Current distribution and coverage of Mexican beech forests *Fagus grandifolia* subsp. *mexicana* in Mexico

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ABSTRACT: *Fagus grandifolia* subsp. *mexicana* (Fagaceae) is a taxon endemic to Mexico and is currently considered to be in danger of extinction. It dominates the canopy at the sites where it grows, forming the plant association known as Mexican beech forest. The objectives of this study were to (1) determine the area currently occupied by beech forests in Mexico, based on a literature review; (2) generate maps showing the distribution and area occupied by the less known beech forests in Mexico (which are located in the state of Hidalgo) based on field observations and using geographic information systems; and (3) propose measures that can be taken to protect and manage this plant association. The results show that the beech forests of Mexico currently cover an area of 155.54 ha, and several fragments have recently disappeared. The largest patches of beech forest are located at 5 sites in the state of Hidalgo and occupy a total area of 106.79 ha (73.9%). Each of the sites is different in size, connectedness, and degree of fragmentation and disturbance. The Mexican beech forests urgently require management and conservation programs, as some of them will otherwise soon disappear due to changes in land use, logging, and climate change. To preserve these forests the following measures are suggested in the short term: increase connectedness between beech forest patches, create core areas, reforest with native species, create seed concentrations, regulate the consumption of beechnuts by humans, and include this plant association in the National System of Natural Protected Areas.

KEY WORDS: Mexican beech forest · *Fagus grandifolia* subsp. *mexicana* · Forest conservation · Forest management · Mexico

INTRODUCTION

The genus *Fagus* (Fagaceae) includes 10 species in the northern hemisphere (Denk 2003, Fang & Lechowicz 2006). Fossil records of *Fagus* in Asia and Europe date from the Miocene and the Pliocene (24 to 1.6 million years ago), and in North America from the Eocene (45 million years ago) (Huntley et al. 1989). Continental drift and climate change have drastically decreased the distribution of *Fagus* (Fonseca et al. 2011, Wilson et al. 2011).

Currently, there are 7 species in eastern Asia: *Fagus engleriana*, *F. hayatae*, *F. longipetiolata* and *F. lucida* in China; *F. crenata* and *F. japonica* in Japan; and *F. multinervis* in Korea (Horikawa 1972). There are also 2 species in Europe and western Asia, *F. orientalis* and *Fagus sylvatica* (Rose et al. 2009, Milad et al. 2011); and 1 in North America, *F. grandifolia* (in

eastern Canada and the USA). The intraspecific taxon at imminent risk of extinction, *F. grandifolia* subsp. *mexicana* (Martínez) A. E. Murray (Valencia & Flores-Franco 2006), is endemic to Mexico (Miranda & Sharp 1950, Williams-Linera et al. 2003, SEMAR-NAT 2010, González-Espinosa et al. 2011).

The first specimens of *Fagus* collected in Mexico were described as a new species, *Fagus mexicana* Martínez. The larger fruits and cuneate base of the leaves were the main characteristics that Martínez (1940) used as a criterion to distinguish it from *F. grandifolia*. However, in later taxonomic treatments, the taxon was classified as *F. grandifolia* var. *mexicana* (Martínez) Little (Little 1965), and recently it has been classified as *Fagus grandifolia* subsp. *mexicana* (Martínez) A. E. Murray (Valencia & Flores-Franco 2006). Although there is still no conclusive evidence to determine whether it is a species, subspecies or variety, it is clear that this taxon has a disjunct distribution and that its populations in Mexico are at grave risk of extinction (Rowden et al. 2004, Téllez-Valdés et al. 2006, Premoli et al. 2007, Frankham et al. 2012). In this study, it is treated as a subspecies, as proposed in the most recent publications.

The 11 small populations of *Fagus grandifolia* subsp. *mexicana* recorded to date are restricted to montane cloud forest in the Sierra Madre Oriental in the states of Hidalgo, Nuevo León, Puebla, San Luis Potosí, Tamaulipas, and Veracruz (Ern 1976, Rowden et al. 2004, Montiel-Oscura 2011). Individuals of this subspecies dominate the canopy at the sites where they grow, forming a plant association known as Mexican beech forest that has specific environmental requirements. They flourish at altitudes of 1400 to 2000 m above sea level (asl) on high, steep, north-facing slopes with little variation in climate. The annual average temperature ranges between 14.8 and 15.6°C and the total annual precipitation exceeds 1741 mm (Ehnis 1981, Peters 1992, Álvarez-Aquino et al. 2004).

Due to its restricted distribution and narrow range of suitable habitat, *Fagus grandifolia* subsp. *mexicana* (Williams-Linera et al. 2003, Fang & Lechowicz 2006, Téllez-Valdés et al. 2006) has been designated as a taxon in danger of extinction by the Mexican legislature (SEMARNAT 2010) and has been included in the Red List of Mexican cloud forest trees (González-Espinosa et al. 2011). Several other species characteristic of the beech forest canopy and sub-canopy are also included in Mexican risk categories (SEMARNAT 2010, González-Espinosa et al. 2011) and/or international registers of threatened species (CITES 2010), e.g. *Clethra mexicana*, *Cyathea fulva*, *Dicksonia sellowiana*, *Magnolia schiede-* *ana*, *Pinus patula*, *Podocarpus matudae*, and *Quercus laurina* (Ehnis 1981, Pérez-Rodríguez 1999, Williams-Linera et al. 2003).

Several authors consider that the information about the distribution, coverage, and conservation status of the beech forests in Mexico is still incomplete (Martínez 1940, Miranda & Sharp 1950, Fox & Sharp 1954, Alcántara & Luna-Vega 2001, Williams-Linera et al. 2003). In this sense, the working hypothesis of the present study is that the current area and distribution of beech forest in Mexico is much more extensive than has been postulated to date, since there are large unexplored, well-conserved areas within the montane cloud forest where climate conditions are ideal for this plant association.

MATERIALS AND METHODS

Compilation of bibliographic data

A literature search was conducted to discover which parts of Mexico are known to contain beech forests and which of these already have adequate information about the area and current status of these forests. According to several of the sources consulted (Alcántara & Luna-Vega 2001, Williams-Linera et al. 2003, Godínez-Ibarra et al. 2007), the state of Hidalgo contains Mexico's largest *Fagus grandifolia* subsp. *mexicana* forests, but the least amount of information is available about them (except for the forest located in La Mojonera in the municipality of Zacualtipán de Ángeles). We therefore chose the state of Hidalgo as a suitable place to gather local data to complement existing national data on the distribution, area, and current status of beech forests.

Study area

The study was carried out in the montane cloud forest in the Sierra Madre Oriental mountain range in the eastern part of the state of Hidalgo, Mexico (20° 19′ to 20° 38′ N, 98° 14′ to 98° 36′ W). The study sites (El Gosco, El Reparo, La Mojonera, Medio Monte, and Tutotepec) are isolated patches imbedded in the cloud forest, and the canopy is dominated by *Fagus grandifolia* subsp. *mexicana* (Fig. 1). This plant association is found between 1557 and 1997 m asl.

The climate where the Mexican beech forests grow is Cf; it is humid temperate with year-round rains, characteristic of a mountain orobiome (García 1988, Peters 1995), it has a relatively high humidity of 60 to

85% (Tinoco-Rueda et al. 2009), is frequently foggy, and has an annual average temperature of 12.7°C and a minimum low of –10°C. The predominant soil is humic and vitric andosol (FAO-UNESCO 1988). The soil texture is sandy clay loam, with volcanic glass in some places, and the pH ranges from 4 to 6 (Peters 1995).

Fieldwork and herbarium review

Fieldwork was carried out in various regions of the state of Hidalgo between 2010 and 2011. The beech forests were located based on: (1) specimens from the herbariums MEXU (Instituto de Biología de la Universidad Nacional Autónoma de México), HGOM (Centro de Investigaciones Biológicas de la Universidad Autónoma del Estado de Hidalgo), and XAL (Instituto de Ecología A.C.); (2) data from previous studies (Miranda & Sharp 1950, Williams-Linera et al. 2003, Rodríguez-Ramírez & Moreno 2010); (3) investigation of towns or localities near the beech forests where environmental conditions were suitable for this plant association (Williams-Linera et al. 2003, Rodríguez-Ramírez & Moreno 2010); and (4) showing photographs of *Fagus grandifolia* subsp. *mexicana* trees and botanical specimens (branches with leaves and inflorescences) to residents of villages near the montane cloud forests, asking them if they were familiar with the species.
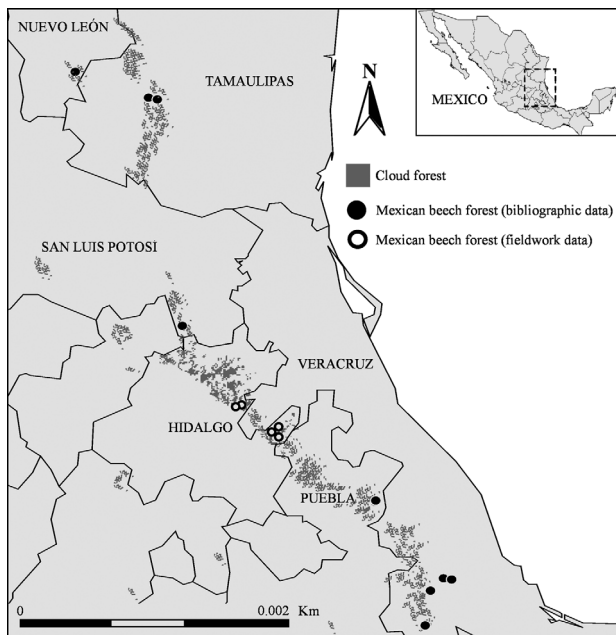

Fig. 1. *Fagus grandifolia* subsp. *mexicana*. Current distribution of Mexican beech forest in Mexico

Patch size estimation

The size of each forest patch was measured by walking around its perimeter and recording geo-references (UTM coordinates, using a GPS map, GARMIN®, 6OCSx). Since the Mexican beech forests grow in rugged terrain, digital elevation models that take into account the depth of slopes and/or ravines were used to collect more reliable data on the area, coverage, distribution, and degree of fragmentation of each forest (Maxwell 1982). Calculations were carried out with the ArcView® V.3.3 program (ESRI 2002). In addition, polygons were drawn of each forest patch using USGS Landsat 2012 images (http://glovis.usgs.gov/) with a 3 m level of resolution. The 'Shape to KML' extension of the ArcView program was used to draw the outlines of each patch on Google Earth® V.6 (2011 and 2012) color photos.

Selecting areas for conservation in each forest patch

In order to draw the core areas, the polygons of each forest patch were used, with buffers of different diameters, using the 'Patch analyst 3.1' extension of the ArcView® V.3.3 program with the 'create core areas' option (Elkie et al. 1999, ESRI 2002, Girvetz & Greco 2007). The core area of each forest was arbitrarily defined as a 'minimally disturbed' site or micro-environment located away from gaps or roads (to avoid the edge effect) and with high moisture uptake (due to the presence of water bodies: rivers, streams, or springs). We believe that the selected core areas are those with the best environmental conditions for conservation and management of this plant association. In addition, the continuity of each patch was examined using USGS Landsat 2012 images (http://glovis.usgs.gov/), as an essential factor for increasing the probability of preserving environmental processes at each site (Forman 1995).

Measurement of fragmentation and connectedness

The 'PatchGrid' extension for ArcView® V.3.3 (Riitters et al. 1995, ESRI 2002), with the 'spatial statistics by regions' option (Elkie et al. 1999), was used to estimate the degree of fragmentation and connectedness of each beech forest. The size metrics, edge metrics, shape metrics, core area metrics, and interspersion metrics statistics were used. In order to find the number of forest patches at each site, the number

of patches (NumP) and mean patch size (MPS) statistics were calculated. The perimeter of each patch was estimated using the total edge (TE) and edge density (ED) indexes, and the shape of each patch was determined using the mean shape index (MSI) and area-weighted mean shape index (AWMSI).

Spatial configuration, adjacency, and degree of interspersion between closely located forest patches were obtained using the interspersion and juxtaposition index (IJI), which indicates how evenly forest patches are distributed. The lower (closer to zero) the value of the index, the more randomly the patches are distributed in the landscape, while higher values (closer to 100) mean that patches are more evenly dispersed (Forman & Godron 1981, Elkie et al. 1999). The distance between nearest patches was estimated using the mean nearest neighbor distance index (MNN; Riitters et al. 1995, Gelet et al. 2010).

RESULTS

Size and current distribution of Mexican beech forest

Based on bibliographic information and field exploration in the state of Hidalgo, 14 areas were found in Mexico where these forests originally existed. However, the Mexican beech forest plant association currently grows in only 11 of these areas. At the remaining 3 (Chucuyul-Chiconquiaco, Hueytemalco-Xiutetelco, and Xilitla), it has disappeared or only a few individuals are left, as a result of human activities (changes in land use and deforestation). No references were found regarding the size of the beech forest at Ojo de Agua de los Indios (Table 1).

The data obtained indicate that there are currently beech forests in the states of Hidalgo, Nuevo León, Tamaulipas, and Veracruz, with a total area of 144.54 ha, and that they have virtually disappeared from the states of Puebla and San Luis Potosí.

Main characteristics of Mexican beech forest in Hidalgo

Information provided by the residents of nearby villages has been very useful for locating, describing, and formulating management and conservation proposals for these forests. The results indicate that beech forests are present in 5 areas and 3 municipalities in the state of Hidalgo, and that they are all different in terms of size, connectedness, degree of frag-

mentation, and disturbance (Fig. 2). The 5 forests (listed below) are known as 'Haya' (beech) in San Bartolo Tutotepec and Zacualtipán de Ángeles and as 'Tototlcal' in Tenango de Doria.

(1) La Mojonera (El Hayal), Zacualtipán de Ángeles municipality (Tables 1 & 2). This is one of the largest, best studied, and least disturbed beech forests in Mexico. Peters (1992) and Williams-Linera et al. (2003) state that its area is 45 ha, but in the present study it was estimated to be 42.5 ha (Table 1). It lies between 1780 and 1950 m asl, with a slope exceeding 20°. This site has *Fagus grandifolia* subsp. *mexicana* seedlings, but they are not as numerous as in other beech forests in Hidalgo. The forest is located in a temperate orobiome (Peters 1992) typical of montane environments, with a summer rainy season and temperatures ranging between 11 and 18°C.

(2) El Reparo site, Zacualtipán de Ángeles municipality (Tables 1 & 2). This beech forest is the most continuous and has the lowest degree of disturbance. It is located 2.4 km from the La Mojonera forest between 1966 and 1987 m asl, with an area of 11.55 ha and pronounced slopes (>40°). This small forest is very important to the residents of the village of El Reparo because they use it for their water supply, and are therefore trying to preserve it. The temperature ranges between 11 and 17°C, and the orobiome is similar to that at La Mojonera, except that in the sheltered areas there are a large number of tree ferns (*Cyathea fulva* and *Dicksonia sellowiana*) and several bodies of water (streams and rivers). Many *Fagus grandifolia* subsp. *mexicana* juveniles were observed, and evidence of anthropogenic disturbance was only present at the edge of the forest near the road.

(3) El Gosco site, Tenango de Doria municipality (Tables 1 & 2). This is the smallest beech forest in Hidalgo (4.5 ha) and the one with the most evident disturbance from illegal logging. The orobiome is similar to that of the La Mojonera forest. This forest is located between 1557 and 1864 m asl in rugged terrain (slopes >40°), with temperatures ranging from 10 to 17°C. The forest is severely fragmented, but some patches grow in steep ravines, out of human reach, so they are barely disturbed. The finding of this forest adds a record to the known distribution of *Fagus grandifolia* subsp. *mexicana* in the state of Hidalgo.

(4) Medio Monte (Las Hayas) site, San Bartolo Tutotepec municipality (Tables 1 & 2). This is one of the largest (34.25 ha) and least disturbed beech forests. It has a similar orobiome to that of El Reparo and Tutotepec, which are the 3 forest sites with the least or no evidence of human disturbance. This

Table 1. *Fagus grandifolia* subsp. *mexicana*. Current distribution and area of Mexican beech forests. 1: good; 2: stable; 3: under threat of extinction; 4: extinct

| State	Locality/municipality	Area (ha)	Elevation (m)	Latitude	Longitude	Status	Source
Hidalgo	Medio Monte/San Bartolo Tutotepec	34.25	1800–1944	20°24′50″N,	98°14′24″W	1	Present study
	Tutotepec/San Bartolo Tutotepec	13.99	1909–1943	20°24′39.14″N,	98°16′52.2″W	1	Present study
	El Gosco/Tenango de Doria	4.5	1557–1864	20°19′37.8″N	98°14′57.1″W	3	Present study
	La Mojonera/Zacualtipán de Ángeles	42.5	1780–1950	20°38′0.33″N	98°36′51.8″W	1	Present study
	El Reparo/Zacualtipán de Ángeles	11.55	1966–1987	20°38′05.8″N	98°35′13.4″W	1	Present study
Nuevo León	Agua Fria/Aramberri	26	1830	24°02′N,	99°42′W	1	Montiel-Oscura (2011)
Puebla	No reference/ Hueytemalco-Xiutetelco	–	1450	19°53′32.1″N	97°19′49.1″W	4	Williams-Linera et al. (2000, 2003)
San Luis Potosí	Xilitla/Xilitla	–	–	21°22′N	99°93′W	4	Williams-Linera et al. (2003)
Tamaulipas	Casa de Piedra, El Cielo Biosphere Reserve/ Gómez Farias	3	1500	23°03′57.8″N	99°12′3.8″W	3	Williams-Linera et al. (2003)
	Ojo de Agua de los Indios, El Cielo Biosphere Reserve/Ocampo	–	1500	23°03′N	99°12′W	3	Williams-Linera et al. (2003)
Veracruz	Mesa de la Yerba/ Acajete	4.05	1900	19°33′37.2″N	97°01′9.8″W	3	Williams-Linera et al. (2003)
	Acatlán Volcano crater/ Acatlán	4.13	1840	19°40′46.9″N	96°51′9.8″W	2	Williams-Linera et al. (2000, 2003)
	Acatlán Volcano top/ Acatlán	0.57	1900	19°40′57.5″N	96°51′15.3″W	2	Williams-Linera et al. (2000, 2003)
	Chucuyul/Chiconquiaco	–	1750	19°46′N	96°48′W	4	Williams-Linera et al. (2003)
Total area		144.54					
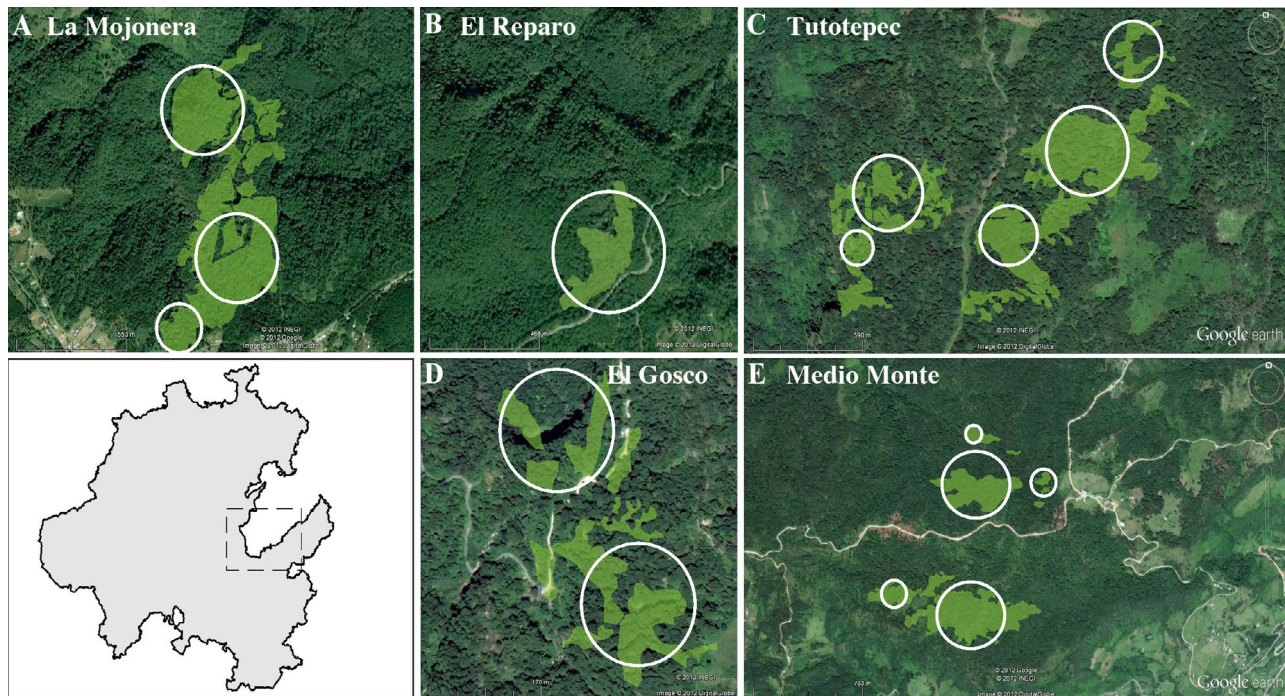
Fig. 2. Size and distribution of Mexican beech *Fagus grandifolia* subsp. *mexicana* forests in Hidalgo State (light green areas in A to E). The circles represent the proposed core areas. Inset: the sampling area in Hidalgo

Table 2. *Fagus grandifolia* subsp. *mexicana*. Size, characteristics, rates of change, and proposed core areas of Mexican beech forests in the state of Hidalgo, Mexico. Numbers listed under 'Proposed core areas' represent circles in respective areas shown in Fig. 2. NumP: no. of patches; MPS: mean patch size; ED: edge density; AWMSI: area-weighted mean shape index; MNN: mean nearest neighbor distance; IJI: interspersion juxtaposition index; (–): data not estimated

	La Mojonera	El Reparo	Locality Tutotepec	El Gosco	Medio Monte
Slope (degrees)					
Min.	1.8	3	0.45	16.1	0.45
Max.	37.8	37.0	24.9	43.8	21.5
Size metrics					
NumP	4	1	7	7	8
MPS (ha)	10.78	11.46	1.99	0.65	4.10
Edge metrics					
ED (m)	350.86	352.49	274.42	1073.08	922.25
Shape metrics					
AWMSI (m)	4.12	3.32	4.56	1.10	4.50
MNN (m)	6.46	0	8.69	12.18	38.53
Interspersion metrics					
IJI (%)	98.5	97.2	80.3	30.4	99.1
Proposed core areas (radius; m)					
1	108.55	310.8	114.71	124.27	227.29
2	216.36	–	86.62	111.19	218.41
3	216.36	–	86.62	–	83.44
4	–	–	68.79	–	83.44
5	–	–	36.94	–	51.53

forest grows between 1800 and 1944 m asl (Rodríguez-Ramírez & Moreno 2010), in shallow ravines (<40°), where the temperature ranges from 9 to 16°C. It is made up of 5 patches located close to each other, but separated by other vegetation types (*Pinus patula*, *Liquidambar styraciflua*, and *Quercus* spp. forests).

(5) Tutotepec (La Cantera) site, San Bartolo Tutotepec municipality (Tables 1 & 2). Like La Mojonera, El Reparo, and Medio Monte, this is one of the best preserved Mexican beech forests. It has an area of 13.99 ha and is located between 1909 and 1943 m asl. It has an orobiome similar to Medio Monte, with temperatures between 9 and 15°C and high humidity; micro-environmental conditions are characteristic of a mature beech forest (Peters 1992, Fang & Lechowicz 2006). Access to this site is difficult because of the steep ravines (>42°).

Proposed core areas

In order to counter the effects on Mexican beech forests of disturbance caused by human activities (changes in land use, climate change, and logging), it is proposed that the connected areas be extended through the creation of core areas. We suggest that 5 core areas be established for the Medio Monte site and the Tutotepec site based on the area, state of conservation, and existence of less perturbed sites in these 2 forests (Table 2). For the La Mojonera site, 3 core areas are proposed based on its area and state of conservation. For the El Reparo site, a single core area is proposed, as this forest covers 11.5 ha, is continuous, and shows little evidence of disturbance (Fig. 2). Two core areas are suggested for the El Gosco beech forest, at the 2 sites least affected by human activity, although both are 'naturally protected' by the inaccessibility of the terrain in the ravines where the forest patches are located (Fig. 2).

Fragmentation and connectedness

The beech forests with the largest number of patches (NumP) are Medio Monte (8), El Gosco (7), and Tutotepec (7), while the El Reparo beech forest is 1 single continuous patch (Table 2). Analysis of the fragmentation, spatial heterogeneity, configuration, and structure of these Mexican beech forests showed that the largest MPS in these forests in Hidalgo is at the El Reparo site (since this forest is a single patch), and the second largest is at the La Mojonera site, with a MPS of 10.78 ha. The smallest MPS (0.65 ha) is at the El Gosco site, where the beech forest is the smallest in the state and also the most affected by human activity.

The analysis of patch shape complexity (ED) showed that the spatial heterogeneity of the landscape mosaic was highest at the El Gosco site and second highest at the Tutotepec site (Table 2). It is likely that higher patch border complexity is related to illegal logging (at El Gosco) or to the type of spatial arrangement (at Tutotepec).

Consistent with the results reported in the previous paragraph, the estimated AWMSI for the El Gosco site was low (1.1), which supports the idea that human disturbance causes patch shape simplification. The higher AWMSI values for the beech forests at the other 4 sites are characteristic of irregular landscapes, possibly more natural and/or less affected by human activity (Table 2).

Configuration is measured by the IJI, which was high (>80%) at sites less affected by human activity (El Reparo, Tutotepec, La Mojonera, and Medio Monte), indicating that the patches there are more evenly distributed and have not undergone significant changes. In contrast, the IJI value was low (30.4%) for the El Gosco beech forest (Table 2).

The Medio Monte beech forest had the highest MNN value (38.53), as it is made up of 8 patches, closer together than the average distance between patches at the other sites. The El Reparo site has a zero MNN value because it is a single continuous forest (Table 2).

DISCUSSION

Size and current distribution of Mexican beech forests

It is estimated that only one-fifth of the world's original forests are in a favorable state of conservation, these being what have been termed 'forest frontiers' (Bryant et al. 1997). Moreover, some 10% of the Earth's tree species are considered to be endangered and will probably become extinct if protective measures are not now put into place (González-Espinosa et al. 2011, 2012, Ponce-Reyes et al. 2012). In the particular case of Mexico's montane cloud forests, some 60% of the tree species in these forests are included in some category of risk according to Mexican legislation (SEMARNAT 2010), and there is scant knowledge of the density, coverage, or distribution of populations of most of these species.

The results of the present study provide information on basic aspects needed for implementation of Mexican beech forest management and conservation programs. Previous studies have concluded that there are only 10 remnants of *Fagus grandifolia* subsp. *mexicana* forest in the world, and that 3 of these are disappearing or have already disappeared. It was also estimated that they cover an area of less than 60 ha (Williams-Linera et al. 2000, 2003, Rowden et al. 2004). However, we found that these forests occupy a total area of 144.54 ha, i.e. more than double the earlier estimate.

The discovery in the field of a new beech forest site in Hidalgo (El Gosco; present study), and recent data from 2 further sites, one at Agua Fria, Nuevo León, and another at El Reparo, Hidalgo (Montiel-Oscura 2011), have increased the known area covered by 40.05 ha. Additionally, references to the existence of beech forests in Tutotepec, Hidalgo (Williams-Linera et al. 2003), enabled us to locate, describe, and measure 2 further forests, which together cover 48.24 ha, considerably increasing the known area of beech forest in Mexico.

The beech forests of Mexico were separated from those of eastern North America during the Pleistocene. Since then, they have been isolated from their northern counterparts (currently by >880 km) and have been growing under specific environmental conditions for 100s of 1000s of years (Little 1965, Peters 1992, Fang & Lechowicz 2006, Premoli et al. 2007, Montiel-Oscura 2011). The evidence shows that, in the past, they underwent contraction rather than expansion (Messier et al. 2011) and, in the present day, rising temperatures and falling moisture availability in the environment caused by global warming (Téllez-Valdés et al. 2006), as well as fragmentation and disappearance of the montane cloud forests where small islands of beech forests grow, are rapidly reducing their coverage and distribution (Price et al. 2011).

Although the area occupied by some of the Mexican beech forests has remained relatively unchanged in recent decades, for example, near the Acatlán Volcano, Veracruz (Williams-Linera et al. 2003), and La Mojonera, in the state of Hidalgo (Alcántara & Luna-Vega 2001, Rowden et al. 2004, present study), other forests survive with a very small number of beech trees or have disappeared altogether (Williams-Linera et al. 2003). The taxon *Fagus grandifolia* subsp. *mexicana* is currently classified as endangered, due mainly to uncontrolled human activity such as changes in land use, forest fires, and illegal logging (Pérez-Rodríguez 1999, Rowden et al. 2004, Téllez-Valdés et al. 2006, SEMARNAT 2010).

Fragmentation in the beech forest of Hidalgo state

The largest Mexican beech forests are in the state of Hidalgo, where their combined area is 106.79 ha (73.9% of the national total). The various forest sites exhibit differing degrees of fragmentation and disturbance; the largest (54.5 ha) and least fragmented in the entire country are those in the municipality of Zacualtipán de Ángeles (La Mojonera and El Reparo), as previously suggested by other authors (Pérez-Rodríguez 1999, Alcántara & Luna-Vega 2001, Williams-Linera et al. 2003). The data of Williams-Linera et al. (2003), Rowden et al. (2004), and the present study show that the Mexican beech forests in San Bartolo Tutotepec (Tutotepec and

Medio Monte), which cover approximately 48.24 ha, are the least affected by human activity.

The beech forest at the El Gosco site (4.5 ha) in the municipality of Tenango de Doria shows a high degree of deterioration, due mainly to clandestine logging, and will likely soon disappear if measures, such as protecting the zone, are not immediately taken to preserve it.

There are significant differences between the Mexican beech forests studied in terms of the number, shape, and size of the patches (Table 2). It is likely that the effect of disturbances (logging, fires, and diseases) will have different impacts on the composition, structure, and ecological processes in each of the forests (Gang 1998, Messier et al. 2011). Fragmentation of the forests analyzed here does not necessarily imply a high degree of disturbance. For example, MNN values were high for Medio Monte, which means that the patches are relatively close to each other, which allows genetic flow between them (Gelet et al. 2010). Additionally, the degree of grouping, measured by the value of IJI, indicates that there are connections between patches in all the forests studied.

Knowledge about the coverage, degree of fragmentation, and distribution of the beech forests in Mexico is fundamental for establishing management and conservation programs (Alexandrov & Dakov 2010, Ghalachyan & Ghulijanyan 2010). Nevertheless, there is still little information about other equally important aspects of these forests, such as species diversity and spatial and temporal dynamics (Alcántara & Luna-Vega 2001, Williams-Linera et al. 2003, Godínez-Ibarra et al. 2007, Rodríguez-Ramírez & Moreno 2010). Such information can only be obtained from longer term studies (Pagiola et al. 2003).

Considering that some patches of these Mexican beech forests will soon disappear (Williams-Linera et al. 2003, Rowden et al. 2004, Premoli et al. 2007; El Gosco site in the present study), it is necessary that management plans and protective measures for the short term be proposed and implemented.

Conservation and management proposals for Mexican beech forests

A viable short-term option is to utilize information from prior studies on other tree species in the same genus (Yilmaz 2010), or in other genera but with similar characteristics or issues to those of *Fagus grandifolia* subsp. *mexicana* (Robinson et al.

2009) that could be used as models for management and conservation of beech forests and of this subspecies. Some relevant examples are *F. multinervis*, endemic to Ulleung Island, Korea, in which genetic studies have helped to preserve the species through maintenance of high heterozygosity (Tomoshi et al. 2006); *F. sylvatica*, for which regeneration programs have been implemented in areas suffering deforestation in central Europe (Geßler et al. 2007); and *F. japonica* (in Japan), *F. multinervis* (in Korea), and *F. engleriana* (in China), for which areas have been prioritized for conservation to enable these species to recover naturally (Peters 1992, Ohkubo et al. 1996). It is possible that similar methods can help preserve the largest genetic reserve of *F. grandifolia* subsp. *mexicana* in Mexico. Molecular level data indicate that genetic variation in this subspecies is positively related to population size (Rowden et al. 2004, Premoli et al. 2007). Since the mortality rate of *F. grandifolia* subsp. *mexicana* seedlings is very high during the first year (Godínez-Ibarra et al. 2007), the persistence of populations depends largely on the implementation of programs to reduce the impact of human activities.

Land ownership

These beech forests are part of community assets or ejido properties, which means that they are owned communally by the people living in nearby villages (Hardin 1968, Pazos 1991, Congreso de los Estados Unidos Mexicanos 1992, Gutiérrez-Lacayo et al. 2002). As a result, all and each of the ejido members benefit directly from exploitation of the natural resources from these forests (lumber, seeds, land use), and the forests are being consumed rapidly and without regulation (the tragedy of the commons sensu Hardin 1968).

This negative dynamic can, however, be reversed if people's awareness is raised and they are educated (through workshops and information meetings) about the increased benefits they can obtain from proper management of natural forest resources. Some of the environmental services provided by Mexican beech forests can be used directly (mainly edible fungi, seeds, and wood), while indirect services include carbon capture, watershed protection, animal habitats, and recreation. A piece of good news is that in mid-2012, the communal owners of the largest Mexican beech forest (the La Mojonera Ejido), began taking con-

crete steps to conserve and manage their forest, with help from Mexican public universities and agencies.

Reforestation of *Fagus* forests with native species

Mexico has reforestation programs that are based on detailed analyses determining what tree species are suitable for each particular environment. For example, native tree species (*Pinus* spp., *Quercus* spp.) are used for reforestation, ideal for the soil type and characteristics where they will be planted (Barry et al. 2010).

In the specific case of Mexican beech forests, the proposal is to increase connectedness between patches through reforestation (Angelsen & Wertz-Kanounnikoff 2009, Yilmaz 2010) using the most structurally significant native tree species in these forests; *Liquidambar styraciflua*, *Magnolia schiedeana*, *Pinus patula*, *Quercus laurina*, and *Symploccus limoncillo* (Williams-Linera et al. 2003, Rowden et al. 2004). The natural coexistence of these species could facilitate the growth of *Fagus grandifolia* subsp. *mexicana* seedlings between patches, minimizing the border effect (Guevara & Laborde 2008, Bezaury-Creel & Gutiérrez 2009) and creating concentrations of seeds.

Four further important recommendations are:

(1) Take into account the opinions and empirical knowledge of the residents living near the areas to be reforested, since they are generally the ones who recognize which native species have the best chance of becoming established (Bennet 1999, Wunder 2006, Barry et al. 2010).

(2) Implement mycorrhizal fungi inoculation techniques in reforestation, to increase tree seedling survival probabilities (Rodríguez-Ramírez 2009, Montoya et al. 2010).

(3) Choose suitable tree species for reforestation, considering the characteristics, stage of succession, and degree of disturbance of each forest or forest patch (Morin et al. 2011). For example, in the patches that require immediate reforestation (e.g. El Gosco, in Tenango de Doria), species that improve soil quality are suggested (Angelsen & Wertz-Kanounnikoff 2009, Morin et al. 2011).

(4) Implement 'reducing emissions from deforestation and forest degradation' (REDD+) programs at the state level that will help ejido members reduce pressure on the natural resources they obtain from beech forests by enabling them to obtain a good price for their agricultural products. The environment and the populations will benefit in the medium- to long term from the reduction in greenhouse gas emissions (CONAFOR 2010).

Beechnut consumption

One of the most critical problems for the survival of *Fagus grandifolia* subsp. *mexicana* populations is related to the tree's life cycle. Beech trees produce seeds synchronously in certain years, called 'mast years,' and the rate of seedling establishment after germination is low (Ehnis 1981, Álvarez-Aquino & Williams-Linera 2002, Godínez-Ibarra et al. 2007). In mast years (which occur every 5 to 8 yr), local residents collect the seeds (beechnuts) to eat and/or sell locally, which could decrease the natural regeneration of trees.

To increase the viability of *Fagus* seeds and the rate of seedling establishment, it is necessary to gradually regulate the practice of seed harvesting, considering the size, degree of disturbance, and fragmentation of each forest. Ejido members and residents of villages near the beech forests must be helped to understand the importance of regulating and controlling *Fagus* seed harvesting, which will benefit the sustainable use of forest resources and, in consequence, development in local communities (Blyth et al. 1995, Saunders et al. 1995).

A practice recommended to increase the population viability of *Fagus grandifolia* subsp. *mexicana* is to produce seedlings raised from seed in nurseries. Further experimental protocols could be used to increase germination and seedling survival (Arriaga et al. 1994), for example, inoculating seeds or seedlings with native fungi (Rodríguez-Ramírez 2009, Montoya et al. 2010).

During field trips undertaken in February 2012, it was observed that *Fagus grandifolia* subsp. *mexicana* trees were flowering synchronously in the 5 beech forests in Hidalgo; the forest floor was abundantly carpeted with beech flowers and pollen. Later, during June and July, the first young fruits were observed, and by mid-September 100s of 1000s of seeds were germinating. It was impossible to walk in the woods without crushing tiny *Fagus* seedlings at every step.

Although in this mast year the majority of seedlings did not survive (Godínez-Ibarra et al. 2007), it is encouraging to know that the Mojonera forest ejido residents are collecting seeds for the tree nursery that they began to build in late September 2012 (pers. comm. from ejido members) to ensure the sur-

vival of more seedlings, promote forest regeneration, and increase the connectivity of the forest fragments by planting trees at suitable sites.

Only by means of a long-term demographic study can the consequences of harvesting the beechnuts be unraveled (Álvarez-Aquino & Williams-Linera 2002, Godínez-Ibarra et al. 2007). Many demographic data on long-lived plants show that even harvesting >90% of the seeds of a population does not lower the intrinsic rate of population growth (Cleavitt et al. 2008, Barna et al. 2009).

Incorporation into the national system of Natural Protected Areas

The results of the present study show that the Mexican beech forests are at imminent risk of extinction, as they have a total area of <160 ha and are decreasing in area both in Hidalgo and nationally. For this reason, we urge that a conservation and management program be implemented for Mexican beech forests, which would be integrated into the national system of Natural Protected Areas, supported by Mexican law. A fact that may help is that this plant association includes a variety of animal, fungus, and plant species that are included in some risk category either under the NOM-059 standard (SEMARNAT 2010) or in the Red List of Mexican cloud forest trees (González-Espinosa et al. 2011). The plants include *Fagus grandifolia* subsp. *mexicana* and *Magnolia schiedeana*, listed as being in danger of extinction; 2 species of tree ferns (*Cyathea fulva* and *Dicksonia sellowiiana*); the less conspicuous ferns *Marattia weinmanniifolia* and *Psilotum complanatum*; and several species of orchids.

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