Biodiversity and Conservation (2006) 15:1095–1107
DOI 10.1007/s10531-004-1868-4

The effects of climate change on the long-term conservation of *Fagus grandifolia* var. *mexicana*, an important species of the Cloud Forest in Eastern Mexico

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Received 23 July 2003; accepted in revised form 22 July 2004

Key words: BIOCLIM, Bioclimatic modeling, Climate change, Cloud forest, *Fagus*, Sierra Madre Oriental

Abstract. We examined the effects of climate change on the future conservation and distribution patterns of the cloud forests in eastern Mexico, by using as a species model to *Fagus grandifolia* Ehr. var. *mexicana* (Martínez) Little which is mainly located in this vegetation type, at the Sierra Madre Oriental. This species was selected because it is restricted to the cloud forest, where it is a dominant element and has not been considered for protection in any national or international law. It is probably threatened due to the fact that it plays an important social role as a source of food and furnishing. We used a floristic database and a bioclimatic modeling approach including 19 climatic parameters, in order to obtain the current potential distribution pattern of the species. Currently, its potential distribution pattern shows that it is distributed in six different Mexican Priority Regions for Conservation. In addition, we also selected a future climate scenario, on the basis of some climate changes predictions already proposed. The scenario proposed is characterized by +2 °C and −20% rainfall in the region. Under this predicted climatic condition, we found a drastic distribution contraction of the species, in which most of the remaining populations will inhabit restricted areas located outside the boundaries of the surrounding reserves. Consequently, our results highlight the importance of considering the effects of possible future climate changes on the selection of conservation areas and the urgency to conserve some remaining patches of existing cloud forests. Accordingly, we believe that our bioclimatic modeling approach represents a useful tool to undertake decisions concerning the definition of protected areas, once the current potential distribution pattern of some selected species is known.

Introduction

The cloud forests represent one of the most interesting biological systems in the Neotropical region (Luna et al. 1999). They are usually rare, vulnerable and threatened in the world. Its northern distribution limit is the Sierra Madre Oriental, in the state of Tamaulipas, Mexico (Briones 1991) and its southern one reaches Argentina (Webster 1995).

In Mexico, the cloud forests are characterized by being island-like or archipelagic. In other words, they are arranged in isolated patches that usually bear a rich flora, with many endemic species (Rzedowski 1996; Luna et al. 2001).

In the last years, the interest for studying the cloud forests, in particular their species richness and conservation, has been raised (Churchill et al. 1995). The reason for this interest is based on the high rates of deforestation and loss of cloud forests due to the introduction of cultivars, especially coffee (Moguel and Toledo 1999), but also to its irrational use for other agricultural activities, as well as for forestry and cattle farming purposes. It is recognized that these forests are threatened all over the world and that the damage that they have suffered is irreversible, due to their high disturbance vulnerability (Luna et al. 1988; McNeely et al. 1995). Fortunately, many of these forests are restricted to inaccessible sites in the mountains and consequently, they are still present and reasonably well conserved. In contrast, those located in places where human being has access have been drastically transformed to secondary pasture and cultivated lands.

A few former studies have attempted the identification of priority areas for the conservation of the Mexican cloud forests, using Parsimony Analysis of Endemicity and other biogeographic approaches (Morrone and Crisci 1995; Morrone and Espinosa 1998). Even though these studies have highlighted the importance and need to protect the cloud forests, they have not considered either the probable effects that the climatic change might cause in their future survival, conservation and distribution patterns, nor the proposal of some general conservation strategies to be undertaken in the coming years. We believe this information is very relevant, in order to focus our efforts and resources to undertake accurate long-term conservation actions that can assure the survival of these unique plant communities.

In particular, we decided to use *Fagus grandifolia* var. *mexicana* as our study model, due to its restricted distribution to the cloud forests. Although, this taxon has been also treated as *F. mexicana* (López and Cházaro 1995), *F. grandifolia* Ehrh. var. *mexicana* (Martínez) Little (Little 1965; Alcántara and Luna 2001), *F. grandifolia* Ehrh. (Johnston et al. 1989), or even as the subspecies *Fagus* subsp. mexicana (Shen 1992) that has not yet been published, we recognize the former as the accepted name.

In accordance with the fossil record, *Fagus grandifolia* was present in eastern Asia during the late Oligocene and in western North America, including Alaska, during late Oligocene and early Miocene. However, its current distribution pattern is restricted to eastern North America (Canada and United States) and small patches of Mexico (Tamaulipas, Hidalgo, Veracruz y Puebla). The latter represent relictual areas of a former extensive cloud forest of *Fagus grandifolia* (Pérez 1994).

Fagus grandifolia Ehrh. var. *mexicana* used to be a dominant and common tree representative of some of the Mexican cloud forests (Williams et al. 2003). Some of these cloud forests are restricted to the Sierra Madre Oriental, from the state of Tamaulipas in northeastern Mexico to the states of San Luis

Potosí, Querétaro, Hidalgo, Puebla and Veracruz in central-eastern Mexico. In addition, we suspect that the species might be also present in the state of Oaxaca (Figure 1), but further fieldwork should be done to prove it. Even though, *Fagus grandifolia* var. *mexicana* is restricted to the cloud forests and plays an important social role, as a source of food and for furnishing activities (Malda 1990), it has not been considered as either a rare, threatened or endangered species (Vovides et al. 1997; Oldfield et al. 1998; Williams et al. 2003). However, some authors have already suggested the species rareness (Malda 1990; López and Cházaro 1995). In particular, Perez (1994, 1999) considers that the species is endangered at the national level. He estimates that the total number of individuals of the species existing at the present is below 20,000. He also points out that the largest and most heterogeneous, genetically speaking, population is located at the state of Hidalgo, where 50% of the total number of individuals estimated for the country is located in this area. In addition, all these authors have highlighted the lack of nation and international laws for protecting and/or conserving the species.

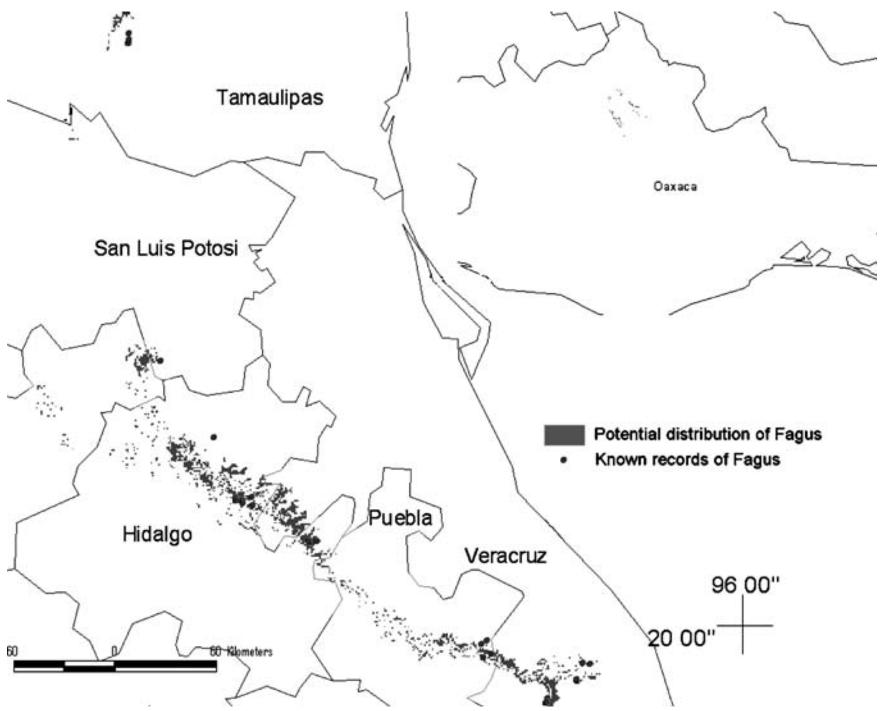

Figure 1. Model of the potential distribution of *Fagus grandifolia* var. *mexicana*, on relationship to the known records. On the right corner the potential distribution of the species in the state of Oaxaca is shown.

Some recent data documenting the wild populations status of the species have been generated, especially in the states of Tamaulipas, Hidalgo and Veracruz (Williams et al. 2003). In some sites the species is considered extinct, whereas, in other places there are still some small patches of what used to be a cloud forest of *Fagus grandifolia*. So far, the species has not been recorded in the cloud forests of Querétaro, which is a neighbor state of Hidalgo and San Luis Potosí and bears similar environmental conditions for hosting the species. Probably the absence of *Fagus* in Querétaro is due to physiographic differences as suggested by Cartujano et al. (2002). However, it might be also possible that the species has been misidentified due to its morphological similarity to *Carpinus* sp., *Ostrya* sp. or *Ulmus* sp., as has been suggested by López and Cházaro (1995).

Thus, the purpose of this work is to undertake a comprehensive review of the current situation of the cloud forests in eastern Mexico by using *Fagus grandifolia* var. *mexicana* as our species model. Consequently, we attempted to undertake the following actions: (1) to document the current recorded distribution of the species in Mexico; (2) to obtain the potential distribution patterns of the species; (3) to assess the effects that the potential distribution pattern of the species might have, under a climatic change scenario; (4) to evaluate the role that the Protected Natural Areas and the Priority Regions of Mexico will be playing for the long-term conservation of cloud forests; (5) to propose a general strategy for attempting the conservation of the oriental Mexican cloud forests.

Accordingly, the approach of this work includes the utilization of bioclimatic models that enable to explain the current situation of the eastern cloud forests of Mexico, on the basis of the potential distribution pattern of a representative species (*Fagus grandifolia* var. *mexicana*) that is used as a model. In addition, we present an attempt to assess the future distribution of the cloud forests, using the species data, once a predicted scenario due to climatic change is included (Téllez and Dávila 2003).

Methods

The plant geographic distribution information that we used in this analysis was obtained from the database of the World Information Network of Biodiversity (REMIB) (http://www.conabio.gob.mx/remib/doctos/remibnodosdb.html). The herbarium data were obtained from the National Herbarium of Mexico (MEXU), from 29 specimens that beard geo-referenced information (i.e. complete latitude, longitude, and elevation). The taxonomical identification of the specimens was undertaken by Drs. Shen Shung-Fu and Kevin Nixon who are important specialists of the Fagaceae. On the other hand, the information concerning the vegetation structure and ecological attributes of the species that is included in the discussion of this work was obtained from relevant literature (Malda 1990; López and Cházaro 1995; Luna et al. 2000; Williams et al. 2003).

The bioclimatic modeling approach used in this work was that of the program ANUCLIM (Houlder et al. 2000). The program uses mathematically and statistically interpolated climatic surfaces (digital files in raster format) that were estimated using the information obtained from a standard network of meteorological stations. The climatic surfaces or digital files were generated using thin plate smoothing spline methods in the ANUSPLIN package (Hutchinson 1991, 1995a, b, 1997; Hutchinson and Gessler 1994). These surfaces include long-term monthly mean values of precipitation and temperature from more than 6200 stations (4000 stations including temperature data and 6000 including precipitation data from the same set of stations). The estimated mean errors for those surfaces were between 8 and 13% for monthly precipitation values and about 0.4–0.5 °C for temperature values. These errors are similar to those found in the standard meteorological instruments (Nix 1986).

We produced a bioclimatic profile for *Fagus grandifolia* var. *mexicana*, using the program BIOCLIM. The derivation of the bioclimatic profile was based on selected-simple-matching thresholds. The values for each of the 19 bioclimatic parameters (Table 1), were assessed by a systematic scanning throughout a grid of data points. We used the profile to predict potential distribution pattern of the species. Using the homoclime matching principle, we identified those points on the climate grid, where the climatic conditions were present within the limits summarized in the bioclimatic profile of the species (Booth et al. 1987).

We matched the bioclimatic profiles against a grid of data points that contained climatic data from the existing network of stations (bioclimatic

Table 1. Bioclimatic profile of *Fagus grandifolia* var. *mexicana* (Fagaceae).

Parameter	Minimum–maximum (Mean ± SD)
Annual mean temperature (°C)	13.4–22.2 (16.6 ± 2.09)
Mean diurnal range (°C)	8.2–15 (11.5 ± 1.88)
Isothermality (2/7) (°C)	0.54–0.62 (0.59 ± 0.02)
Temperature seasonality (C of V) (%)	0.61–1.1 (0.78 ± 0.17)
Maximum temperature of warmest period (°C)	22.4–33.5 (26.3 ± 3.04)
Minimum temperature of coldest period (°C)	5–9.9 (6.8 ± 1.16)
Temperature annual range (5–6) (°C)	14.5–24.4 (19.5 ± 2.93)
Mean temperature of wettest quarter (°C)	14.3–24.7 (18 ± 2.72)
Mean temperature of driest quarter (°C)	12.3–19.5 (14.6 ± 1.59)
Mean temperature of warmest quarter (°C)	15.5–25.6 (19.1 ± 2.48)
Mean temperature of coldest quarter (°C)	11–17.6 (13.4 ± 1.4)
Annual precipitation (°C)	824–2458 (1401 ± 367.19)
Precipitation of wettest period (°C)	46–127 (75 ± 17.59)
Precipitation of driest period (°C)	0–15 (1 ± 3.67)
Precipitation seasonality (C of V) (%)	66–88 (77 ± 7.28)
Precipitation of wettest quarter (°C)	418–1164 (691 ± 168.35)
Precipitation of driest quarter (°C)	52–201 (109 ± 42.39)
Precipitation of warmest quarter (°C)	243–647 (397 ± 78.18)
Precipitation of coldest quarter (°C)	52–239 (126 ± 54.41)

parameters file). We used a regular grid of 30 arc seconds (0.00083° or approximately 1 km^2) of spatial resolution.

The geocoding errors were detected using the program ArcView 3.2. In addition, for a more detailed detection of anomalies and potential errors on the bioclimatic profiles, we used the program BIOCLIM (Houlder et al. 2000). Whenever possible, we corrected errors by using a 1:50,000 scale topographic maps. Fortunately, a single anomalous record was detected and removed.

Finally, although the magnitude of climate change is uncertain and many different future scenarios have been proposed, we generated just one climate scenario, as proposed by Karl (1998) and some other authors, whom have predicted similar future climatic conditions (Canziani and Diaz 1998; Giorgi et al. 1998; Neilson 1998). The program BIOCLIM was used, in order to set up the proposed future climate change scenario (year 2050), which shows a temperature increment of 2 °C and a precipitation decrement of 20%, for any given present point, at the latitude and longitude where the range and the localities of the species are located.

For inserting the climate change scenario, we produced a grid of indices in ARCINFO ASCIIGRID format through the BIOCLIM program and the Digital Elevation Model (DEM). The predicted distribution patterns of the selected species were plotted to represent the future potential distribution patterns found, after climate change conditions were entered. In this paper we only present the results of an extreme scenario for assessing the role the Priority Regions for Conservation (PRCs) proposed by CONABIO (Arriaga et al. 2000), will play in the future. The area covered by the potential distribution of the species was calculated with ArcView 3.2 (ESRI 2000).

Results

The results obtained suggest that the present distribution pattern known for *Fagus grandifolia* var. *mexicana*, is indeed correct and complete, due to the fact that in all cases, the collecting sites fitted within the limits of the potential distribution area obtained in the analysis (Figure 1). Thus, the species is restricted to the Sierra Madre Oriental from the state of Tamaulipas to southern Veracruz, as has been stated by Williams et al. (2003). However, on the basis of the potential distribution assessment of the species, we believe that probably its southern limit might extend to the state of Oaxaca.

However, field verifications should be done before we can assure it (Figure 1). The results also point out that the species is restricted to unique climatic conditions in the Sierra Madre Oriental, as it is shown in its bioclimatic profile (Table 1). Its climatic uniqueness represents the specific spots or areas along the Oriental Sierra Madre where it can grow. In other words, although we state that *Fagus grandifolia* var. *mexicana* grows along the Sierra Madre, the fact is that it only grows in some specific areas that have a unique combination of climatic attributes and do not grow in others that have other climatic features.

On the basis of the species current potential geographic range, it is evident that it would be distributed in six Priority Regions for Conservation (Arriaga et al. 2000): (1) El Cielo Biosphere Reserve in the State of Tamaulipas, (2) Sierra Gorda-Río Moctezuma in the State of Querétaro, (3) Cloud Forest of the Sierra Madre Oriental in the States of Hidalgo, Veracruz and Puebla, (4) Cuetzalan in the State of Puebla, (5) Pico de Orizaba-Cofre de Perote in the State of Veracruz and, (6) Oaxacan northern Sierra.

The current potential distribution model of *Fagus* (the climatically suitable environments for the development of this species), covers about 5800 km^2. However, once the climate change scenario was introduced, its potential distribution pattern contracts drastically in more than 66%. The remaining sites that will be suitable for the establishment of *Fagus* populations will be covering about 1700 km^2 or in other words, about 1/3 of the original potential distribution range, including parts of the states of Querétaro, Hidalgo, Puebla, and a very small portion of the state of Veracruz (Figure 2).

Due to its drastic distribution pattern contraction, the remaining *Fagus* patches will probably coincide with only three of the Priority Regions for Conservation (PRCs 2, 3 and 4) in the states of Querétaro, Hidalgo and Puebla and none will be present in the state of Veracruz (Figure 2).

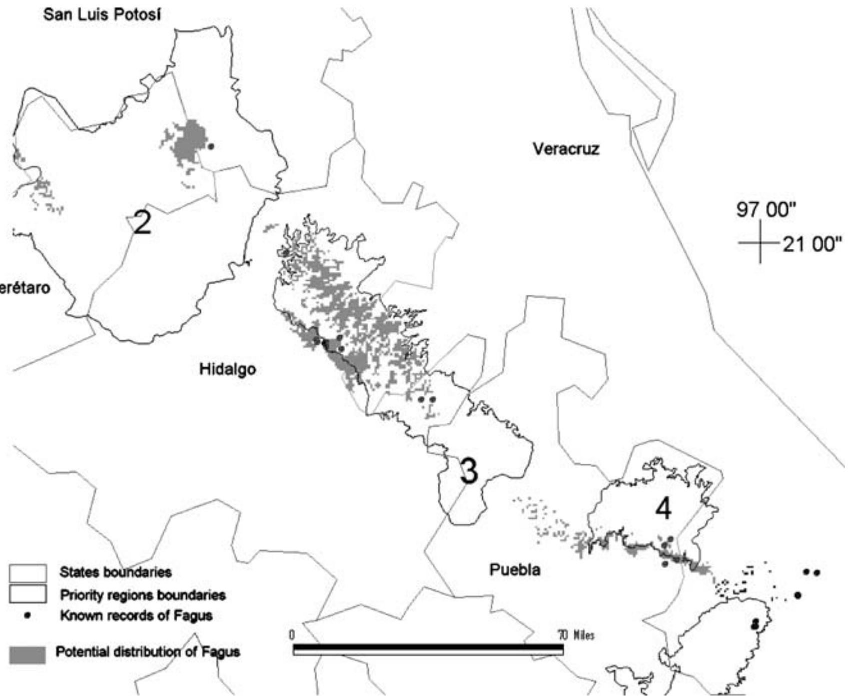

Figure 2. Model of the potential distribution of *Fagus grandifolia* var. *mexicana* on relationship to the Priority Regions for Conservation (CONABIO), once the proposed climate change scenario was entered.

Discussion

Independently of the taxonomical uncertainty of the studied taxon (whether it is a species, a variety or a subspecies), evidently, it is seriously threatened due to its intensive wood extraction, habitat fragmentation and the expansion of the agricultural land use in areas where it naturally grows. In addition, its restricted presence in the cloud forests increases its risk.

Currently, the populations of *Fagus grandifolia* var. *mexicana* are distributed within the boundaries of at least five Priority Regions for Conservation (Arriaga et al. 2000), although the one from Oaxaca, remains to be proved. From them, the El Cielo Biosphere Reserve represents the only Protected Natural Area that has been officially declared. Consequently, the future protection of the cloud forest, *Fagus grandifolia* var. *mexicana* and other animal and plant species of the area is uncertain.

The protection uncertainty of *Fagus*, has already been pointed out by Williams et al. (2003) and mentioned the extinction of the species populations from Teziutlán, Puebla. In the case of the populations located at the Biosphere Reserve of El Cielo, in the state of Tamaulipas, the agricultural and cattle farming activities have caused a dramatic reduction of the cloud forest.

Now, when the climatic change scenario is added to the current situation, the questions to be answered are the following: (1) Is it feasible to have a long-term conservation strategy to protect the cloud forest of the state of Tamaulipas and Puebla? and (2) Where do we have higher probabilities of conserving well-preserved cloud forests in Mexico?

It is clear that the cloud forest of Tamaulipas is already under strong disturbance pressures and consequently its structure and diversity has been already drastically altered. On the other hand, we believe that these communities are currently less modified in the states of Querétaro and Hidalgo. Now, if in addition, the climate changes occur as it is proposed, the results obtained show that these states also seem to be the adequate cloud forest reservoirs, as has been partially suggested formerly by Luna et al. (2000).

Alcantara and Luna (1997), mentioned that Hidalgo represents the state where the cloud forests in Mexico reach their larger extent. They also pointed out that in the central-eastern part of Hidalgo, this plant community still remains in the form of wealthy patches that cover around 100 km^2 or more. In these patches, a total of 114 families, 301 genera and 452 species have been recorded by them. Several species of the region are listed in the Mexican Norm NOM-059-ECOL-2000 (Anónimo 2000), as vulnerable or in danger of extinction, such as *Cyathea fulva*, *Deppea hernandezii*, *Nopalxochia phyllanthoides*, *Magnolia schiedeana*, *Rhynchostele rosii*, *Chamaedorea elegans*, *Psilotum complanatum*, *Symplocos coccinea* and *Ceratozamia mexicana* (Vovides et al. 1997; Alcantara and Luna 1997).

Consequently, Luna and Alcántara (2002) emphasize the need to focus the cloud forest conservation efforts in the state of Hidalgo, where many endemic plant species for Mexico have been recorded, such as *Bouvardia martinezii*, *Carya palmeri*, *Ceratozamia mexicana*, *Cyathea mexicana*, *Dalbergia palo-escrito*, *Deppea hernandezii*, *D. microphylla* and *Magnolia dealbata*, among others. In addition, these authors pointed out that some other taxa of the cloud forests that are disjunct between Mexico and the United States show very restricted distribution ranges in Mexico, as in the case of *Illicium floridanum*, *Nyssa sylvatica* and *Schizandra glabra*. In summary, this mixture of hardly known, rare and threatened species is part of a unique natural system that not only bears taxa from different ancestral biotas, but also has high rates of species richness and endemicity, as well as, a very fragile habitat that unfortunately do not have any kind of protection.

In the case of the cloud forests of the states of Querétaro, it is documented that it bears a very rich flora and plant communities. Cartujano et al. (2002), recorded 130 families, 465 genera and 774 species of vascular plants in the cloud forests of the eastern portion of this State. Among this diverse flora, a number of endemics to Mexico or restricted endemics to the Sierra Madre Oriental are included (*Cinnamomum bractefoliaceum*, *Clethra kenoyeri*, *C. pringlei*, *Ilex condensata* and *Inga huastecana*, among others), as well as, some species listed as vulnerable, rare, or threatened (*Magnolia dealbata*, *Tilia mexicana*, *Carpinus caroliniana* and *Litsea glaucescens*, among others) under the Mexican Norm of Endangered Species NOM-059-ECOL-2000.

Despite the floristic richness and rareness of the cloud forests, timber extraction, livestock grazing and conversion of forest to farmland, which is risking its long-term conservation, represent the main recent disturbance sources of these forests. Unfortunately, precise assessments of the current destruction rate of these forests have not been done (Pérez 1994, 1999).

Although, in the particular case of cloud forests there is not any former record documenting their probable shifts due to climate change in Mexico. A similar exercise assessing future distribution patterns of some cacti species was done by Téllez and Dávila (2003), in a semiarid region of central Mexico. They showed the drastic contraction of some of the cacti species potential distribution patterns, once the climatic changes conditions were included.

In summary, in this work we attempted to highlight the importance of including the best biological knowledge available (geographic distribution, vegetation structure and ecology) and a bioclimatic modeling technique to assess the possible present and future role of any reserve or protected area. We also wish to emphasize the need to include Information concerning current and future environmental conditions and the potential distribution patterns of plants and animals, should be included in the decisions for selecting and establishing any reserve or protected area.

Due to the methodology and the available data used, it is important to consider that the results obtained in this study might be slightly biased by some unrecorded errors or even by the lack of enough information. The inclusion of only 29 records data for the model generation, might seems not representative of the species distribution pattern. However the records used cover, in general terms, all the environmental conditions that theoretically the species might occupy (the geographic, ecological and altitudinal range of the taxon).

In addition, natural systems complexity represents a challenge for undertaking a modeling approach. In particular, the evident limitation of the bioclimatic models is the lack of inclusion of information concerning biotic interactions, evolutionary changes, as well as relevant biological processes such as dispersion (Pearson and Dawson 2003). Consequently, the existence of certain degree of errors is probably unavoidable.

Also, the bioclimatic data, due to its own nature, shows two kinds of errors: (1) the omission (= the lack of consideration of the space that is occupied by the niche; (2) commission (= the consideration of a space that is not occupied by the niche). Consequently, each algorithm used to model a species ecological niche, has a combination of commission and omission errors (Peterson and Vieglais 2001).

Even though, the existence of these errors is recognized, we believe that the bioclimatic modeling represents a useful tool or starting point for understanding the current and potential distribution patterns of animals and plants. Its usefulness has already been proved for some species at certain scales, in which this approach has generated relevant information (Pearson and Dawson 2003).

In the case of this study, the model clearly reflects that the spatial climatic resolution used to correlate it to the species records that were included, enabled a precise and solid bioclimatic profile of *Fagus*.

Finally, we believe that with the present biological information, it is feasible and recommendable to carry out a similar exercise for other plant groups. Endemic species and main elements of plant communities should be especially important to be submitted to a bioclimatic modeling. By this means, we can increase the probability of proposing adequate conservation strategies. In the particular case of this study, the results obtained show that through the bioclimatic approach, we can be able to focus in long-term management, planning, and development of new, flexible, and dynamic forms of wildlife and resource conservation (Nix 1986; Lindenmayer et al. 1991; Téllez and Dávila 2003).

Acknowledgements

We thank to the anonymous reviewers for their valuable comments and corrections. To PAPCA 2002 program of the FES Iztacala UNAM for the financial support to carry out part of this study.

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