

Received:

24 August 2018

Revised:

27 November 2018

Accepted:

21 March 2019

Cite as: L. López-Arce,  
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Identifying cloud forest  
conservation areas in Mexico  
from the potential distribution  
of 19 representative species.  
Heliyon 5 (2019) e01423.  
doi: [10.1016/j.heliyon.2019.  
e01423](https://doi.org/10.1016/j.heliyon.2019.e01423)



# Identifying cloud forest conservation areas in Mexico from the potential distribution of 19 representative species

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## Abstract

Cloud forest is a sensitive and vulnerable ecosystem that is threatened by human activities as well as climate change. Previous studies have shown how transitional ecosystems such as cloud forests will be the most negatively impacted by the global increase in temperature. Therefore, the niche modeling framework was used in this study to geographically identify the areas with the climatic potential to host the largest number of key tree species in this ecosystem and to propose them as priority conservation areas. A total of 19 species were modeled using the MaxEnt algorithm; binary maps were generated for each species and combined to produce one potential suitability map and identify climatic priority areas. Thus, 7% of the national area of Mexico shows suitability for the cloud forest ecosystem, although it is currently distributed in less than 1% of the country. Finally, potential suitability areas were compared with natural protected areas, current land use and priority conservation areas. We found that

of the current suitable area, only 5% coincides with some federal or state protection regime. Natural protected areas have proven to be a mechanism for forest conservation, so we must consider increasing the number and area of those protected areas that favor the conservation of these key cloud forest species.

Keywords: Environmental science, Geography, Bioinformatics, Computational biology, Ecology, Plant biology

## 1. Introduction

Tropical montane cloud forest (CF) is an ecosystem with restricted and limited distribution. These are transitional forest communities in humid tropical and subtropical mountains (González-Espinosa et al., 2012). The importance of CF as a biodiversity habitat shows that the ecosystem is the only of its kind due to its extreme diversity, although it covers less than 1% of the land in Mexico (Rzedowski, 1996). CF is home to the largest diversity of tree species (Pounds et al., 1999) and supports the highest concentration of plant and animal diversity of any other Mexican ecosystem (Ponce-Reyes et al., 2012).

CF is one of the ecosystems most threatened by natural (hurricanes, landslides) and anthropogenic (illegal logging, land use change) changes. Human-induced climate change could constitute a great danger in the near future for CF (Ponce-Reyes et al., 2012). Half of the Mexican CF coverage has been transformed (Williams-Linera, 2007; CONAFOR, 2009), and future predictions suggest a serious threat to Mexico, particularly for at least 60% of the trees that make up these plant communities (González-Espinosa et al., 2012).

The relationship between climate and species distribution has been studied in CF (Still et al., 1999), but there is still a need to better understand their connection. In Mexico, cloud forests exist in specific montane topography and cloud-related microclimates. A geographic vision of the ecosystem (Sierra et al., 2002) and spatial distribution is needed to determine the possible impacts that phenomena such as climate change may have on this ecosystem. Based on the foregoing, it is important to determine the environmental suitability of different areas for the growth and development of species that are part of the CF in Mexico.

We decided to use one of the most commonly used ecological tools in terms of assessing impacts on climate change conditions: ecological niche modeling (Peterson et al., 2011). Species distribution models and ecological niche models have become areas of study with great development in the field of conservation biogeography (Richardson and Whittaker, 2010). These models project the geographical-ecological space under past and future conditions. The term ‘potential distribution’ (Jackson and Overpeck, 2000) is derived from theoretical bases of the ecological

niche first suggested by Grinnell (1917) and Hutchinson (1957) and refers to the geographical area with the environmental conditions needed for it to be occupied by a species.

Cloud forests and niche modeling in Mexico have been studied previously. Research focusing on finding better environmental variables for modeling (Cruz-Cárdenas et al., 2014) or assessing climate change impact (Ponce-Reyes et al., 2012, 2013) on cloud forests has shown future unsuitability for the ecosystem. These studies need to be updated since they were made with previous climate change scenarios (i.e., SRES A1B, A2). Rojas-Soto et al. (2012) observed a 54–76% reduction of the eastern and southern Mexico cloud forest by 2050, mainly in the Sierra Madre Oriental and on the Pacific slope of Chiapas. The potential distribution findings by Ponce-Reyes et al. (2012) show that 68% of Mexico's cloud forest could vanish by 2080 because of climate change. Trejo et al. (2011) assessed the impact on plant communities and mammals in Mexico, and modeling has also included butterflies and moths (Hernández-Baz et al., 2016), spotted wing drosophila pests (Castro-Sosa et al., 2017) and the potential distribution of maize (Ureta et al., 2012). Thus, modeling has shown credible results for ecosystems and species.

The objective of this study was to find viable areas for the conservation of CF by modeling the potential distribution of 18 tree species and one fern species, all representative of the CF ecosystem. It is noteworthy that among these species, we include some "panchronic" genera, that is, living fossils, such as *Cyathea*, *Magnolia*, and *Podocarpus* (Challenger, 1998). The general objective was subdivided into three: 1) to determine the potential distribution of the 19 species by modeling their potential distribution area using one of the most known and used algorithms, 'MaxEnt'; 2) to overlay the individual binary maps to find areas of greater richness that can represent priority areas for conservation and 3) to compare the map with current land use and current natural protected areas to determine the percentage of this valuable ecosystem that is currently being protected and how it will be protected under climate change conditions (CONANP, 2017; CONABIO, 2015). Finally, the areas proposed for conservation are discussed: a) those where there is currently no CF, but there are potential distribution areas, and b) those where there is currently CF, but it is not protected. We consider that our results provide basic information and update other studies previously made for future studies on regions to recover representative communities of CF in Mexico.

## 2. Methods

### 2.1. Data and variables

From these communities, a total of 19 representative species of CF were selected in Mexico. The selection was based on available studies assessing the

representativeness and value of importance of the species in different CF plant communities in Mexico (Monterroso-Rivas et al., 2013). According to Curtis and McIntosh (1951), the importance value defines which of the present species contribute to the character and structure of an ecosystem. This value is obtained by the sum of the relative frequency, the relative density and the relative dominance. The CF is currently distributed in at least 12 Mexican states, with different environmental characteristics that describe more than 40 associations and 19 ecotones best described in Gual-Díaz and Rendón-Correa (2014). It is known that the montane cloud forest hosts between 10 and 12% of all plant species in the country. We also follow Alcántara and Luna (1997, 2001), who identified all species we studied in cloud forests of the Hidalgo state; Catalán et al. (2003) refer to *Oreopanax xalapensis* (Kunth) Decne. & Planch and *Persea schiedeana* Nees as being among the most important species in cloud forests; Fortanelli-Martínez et al. (2014) described wide distribution (*Liquidambar styraciflua* L., *Quercus germana* Schltld. & Cham.) and discontinuous distribution (*Magnolia schiedeana* Schltld., and *Ostrya virginiana* (Mill.) K. Koch) in San Luís Potosí cloud forests. Nevertheless, some species such as *O. virginiana* are not exclusive to cloud forests (Niembro et al., 2010). *Magnolia schiedeana* (also known as pagua) is currently rare in Mexican forests because of its small populations, composed of 25–40 individuals, with specific requirements for pollination (Niembro et al., 2010) and is considered endangered on the IUCN Red List of Threatened plants.

A total of eighteen tree species and one fern were used: 1) *Carpinus caroliniana* Walter (recorded in Canada, USA, Mexico, Guatemala and El Salvador); 2) *Oreopanax xalapensis* (Kunth) Decne. & Planch (recorded from Mexico to Panama); 3) *Carya ovata* (Mill.) K. Koch (recorded in Canada, USA and Mexico); 4) *Quercus germana* Schltld. & Cham. (recorded only in Mexico); 5) *Clethra alcoceri* Greenm. (recorded only in Mexico); 6) *Magnolia schiedeana* Schltld. (recorded only in Mexico); 7) *Quercus eugeniifolia* Liebm. (recorded from Mexico to Panama); 8) *Clethra mexicana* DC. (recorded from Mexico to Colombia); 9) *Quercus candicans* Née (recorded in Mexico and Guatemala); 10) *Ternstroemia lineata* DC. (recorded in Mexico and Honduras); 11) *Cornus disciflora* Moc. & Sessé ex DC. (recorded from Mexico to Panama); 12) *Cyathea mexicana* Schltld. & Cham. (fern recorded in Mexico, Guatemala, Panama and Ecuador); 13) *Eugenia xalapensis* (Kunth) DC. (recorded in Mexico and Belize); 14) *Liquidambar styraciflua* L. (recorded from USA to Honduras); 15) *Ostrya virginiana* (Mill.) K. Koch (recorded from Canada to Honduras); 16) *Persea schiedeana* Nees (recorded from Mexico to Colombia); 17) *Platanus mexicana* Moric. (recorded in Mexico and Guatemala); 18) *Podocarpus reichei* J. Buchholz & N.E. Gray (recorded in Mexico and Costa Rica) and 19) *Trophis mexicana* (Liebm.) Bureau (recorded from Mexico to Ecuador). All species have been studied before in Mexico (see Table 1, distribution

**Table 1.** Potential area occupied (%) by species and suitability class.

	Environmental suitability class*					Reference in montane cloud forest studies
	0.0–0.20	0.21–0.40	0.41–0.60	0.61–0.80	0.81–1.0	
<i>Quercus candicans</i> Née	83.9	8.5	4.9	2.6	0.1	Rubio-Licona et al., 2011
<i>Clethra mexicana</i> DC.	89.3	5.2	3.6	1.8	0.1	Rubio-Licona et al., 2011
<i>Trophis mexicana</i> (Liebm.) Bureau	90.2	4.9	3.0	1.8	0.1	Ponce-Vargas et al., 2006
<i>Magnolia schiedeana</i> Schltld.	93.1	4.3	1.6	0.7	0.3	Alcántara and Luna, 2001
<i>Quercus germana</i> Schltld. & Cham.	94.1	3.5	1.4	0.8	0.2	Fortanelli-Martínez et al., 2014
<i>Podocarpus reichei</i> J. Buchholz & N.E. Gray	92.1	4.2	2.2	1.4	0.2	Alcántara and Luna, 1997
<i>Eugenia xalapensis</i> (Kunth) DC.	90.7	5.9	2.0	1.1	0.3	García-De La Cruz et al., 2013
<i>Carya ovata</i> (Mill.) K.Koch	94.4	2.8	1.5	1.0	0.3	Valdez et al., 2003
<i>Carpinus caroliniana</i> Walter	89.4	5.8	3.0	1.5	0.3	Catalán et al., 2003
<i>Platanus mexicana</i> Moric.	80.7	13.3	3.9	1.7	0.4	Arellano et al., 2005
<i>Quercus eugeniifolia</i> Liebm.	96.3	2.0	1.0	0.6	0.1	Alcántara and Luna, 2001
<i>Oreopanax xalapensis</i> (Kunth) Decne. & Planch	89.5	6.4	2.7	1.2	0.1	Catalán et al., 2003
<i>Clethra alcoceri</i> Greenm.	93.4	3.7	1.8	0.9	0.2	Alcántara and Luna, 2001
<i>Cornus disciflora</i> Moc. & Sessé ex DC.	91.6	4.6	2.3	1.3	0.2	Luna et al., 1994
<i>Ostrya virginiana</i> (Mill) K. Koch	88.6	6.2	3.0	1.9	0.3	Fortanelli-Martínez et al., 2014
<i>Liquidambar styraciflua</i> L.	94.1	2.7	1.5	1.4	0.2	García-De La Cruz et al., 2013
<i>Ternstroemia lineata</i> DC.	98.7	0.6	0.4	0.3	0.0	Rubio-Licona et al., 2011
<i>Persea schiedeana</i> Nees	95.0	2.8	1.2	0.8	0.3	Lorea-Hernández, 2002
<i>Cyathea mexicana</i> Schltld. & Cham.	93.1	3.9	1.6	1.0	0.4	Luna et al., 1994

\*Environmental suitability refers to the potential distribution area of each species, presented here in five classes, with 0–0.2 null as the no distribution potential category and 0.81–1.0 the highest potential category. The authors consider that above 0.21, there is some degree of potential.

reported by [tropicos.org](http://tropicos.org)), and the authors suggest that they are key species in Mexico.

Geographic occurrences (records with geographical coordinates) of the species studied were obtained from the Mexican National Forestry Inventory (CONAFOR, 2012) and the Global Biodiversity Information Facility (GBIF, 2016, 2018). The second data source was used to add data for species with few records in the national inventory. Duplicate data were removed as well as those within urban areas, water bodies or human settlements according to the recent land use cartography (INEGI, 2016). We removed those records that were not within a known distribution area for each species, according to the hypothesis that those plants had been introduced to the ecosystems. Of the species studied, 16 had a minimum of 26 and a maximum

of 122 records at a resolution of 10 km<sup>2</sup>. In the case of *Quercus candicans*, *Clethra mexicana* and *Trophis mexicana*, data were found agglomerated in some regions, so it was decided to use the *spThin* tool in R (Aiello-Lammens et al., 2015), recommended to reduce the number of data and avoid bias in modeling if there was a bias in the sampling. In these three species, the number of records was between 135 and 285 with a resolution of 8 km<sup>2</sup> (Supplementary material SM2 and SM3).

A total of 19 bioclimatic predictors from Worldclim 1.4 (2015) were obtained based on the climatic influence areas of Gómez et al. (2008) at a resolution of 500 × 500 meters for the territory of Mexico. These bioclimatic variables represent annual, temporary trends and extreme conditions throughout the year (see SM2, where the presence by species and bioclimatic variables are shown). These tendencies purportedly have greater biological significance than annual averages. The 19 predictors for the *M*-areas of each species were cut. The *M* area refers to the *BAM* diagram of Soberón and Peterson (2005), which indicates the available area of each species in geographic and ecological terms. This *M* was formed from the selection of all ecoregions (INEGI, 2008) in which there would be at least one record. As recommended by Elith et al., 2011, a preselection of candidate covariates was performed before modeling. A Pearson correlation analysis was carried out, keeping only the variables whose correlation values were  $r > 0.9$ . The set of bioclimatic variables was reduced and was variable for each species (see SM1 and SM2). A smaller number of variables improves the ability to extrapolate and reduces uncertainty (Steen et al., 2017) in generating the model.

## 2.2. Potential distribution areas

After selecting the variables, the Maxent algorithm was applied (Phillips et al., 2006). There are several types of algorithms allowing the identification of climatically appropriate geographic areas for a species (Peterson et al., 2011), but Maxent has been evaluated as one of the algorithms with better performance (Elith et al., 2011); therefore, we decided to use it. Since the result of the algorithm can vary according to the decisions made regarding which parameters to use, a tool known as *ENMeval* (Muscarella et al., 2014) was suggested. This tool facilitates the comparison of different models using different features and regularization multiplier values. The selection criteria for the best model were AICc (the sample-corrected Akaike information criterion) and AUC (area under the curve), which evaluate the prediction capacity and principle of parsimony (the model with the least number of parameters). The AICc is a criterion that penalizes the complexity of the model, an element that is important to control to increase the extrapolation capacity (Moreno-Amat et al., 2015). However, it is also important to take into account the prediction capacity of the model and therefore the value obtained from AUC.

Based on the results of the best model suggested by *ENMeval* (see SM8), parameters were obtained to perform the potential distribution modeling using the MaxEnt 3.4.1 program in each of the species. A total of 80% of geographical occurrence data was defined as training data, and the remaining 20% was defined as testing data. In addition, ten replicates of the models in each species studied were carried out (see SM4). The average map of suitability values was used in each species, and these values were classified in quintiles using ArcMap to obtain greater readability in the distribution of climatically suitable areas of each species.

### 2.3. Viable areas for conservation

The average suitability value of the species maps was transformed into binary maps using ArcMap, and the minimum logistical threshold for the presence of training was used as the average value in each species. Then, the 19 binary maps were merged into one to obtain the joint climatic suitability of all the species studied (see SM5).

The map resulting from the merge contains values from 1 to 19 that characterize a geographical space and denote the number of species for which the space is a suitable area. Subsequently, three suitability classes were made: the first is from 1 to 9 species that coincide, the second class from 10 to 15 species and the third class from 16 to 19 species. We propose that this last category harbors the maximum climatic suitability for the ecosystem because it is climatically optimal for a greater number of key tree species of this system. We use these classes to highlight the results of the pairings of 19 species to ensure the presence of montane cloud forests. Finally, we intersect this map with current CF coverage maps and natural protected areas. In this way, we identify areas with climatic aptitude and unprotected areas as potential areas to be conserved or where the reintroduction of the species under study could be facilitated.

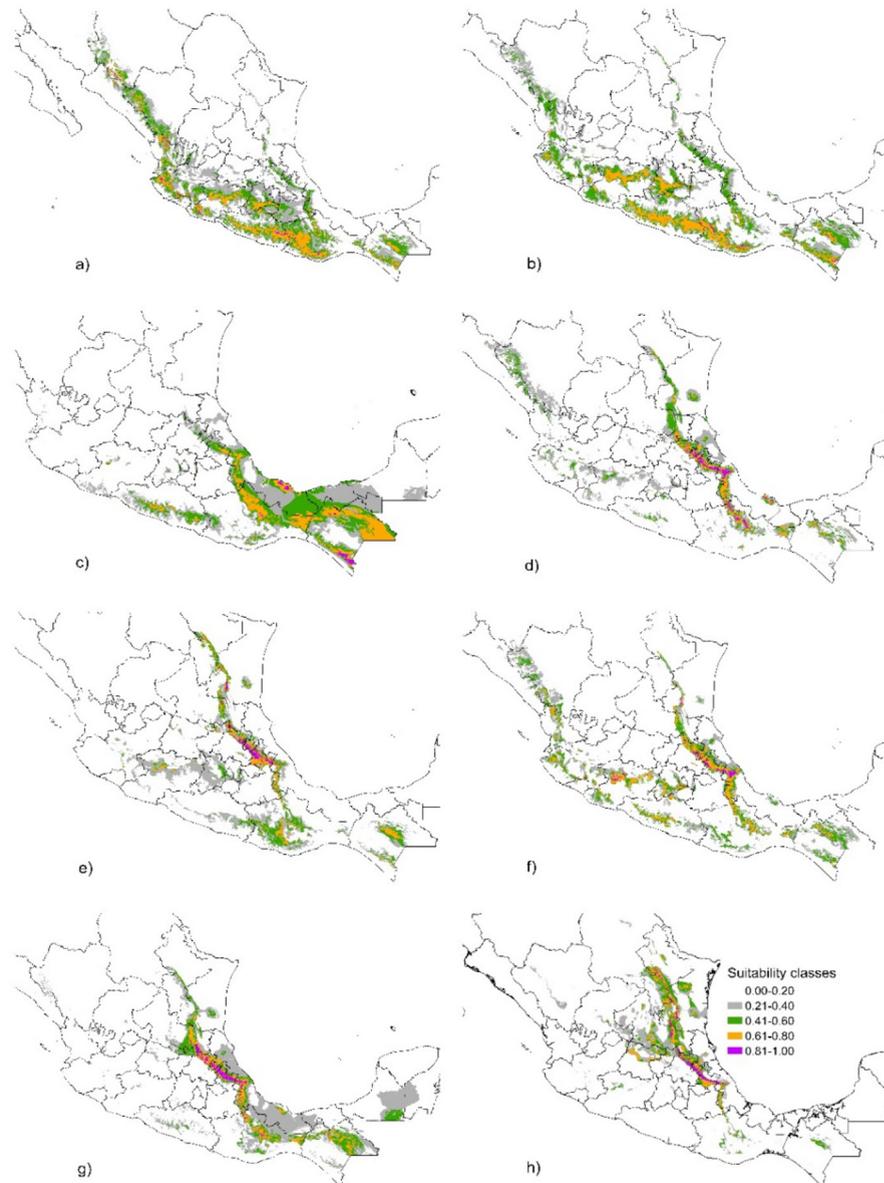
## 3. Results

The species with the highest number of records was *Quercus candicans* with 285, and *Cyathea mexicana* and *Persea schiedeana* had the smallest number, with 26 records. According to the preselection of bioclimatic variables, those that prevailed for all species were bio01, bio02, bio03, bio04, bio05, bio07, bio12, bio15, bio18 and bio19. The supplementary material SM2 shows the number of records, the relationship of the bioclimatic variables for each species, and the values indicated in the evaluation of *ENMeval* to carry out potential distribution models.

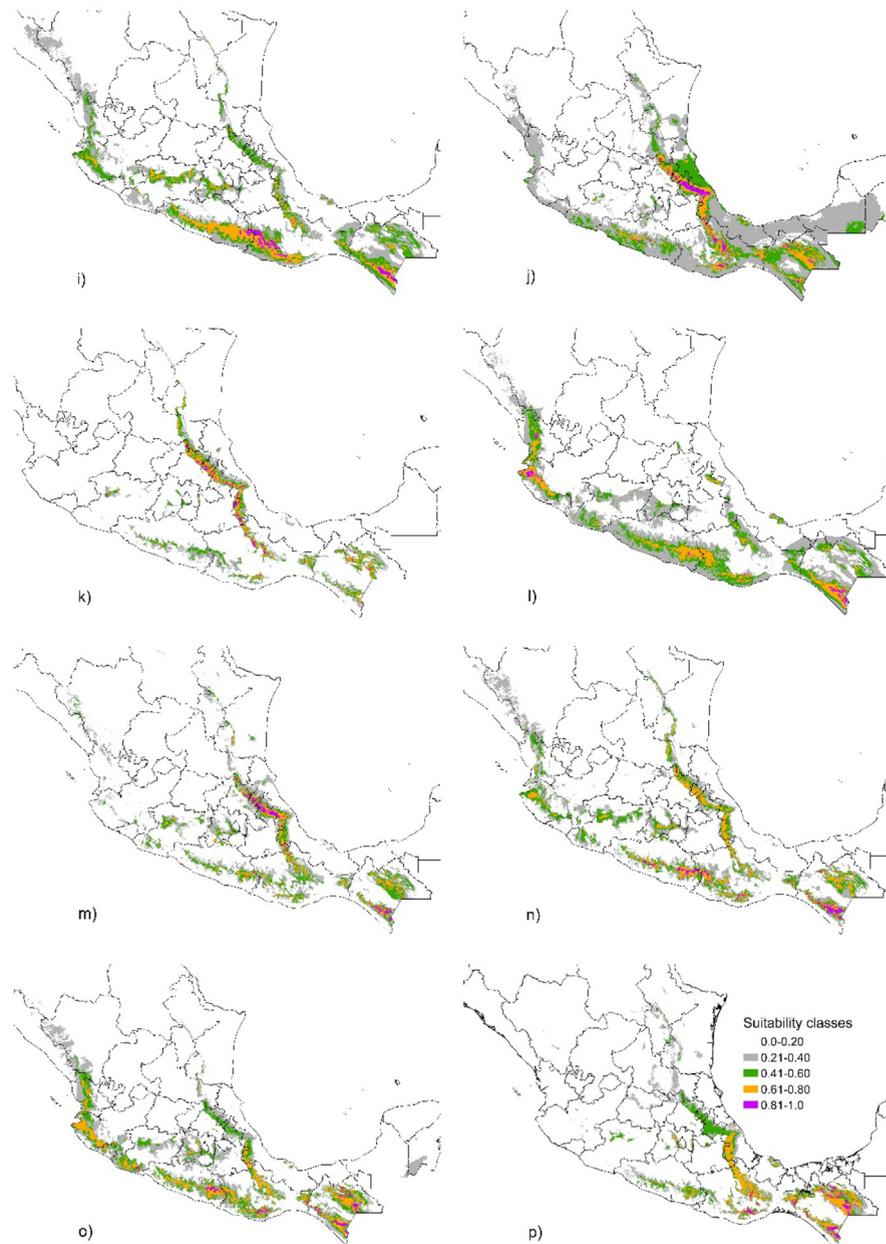
Total area values under the curve (AUC) obtained from the modeling process of species were between 0.895 and 0.984, and the standard deviation obtained ranged from 0.007 to 0.068 (see SM6). The species with the largest area of environmental suitability in the range between 0.81 and 1.0 were *Platanus mexicana* and *Cyathea*

*mexicana*, which represents 0.4% of the national area. At the suitability class between 0.61 and 0.80, *Ostrya virginiana* and *Platanus mexicana* had the largest areas. Table 1 shows the area occupied with respect to the country area.

The potential surfaces with some degree of environmental suitability (those in classes greater than 0.21) are distributed discontinuously over the Sierra Madre Occidental, the Sierra Madre Oriental, the Sierra Madre del Sur de Guerrero and Oaxaca, the Sierra Norte de Oaxaca and the Sierra Madre de Chiapas (Figs. 1, 2, and 3). Areas with very low or no suitability (0–0.20) represent the most abundant



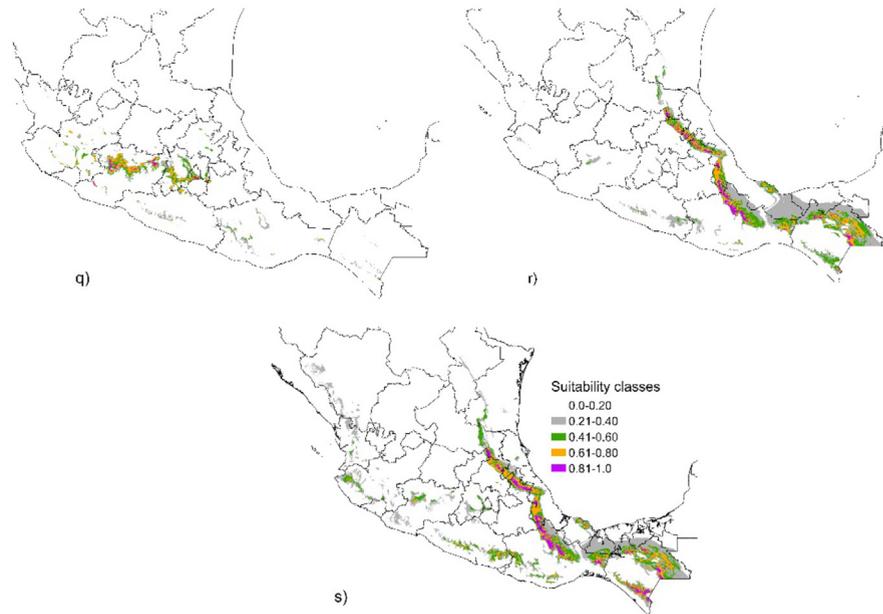
**Fig. 1.** Potential distribution of environmental suitability for a) *Quercus candicans*, b) *Clethra mexicana*, c) *Trophis mexicana*, d) *Magnolia schiedeana*, e) *Quercus germana*, f) *Podocarpus reichei*, g) *Eugenia xalapensis* and h) *Carya ovata*.



**Fig. 2.** Potential distribution of environmental suitability for i) *Carpinus caroliniana*, j) *Platanus mexicana*, k) *Quercus eugeniifolia*, l) *Oreopanax xalapensis*, m) *Clethra alcozeri*, n) *Cornus disciflora*, o) *Ostrya virginiana* and p) *Liquidambar styraciflua*.

area compared to the rest of the classifications. *Ternstroemia lineata* had more extensive suitable areas compared to the other species, since its potential areas are located mainly in the states of Michoacán, Puebla and Mexico City.

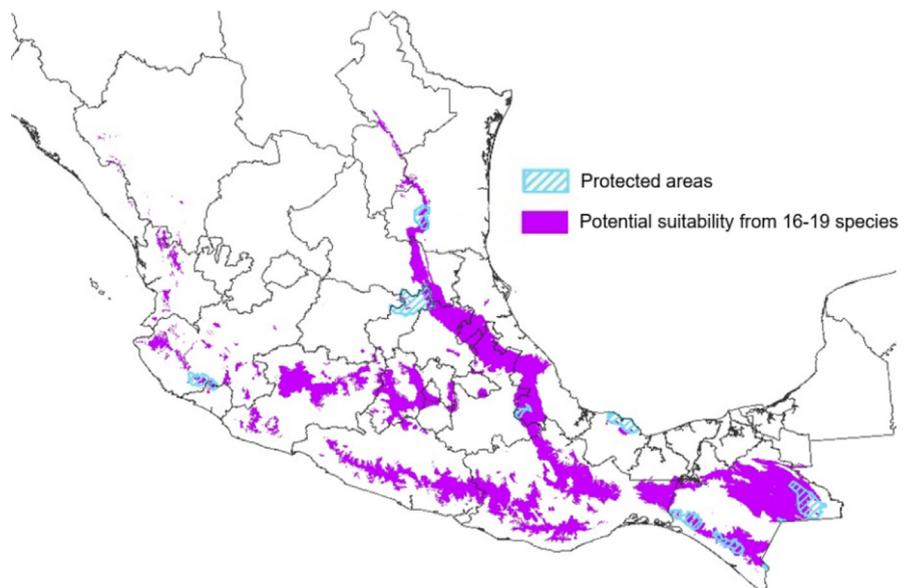
The climatic suitability maps of the species were overlapped, and an environmental suitability map was obtained showing the richest areas. The map was classified according to the number of species that coincided in a geographical space (SM7).



**Fig. 3.** Potential distribution of environmental suitability for q) *Ternstroemia lineata*, r) *Persea schiedeana* and s) *Cyathea mexicana*.

The class with the most potential matches (16–19 species) represents 7% (137,625.7 km<sup>2</sup>) of the Mexico (Fig. 4).

Then, we compared the area of greater potential coincidence with the current land use in Mexico (INEGI, 2016) and found that only 11.9% (16,397.5 km<sup>2</sup>) of the



**Fig. 4.** Comparison of areas of potential suitability with natural protected areas for cloud forest in Mexico.

potential area contains CF. We also found that only 5% (7,107.8 km<sup>2</sup>) of the cloud forest is included in a protected natural area. The five natural areas with larger potential for CF are El Triunfo, Lagunas de Montebello, Cañón del Río Blanco, Montes Azules and Tacaná Volcano (Table 2).

#### 4. Discussion

The potential distribution of the analyzed species observed with our method confirms what has already been observed in the literature. Cloud forest is currently dispersed in ecological enclaves of the mountains of the Sierra Madre Occidental, the Sierra Madre Oriental, the Sierra Madre del Sur of Guerrero and Oaxaca, the Sierra Norte de Oaxaca and the Sierra Madre de Chiapas (Challenger, 1998). Our results are similar to those of Catalán et al. (2003), Alcántara and Luna (1997, 2001) in Hidalgo state and Ponce-Vargas et al. (2006) studying the high and low arboreal stratum of cloud forests. Potential areas obtained for *Q. eugeniifolia* are restricted, and those of *Cyathea mexicana* are even more restricted (Romero et al., 2015). Pennington and Sarukhán (2005) assume that the distribution for *Carpinus caroliniana* is probably from the southeast of Nuevo León and the center of Tamaulipas to the north of Oaxaca and north of Chiapas, all along the Sierra Madre Oriental and in the Tuxtla Mountains, Veracruz, in the Pacific slope, in the mountainous areas from Nayarit, Jalisco to Chiapas, which coincides with our results.

The distribution of *Magnolia schiedeana* (also known as pagua) is currently low in Mexican forests because of its small populations, composed of 25–40 individuals,

**Table 2.** Total area and environmental suitability (km<sup>2</sup>) for the CF in natural protected areas (NPA) in Mexico.

Name	Area (km <sup>2</sup> )	Potential environmental suitability (16–19 species) in NPA (km <sup>2</sup> )	% with potential in the NPA
El Triunfo	1201.8	1193.2	99.3
Lagunas de Montebello	64.5	58.7	91.1
Cañón del Río Blanco	485.9	389.5	80.1
Montes Azules	3288.6	2035.1	61.9
Volcán Tacaná	64.5	39.7	61.5
La Sepultura	1682.4	895.8	53.2
El Cielo	1373.7	723.0	52.6
Sierra de Manantlán	1388.0	573.2	41.3
Sierra Gorda	3804.7	996.5	26.2
Los Tuxtlas	1545.3	203.2	13.1
<b>Total</b>	<b>14899.4</b>	<b>7107.8</b>	

with specific requirements for pollination (Niembro et al., 2010). Vázquez-García (1994) identified 14 restricted populations in the states of Querétaro, Hidalgo, Veracruz, Guerrero and Oaxaca and recorded populations of *M. schiedeana* at elevations of 1000–2000 meters in the southwest of Tamaulipas. Niembro et al. (2010) report their distribution in the states of Chihuahua, Durango, Oaxaca, Puebla, Sinaloa, Sonora and Veracruz (Acosta, 1997, 2004). The species is considered endangered according to the IUCN Red List of Threatened Plants and in a similar Mexican law known as *Norma Oficial Mexicana* NOM-059-SEMARNAT-2001 (Cicuzza et al., 2007).

From the 19 species modeled, we obtained similar results as Ponce-Reyes et al. (2013), who studied three species under climate change scenarios in three different regions of the Mexican cloud forest. We consider that it is possible to discuss the results for the forest ecosystem on the basis of the combination of individual results of the modeled species. Here, it is important to remember that CF needs very specific environmental conditions (Hamilton et al., 1995; Bruijnzeel et al., 2011) and occupies just under 1% of the country (18,534 km<sup>2</sup>).

Our results show environmental suitability for the ecosystem in 7% of the national territory (137,625 km<sup>2</sup>), and only 5% of that (7,108 km<sup>2</sup>) is included in a natural protected area. The potential area estimated in this study is greater than the areas currently covered by montane cloud forests. Land use change in the CF ecosystem has been a problem (Ponce-Reyes et al., 2012) and has reduced cloud forests to very small fragments. Some current protected areas could encompass more than 90% of the cloud forest, mainly in the El Triunfo and Lagunas de Montebello protected areas in the state of Chiapas. Our results are similar to those of Ponce-Reyes et al. (2012), who found that Chiapas has the largest extent of cloud forests (6,037 km<sup>2</sup>) with approximately a quarter of those forests protected. They suggest the state of Oaxaca, and we suggest Chiapas, as key regions for cloud forest conservation. It is important to improve conservation efforts, perhaps by raising the profile of some key sites in Oaxaca and Chiapas internationally through a program such as KBA (key biodiversity areas: <http://www.keybiodiversityareas.org>). The pressure on the ecosystem is high (Martínez et al., 2009), so it is urgent to make more efforts for conservation.

When cross-mapping between the previous maps, we found three variants: a) areas with environmental suitability, currently with cloud forest cover and protected; b) areas with environmental suitability, cloud forest cover but currently unprotected; and c) areas with environmental suitability but no cloud forests and currently unprotected.

For the first areas, we suggest continuing with the CF conservation efforts. El Triunfo Biosphere Reserve has the highest percentage (99.3%) of area with suitability for the CF. In fact, Martínez-Meléndez et al. (2008) studied the ecosystem in the reserve. In contrast, Los Tuxtlas Biosphere Reserve is a protected area in which

13.1% of its area is at least somewhat suitable. This suggests that to protect the CF in Mexico, we should continue with the support where the CF is currently protected in natural areas. Protected natural areas have proven to be an adequate conservation mechanism for CF. However, we should consider maintaining and increasing the number and areas of ecosystem protection. There are still regions with CF presence that could be protected.

In those places where the ecosystem is not being protected but there is environmental suitability and CF presence, we suggest that there is the potential to promote management and conservation actions. Because the potential distribution area is mostly located outside the current CF coverage, we consider that there are favorable environmental conditions in the surroundings for the reintroduction of these species and, therefore, the potential to increase the current forest area. In some cases, CFs are small areas or relicts that are unable to maintain viable long-term populations of many species of flora and fauna typical of this habitat. Instead, they are potential areas to join through biological corridors.

We also compared our results with the zoning of priority areas for the conservation of cloud forest done by CONABIO (2010), finding a match in 85% of the area. Although we do not agree with the same selection of species, we agree with some regions and the need to promote conservation actions. Our study reinforces the results obtained by CONABIO slightly more than eight years ago.

Thus, in all the ideal areas for the CF ecosystem, there are opportunities to plan protection and management actions that will allow its conservation. There are different strategies that can be studied locally, such as the connection of undisturbed forest areas (Williams-Linera, 2002); we do not exclude assisted colonization (Hoegh-Guldberg et al., 2008) or assisted migration (Sáenz-Romero et al., 2012). The species *Carya ovata* has been used in restoration trials and showed high survival with the potential to be used in the rehabilitation of degraded and disturbed areas of CF (Williams-Linera, 2007) and is a good candidate for restoration programs focused on expanding cloud forest (in the region of Veracruz). Oaks are the dominant trees in several fragments of the forest; they are key species in the restoration of cloud forest (Williams-Linera, 2007) since their seedlings have a high survival rates inside and outside the forest, in deforested and degraded areas or very disturbed areas and in secondary forest, known in Mexico as *acahuals*. In plant communities of cloud forest in Veracruz, trees such as *Liquidambar* and *pepinque* (*Carpinus caroliniana*) have been planted, and the results have shown intermediate survival and rapid growth; thus, they are appropriate in almost all reforestation initiatives (Williams-Linera, 2007). Given that a climatically suitable area was identified for the majority of the species studied, detailed local studies are required, integrating various social and environmental aspects to ensure the survival and permanence of future plant colonization.

Finally, we believe that these results serve as a basis for further studies on potential areas of other important species; for monitoring systems *in situ*, locally and in regions already identified as having potential or low potential; for suggesting the location of nurseries; or even for projecting reforestation costs and forest management strategies. In addition, it is time to start restoration efforts for cloud forest plant communities in Mexico. For this purpose, it is necessary to analyze these areas in more detail to obtain information that will allow the achievement of restoration objectives.

## 5. Conclusions

The potential distributions of the studied species showed high similarity where the montane cloud forest is currently reported. However, cloud forest potentially occurs in a larger area than the current area, as expected. Hence, species modeling provides useful cartography for supporting better spatial decisions. The montane cloud forest ecosystem is characterized by a restricted climate, and this can be used to model its future distribution. This topic should be studied further. An overlay suitability map (from 19 species) proved to be an adequate tool for discussing the current distribution of montane cloud forest. Additionally, it was observed that there is a viable surface in which to protect the ecosystem, in addition to that which is already in some natural protected areas. There are currently natural protected areas that protect the montane cloud forest, so it is essential to continue supporting these areas. We are still a long way from perfecting ecosystem modeling, but we believe that it is a route that must be studied in the future given its value and high complexity.

## Declarations

### Author contribution statement

Lucia Guadalupe López Arce, Carolina Ureta: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Diodoro Granados-Sánchez, Luz Judith Rodríguez Esparza: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Alejandro I. Monterroso-Rivas: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

## Funding statement

Lucia Guadalupe López Arce was supported by a CONACYT grant.

## Competing interest statement

The authors declare no conflict of interest.

## Additional information

Supplementary content related to this article has been published online at <https://doi.org/10.1016/j.heliyon.2019.e01423>.

## Acknowledgements

We thank the Departamento de Suelos, Programa de posgrado en Ciencias Forestales, CIRENAM and DGIP of the Universidad Autónoma Chapingo; Instituto de Ecología and Centro de Ciencias de la Atmosfera of the Universidad Nacional Autónoma de México, where the research was carried out. We gratefully acknowledge the comments and suggestions of the anonymous reviewers whose comments have substantially improved the paper.

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