



# Amphibian areas of endemism: A conservation priority in the threatened Mexican cloud forest

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<http://zoobank.org/45D1DB81-72D5-4396-B82E-E4463FD1DB70>

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Academic editor Raffael Ernst | Received 26 August 2021 | Accepted 11 March 2022 | Published 25 May 2022

**Citation:** Montiel Canales G, Goyenechea Mayer Goyenechea I (2022) Amphibian areas of endemism. A conservation priority in the threatened Mexican cloud forest. *Vertebrate Zoology* 72 235–244. <https://doi.org/10.3897/vz.72.e73534>

## Abstract

Amphibians of the Mexican Cloud Forest have a great diversity but are highly threatened. Forest endemisms are useful for recognizing biodiversity hotspots; furthermore, the interaction of historical and current events has generated areas of endemism that can be used for biological conservation in forest fragments; therefore, their identification is an essential part of the management and planning of biological conservation. Thus, our objective was to identify areas of endemism in the cloud forests of Mexico through the analysis of geographical distribution of 126 species of amphibians, as well as their conservation status to obtain information that supports the selection of priority areas for conservation. For this, the endemism analysis method was used with three spatial scales,  $1^{\circ} \times 1^{\circ}$ ,  $0.5^{\circ} \times 0.5^{\circ}$  and  $0.25^{\circ} \times 0.25^{\circ}$  (lat/long), to achieve more complete results and avoid visual overrepresentation of areas of endemism. Seventeen consensus areas distributed in four of the five provinces of the Mexican Transition Zone were identified. The province of the Sierra Madre del Sur exhibited the highest amount of endemism areas, followed by the Sierra Madre Oriental, the East of the Trans-Mexican Volcanic Belt, and the Altos de Chiapas. Results indicate that the endemic areas of the Sierra Madre Oriental and Sierra Madre del Sur provinces are composed of amphibians included in the IUCN red list and the Official Mexican Standard NOM-059. Thus, the small areas of endemism in eastern and western Sierra Madre del Sur, nested within larger ones may be used to increase the protected areas of cloud forests in Mexico.

## Keywords

Biogeography, conservation priorities, NDM/VNDM, threatened species

## Introduction

Areas of endemism (AoE) or distribution patterns are generated from the spatial congruence of biotas (Liria et al. 2020). They are the basic units in historical biogeographic studies (Morrone, 1994), as well as for conservation biology (Whitaker et al. 2005). Areas of endemism in transition zones represent regions where biotas combine,

and different evolutionary lineages coexist as a consequence of a common history, which has important implications for conservation, especially when areas with high richness of different biological groups coincide (Morrone 2020). Different authors have highlighted that the identification of areas of endemism is crucial when considering

regional conservation planning and management (Myers et al. 2000; Noroozi et al. 2018). Likewise, using multiple spatial scales is a good strategy to obtain more complete results when searching for AoE. Endemicity analysis through NDM/VNDM software (Goloboff 2018) is a suitable method for searching for AoE that allows finding biotas with spatial congruence and exploring different spatial scales because it evaluates spatial congruence of taxa over a set of cells (Szumik et al. 2002; Szumik and Goloboff 2004; Ocampo et al. 2019) and considers the general concept of areas of endemism. This analysis identifies nested, overlapping and disjoint areas (Casagrande et al. 2009, 2012) and allows a variety of analytical possibilities (see Escalante et al. 2013; Weirauch et al. 2016). Therefore, the resulting areas of endemism (biogeographic patterns) can be used as surrogates of biodiversity for identifying conservation priorities based on the diversity of co-occurring endemic species, because when used as surrogates for biodiversity, both, species richness of the areas, and historical richness, are preserved (Lamoreux et al. 2006; Luna-Vega et al. 2010).

To achieve biological conservation, it is vital to identify regions with high numbers of endemic species experiencing extreme loss of habitat and their populations, such as the amphibians of the mountain mesophytic forest or Mexican Cloud Forest (Myers et al. 2000). The cloud forest is one of the most threatened ecosystems on the planet. In Mexico, it is a highly threatened ecosystem with less than 1% of the surface; however, it is recognized as the type of vegetation that provides the highest diversity of species per unit area for the biota of the Mexican Transition Zone (Toledo-Aceves et al. 2011; Gual-Díaz and Rendón-Correa 2014).

In the remaining fragments of the world's cloud forests a high diversity of amphibians has been recorded, where 65% of the species are endemic to Mexico, including some exclusive to the cloud forest where we can find taxa associated with Nearctic and Neotropical forests. The diversity of endemic species in cloud forests for Mexico has increased from 183 species registered in 2014 (Gual-Díaz and Goyenechea 2014) to 194, due to taxonomic advances and description of new species (Grünwald et al. 2019; Parra-Olea et al. 2020). However, a considerable number of endemic amphibians with distribution in the cloud forests are in some risk category under different lists such as the IUCN red list and the Official Mexican Standard NOM-059.

This highlights the need to create new habitat protection areas that allow ecological and evolutionary processes to persist on spatial and temporal scales. The aim of this study was to identify areas of endemism with different spatial scales, as well as the conservation status of the amphibians of the Mexican cloud forest inhabiting those areas, to obtain biogeographic information that supports the identification of priority areas and conservation strategies in the cloud forests in Mexico.

## Methods

### Study area

We followed the distribution of the cloud forest from the description of Gual-Díaz and Rendón-Correa (2014), and the Soil and Vegetation Use layer of the National Institute of Statistics and Geography (INEGI series VI 2017). With this layer, cloud forests are visualized as fragments in the mountainous and humid regions of the Mexican Transition Zone (ZTM; Figure 1); in addition, they represent the limits between the Nearctic and Neotropical regions (Ferro and Morrone 2014).

### Data acquisition

A list of 115 endemic Mexican amphibians with distribution in cloud forests was obtained from Gual-Díaz and Rendón-Correa (2014), additionally eleven new endemic species described since 2014 were included, for instance *Chiropetrotriton cieloensis* Rovito and Parra-Olea 2015, *Sarcohyala toyota* Grünwald, Franz-Chávez, Morales-Flores, Ahumada-Carillo and Jones, 2019, and *Chiropetrotriton melipona* Parra-Olea, García-Castillo, Rovito, Maisano, Hanken and Wake, 2020. We followed the taxonomy proposed by Frost (2021).

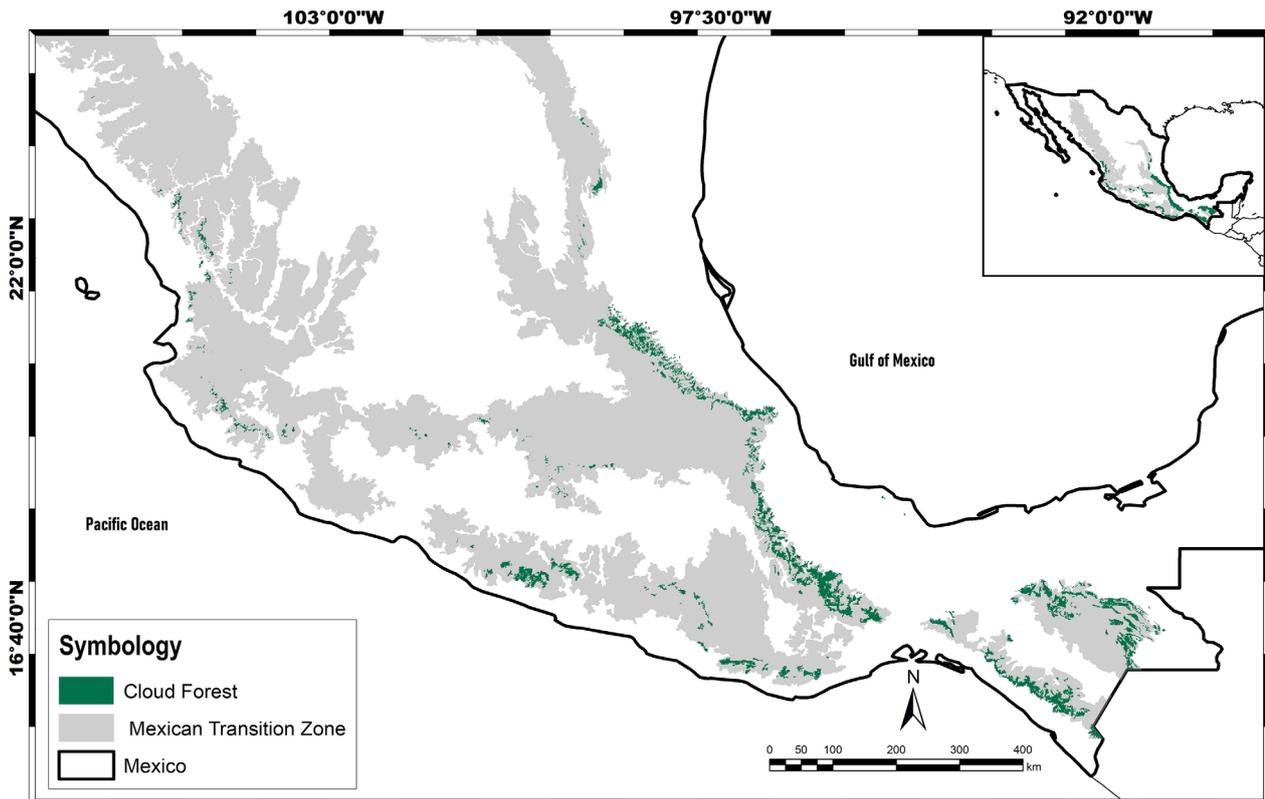
Geographic data to perform the analyses were obtained through the review of specialized literature, taxonomic and biogeographic databases of the Mountain Mesophilic Forest Information System (SI-BMM) of the CONABIO (National Commission for the Knowledge and Use of Biodiversity) (Gual-Díaz et al. 2013), and the database from the National Collection ECO-SC-H of El Colegio de la Frontera Sur, San Cristóbal de las Casas Unit, Mexico.

Distribution data of each species was corroborated with current geographic range maps available online from the IUCN (2020); verified geographic data were imported as shapefiles to validate occurrences; species occurrences not reliably recorded were eliminated.

### Identification of areas of endemism

A database of 1781 records from 126 endemic amphibian records was used to perform the endemicity analysis using the software NDM/VNDM v. 3.1 (Goloboff 2018).

This software uses an optimality criterion to calculate areas of endemism as well as an endemicity index for each taxon within the area of endemism. This index takes into account the number of endemics and the distributional restriction of the taxa in a given area (Szumik et al. 2002). The endemicity index value depends on the number of species assembling an area; a higher number of endemic taxa will yield a higher endemicity index value (Szumik and Goloboff, 2004). A species was given a value of 1 when it was found in each of the evaluated cells and absent in the remaining cells (Noguera-Urbano and Escalante, 2015). Each area of endemism was sup-



**Figure 1.** Distribution of the cloud forest in Mexico over the mountain ranges of the Mexican Transition Zone

ported by the sympatry of at least two species (Szumik et al. 2002; Szumik and Goloboff, 2004).

The method requires to divide the study area into grids defined by the user. Thus, three different spatial scales with three grid sizes  $1^{\circ} \times 1^{\circ}$  (lat/long),  $0.5^{\circ} \times 0.5^{\circ}$  (lat/long), and  $0.25^{\circ} \times 0.25^{\circ}$  (lat/long), with the same latitudinal and longitudinal origin (33.50–118.0) were used.

A list of 126 species was used, with their respective geographic coordinates, and a matrix of presences (1) and absences (0) was constructed with each of the three grid-cells from the Cloud forest.

The areas of endemism were selected using a heuristic search with 100 replicates. For each analysis, the value of the random seed was modified in each replicate (initial seed = 1; random numbers from 1–1,500); the explored seeds maintained a stable number of solutions, and the percentage of unique species to retain overlapping areas was 90%.

From the subsets of areas obtained, those species with a minimum score of 0.7 were chosen and the consensus of these selected areas were calculated considering 30% species similarity under a strict consensus (Aagesen et al. 2013; Szumik and Goloboff 2015), to avoid overrepresentation and ambiguity (Aguado-Bautista and Escalante 2015). Consensus endemism areas were validated by overlapping the geographic distribution of endemic species inhabiting each of the AoE with distribution maps available from the IUCN (2020). The sets of identified areas were saved and exported as shapefiles to assign them to a biogeographic province of Mexico according to the classification proposed by Morrone et al. (2017). Finally, a search was carried out to identify if the species from the

AoE were listed in any risk classification of the IUCN Red List and the Official Mexican Standard (NOM-059-SEMARNAT-2010).

## Results

A total of 17 consensus areas located in four of the five biogeographic provinces of the Mexican Transition Zone were obtained (Figure 2 ABC): Sierra Madre Oriental (2 areas in 5 sets), Trans-Mexican Volcanic Belt (2 areas in 4 sets), Sierra Madre del Sur (11 areas in 30 sets), Altos de Chiapas (2 areas in 10 sets). These areas are well supported with high endemic indices. In contrast, no AoE was identified in the Sierra Madre Occidental. Of the obtained areas (Table 1), eight were identified with the  $1^{\circ}$  grid (endemicity index from 2 to 11.65 and 61 species), five were identified with the  $0.5^{\circ}$  grid (endemicity index from 2 to 7.1 and 29 species), and four with the  $0.25^{\circ}$  grid (endemicity index of 2 to 6.0 and 22 species). AoE 17, located in the Southeastern portion of the Sierra Madre Oriental, was identified with the same taxa using the three spatial scales. It corresponds to continuous consensus areas 8 and 13 with scales of  $1^{\circ}$  and  $0.5^{\circ}$  while area 17 was identified as a disjunct area with the finest scale (Figure 2).

In addition, Table 1 shows the taxonomic composition of the consensus areas obtained, as well as the number of genera included in them. Areas of endemism 3 and 7 found on Northern and Southern Sierra Madre Oriental show the greatest diversity of amphibian species and gen-

**Table 1.** Results of the endemism analysis with 126 taxa of amphibians from the Mexican cloud forest and different spatial scales  $1^\circ \times 1^\circ$ ,  $0.5^\circ \times 0.5^\circ$ , and  $0.25^\circ \times 0.25^\circ$  (lat/long). IUCN ratings (Red List Website) CR: Critically Endangered, E: Endangered, VU: Vulnerable, NT: Near Threatened, and LC: Least Concern. NOM- 059-SEMARNAT-2010 (updated 2019) P: Risk of extinction, A: Threatened, Pr: Special protection. NS: not listed.

| Provinces of the MTZ                    | AoE | Consensus sets 30% | Endemic amphibians                    | Endemism index | IUCN red list | NOM-059 | Grid size |
|---|-----|--------------------|---------------------------------------|----------------|---------------|---------|-----------|
| Western Sierra Madre del Sur            | 1   | 3                  | <i>Charadrahyla pinorum</i>           | 2.65–4.15      | VU            | NS      | 1°        |
|   |     |                    | <i>Exerodonta melanomma</i>           |                | VU            | PR      |           |
|   |     |                    | <i>Ptychohyla leonhardschultzei</i>   |                | LC            | PR      |           |
|   |     |                    | <i>Sarcohyla pentheter</i>            |                | VU            | NS      |           |
|   |     |                    | <i>Sarcohyla thorectes</i>            |                | EN            | PR      |           |
|   |     |                    | <i>Lithobates sierramadrensis</i>     |                | LC            | PR      |           |
| Eastern Sierra Madre del Sur            | 2   | 2                  | <i>Charadrahyla nephila</i>           | 8.00–8.75      | EN            | NS      | 1°        |
|   |     |                    | <i>Megastomatohyla mixe</i>           |                | CR            | PR      |           |
|   |     |                    | <i>Sarcohyla calvicollina</i>         |                | CR            | NS      |           |
|   |     |                    | <i>Sarcohyla cyanomma</i>             |                | CR            | A       |           |
|   |     |                    | <i>Sarcohyla hazelae</i>              |                | VU            | PR      |           |
|   |     |                    | <i>Pseudoeurycea aquatica</i>         |                | CR            | NS      |           |
|   |     |                    | <i>Pseudoeurycea juarezi</i>          |                | EN            | A       |           |
|   |     |                    | <i>Thorius arboreus</i>               |                | CR            | NS      |           |
|   |     |                    | <i>Thorius boreas</i>                 |                | EN            | NS      |           |
|   |     |                    | <i>Thorius insperatus</i>             |                | CR            | NS      |           |
|   |     |                    | <i>Thorius maddougalli</i>            |                | EN            | PR      |           |
| Northern Sierra Madre Oriental          | 3   | 2                  | <i>Craugastor decoratus</i>           | 3.53–6.08      | LC            | PR      | 1°        |
|   |     |                    | <i>Eleutherodactylus verrucipes</i>   |                | LC            | PR      |           |
|   |     |                    | <i>Charadrahyla taeniopus</i>         |                | VU            | A       |           |
|   |     |                    | <i>Sarcohyla charadricola</i>         |                | CR            | A       |           |
|   |     |                    | <i>Sarcohyla robertsororum</i>        |                | VU            | A       |           |
|   |     |                    | <i>Tlalocohyla godmani</i>            |                | VU            | A       |           |
|   |     |                    | <i>Aquiloerycea cephalica</i>         |                | LC            | A       |           |
|   |     |                    | <i>Chiropterotriton chondrostega</i>  |                | EN            | PR      |           |
|   |     |                    | <i>Chiropterotriton multidentatus</i> |                | EN            | PR      |           |
|   |     |                    | <i>Isthmura gigantea</i>              |                | EN            | NS      |           |
| Western Sierra Madre del Sur            | 4   | 2                  | <i>Craugastor saltator</i>            | 3–50–5.25      | EN            | PR      | 1°        |
|   |     |                    | <i>Quilticohyla erythromma</i>        |                | EN            | PR      |           |
|   |     |                    | <i>Sarcohyla mykter</i>               |                | EN            | A       |           |
|   |     |                    | <i>Lithobates omiltemanus</i>         |                | EN            | P       |           |
|   |     |                    | <i>Pseudoeurycea mixcoatl</i>         |                | CR            | NS      |           |
|   |     |                    | <i>Pseudoeurycea tenchalli</i>        |                | CR            | NS      |           |
| Northern Altos de Chiapas               | 5   | 3                  | <i>Craugastor montanus</i>            | 3.1–3.6        | EN            | PR      | 1°        |
|   |     |                    | <i>Duellmanohyla schmidtorum</i>      |                | NT            | PR      |           |
|   |     |                    | <i>Plectrohyla acanthodes</i>         |                | EN            | PR      |           |
|   |     |                    | <i>Plectrohyla lacertosa</i>          |                | EN            | PR      |           |
|   |     |                    | <i>Dendrotriton xolocalcae</i>        |                | VU            | PR      |           |
| Sierra Madre del Sur / Altos de Chiapas | 6   | 5                  | <i>Charadrahyla chaneque</i>          | 2.6–2.94       | VU            | PR      | 1°        |
|   |     |                    | <i>Exerodonta chimalapa</i>           |                | EN            | NS      |           |
|   |     |                    | <i>Cryptotriton alvarezdeltoroi</i>   |                | EN            | PR      |           |

era. The Sierra Madre del Sur stands out as having the highest amount of AoE and therefore the highest diversity of amphibians in geographical congruence to the cloud forest fragments of this province.

Our results show that all AoE recovered contain a high number of amphibians in the IUCN Red list and the Official Mexican Standard NOM-059; Area of endemism 2, located in Eastern Sierra Madre del Sur is composed by 11 species, all of them listed under risk categories of the

IUCN. According to the NOM-059-SEMARNAT 2010, two species are listed as A (threatened), three species are listed as PR (special protection) and six species have not been evaluated.

The area of endemism 3, located in the northern Sierra Madre Oriental, is assembled by the geographic congruence of ten species, following the IUCN species under three categories are found here; CR (one species), EN (three species) and VU (three species). While, *Craugastor*

| Provinces of the MTZ              | AoE | Consensus sets 30% | Endemic amphibians                   | Endemicity index | IUCN red list | NOM-059 | Grid size |
|-----------------------------------|-----|--------------------|--------------------------------------|------------------|---------------|---------|-----------|
| Sierra Madre Oriental Sur         | 7   | 3                  | <i>Incilius cristatus</i>            | 6.33–11.65       | EN            | PR      | 1°        |
|                                   |     |                    | <i>Bromeliohylla dendroscarta</i>    |                  | EN            | PR      |           |
|                                   |     |                    | <i>Charadrahyla taeniopus</i>        |                  | VU            | A       |           |
|                                   |     |                    | <i>Megastomatohylla mixomaculata</i> |                  | EN            | A       |           |
|                                   |     |                    | <i>Megastomatohylla nubicola</i>     |                  | CR            | A       |           |
|                                   |     |                    | <i>Sarcohylla arborescendens</i>     |                  | NT            | PR      |           |
|                                   |     |                    | <i>Sarcohylla charadricola</i>       |                  | CR            | A       |           |
|                                   |     |                    | <i>Sarcohylla robertsororum</i>      |                  | VU            | A       |           |
|                                   |     |                    | <i>Tlalocohyla godmani</i>           |                  | VU            | A       |           |
|                                   |     |                    | <i>Aquiloerycea cafetalera</i>       |                  | VU            | NS      |           |
|                                   |     |                    | <i>Aquiloerycea cephalica</i>        |                  | LC            | A       |           |
|                                   |     |                    | <i>Chiropterotriton chiropterus</i>  |                  | CR            | PR      |           |
|                                   |     |                    | <i>Chiropterotriton nubilus</i>      |                  | CR            | NS      |           |
|                                   |     |                    | <i>Isthmura gigantea</i>             |                  | EN            | NS      |           |
|                                   |     |                    | <i>Parvimolge townsendi</i>          |                  | VU            | P       |           |
|                                   |     |                    | <i>Pseudoeurycea lineola</i>         |                  | EN            | PR      |           |
|                                   |     |                    | <i>Pseudoeurycea lynchi</i>          |                  | EN            | NS      |           |
|                                   |     |                    | <i>Thorius pennatulus</i>            |                  | EN            | P       |           |
| Southeastern Sierra Madre del Sur | 8   | 1                  | <i>Charadrahyla altipotens</i>       | 2.0–2.25         | EN            | PR      | 1°        |
|                                   |     |                    | <i>Megastomatohylla pellita</i>      |                  | CR            | NS      |           |
| Western Sierra Madre del Sur      | 9   | 4                  | <i>Craugastor saltator</i>           | 2.4–4.8          | EN            | PR      | 0.5°      |
|                                   |     |                    | <i>Quilticohyla erythromma</i>       |                  | EN            | PR      |           |
|                                   |     |                    | <i>Sarcohylla mykter</i>             |                  | EN            | A       |           |
|                                   |     |                    | <i>Lithobates omiltemanus</i>        |                  | EN            | P       |           |
|                                   |     |                    | <i>Pseudoeurycea mixcoatl</i>        |                  | CR            | NS      |           |
|                                   |     |                    | <i>Pseudoeurycea tenchalli</i>       |                  | CR            | NS      |           |
| Eastern Sierra Madre del Sur      | 10  | 5                  | <i>Ptychohylla zophodes</i>          | 2.3–7.1          | VU            | NS      | 0.5°      |
|                                   |     |                    | <i>Sarcohylla calvicollina</i>       |                  | CR            | NS      |           |
|                                   |     |                    | <i>Sarcohylla cyanomma</i>           |                  | CR            | A       |           |
|                                   |     |                    | <i>Sarcohylla hazelae</i>            |                  | VU            | PR      |           |
|                                   |     |                    | <i>Pseudoeurycea juarezi</i>         |                  | EN            | A       |           |
|                                   |     |                    | <i>Thorius arboreus</i>              |                  | CR            | NS      |           |
|                                   |     |                    | <i>Thorius aureus</i>                |                  | CR            | NS      |           |
|                                   |     |                    | <i>Thorius boreas</i>                |                  | EN            | NS      |           |
| <i>Thorius macdougalli</i>        | EN  | PR                 |                                      |                  |               |         |           |
| Eastern Trasmexican Volcanic Belt | 11  | 3                  | <i>Incilius cristatus</i>            | 3.9–5.4          | EN            | PR      | 0.5°      |
|                                   |     |                    | <i>Megastomatohylla mixomaculata</i> |                  | EN            | A       |           |
|                                   |     |                    | <i>Megastomatohylla nubicola</i>     |                  | CR            | A       |           |
|                                   |     |                    | <i>Aquiloerycea cafetalera</i>       |                  | VU            | NS      |           |
|                                   |     |                    | <i>Chiropterotriton chiropterus</i>  |                  | CR            | PR      |           |
|                                   |     |                    | <i>Chiropterotriton nubilus</i>      |                  | CR            | NS      |           |
|                                   |     |                    | <i>Parvimolge townsendi</i>          |                  | VU            | P       |           |
|                                   |     |                    | <i>Pseudoeurycea lineola</i>         |                  | EN            | PR      |           |
|                                   |     |                    | <i>Thorius pennatulus</i>            |                  | EN            | P       |           |

*decoratus*, *Eleutherodactylus verrucipes* and *Aquiloerycea cephalica* are listed under LC. Taking into account the 2019 updated version of the NOM-059-SEMARNAT 2010, nine out of ten species are listed. Five species are listed under the A category, and four under PR. The salamander *Isthmura gigantea* is the only not listed species.

The area of endemism 4, located in the western Sierra Madre del Sur, is supported by the geographical congruence of six amphibians. Two species under the CR cate-

gory, and four species under EN. In contrast, NOM-059-SEMARNAT 2010 list four of the six species under three categories (A, P and PR) while two salamanders *Pseudoeurycea mixcoatl* and *Pseudoeurycea tenchalli* have not been evaluated.

The area of endemism 7, located in the southern Sierra Madre Oriental, was the best supported area with 18 species of amphibian species of the Cloud Forest. According to the IUCN 16 species out of 18 are listed under different

| Provinces of the MTZ               | AoE | Consensus sets 30% | Endemic amphibians                  | Endemicity index | IUCN red list | NOM-059 | Grid size |
|------------------------------------|-----|--------------------|-------------------------------------|------------------|---------------|---------|-----------|
| Northern Altos de Chiapas          | 12  | 2                  | <i>Craugastor montanus</i>          | 2.10–2.3         | EN            | PR      | 0.5°      |
|                                    |     |                    | <i>Dendrotriton xolocalcae</i>      |                  | VU            | PR      |           |
|                                    |     |                    | <i>Plectrohyla lacertosa</i>        |                  | EN            | PR      |           |
| Southeastern Sierra Madre del Sur  | 13  | 1                  | <i>Charadrahyla altipotens</i>      | 2.00–2.5         | EN            | PR      | 0.5°      |
|                                    |     |                    | <i>Megastomatohyla pellita</i>      |                  | CR            | NS      |           |
| Western Sierra Madre del Sur       | 14  | 4                  | <i>Craugastor saltator</i>          | 2.00–3.89        | EN            | PR      | 0.25°     |
|                                    |     |                    | <i>Quilticohyla erythromma</i>      |                  | EN            | PR      |           |
|                                    |     |                    | <i>Sarcohylla chryses</i>           |                  | EN            | PR      |           |
|                                    |     |                    | <i>Sarcohylla mykter</i>            |                  | EN            | A       |           |
|                                    |     |                    | <i>Lithobates omilemanus</i>        |                  | EN            | P       |           |
|                                    |     |                    | <i>Pseudoeurycea mixcoatl</i>       |                  | CR            | NS      |           |
|                                    |     |                    | <i>Pseudoeurycea tenchalli</i>      |                  | CR            | NS      |           |
| Eastern Transmexican Volcanic Belt | 15  | 1                  | <i>Megastomatohyla mixomaculata</i> | 3.37–3.62        | EN            | A       | 0.25°     |
|                                    |     |                    | <i>Megastomatohyla nubicola</i>     |                  | CR            | A       |           |
|                                    |     |                    | <i>Aquiloerycea cafetalera</i>      |                  | VU            | NS      |           |
|                                    |     |                    | <i>Chiropterotriton chiropterus</i> |                  | CR            | PR      |           |
|                                    |     |                    | <i>Thorius pennatulus</i>           |                  | EN            | P       |           |
| Eastern Sierra Madre del Sur       | 16  | 2                  | <i>Sarcohylla calvicollina</i>      | 5.50–6.00        | CR            | NS      | 0.25°     |
|                                    |     |                    | <i>Sarcohylla cyanomma</i>          |                  | CR            | A       |           |
|                                    |     |                    | <i>Sarcohylla hazelae</i>           |                  | VU            | PR      |           |
|                                    |     |                    | <i>Pseudoeurycea juarezi</i>        |                  | EN            | A       |           |
|                                    |     |                    | <i>Thorius arboreus</i>             |                  | CR            | NS      |           |
|                                    |     |                    | <i>Thorius aureus</i>               |                  | CR            | NS      |           |
|                                    |     |                    | <i>Thorius boreas</i>               |                  | EN            | NS      |           |
|                                    |     |                    | <i>Thorius maddougalli</i>          |                  | EN            | PR      |           |
| Southeastern Sierra Madre del Sur  | 17  | 1                  | <i>Charadrahyla altipotens</i>      | 2.00–2.25        | EN            | PR      | 0.25°     |
|                                    |     |                    | <i>Megastomatohyla pellita</i>      |                  | CR            | NS      |           |

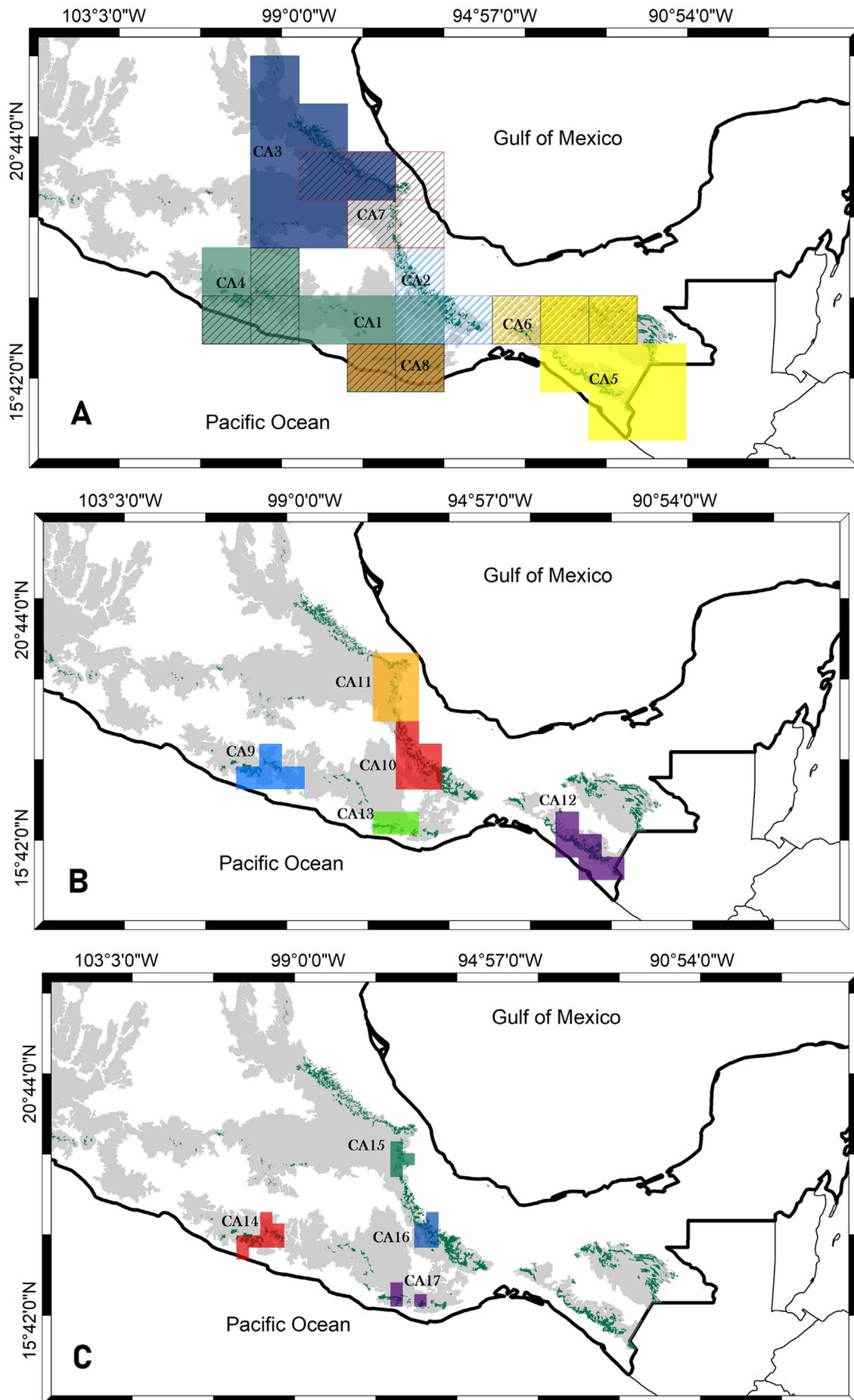
threat categories: CR (four species), EN (seven species), VU (five species). Only *Sarcohylla arborescandens* is considered as NT not threatened, and *Aquiloerycea cephalica* is listed as less concern LC. While 14 species out of 18 are listed under threatened categories (A, P or PR) following NOM-059-SEMARNAT 2010.

## Discussion

The ZTM is a complex area characterized by biotic combination, due to historical and ecological changes, allowing the mixture of biotas and areas of endemism (Ferro and Morrone 2014; Morrone 2015). Morrone (2014) mentioned that, when identifying areas of endemism, adopting grids as units is highly recommended, but identification of AoE with different grid sizes yields complex though fragmented distributions such as that of the cloud forests of Mexico because forests are heterogeneous, exhibiting contrasting associations that differ from one province to another. Despite this complexity, we used three different grid sizes. Seventeen AoE were retrieved for the ZTM through the three grid sizes (1°, 0.5° and 0.

25°) in four of its five provinces, where the Sierra Madre del Sur is the one with the highest number of AoE. Some areas were recovered through the three grid sizes, for example AoE 4 was identified with the 1° grid, and recovered with the 0.5° scale as AoE 9, both supported by the same six species (Table 1). This area is also recovered using the lowest scale 0.25° as AoE 14 supported by seven species, AoE 9 six species plus *Sarcohylla chryses*. These results led us to say that the better scale for this particular AoE is 0.25° because it is identified with more species.

Moreover, different scales allowed us to recognize smaller AoE that could only be discovered by exploring different sizes of cloud forest fragments. When using the 1° grid, we obtained the higher number of AoE; fewer areas were identified with the 0.5° grid, and finally, with the finer 0.25° grid we also recovered small nested AoE within larger ones and that, in fact, better fit the diversity of fragment sizes where the cloud forest is distributed. The AoE recovered with the 1° grids are more extensive and include, in addition to the cloud forest, other types of vegetation associated with it, such as Pine-Oak forests. The first eight areas of endemism, located in the Sierra Norte de Oaxaca and the patterns identified in the cloud forests of Guerrero and Hidalgo correspond to the largest scale, where smaller areas are restricted to cloud for-



**Figure 2.** Consensus areas of Mexican cloud forest amphibians A consensus areas 1–8 grid 1°×1°, B consensus areas 9–13 grid 0.5°×0.5°, C consensus areas grid 0.25°×0.25°.

est, corresponding to the 0.5 ° and 0.25 ° grids (Figure 2 B, and C). Therefore, it is important to explore different grid sizes to obtain more complete results, as mentioned by other authors who used different scales with different taxonomic groups and biogeographic regions in America (Casagrande et al. 2009; DaSilva et al. 2015; Bertelli et al. 2017).

Studies carried out with different groups of animals have allowed identifying patterns throughout Mexico, some of these located in cloud forests; Ochoa-Ochoa and Flores-Villela (2006) identified AoE for Mexican herpetofauna and recognized areas (central Veracruz, southern Oaxaca, and Sierra Madre Oriental) that partially coincide with our results. Likewise, Escalante et al. (2009) identified AoE of mammals in Mexico and their results coincide with those described here since they found an area in the Eastern portion of the Trans-Mexican Volcanic Belt. Furthermore, Bertelli et al. (2017) identified AoE with birds, which partially agree with the patterns identified here throughout the provinces of the Sierra Madre Oriental, Sierra Madre del Sur, and the Altos de Chiapas.

Regarding vascular plants, the patterns identified in the cloud forests of Mexico by Luna-Vega et al. (1999) coincide only partially with the AoE of the Sierra Madre del Sur and Sierra Madre Oriental recovered in this work. Those studies, however, do not recover any pattern in the forests of the Trans-Mexican Volcanic Belt, while we documented an AoE composed of nine species of amphibians located east of the Trans-Mexican Volcanic Belt. Interestingly, we did not recover, any AoE within the Sierra Madre Occidental, contrasting with the results of Estrada-Sánchez et al. (2019), who identified an AoE in western Mexico in the Sierra Madre Occidental using epiphytes, bromeliads, and cloud forest orchids. Gual-Díaz and Rendón-Correa (2014) pointed out that cloud forests of this province are distributed in a scattered way and are generally less humid than forests of the Sierra Madre Oriental and the Sierra Madre del Sur, thus humidity appears to be an important factor that limits the recognition of amphibian AoE. Therefore, future analyzes might incorporate more data and taxonomic groups that might contribute to finding biogeographic patterns in every cloud forest of the country.

On the other hand, AoEs with the highest endemism indexes are located within the SMS with values ranging from 8-8.75 in AoE2, and 6.3-11.65 in AoE7, as well as in the SMO, where AoE3 has an index of 3.53-6.08. High values of endemism indexes reveal high geographic congruence between cloud forest amphibian species composing AoEs through different spatial scales. Thus, the endemism index by itself can be used as a surrogate for prioritizing conservation areas, ordering them by decreasing values (Escalante and Morales, 2017).

Moreover, our results using the endemism index along with risk categories expose a powerful way to prioritize conservation areas. More than 60% of the endemic species of amphibians (Table 1) within the identified AoE are in some risk category (SEMARNAT 2010; IUCN 2021) and require immediate attention for their protection. Considering that only 31.6% of cloud forests are under some

protection scheme within the 21 protected natural areas, including cloud forests in Mexico (Ochoa-Ochoa et al. 2017) our results indicate the need to increase protection areas through the Sierra Madre Sur and the Sierra Madre Oriental, since they contain the greatest amphibian diversity, as well as the highest values of endemism indexes.

These results are congruent with the conservation proposal for the cloud forest suggested by Ochoa-Ochoa et al. (2017), which consider the ecoregions and biogeographic provinces of the Sierra Madre Oriental, Sierra Madre del Sur, the Trans-Mexican Volcanic Belt, and the Highlands of Chiapas.

To increase the protected areas of cloud forests in Mexico, active forest restoration has been used for recovering abundance of amphibians (Díaz-García et al. 2020). Therefore, ecological restoration to conserve cloud forests could be established and island-type reserves could be implemented, allowing continuity between two types of corridors (Gual-Díaz and González-Medrano 2014). In this way, our results can be used by decision makers and those in charge of mitigating the deterioration and threats in the Mexican cloud forests to propose this type of reserves.

## Conclusions

1. We were able to identify 17 areas of endemism in the cloud forests of Mexico based on 126 species of amphibians.
2. We indicated that AoE were identified in four of the five provinces of the Mexican Transition Zone.
3. The province of the Sierra Madre del Sur exhibited the highest endemism indexes and amount of endemism areas, followed by the Sierra Madre Oriental, the East of the Trans-Mexican Volcanic Belt, and the Altos de Chiapas.
4. The endemic areas of the Sierra Madre Sur and Sierra Madre Oriental provinces comprise amphibians included in the IUCN red list and the Official Mexican Standard NOM-059.
5. The small areas of endemism in eastern and western Sierra Madre del Sur nested within larger ones may be used to increase the protected areas of cloud forests in Mexico.

## Acknowledgements

A. Muñoz Alonso is acknowledged for assistance and data retrieved from the Herpetological Collection at ECOSUR Unidad San Cristóbal. The first author acknowledges CONACyT for grant 660404 and the Instituto Politécnico Nacional for the support provided in the realization of this project. We also thank N. Manríquez-Morán, C. Hornung-Leoni,

and U. Iturbe-Acosta for improving the English version of the manuscript. We also acknowledge the critical revision of Larry D. Wilson and Raffael Ernst which improved the manuscript.

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