conservación

A pesar del aumento en los esfuerzos de conservación de los psitácidos en México, detectamos algunos vacíos importantes para la protección a largo plazo del loro corona lila. En primer lugar, estos importantes esfuerzos se han dirigido principalmente a la reducción de la destrucción del hábitat, la realización de nidos artificiales, la vigilancia de nidos, la reubicación de individuos y la cría en cautividad (Enkerlin, 2000a), así como al establecimiento de refugios o áreas de conservación (Íñigo -Elías, 2000a). Sin embargo, no es solo más tierra e individuos lo que se necesita para garantizar la conservación a mediano y largo plazo de *A. finschi*. Las futuras acciones de gestión también deberían centrarse en mantener hábitats adecuados en áreas no protegidas, en la mitigación de los impactos del CCG y del uso de la tierra. Pero, este tema sigue siendo poco estudiado. En segundo lugar, como mostraron los resultados, es probable que la proporción de áreas de distribución de especies contenidas dentro de las APs disminuya sustancialmente en el futuro, y que la mayoría de las áreas prioritarias que son altamente resilientes al CCG y al cambio de uso de la tierra estén ubicadas fuera de las APs actuales (Cuadro 2). Esto refuerza la idea de que las APs actuales ahora no son efectivas ni suficientes para salvaguardar la biodiversidad en el futuro. Esto era algo esperado considerando que el BST muestra actualmente una baja proporción de superficie (<10%) y una inadecuada representatividad de la biota dentro de las APs (Banda *et al*., 2016; Prieto-Torres *et al*., 2018).

Por lo tanto, los esfuerzos futuros para maximizar el desempeño de la red de APs y la protección de especies deben planificarse de manera diferente.

Desde esta perspectiva, las áreas de conservación prioritarias identificadas (Fig. 3) brindan información sobre dónde enfocar los futuros esfuerzos de conservación. Estos sitios identificados en los estados de Colima, Jalisco y Oaxaca representarían "lugares seguros", los cuales son sitios con altos recursos de especies donde no se esperan cambios inducidos por el hombre en un futuro cercano. Por lo tanto, los recursos y esfuerzos deben dirigirse a su mantenimiento y preservación a largo plazo. Una opción para esto podría ser el establecimiento de corredores biológicos naturales y programas de ecoturismo que incluyan a la población local y con ello ayuden a reducir la extracción de esta y otras especies. Además, este enfoque podría aplicarse para estudiar el estado de conservación de otras especies de loros en México, especialmente considerando que más del 86% de estos taxones muestran reducciones importantes (>80-86%) de los rangos originales a escala nacional (Ríos-Muñoz y Navarro-Sigüenza, 2009). Se espera que estos nuevos hallazgos despierten el interés de conservacionistas y legisladores y los motiven a profundizar más en la conservación de esta especie endémica y otros loros en México.

CONCLUSIÓN GENERAL

En un futuro cercano, los impactos combinados de cambios drásticos en el clima y el uso de la tierra disminuirían considerablemente las oportunidades de conservación para el loro corona lila en México. Además, es importante tener en cuenta que el analizar los impulsores individuales de los cambios globales podría promover políticas inexactas a largo plazo en biodiversidad, especialmente para aquellas especies endémicas y en peligro de extinción, como *A. finschi*. Asimismo, no debemos esperar respuestas uniformes o coincidentes entre especies para el futuro.

Esto es importante porque para lograr una planificación eficiente de la conservación de estas especies, no solo se necesita más tierra. Como muestran los resultados, comprender el riesgo de extinción de la especie y el desglose de sus asociaciones ecológicas es un paso fundamental para facilitar la elaboración de futuras estrategias de gestión y planes de conservación. Aquí, identificamos oportunidades importantes para mejorar el nivel de protección a largo plazo de estas especies al ubicar las APs estratégicamente en esos "lugares seguros", siempre y cuando también existe la voluntad política necesaria para la implementación de los programas necesarios.

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