Ecological niche modeling on the effect of climatic change and conservation of *Ternstroemia lineata* DC. (Ternstroemiaceae) in Mesoamerica

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Abstract: A bioclimatic modeling of the tree *Ternstroemia lineata* DC. (Ternstroemiaceae) was undertaken. The genus itself is considered as diagnostic or characteristic of the Mexican cloud forest. *Ternstroemia lineata* has the broadest distribution of all species in this family in Mexico and northern Central America. This species consists of two subspecies, *T. lineata* subsp. *lineata* and *T. lineata* subsp. *chalicophila* (Loes.) B.M. Barthol. Ecological niche models for both subspecies were generated using the genetic algorithm for rule-set production method. The ecological models for the years 2020, 2050, and 2080 were obtained under the effects of global climatic change considering two emission scenarios (A2a and B2a). When climatic change values were introduced, the ecological niche representation for both subspecies contracted in such a way that they became almost lost throughout their entire geographical range. In both cases, predictions for all years in both scenarios contracted more than 90%. This species may not be able to adapt to modifications caused by climatic change to future conditions, so it is at risk of extinction in the immediate future.

Key words: conservation assessment, ecological niche model, global climate change, Guatemala, Mexico, *Ternstroemia lineata*, Ternstroemiaceae.

Résumé : Les auteurs ont mis sur pied la modélisation mathématique d'un arbre, le *Ternstroemia lineata* DC. (Ternstroemiaceae). On considère ce même genre comme diagnostique des caractéristiques de la forêt ombrophile du Mexique. Le *T. lineata* possède la plus large distribution de toutes les espèces de cette famille de la partie mexicaine nordique en l'Amérique Centrale. Cette espèce comporte deux sous espèces, le *T. lineata* subsp. lineata et le *T. lineata* subsp. *chalicophila* (Loes.) B.M. Martol. Les auteurs ont généré des modèles de niches écologiques pour les deux sous espèces, à l'aide de GARP. Ils ont obtenu les modèles écologiques pour les années 2020, 2050, et 2080 sous l'influence des effets du changement climatique global, en considérant deux scénarios (A2a et B2a). Lorsqu'on introduit des valeurs de changement climatique, la représentation des niches écologiques pour les deux sous espèces se contracte à tel point qu'elles disparaissent presque totalement de l'aire géographique. Dans les deux cas, les prédictions pour toutes les années selon les deux scénarios se contractent à plus de 90 %. Cette espèce pourrait ne pas être en mesure de s'adapter aux modifications du changement climatique dans l'avenir, conséquemment elle risque l'extinction dans un future immédiat.

Mots-clés : évaluation de la conservation, modèle de niche écologique, changement climatique global, Guatemala, Mexique, *Ternstroemia lineata*, Ternstroemiaceae.

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Introduction

The impact of anthropogenic activities (e.g., pollution, land use change, introduction of exotic species) in natural environments has caused modifications at different levels. These modifications include alterations of the Earth's climate caused by the emission of greenhouse gases, resulting from the industrial development of the world and the combustion of fossil fuel (Arvizu-Fernández 2004). The amount of greenhouse gases has increased since the last decades of the 20th century, producing a temperature increase and modifying the precipitation regimes in different zones of the planet (Cuatecontzi and Gasca 2004; Arvizu-Fernández 2004).

Even if interactions between species and climate have been

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widely considered in management and conservation programs, the biological effects of global climatic change can produce shifts or changes that can affect species distribution (Mawdsley et al. 2009). A species geographical range may contract, disappear, or expand, depending on the species ability to adapt to the new conditions (Peterson et al. 2002*b*; Téllez-Valdés and Dávila-Aranda 2003; Mawdsley et al. 2009). Using ecological niche modeling, it is possible to obtain a representation of the ecological niche requirements of the species and to project them on different scenarios of future climatic change (e.g., Peterson et al. 2002*a*, 2002*b*; Téllez-Valdés and Dávila-Aranda 2003; Ballesteros-Barrera et al. 2007). This approach is useful in the identification of priority zones for conservation and (or) for considering the geographical representation of the environmental factors required by the species where the conditions may or may not be maintained in the future.

There are few studies considering Mexican biodiversity under scenarios of climatic change where ecological niche models have been used; these models are based on hypothetical conditions, generally evaluating only one future time slice. Studies with Mexican plants have used a bioclimatic envelope (Bioclim; Nix 1986) with Cactaceae species in the Tehuacán-Cuicatlán Valley Biosphere Reserve, a Mexican Natural Protected Area (Téllez-Valdés and Dávila-Aranda 2003). Another method that has been explored is the genetic algorithm for rule-set production (GARP; Stockwell and Peters 1999), which has proven to be a useful tool in the climatic change approach; it has been used with species of oaks and pines inhabiting Mexico (Gómez-Mendoza and Arriaga 2007), where expectations include important reductions of several endemic species.

Climatic change modeling can provide detailed knowledge about the climatic factors determining the distributional patterns of selected organisms. In plant research, ecological niche modeling has been applied in Mexico to predict plant species distributions (Villaseñor and Téllez-Valdés 2004), for conservation assessments of a particular species (Téllez-Valdés et al. 2006; Solano and Feria 2007; Yberri 2009; Contreras-Medina et al. 2010), and for climatic change impact assessments (Téllez-Valdés and Dávila-Aranda 2003; Téllez-Valdés et al. 2006; Gómez-Mendoza and Arriaga 2007).

The genus *Ternstroemia* (Ternstroemiaceae, Tricolpates: Ericales *sensu* Judd et al. 2002 or Pentaphylacaceae *sensu* Stevens 2001 and onwards; APG III 2009) is an angiosperm with a widespread distribution throughout the tropics and subtropics of the world (in Asia, Africa, America, and Australia) (Luna-Vega and Contreras-Medina 2000). It is composed of about 110–160 species of medium-sized trees and shrubs. In Mexico, *Ternstroemia* together with some other genera of flowering plants like *Carpinus*, *Clethra*, *Liquidambar*, *Magnolia*, *Nyssa*, *Ostrya*, *Styrax*, *Symplocos*, and *Zinowiewia*, among others, are structurally important elements characterizing cloud forest conditions (Rzedowski 1996; Luna-Vega et al. 2006). This genus itself is considered a diagnostic or preferential taxon of the Mexican cloud forest (Rzedowski 1996; Alcántara et al. 2002). Tropical montane cloud forests are strongly linked to regular cycles of cloud formation (Still et al. 1999) and are ecosystems that harbor a high proportion of endemic species (Flores-Villela and Gerez

1994). Nadkarni and Solano (2002) recently determined that global climate change models are useful for predicting the reduction of clouds (horizontal precipitation) in tropical montane cloud forests.

In Mexico, only seven species of *Ternstroemia* are represented (Luna-Vega et al. 2004). These species are not clearly morphologically separated, so it is common to find specimens misidentified in the herbarium collections (Luna-Vega and Ochoterena 2004). This fact is especially evident with the two subspecies of *T. lineata*, which are distinguished by slight external morphological differences (Kobuski 1942; Bartholomew 1988; Bartholomew and McVaugh 1997). Both subspecies are currently being studied to test if they are independent lineages (O. Alcántara, personal communication). In this family, some other taxa also constitute species complexes with slight morphological differences among them (i.e., *T. tepezapote* complex).

Ternstroemia lineata is a Mesoamerican endemic species associated with mountainous zones. Two subspecies have been described: *T. lineata* subsp. *lineata* from central to southern Mexico and *T. lineata* subsp. *chalicophila* from southern Mexico to Honduras. At this time, we have a database containing detailed distribution information for this species, which has been compiled over more than 10 years and is based on the revision of herbarium specimens and field work. On the basis of this information, we consider *T. lineata* to be a suitable test model for evaluating the effects of changing climatic conditions in mountainous zones in Mesoamerica, and this information can be compared with the effects of the climatic change on other plant taxa that also inhabit mountainous areas, such as pines, other conifers, oaks, and other montane humid angiosperm species.

In this study, we analysed the geographic distribution patterns of the two subspecies of *T. lineata*. These distribution patterns may be used as a tool for assessing the conservation status of the subspecies in the face of coming global climatic changes. Populations of this species generally consist of a few individuals with an archipelagic distribution, mainly in the montane areas of the Mexican Transition Zone. Although we do not have enough information to propose ways of mitigating the effects of climatic change *sensu* Sáenz-Romero et al. (2010), climate change will probably cause drastic modifications to the distribution of this species owing to changes in environmental conditions, which we evaluated through ecological niche modeling.

Materials and methods

Input occurrence data

Geographic distribution data of the two subspecies of *T. lineata* were obtained from the revision of more than 600 specimens deposited in the following herbaria: Instituto de Biología, Universidad Nacional Autónoma de México (MEXU), Instituto Politécnico Nacional (ENCB), Instituto de Ecología in Xalapa (XAL) and Pátzcuaro (IEB), Facultad de Ciencias, Universidad Nacional Autónoma de México (FCME), New York Botanical Garden (NY), Missouri Botanical Garden (MO), and Royal Botanic Gardens Kew (K). Also we consulted the following databases: Tropicos (Missouri Botanical Garden) and NYBG (New York Botanical Garden). Additional data for specimens from Guatemala

were kindly provided by Mario Véliz from the Universidad de San Carlos en Guatemala (BIGUA) herbarium. Field work was done by the two first authors. The herbarium specimens were carefully reviewed to avoid misidentifications and synonymy, because both subspecies have important taxonomic problems, especially in its delimitation (Luna-Vega et al. 2004).

A database was constructed that included information from all 143 available specimens reviewed and from other databases. Geographic coordinates for Mexican localities (100% for *T. lineata* subsp. *lineata* and 66.6% for *T. lineata* subsp. *chalicophila*) were obtained, updated, or corrected by using topographic charts with scales 1 : 50 000 and 1 : 250 000 produced by the Instituto Nacional de Estadística, Geografía e Informática (e.g., INEGI 1982). Geographic coordinates for Central American localities (Guatemala and Honduras, 33.4% for *T. lineata* subsp. *chalicophila*) were obtained, updated, or corrected using GeoNames (http://www.geonames.org). The georeferences were obtained with a precision of 0.01°, which represents the resolution of the grid-cell used in the layers for the ecological niche modeling.

Environmental data sets

To characterize present environmental conditions of the *T. lineata* subspecies, we used 19 environmental bioclimatic variables with a resolution of $0.083° \times 0.083°$ (approx.1 km^2 × 1 km^2) per pixel. These layers correspond to interpolated mean information from 1950 to 2000 from climate stations around the world (Table 1, http://www.worldclim.org, Hijmans et al. 2005). Future climates were used via parallel data sets containing the same layers summarizing four general circulation models (GCM: CCCMA: CGCM2; CSIRO: MK2; HCCPR: HADCM3; and NIES99) for years 2020, 2050, and 2080, in two gas emission scenarios based on socioeconomic factors (A2a and B2a) generated by the Intergovernmental Panel on Climate Change (IPCC 2001). Future layers were obtained from the Centro Internacional de Agricultura Tropical (CIAT, Ramírez-Villegas and Jarvis 2008) and were downscaled using the delta method (Ramírez-Villegas and Jarvis 2010), which is based on the sum of interpolated anomalies to high resolution monthly climate surfaces from Worldclim (Hijmans et al. 2005). The method produces an interpolated surface of the climate anomalies that is applied to the baseline climate; it considers the bias owing to different baselines (Ramírez-Villegas and Jarvis 2010). Although this method assumes continuity in climates over large distances, we decided to use these environmental layers because they were generated based on the same information as the present climate layers and they represent the only source of downscaled grid information in the region.

Ecological niche modeling

We generated ecological niche models based on the genetic algorithm for rule-set production (GARP) through the OpenModeller interface (De Sousa-Muñoz et al. 2011). GARP is a method widely used in climate change studies because of its capacity to project information in situations statistically independent of the training data (Peterson et al. 2008). It is based on an evolutionary computing method that builds ecological niche models through nonrandom associations between biological data and environmental layers. The performance of the model is based on the creation of rules in an iterative process. The first rule is created randomly from a set of inferential tools (atomic, range, and logistic regression); the genetic algorithm then modifies the initial rules through specially defined operators (e.g., crossover mutations) originating a new set of rules that have been modified (evolved). For each generation, the rules are tested and a limited number of the best rules are retained to be modified in the next generation. The evaluation of the rules is made intrinsically in the process, which is the reason to keep an independent verification (extrinsic testing data set) that gives more reliable estimation of the rule performance (Stockwell and Noble 1992; Stockwell and Peters 1999). The result is a set of rules projected on a map that have a geographic representation of the ecological niche of the taxon; in this study we projected the rules not only based on the present layers but also in each of the GCM and emission scenarios.

The biological data set was split so that 80% of occurrence data were used to train the model (training data) and the remaining 20% was used as an independent data set or extrinsic testing data. We used a limit of convergence where the rules produced do not improve models by more than 1% and a maximum of 1000 iterations, to obtain 100 models for each taxon analyzed. Each model was evaluated through a threshold-dependent test (χ^2), which is used to approximate the binomial probability (Peterson et al. 2011). Once the models were generated, we decided to keep only those models that presented less omission error and a moderate commission error (best subsets), which according to Anderson et al. (2003) represent the models with the best performance. We considered 10% of omission as possible errors in the georeferencing of biological data, which is a very common problem in old specimens housed in scientific collections (Murphey et al. 2004).

Model evaluation

We evaluated the ability of models to predict independent test points accurately based on the receiver operating characteristics curve (Fielding and Bell 1997), which is a threshold-independent test to evaluate the final model generated on the best subsets obtained by the GARP. Receiver operating characteristics curves consider commission and omission errors in different thresholds, and they also consider the area under the curve (AUC) as the value to examine them that is formed when comparing those errors (AUC < 0.5 indicates only true or absence evaluation data better than expected by chance).

Model comparison

To compare the models in a temporal series, we used an ensemble–consensus approach (Araújo and New 2006). The calculation of potential effects of climate change was based on the variation (2020, 2050, and 2080) that could be found in each pixel with respect to the present prediction, generating different comparisons considering separately two emission scenarios (A2a and B2a). The assessment of the variation of models in relation to the current range was analyzed by the range lost and the range gained, hypothesizing that both subspecies could reach new potential sites. Visualization of the resulting maps was done using ArcView 9.3 (ESRI 2009).

Table 1. Bioclimatic variables, derived from temperature and precipitation, used in the analysis.

Bio1	Annual mean temperature
Bio2	Mean diurnal range (mean monthly min. temp. – mean monthly max. temp.)
Bio3	Isothermality (Bio2 / Bio7) × (100)
Bio4	Temperature seasonality (standard deviation × 100)
Bio5	Maximum temperature of the warmest month
Bio6	Minimum temperature of the coldest month
Bio7	Temperature annual range (Bio5–Bio6)
Bio8	Mean temperature of the wettest quarter
Bio9	Mean temperature of the driest quarter
Bio10	Mean temperature of the warmest quarter
Bio11	Mean temperature of the coldest quarter
Bio12	Annual precipitation
Bio13	Precipitation of the wettest month
Bio14	Precipitation of the driest month
Bio15	Precipitation seasonality (coefficient of variation)
Bio16	Precipitation of the wettest quarter
Bio17	Precipitation of the driest quarter
Bio18	Precipitation of warmest quarter
Bio19	Precipitation of coldest quarter

Note: Values of the bioclimatic variables correspond to the means of climatic stations from 1950 to 2000 (http://www.worldclim.org, Hijmans et al. 2005). Temperature values are °C × 10, while precipitation is measured in millimetres.

Determination of important variables

We analyzed the present distribution of both subspecies in relation to the environmental variables through a recursive partitioning analysis, which is a statistical technique based on nonparametric regression methods (Zhang and Singer 2010), because the rules generated in GARP are not explicit and it is not possible to access them (they are only an intrinsic part of the algorithm). In this case, a classification and regression tree was used to identify the most important variables for explaining the potential distributions in the present time.

We resampled the extent of each subspecies using a point net separated every 0.5°. This net represented the original proportion of the present/absent pixels that formed the potential distributions. To identify the important variables, it was necessary to avoid correlation among them. Using a correlation matrix in PAST 2.14 (Hammer et al. 2001), we were able to eliminate eight variables highly correlated for each subspecies (Bio1, Bio4, Bio5, Bio6, Bio8, Bio9, Bio16, and Bio17 for *T. lineata* subsp. *lineata*, and Bio1, Bio5, Bio6, Bio8, Bio9, Bio11, Bio16, and Bio17 for *T. lineata* subsp. *chalicophila*). With the remaining variables, we generated a classification and regression tree using JMP 9 (SAS Institute Inc. 2010); also the presence and absence data from the resampled point data and the noncorrelated variables were analyzed. The analysis produced a decision tree (represented in Tables 2 and 3), where it is possible to identify the variable values and the percentage of contribution for each subspecies by maximizing the sum of the squares between groups and, at the same time, minimizing the sum of squares within groups (SAS Institute Inc. 2010). The values in the analysis are shown as cumulative probability, explaining more than the 96% of the resampled data in both subspecies.

Results

Our database comprises 263 spatially unique records for *T. lineata* subsp. *lineata* distributed in the mountainous zones

Table 2. Probabilities of presence according to the recursive partitioning analysis of environmental values and variables for *Ternstroemia lineata* subsp. *lineata.*.

Cumulative environmental variables	Cumulative probability	Contribution (%)
Bio12 ≥ 718	0.34	0.34
Bio10 < 249	0.72	0.38
Bio12 < 2154	0.78	0.06
Bio12 ≥ 848	0.85	0.07
Bio11 ≥ 100	0.9	0.05
Bio11 < 205	0.93	0.03
Bio15 < 110	0.96	0.03
Bio12 < 1862	0.97	0.01

Table 3. Probabilities of presence according to the recursive partitioning analysis of environmental values and variables for *Ternstroemia lineata* subsp. *chalicophila.*.

Cumulative environmental variables	Cumulative probability	Contribution (%)
Bio10 < 232	0.33	0.33
Bio18 ≥ 419	0.46	0.13
Bio19 < 228	0.62	0.16
Bio15 < 89	0.72	0.10
Bio12 < 2067	0.78	0.06
Bio10 ≥ 125	0.83	0.05
Bio18 ≥ 435	0.89	0.06
Bio14 ≥ 9	0.93	0.04
Bio14 < 37	0.96	0.03
Bio10 < 207	0.99	0.03

of Mexico (except Sierra Madre Oriental) (Fig. 1) and 32 spatially unique records for *T. lineata* subsp. *chalicophila*, which has a restricted distribution in the mountainous zones of Chiapas and northern Central America (Fig. 2).

The AUC obtained from the receiver operating characteris-

Fig. 1. *Ternstroemia lineata* subsp. *lineata*. Black points represent the biological data used in the analysis and gray areas represent the potential distribution in the present.
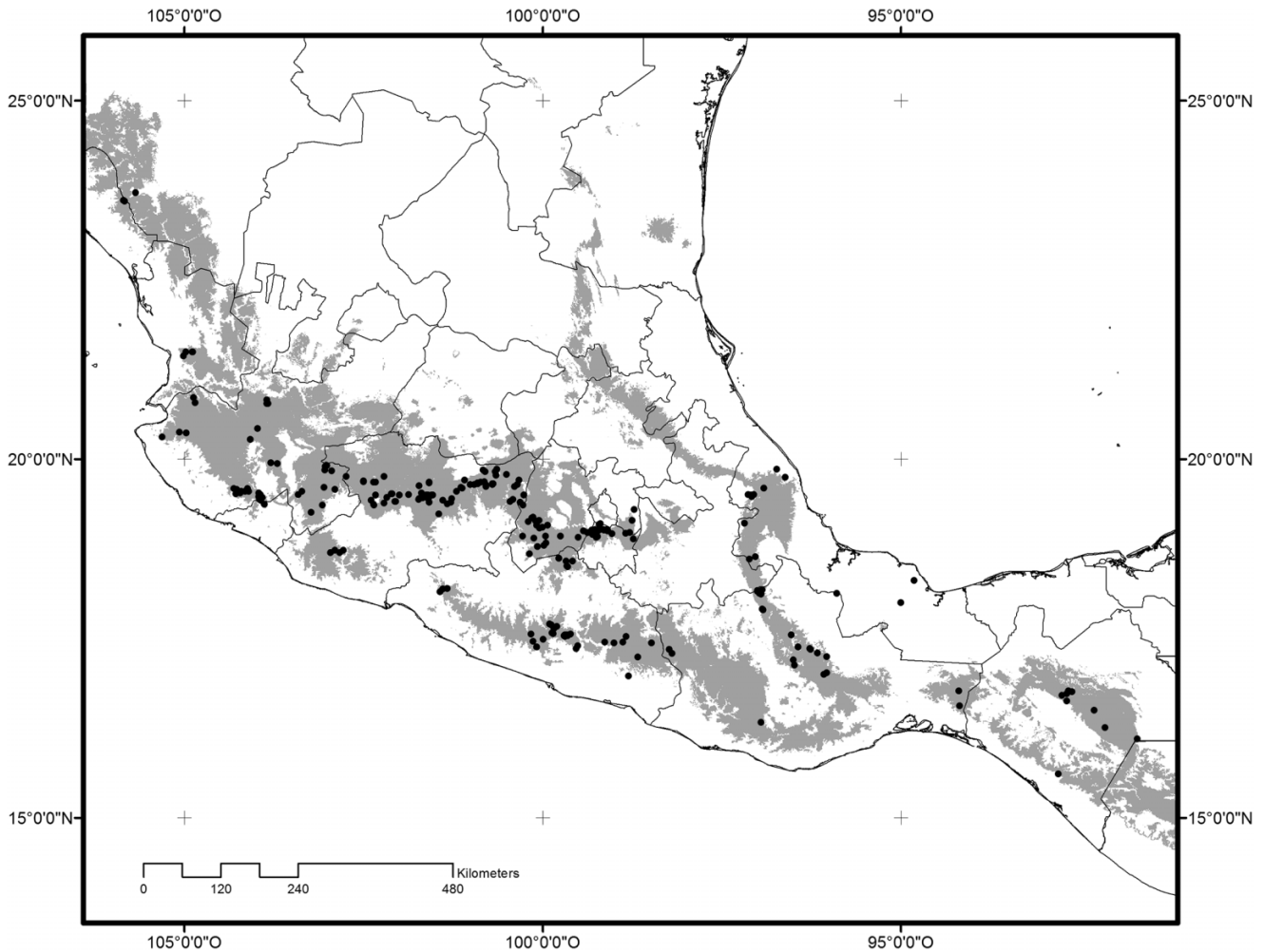
tics analyses showed that the models performed well and had a high predictive accuracy, compared to a null model (*T. lineata* subsp. *lineata* AUC = 0.91 and *T. lineata* subsp. *chalicophila* AUC = 0.90).

The recursive partitioning analysis showed that different values and combinations of Bio10 and Bio12 were the most informative bioclimatic variables for *T. lineata* subsp. *lineata* explaining up to 85% of its present distribution. The present distribution of *T. lineata* subsp. *chalicophila* was explained by a great number of variables, with Bio10, Bio18, and Bio19 explaining 62% of the distribution. Comparing both subspecies, we suggest that 96% of the distribution of *T. lineata* subsp. *lineata* may be explained with four variables (two related to precipitation and two to temperature), and in *T. lineata* subsp. *chalicophila* there are six different variables involved (one related to temperature and five to precipitation) (Tables 2 and 3).

Comparisons among the four general circulation models in both scenarios for the two subspecies (Figs. 3 and 4) showed a tendency of deterioration of the ecological niche conditions for both subspecies, in relation to the present and increasing with time. In both cases, the A2a scenario presented a more drastic percentage of loss than B2a (Figs. 3*e*, 3*f*, 4*e*, 4*f*), although percentage of current range was maintained

(Figs. 3*a*, 3*b*, 4*a*, 4*b*) and percentage of range gained was similar (Figs. 3*c*, 3*d*, 4*c*, 4*d*).

Ensemble output maps showed congruence between the different GCM in the two emission scenarios (Figs. 5 and 6). In general, there was more congruence among the GCM in both range lost (red) and range gained (blue) when time projection increased. Paler tonalities show the modifications predicted for one model, while darker tonalities illustrate an increase in the consensus. We identified that the emission scenario A2a showed an increase in the consensus in relation to B2a.

The surrounding areas of the current range are the zones prone to be lost in all the GCM, and the availability of range gained is restricted to higher altitudes. In *T. lineata* subsp. *lineata*, some areas maintained the current range in the different year projections in both scenarios; these areas are Sierra Norte de Oaxaca, Sierra Madre del Sur, and Sierra Madre de Chiapas. In addition, some new sites were gained in the central part of the Trans-Mexican Volcanic Belt (Fig. 5). *Ternstroemia lineata* subsp. *chalicophila* is expected to experience dramatic changes in its environmental conditions, leaving some fragments of current range in central Guatemala, and gaining sites in the mountains of southwestern Guatemala (Fig. 6).

Fig. 2. *Ternstroemia lineata* subsp. *chalicophila.* Black points represent the biological data used in the analysis and gray areas represent the potential distribution in the present.
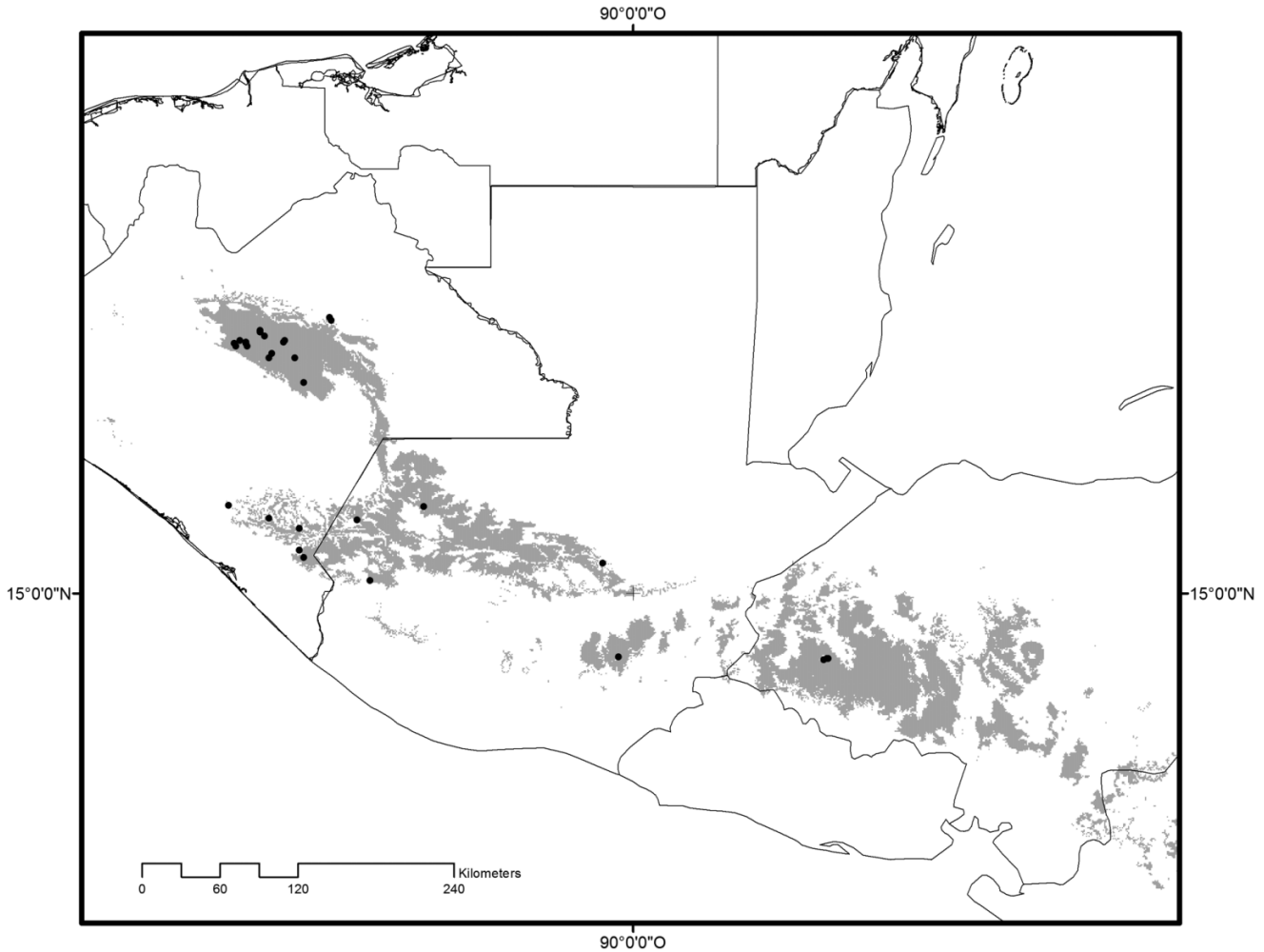
Discussion

This study represents and includes the most complete inventory for *Ternstroemia lineata* made until now. For this reason, we can assume that the geographical range comprised by our point presence data cover the ecological space conditions where the species can live. Consequently, the environmental conditions represented by the ecological models coincide, in general, with the known distribution of both subspecies (Luna-Vega et al. 2006).

As Feeley and Silman (2010) recently stated, species distribution models are essential for predicting the effects of global change on species distribution. These authors have shown the impacts of georeferencing errors, and the need to use rigorous data filters, to avoid the mischaracterization of climatic conditions owing to errors in the collection data, which are particularly problematic in mountainous areas. In this study, the georeferences were obtained with a precision of 0.01°, minimizing many of the problems considered.

Ecological niche modeling has been used to identify distribution areas of the species (e.g., Villaseñor and Téllez-Valdés 2004; Contreras-Medina et al. 2010). However, the geographical distribution of species is influenced by biological interactions and historical factors that are not considered in the

modeling algorithms (Peterson et al. 2002*a*; Illoldi-Rangel and Escalante 2008). For this reason, ecological niche modeling should be interpreted as the geographical representation of environmental conditions required by the species (Peterson 2003; Martínez-Meyer 2005).

Species of Mesoamerican *Ternstroemia* have been stated as quantitatively important to depict cloud forest conditions. Its species are better distributed at altitudes > 1000 m a.s.l. within the Región Mesoamericana de Montaña sensu Rzedowski (1981). These mountainous zones have been proposed as diversification areas for the genus, as well as for other plant genera (e.g., *Cletra*, *Magnolia*, *Meliosma*, *Styrax*, *Simplocos*, *Pinus*, and *Quercus*). These diversification areas are characterized by a high percentage of endemism of other groups like reptiles (Flores-Villela 1998) and birds (Challenger 1998). In this sense, Cracraft and Prum (1988) support that the speciation rate is incremented in areas of high topographic complexity.

Our present results show that ecological niche representation, in general, coincides with the geographic distribution based on herbarium specimens and field work of both subspecies of *T. lineata*, corroborating that niche conditions of the species are represented in the known geographic range (Luna-Vega et al. 2004; CONABIO 2008). There are large

Fig. 3. *Ternstroemia lineata* subsp. *lineata.* Percentage of current range maintained, range gained, and range lost as predicted using presence by pixel for 2020, 2050, and 2080. The two columns represent the scenarios A2a and B2a under the four general circulation models (CCCMA, CSIRO, HADCM3, and NIES99).
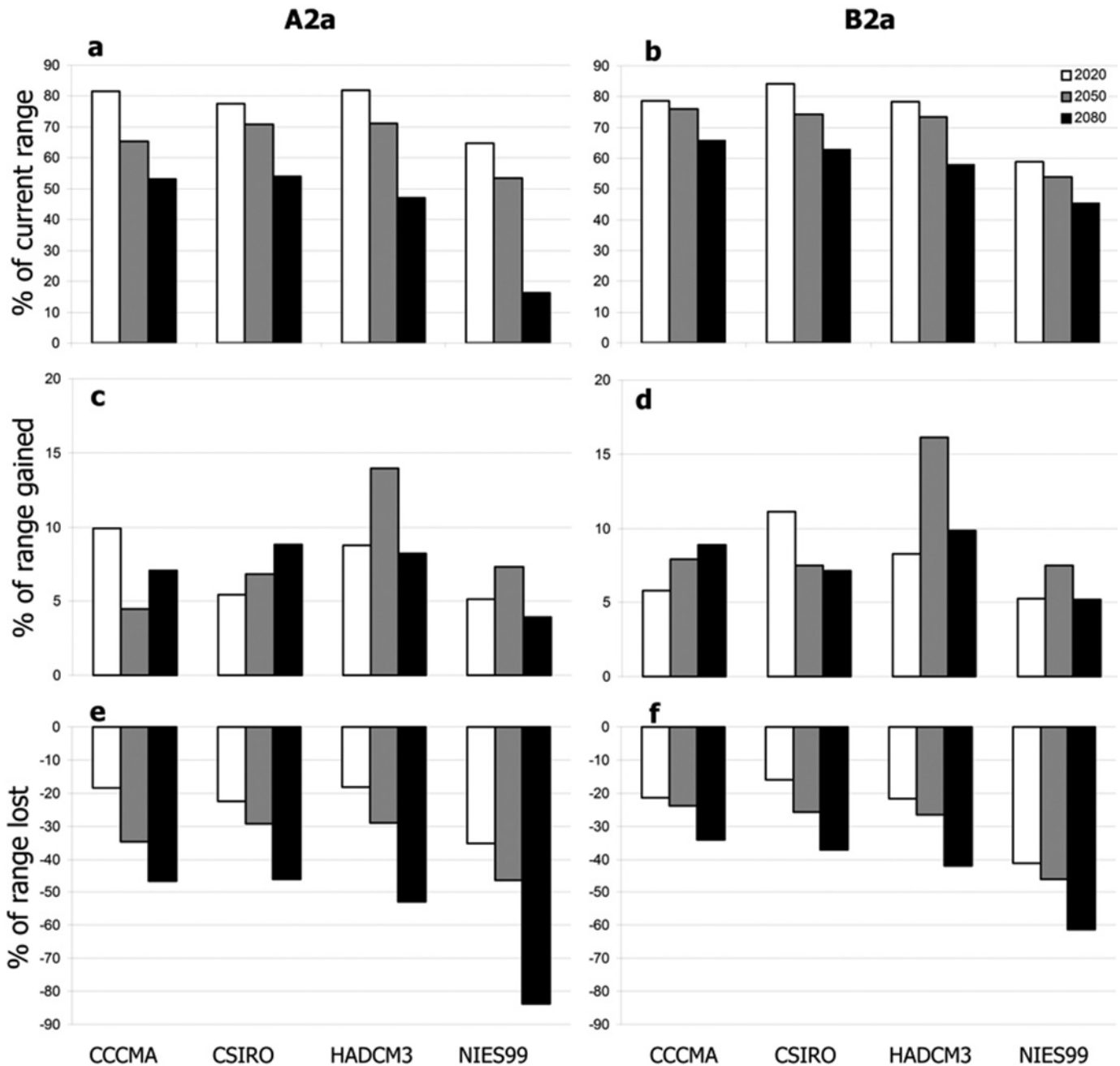

areas where the niche model predicts that both subspecies of *T. lineata* could occur at the present time, but there is no biological information supporting their presence (Figs. 1 and 2). We can attribute these biological gaps to the absence of extensive collection efforts in many of the Mexican mountainous areas (e.g., Sierra Madre Occidental) where floristic inventories are needed. There are other factors influencing the ecological niche models that are difficult to discern in their geographical representation and that could have direct effects on the results obtained, such as grid-cell size of the environmental layers. The environmental layers are generally downscaled from indirect sources (Ramírez-Villegas and Jar-

vis 2010) or obtained from raw data from meteorological stations (Hijmans et al. 2005); in some cases, they are the only source of available information. A different bias could be caused by the modeling algorithm or the evaluation methods used (Lobo et al. 2008; Peterson et al. 2007, 2008).

The determinant variables that explained the ecological conditions in the present time correspond to specific values of precipitation and the mean temperature during the warmest season. These specific variables are characteristic of many diagnostic tree species associated with cloud forests (e.g., *Clethra*, *Magnolia*, *Meliosma*, *Styrax*, and *Symplocos*; Alcántara et al. 2002). The preference of *T. lineata* to relatively hot

Fig. 4. *Ternstroemia lineata* subsp. *chalicophila*. Percentage of current range maintained, range gained and range lost as predicted using presence by pixel for 2020, 2050, and 2080. The two columns represent the scenarios A2a and B2a under the four general circulation models (CCCMA, CSIRO, HADCM3, and NIES99).
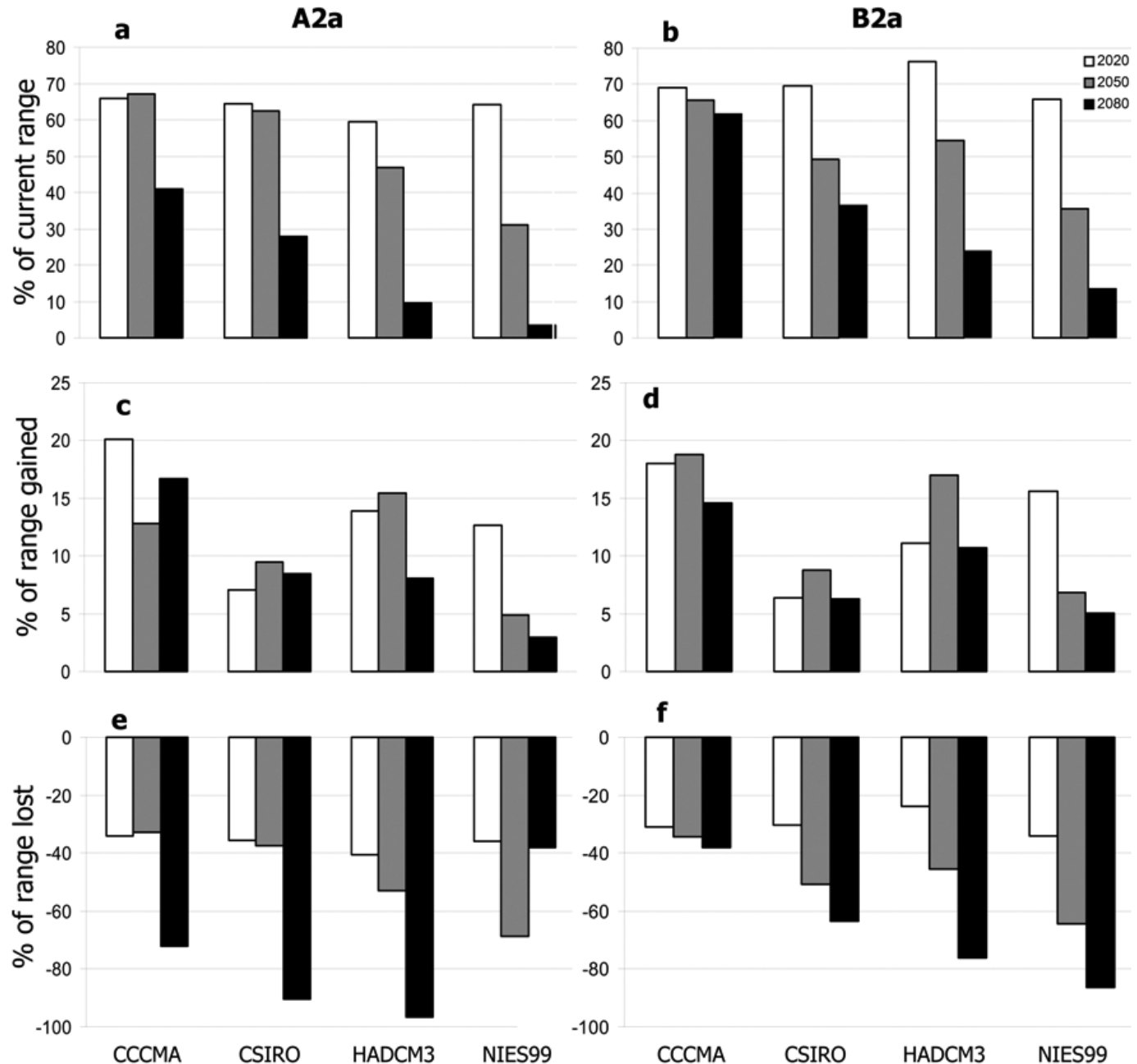

temperatures in the warmest season of the year reflects the preference of both subspecies to specific Mesoamerican cloud forests. Temperature and precipitation conditions vary greatly within the Mesoamerican cloud forests (Rzedowski 1981), following a latitudinal and altitudinal pattern, but also microclimatic and local conditions influence the restrictiveness of these subspecies.

Climate change predictions are only based on the transferability of climatic variables to different temporalities (Peterson et al. 2011); nevertheless, the predictions obtained can indicate new areas where the taxon is not known now, and where validation is impossible because we do not know the adaptation capabilities of the species (Martínez-Meyer 2005).

Our predictions for *T. lineata* in all GCM and the two emission scenarios showed the tendencies of reduction in geographical space through time, which are the consequence of the determinant variables for both subspecies caused by the accumulation of greenhouse gases. Different taxa have shown an upward movement in terms of environmental conditions in an altitudinal perspective, to adapt to the new changing conditions, such as it is expected for both subspecies of *T. lineata* in low altitudes. This is also the case of 50 anuran species in Monteverde, Costa Rica (Pounds et al. 1999), and the volcano rabbit (*Romerolagus diazi* (Ferrari-Pérez in Díaz)), endemic to the central part of the Trans-Mexican Volcanic Belt (Domínguez-Pérez 2006), where changes in envi-

Fig. 5. Range modifications of the ecological niche for *Ternstroemia lineata* subsp. *lineata*. The maps represent the consensus of the general circulation models in range lost (red tonalities) and range gained (blue tonalities) for both emission scenarios (A2a and B2a). Darker colors represent more congruence between general circulation models. Gray color represents the current range maintained through time.
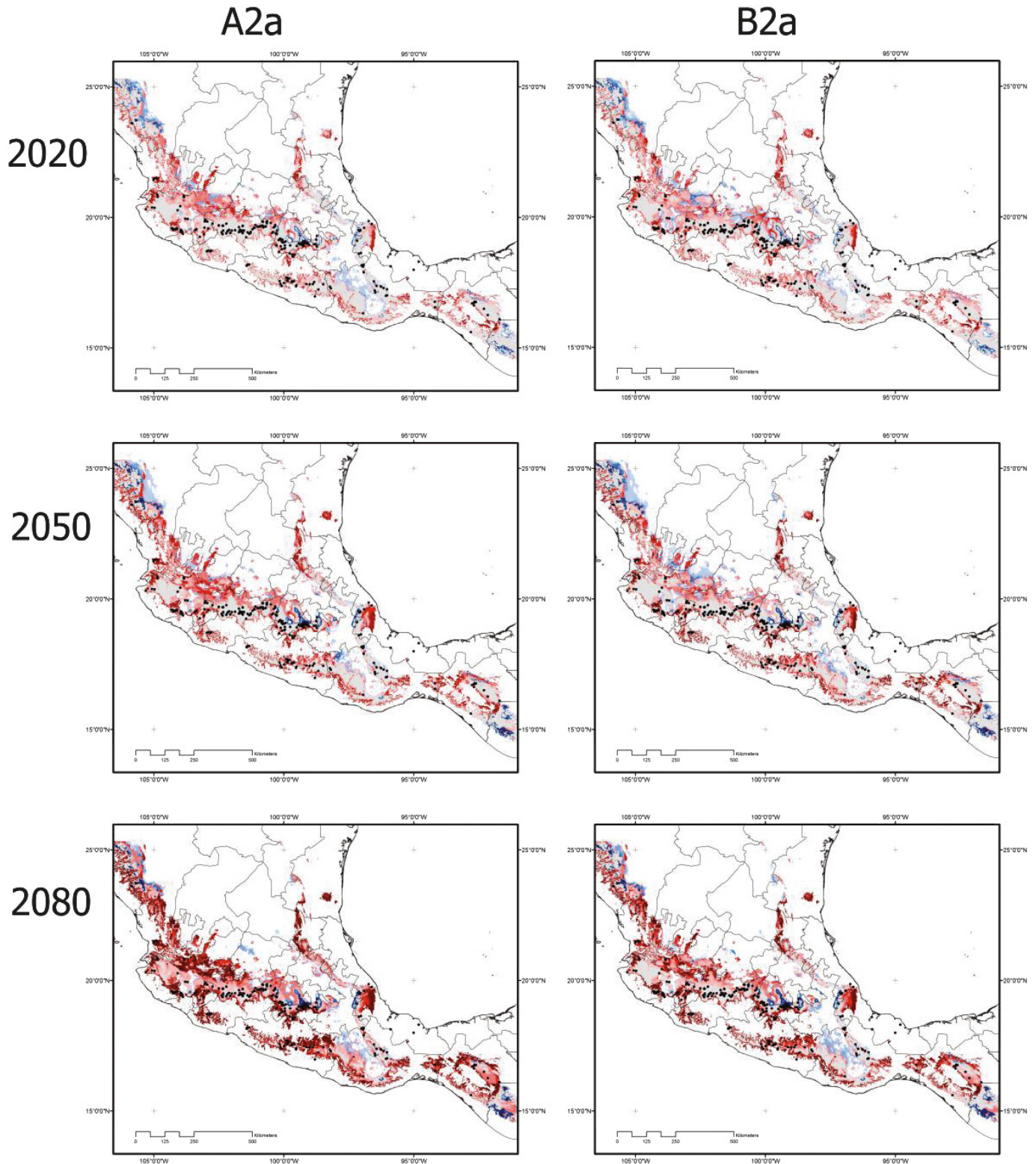

ronmental conditions showed how these species have been moving upwards in recent years.

The modification of important climatic variables could represent a general pattern that illustrates the effects of

changes in environmental conditions of temperate humid montane plant species. Other taxa have been analyzed, such as pines and oaks, where modifications of the environmental conditions are evident in the Sierra Madre Occidental and the

Fig. 6. Range modifications of the ecological niche for *Ternstroemia lineata* subsp. *chalicophila.* The maps represent the consensus of the general circulation models in range lost (red tonalities) and range gained (blue tonalities) for both emission scenarios (A2a and B2a). Darker colors represent more congruence between general circulation models. Gray color represents the current range maintained through time.
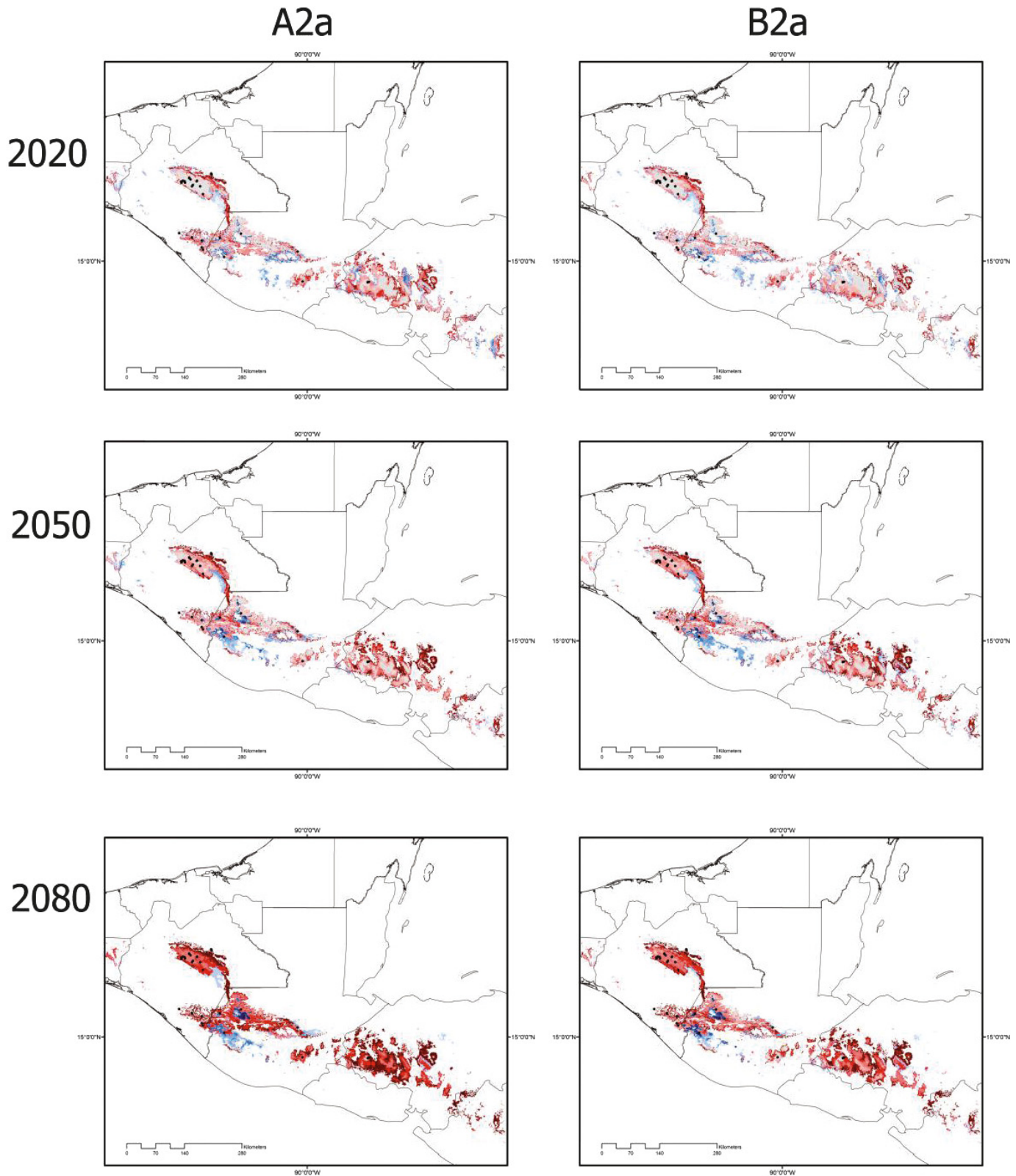
Sierra Madre Oriental (Gómez-Mendoza and Arriaga 2007); however, in this last study, the authors only tested one hypothesis based on a projection to the year 2050, which limits

the understanding in a temporal framework and impedes the comparison of different hypotheses of GCM to evaluate general tendencies. Another example is the reduction by 33.33%

of the expected distribution of *Fagus grandiflora* var. *mexicana* in the Sierra Norte de Oaxaca at high altitudes (Téllez-Valdés et al. 2006).

There is little information concerning biodiversity effects related to climatic change in Central American plants; Still et al. (1999) proposed that a reduction in cloud cover and an increase in evapo-transpiration in tropical montane cloud forests in Costa Rica may cause changes in microclimates (mainly owing to the changes in the height of orographic cloud formation) and a consequent invasion of premontane species. These changes could have serious conservation implications, mainly because these ecosystems harbor a high proportion of endemic species. Recently, Nadkarni (2010) studied the potential effects of global climate change on epiphytes from Monteverde, Costa Rica, concluding that cloud water is required for the maintenance of this epiphytic layer.

Predictions obtained in our study showed important changes in environmental conditions for *T. lineata* subsp. *chalicophila*. It is especially important to study this effect in the Guatemalan Highlands, to promote conservation strategies in this area, where 53% of the flora of Central America is found (Knapp and Davidse 2006).

Some inconsistencies observed in our results may be produced by the transferability of the present conditions to the future scenarios, even if GARP transfers the exact conditions showed in the present time. It is possible to find some combinations of environmental characteristics that do not match with the variable values identified as important in the cumulative probability and that are not necessarily found in the projected scenarios (Pearson et al. 2006). Also, the downscaling of the original resolution of the GCM may produce erroneous information that could be represented in the final models (Russo and Zack 1997). However, these inconsistencies do not alter the general pattern found, showing a severe scenario (A2a) characterized by a high energy requirement, produced by a population increase with economic and technological growth, and another (B2a) where populations are growing, but rates in energy consumption are considered low and energy requirements are moderate (IPCC 2001). It is possible to observe that both taxa predictions to 2050 under HADCM3 GCM showed high discrepancies (Figs. 3*c*–3*d*; 4*c*–4*d*), possibly owing to errors in the calculation algorithms to create the environmental layers, so their interpretation should be considered with care.

Environmental modifications produced by climatic change under both emission scenarios are only hypotheses of the changes in the environmental requirements (niche) of the species. Given that responses to climatic change are individual to each species, there are different possibilities that are not considered in the bioclimatic models (Pearson and Dawson 2003). A crucial factor for the species is the ability to adapt to new conditions or to migrate to new places where the environmental conditions are more favorable (Pearson and Dawson 2003). It is also possible that species do not adapt to new changes, and that the range lost automatically represents the total disappearance, minimally or in part, of its geographical range. In addition, the modification of land use change should be considered, because a species is not only subject to climatic modifications but also can be affected by local conditions that could end the prevalence of the species in some areas (e.g., Peterson et al. 2006; Ríos-Muñoz and

Navarro-Sigüenza 2009; Contreras-Medina et al. 2010). Both factors can considerably affect the survival of species and populations in the future (Ballesteros-Barrera et al. 2007). Other factors that can alter the distribution are biotic interactions, evolutionary change, and dispersal ability (Pearson and Dawson 2003); these are important aspects that must also be considered in a more realistic simulation of the impact of climatic change. Notwithstanding, the importance of ecological niche models should not be underestimated and must be interpreted with caution; these models represent a first approximation to a more complex response to future climatic change (Pearson and Dawson 2003).

Habitat loss is considered a threat for both subspecies, and the values of the most important climatic variables play a crucial role in the identification of the environmental conditions required by them. Use of *T. lineata* as a medicinal plant may represent another threat, but this point has yet not been completely evaluated (e.g., Aguilar-Santamaría and Tortoriello 1996; Balderas et al. 2008). Direct human impact, such as the collection of fruit from the species *T. lineata*, should be considered in conservation plans and in more realistic simulations of the future conditions.

In this study, the two subspecies of *T. lineata* were considered separately. *Ternstroemia lineata* subsp. *lineata* (as *T. lineata*) and *T. lineata* subsp. *chalicophila* (as *T. chalicophila*, or *T. impressa*) were considered to be different lineages by the main experts in the group (e.g., Kobuski 1942). In this study, we observed slight differences between the subspecies, supporting their separation in two different entities.

The results of our study contrast with those obtained by Sperling et al. (2004) for laurel forests because their results do not predict an upward shift of the cloud base.

Important considerations should be taken into account when deciding on conservation strategies. The implementation of natural protected areas does not guarantee the prevalence of species; this fact represents an important task in many Latin American countries, where the greatest percentage of biodiversity of the world is concentrated (i.e., Brazil, Colombia Ecuador, Peru, and Mexico). Unfortunately, political and financial problems make it difficult to maintain and manage natural protected areas (Flores-Villela and Gerez 1994). Modifications in their geographical ranges can mean that the species will lose their distributional and ecological space in protected areas and that they may become vulnerable and restricted to niche conditions in the immediate future.

Our models of potential distributions using 19 environmental parameters associated with plant species distributions and some proposed climate-change scenarios that may occur in the coming years represent an important source of additional information for assessing the role that the natural protected areas should play in long-term conservation (Téllez-Valdés and Dávila-Aranda 2003; Téllez-Valdés et al. 2006).

The Mexican Official Norm NOM-059-ECOL-2010 (SEMARNAT 2010) is the official document published by the Mexican government that lists native threatened taxa, including about 1000 species of Mexican flora; notwithstanding, detailed knowledge of their conservation status exists for only approximately 10% of the species. Ternstroemiaceae is one of many families of vascular plants not yet included in this official document. This family, and many others such as

Styracaceae, Clethraceae, Myrsinaceae, Symplocaceae, and Garryaceae, includes important taxa inhabiting the cloud forests and other temperate humid mountainous vegetation types in Mexico (Luna-Vega et al. 2004). Cloud forest is considered a threatened vegetation type (Churchill et al. 1995; Luna-Vega et al. 2006, 2010; Bruijnzeel et al. 2010). *Ternstroemia lineata* subsp. *chalicophila* is considered a restricted endemic taxon as a result of its known distribution (Luna-Vega et al. 2004). Recently, *T. lineata* subsp. *lineata* and *T. lineata* subsp. *chalicophila* were considered in the Red List of Mexican cloud forest trees (González-Espinosa et al. 2011). However many other possibly sensitive taxa of the about 13 000 endemic species of Mexican flora are not yet included in conservations lists by any National or International agencies.

The Mexican Official Norm NOM-059-ECOL-2010 (SEMARNAT 2010) applies several criteria originally proposed in 2000 by the IUCN (2010) and modified by the Comisión Nacional para el uso y conocimiento de la Biodiversidad (CONABIO) to include threatened taxa for protection. The evaluation within the NOM-059-ECOL-2010 is based on a risk evaluation method comprised of four different criteria. The conservation status of many Mexican plant and animal taxa is uncertain because they are not considered rare or endangered by official world and national agencies, owing to the absence of detailed conservation assessments (Luna-Vega et al. 2010). Many protected areas of the country are not significant in terms of protection of biodiversity and they do not perform their role in conservation because they were assembled over the past 60 years as a result of a wide variety of motivations, including historical significance, recreational use, scenic beauty, and watershed protection (Peterson et al. 2000); rarely has the conservation of key species or biodiversity been considered (Jackson et al. 2009). Improved strategies are necessary for long-term conservation of Mexican biodiversity where actions carried out in these protected areas play a major role in their maintenance and preservation. Fifteen species of *Ternstroemia* from other parts of the world are included in the IUCN Red List of Threatened Species, mainly from the Greater Antilles and Indonesia. Recently, six species of Mexican *Ternstroemia* were included in the Red List of Mexican cloud forest trees (González-Espinosa et al. 2011).

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