TREE-RING RESEARCH, *Vol. 74(1), 2018, pp. 108–119*
DOI: http://dx.doi.org/10.3959/1536-1098-74.1.108

DENDROCHRONOLOGICAL RECONSTRUCTION OF ENVIRONMENTAL HISTORY OF *FAGUS GRANDIFOLIA* SUBSP. *MEXICANA* IN MEXICO

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ABSTRACT

Growth-ring analysis is a valuable source of information for reconstructing environmental history. In this study, ring-width series of a sample of *Fagus grandifolia* subsp. *mexicana* were used to identify the main events that have affected populations of this species. Core samples were extracted in three representative beech forests in Mexico. These are forests where *F. grandifolia* subsp. *mexicana* dominates the canopy. A total of 3355 years of growth rings were measured and three ring-width chronologies were generated. Average annual ring widths were similar between the three sites and ranged from 0.98 to 1.08 mm. A pattern of multiple suppressions and releases was observed, mainly associated with local events, but with a slight climatic influence. Correlations between the ring-width index and climate variables were not statistically significant, with the exception of a seasonal January–June precipitation pattern (1982–2001). There has not been a large-scale disturbance of natural or human origin in the beech forests of the state of Hidalgo in the past 150 years, except in El Gosco, where anthropogenic disturbances have increased in the past decade.

Keywords: cloud forest, disturbance, *Fagus grandifolia*, environmental history, releases, ring width, suppressions, tree ring.

INTRODUCTION

Shade-tolerant species that dominate the canopy of temperate forests, such as *Fagus* spp., are particularly suitable for dendrochronological studies because of their high capacity for regeneration following a disturbance (Peters 1997; Scharnweber *et al*. 2013; Ariya *et al*. 2016) and for their longevity, with some individuals exceeding 500 years old (Di Filippo *et al*. 2015).

Fagus grandifolia and *F. sylvatica* are ecologically and economically important species in North America and Europe, respectively. Therefore, they have been the subject of many dendrochronology studies to quantify the historical relationship between growth and climate and to predict the impact of potential climate change scenarios on future growth (Rozas 2001; Busby *et al*. 2008; Scharnweber *et al*. 2013; Zimmermann *et al*. 2015; Rohner *et al*. 2016).

The establishment and growth of forests dominated by *Fagus grandifolia* in North America is the result of a complex history of human and natural disturbances over several centuries (Cowell and Hayes 2007; Busby *et al*. 2008; Takahashi and Takahashi 2016). *Fagus grandifolia* subsp. *mexicana* is an endemic taxon in Mexico with restricted distribution and is classified as "in danger of extinction" (NOM-059-SEMARNAT-2010). The most likely reasons for this risk category are

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Table 1. Geographical characteristics of the sampling sites.

Place/Municipality	Area (ha)	Elevation (m)	Latitude N (degrees)	Longitude W (degrees)
San Bartolo Tutotepec/Medio Monte–Tutotepec	48.24	1800–1944	20.411	98.240
Tenango de Doria/El Gosco	4.50	1557–1864	20.327	98.249
Zacualtipán de Ángeles/La Mojonera	54.05	1780–1987	20.635	98.614

anthropogenic disturbances (Williams-Linera *et al.* 2003; Rodríguez-Ramírez *et al.* 2013; Ortiz-Quijano *et al.* 2015), but the influence of climate change on this species has not been established with certainty (Tellez-Valdes *et al.* 2006).

There is interest in all parts of the world in searching for species with dendrochronological potential and in generating dendrochronological series in order to understand climate variability and the influence of extreme climatic events that may affect it (Kwiaton and Wang 2015; Stahle *et al.* 2016), and in finding solutions to ecological, archaeological, and water use issues (Villanueva *et al.* 2003). This case study is a contribution to dendrochronological knowledge of a tree species in Mexico. The main objectives are (1) to reconstruct the recent environmental history of the beech forests in the state of Hidalgo, the largest and least-disturbed beech forests in Mexico, by building a ring-width chronology of the dominant species in the canopy, *Fagus grandifolia* subsp. *mexicana*, and (2) to identify the main natural and anthropogenic environmental factors related to periods of suppression and/or release of *Fagus grandifolia* subsp. *mexicana* growth rings to serve as a technical reference for developing Mexican beech forest management and conservation strategies to reduce extinction risk currently faced by these forests.

MATERIALS AND METHODS

Study Area

Field work was conducted in beech forests at three sites in three different municipalities (county equivalents) in the state of Hidalgo, Mexico (El Gosco, La Mojonera and Medio Monte) at elevations ranging from 1557 to 1987 m a.s.l. (Table 1, Figure 1). Beech forests in other parts of the world occur at more northern latitudes than the Mexican beech forests. Mexican beech forests are the only occurrence of beech forests in warm-temperate or subtropical climates (Pignatti *et al.* 2006). The climate is C(fm), *i.e.* humid temperate with rainfall throughout the year, frequent fog and an annual average temperature of 12.7°C (García 1988). Total annual rainfall is 1200 to 2050 mm. The species thrives in rugged terrain with talus slopes (Williams-Linera *et al.* 2003; Rodríguez-Ramírez *et al.* 2013).

Sampling and Estimation of Tree Age

At each site, 12 healthy mature beech trees were selected for coring (no external evidence of decay or disease in the bark). Three specimens were selected from each diameter class (measured at 1.30 m above ground level): 18 to 36 cm, 36.1 to 55 cm, 55.1 to 72 cm, and 72.1 to 91 cm. Two increment cores were drilled from each sampled tree at a height of 1.3 to 1.5 m, to reach the pith. The 72 increment cores were dried in direct sunlight, mounted on wooden supports and then polished with a series of sandpapers of successively finer grit sizes (Stokes and Smiley 1968). The ring-width series was based on a sample depth of 66 cores. The number of samples taken for the analysis was limited to avoid damage of a species considered at risk of extinction (NOM-059-SEMARNAT-2010).

Release and Suppression Events

The ring widths were measured to 0.001-mm accuracy using the Velmex measuring system (Robinson and Evans 1980). Quality of the dating and measurement of the growth series was confirmed by the COFECHA program v. 6.06P (Holmes 1983), using subperiods of 50 years overlapping by 25 years to observe the affinity between series. The ring-width measurements (mm) were used to estimate annual mean widths by sample and by site.

Release and suppression periods were estimated based on changes in percent growth (%CG)

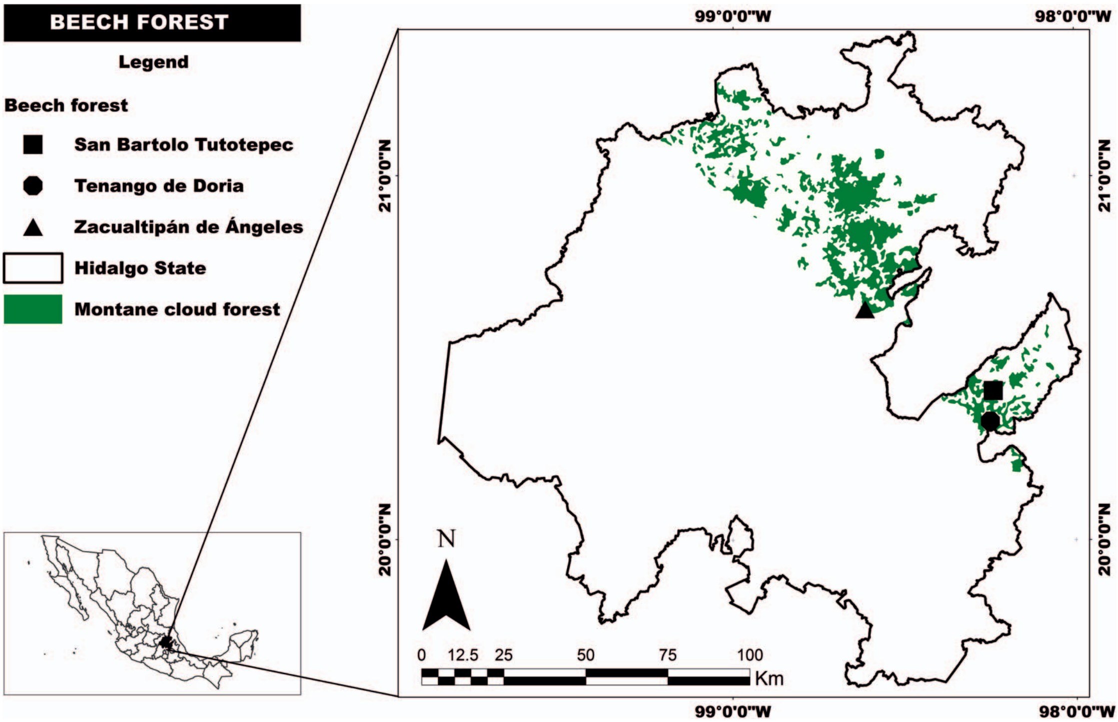

Figure 1. *Fagus grandifolia* subsp. *mexicana* forest sites and nearby weather stations in the state of Hidalgo, Mexico (Ortiz-Quijano *et al*. 2016).

sustained for periods of 5 consecutive years (Herrera *et al*. 2002; Rozas 2004):

$$\%CG = [(M1 - M2)/M1] \times 100,$$

where %CG = percent change in growth between the mean of the preceding and subsequent five years of ring widths, M1 = arithmetic mean of ring widths for the five previous years, M2 = arithmetic mean of ring widths for the five subsequent years.

When the percentage change is a positive value, it means that the growth rate was higher in subsequent years (release). Negative change indicates that the growth rate was lower (suppression) than in the previous period. The formula for %CG assumes that trees respond to a disturbance with a one-year lag, and that the maximum width of the ring is that of the years immediately prior to a sudden change in growth (Nowacki and Abrams 1997).

The ARSTAN program was used to standardize the ring-width measurements and to build the chronologies for each site (Cook and Holmes 1984; Cerano-Paredes *et al.* 2013).

Relationships between Chronologies, Climate and Disturbance Events

A simple linear correlation was used to find the degree of association between (a) the chronologies obtained in this study and a 100-year-long chronology based on *Pseudotsuga menziesii* built from a nearby site called Jaramillo in the state of Hidalgo (Stahle *et al.* 2016), (b) the ring-width indices and total annual and seasonal rainfall, and minimum, maximum and average annual temperature data obtained from weather stations near the study sites (Eric III 2013) for the period 1942–2011 (Tenango de Doria and Zacualtipán de Ángeles weather stations) and for the period 1973–2003 (Agua Blanca, Binola, Metztitlán and Palo Bendito weather stations), and (c) the ring-width index series and percentage change in growth with respect to dry and wet years based on the Palmer Drought Severity Index (PDSI) estimated from the Mexican Drought Atlas (Stahle *et al*. 2016). Data on disturbance events caused by human activity and of natural origin were obtained from the work of

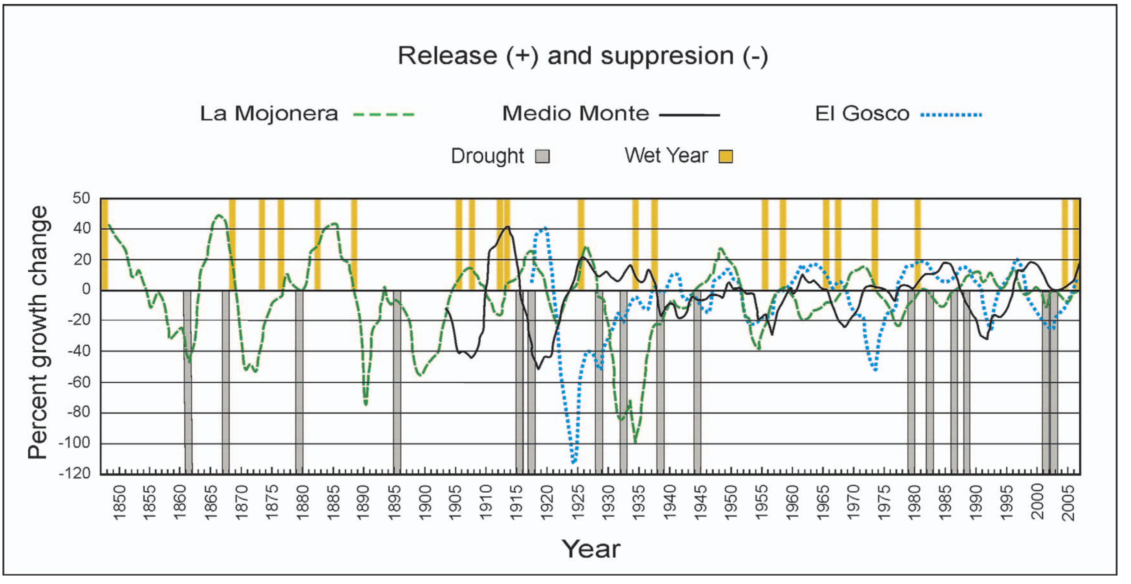

Figure 2. Percentage growth rate (suppressions and releases) determined from average radial growth in one-year and in five-year periods at the three study sites. The most conspicuous dry and wet years in the study area are included (Stahle *et al*. 2016).

Ortiz-Quijano *et al*. (2015) and were qualitatively compared with suppression and release events detected in the chronologies.

RESULTS

Releases and Suppressions in Growth Rings by Site

Average ring width, by site, ranged from 0.98 to 1.083 mm/year in the growth series analyzed. At El Gosco, five periods were identified with abrupt suppressions lasting more than five years, *i.e.* 1923 to 1931, 1952 to 1958, 1970 to 1977, 1992 to 1997, and 2000 to 2005. Two long-release periods were identified, one from 1959 to 1969 and the other from 1977 to 1991 (Figure 2). Two short periods showed higher release percentages, *i.e.* 1918 to 1921 and 1995 to 1998. At the Medio Monte site, six suppression events were identified. The periods 1904–1910, 1916–1924 and 1988–1996 corresponded to the highest and longest %GC. Four release events were identified. The strongest releases took place from 1911 to 1915 and from 1925 to 1938 (Figure 2). At La Mojonera, two suppression periods (1889–1899 and 1929–1944), and five release periods (1849–1854, 1863–1868, 1877–1889, 1945–1950 and 1969–1974) lasting six or more years were identified (Figure 2).

Dendrochronological Analysis

The longest beech chronology spanned from 1845 to 2012 and was obtained for the Mojonera site. Some of the oldest specimens were part of a cohort that was established in 1778. At the Medio Monte site, trees over a hundred-years old were common, with a recruitment date of 1842. At El Gosco, the oldest individuals were from an 1864 cohort (Figure 2).

A total of 3355 growth rings were measured from the three study sites. The series intercorrelation calculated using COFECHA was 0.43 for El Gosco and 0.33 for both La Mojonera and Medio Monte. Table 1 shows the overall results obtained using the ARSTAN program for each of the sites. The common period, in which the largest number of samples coincided for the three stands, was from 1950 to 2012. Average sensitivity values for *Fagus grandifolia* subsp. *mexicana* ranged from low to intermediate, and autocorrelations between series were low, which is desirable for climate reconstructions (Table 2).

Table 2. Basic statistics of the standard chronologies derived from ARSTAN output.

	Site		
Parameter	El Gosco	La Mojonera	Medio Monte
Chronology length	1914–2012	1845–2013	1900–2012
Total no. of years	99	169	113
Common interval	1951–2012	1950–2010	1951–2012
Number of trees	12	12	10
Number of samples	21	18	14
Average mean sensitivity	0.18	0.23	0.18
Standard deviation	0.19	0.19	0.20
Series intercorrelation	0.43	0.33	0.33
First-order autocorrelation	0.41	0.35	0.14

Tree-Ring Width Indices

The lowest standardized values for ring widths occurred for different years at each of the three sites, *i.e.* in 1919, 1954, 1974 and 1998 at El Gosco, in 1855, 1862, 1869, 1928, 1931 and 1988 at La Mojonera, and in 1905, 1916, 1939 and 1955 at Medio Monte. The highest values also did not coincide at the three sites, *i.e.* at El Gosco they occurred in 1917, 1949 and 1975; at La Mojonera in 1852, 1861, 1864, 1882 and 1989; and at Medio Monte in 1911, 1923, 1940 and 1958 (Figures 3A, B, C).

Comparison between Chronologies, Climate and Historical Events

The correlation coefficients between chronologies from the three sites were not statistically significant (not shown). Correlation with the reference chronology (Presa Jaramillo, Hidalgo) was significant for the La Mojonera site ($r = 0.73$ $p < 0.05$, 1915–2001; Figure 3D). Similar trends in ring-width indices were found for the three sites in the years/periods 1919, 1973, 1975–1979, and 1998. The indices were similar for the La Mojonera and Medio Monte chronologies for the years 1973, 1919–1920, 1922–1930, 1937–1939, and 1975–1978, and between the La Mojonera and Presa Jaramillo chronologies for the years 1922, 1931–1937, 1950, 1956, 1976, 1982, 1986, 1988, and 1998 (Figures 3A, B, C, D).

The correlation coefficients between ring-width indices and climate variables (total annual rainfall, minimum, maximum and average temperature) by site were not significant. However, when the series from all three sites were combined into a single chronology, and this was compared with records of cumulative rainfall from nearby weather stations (Agua Blanca, Binola, Metztitlán and Palo Bendito) from January to June for the period 1982–2000, the correlation coefficient was highly significant ($r = 0.66$, $P < 0.01$; Figure 4).

Correlations between the PDSI, ring-width indices, and percentage growth rate change (PGC), by site, were not statistically significant except for the correlation between PDSI and PGC at La Mojonera ($r = 0.15$, $P \leq 0.05$). Figure 2 shows that there were not many suppression or release events in the population analyzed. Some suppression events coincided with periods of drought, and some release events with high levels of moisture. The relationships between major historical events recorded by Ortiz-Quijano *et al.* (2015) for each of the sites and decreases (suppression) and increases (release) in the ring-width series are shown in Figure 5.

DISCUSSION

Dendrochronological techniques enabled us to determine dates of recruitment of beech populations and the influence of climate variability and anthropogenic disturbances for the past hundred years (Melandri *et al.* 2007; Ortiz-Quijano *et al.* 2016).

In the present study, average ring widths were similar between sites, with values ranging from 0.98 to 1.08 mm. These values are consistent with those estimated by Peters (1997) in mature beech trees in the La Mojonera ejido, who reported ring widths from 0.92 to 2.6 mm, although they were lower than those reported from a beech population at

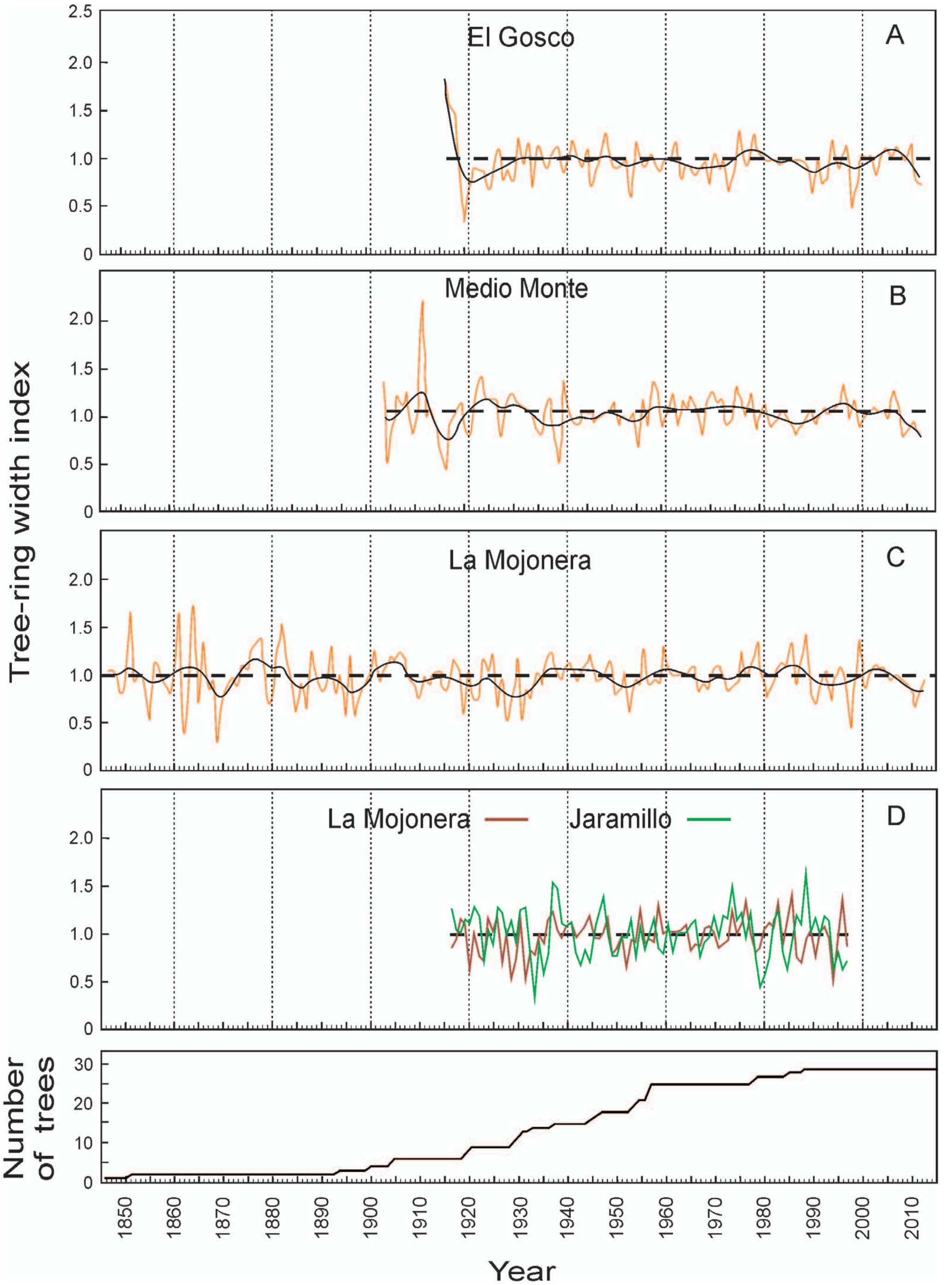

Figure 3. Chronologies of *Fagus grandifolia* subsp. *mexicana* at the three study sites (A, B and C) based on ring-width indices (the solid line represents the flexible 10-year spline fit to the annual data to highlight low-frequency events). D. Correlation between chronologies (1915–2001) from La Mojonera and Presa Jaramillo ($r = 0.73$; $P < 0.05$).

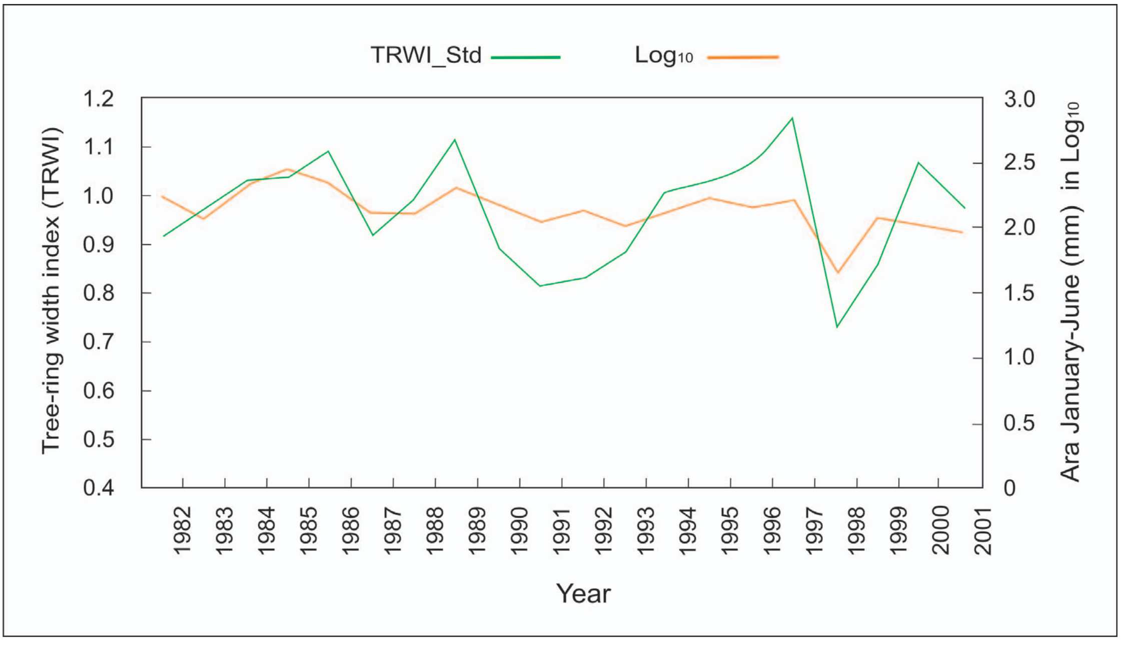

Figure 4. Comparison between a representative dendrochronological series for the three sites and records of average (Ara) seasonal January–June rainfall.

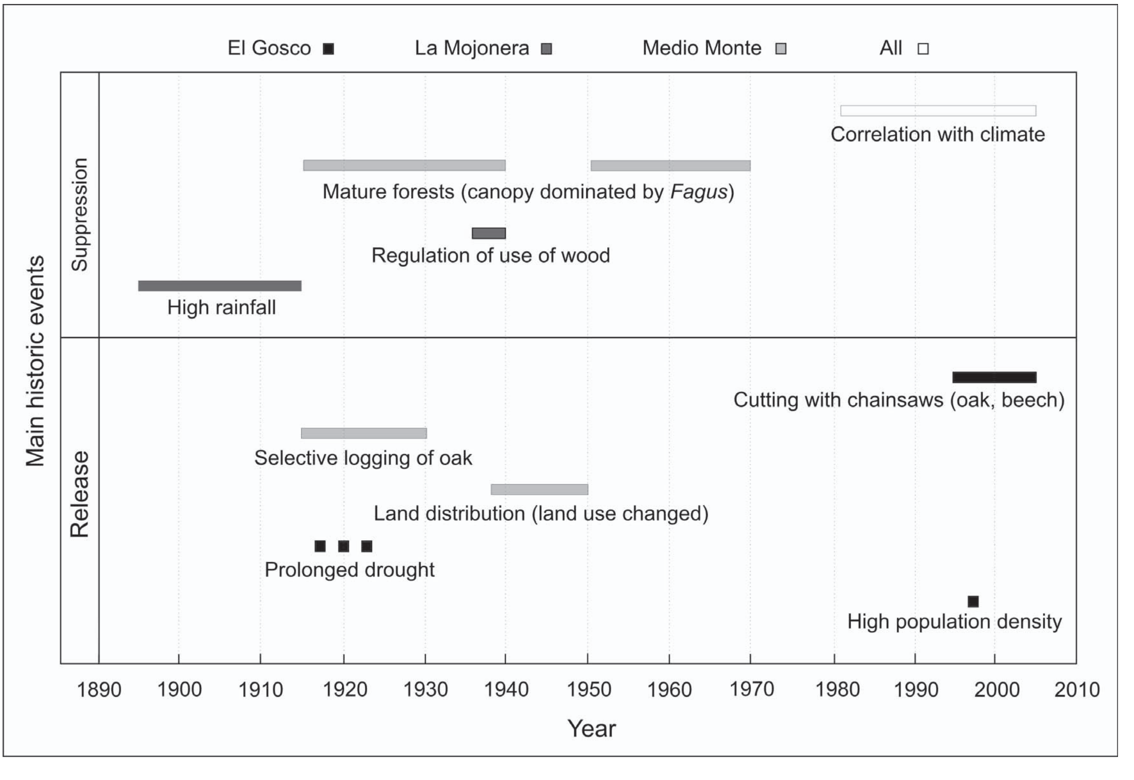

Figure 5. Relationship between suppressions and releases in growth for *Fagus grandifolia* subsp. *mexicana* and major historical events by site, according to Ortiz-Quijano *et al*. (2015).

the Acatlán Volcano in Veracruz, with an average annual radial increase of 2.35 mm. According to Williams-Linera *et al.* (2000) and Busby *et al.* (2008), the larger annual radial increase for the Acatlán stand could be associated with a forest fire, which resulted in greater recruitment and monodominance of *Fagus* in the canopy.

The results showed that some individuals of *Fagus grandifolia* subsp. *mexicana* were more than 150 years old. At the La Mojonera site, trees 234 years old (1778) were found. At the Medio Monte site, individuals dating back to 1842 were present, and at El Gosco, trees dating back to 1864 were found. These ages are slightly greater than those reported for the beech population at the Acatlán Volcano in the state of Veracruz, where trees up to 135 years old were observed (Williams-Linera *et al.* 2000) and are similar to ages recorded in various populations of *F. grandifolia* in Canada (Tardif *et al.* 2001; Kwiaton and Wang 2015), and the United States (Busby *et al.* 2008), which had individuals over 200 years old. In other beech species distributed in Europe, such as *Fagus sylvatica*, trees 200 to 300 years old are common, and in exceptional cases over 400 years old (Brunet *et al.* 2010; Di Filippo *et al.* 2015).

The abrupt decrease in growth observed for the early dates of the studied beech populations may be a consequence of lower sample depth in the ring-width chronology (Mérian and Lebourgeois 2011; Kwiaton and Wang 2015). As Lindholm *et al.* (2000) noted, when increment cores are obtained from a representative number of trees, the variation in average ring width is narrower compared to the variation observed for this parameter involving one or a few trees, because individual variation is reduced in the averaging process.

However, reliability in climate sensitivity can vary drastically between species, therefore the sampling effort should take into consideration the ecological characteristics of each species (Merian and Lebourgeois 2011). In several ecological studies with populations of *Fagus grandifolia* and *F. sylvatica* using a representative sample size, the pattern of interannual variation and decrease in ring width was similar to that observed in the present study, which may be related to the natural trend of the species to decrease in average sensitivity and to produce narrower rings as the tree ages because of geometrical constraints (Tardif *et al.* 2001; Čufar *et al.* 2008; Kwiaton and Wang 2015).

Climate conditions at the study localities are apparently optimal for beech growth (Peters 1997; Rodriguez-Ramirez *et al.* 2013). This explains the low to intermediate mean sensitivity of the chronologies, which have a range of 0.18–0.23. These values are similar to those recorded in other studies with *Fagus grandifolia* in Canada and the United States, where the growth of the species is limited by precipitation more than by temperature (Tardif *et al.* 2001; Kwiaton and Wang 2015; Takahashi and Takahashi 2016). Nevertheless, the interannual ring-width variation depends on numerous environmental variables, plant physiological processes, and human-induced disturbances (Mérian and Lebourgeois 2011).

At all three sites, a pattern of multiple releases and suppressions was found, suggesting that individuals have grown under a wide range of microenvironmental conditions. This pattern, similar to that recorded in *Fagus grandifolia* forests in Canada (Takahashi and Takahashi 2016) and the United States (Canham 1990), in *F. sylvatica* forests in Europe (Hachet-Pain *et al.* 2016; Latte *et al.* 2016), and *F. crenata* in Japan (Ariya *et al.* 2016), can be explained on the basis of canopy dynamics. That is, when a clearing opens after natural treefall (small- to moderate-scale disturbance), it stimulates the growth of individuals (juveniles and adults). Most release and suppression events observed in the analysis were therefore not related to historical records in land-use changes, larger-scale disturbances (Ortiz-Quijano *et al.* 2015; Ariya *et al.* 2016) or drought periods (Stahle *et al.* 2016).

In any case, some of the release events, such as those that took place in 1914 at La Mojonera and in 1867 and 1886 at Medio Monte may have had other causes. It is likely that the 1914 release event was the result of local economic activity. From 1915 to 1930, rural refineries of brandy ("aguardiente") were located on the banks of the river that now delimits the Medio Monte beech forest, because the industrial processes in these factories needed water and oak firewood (Ortiz-Quijano *et al.* 2015). Oak and pine have a variety of uses in Mexico, especially for timber and firewood (Pérez *et al.* 2000). Some species, such as *Quercus corrugata*, *Q. delgadoana* and *Q. xalapensis*, are typical elements of the canopy of Mexican beech forests (Williams-Linera *et al*. 2003; Ortiz-Quijano *et al*. 2016), so it is possible that clearings formed by selective removal of oak trees (reducing competition) for use as fuel in the refineries, combined with a period of high rainfall in 1913 (Stahle *et al*. 2016) are related to the 1914-release event. The residual chronology shows the prevalence of benign environmental conditions for *Fagus* in 1911, which falls within one of the highest rainfall periods in Mexico (1895 to 1914) (Melandri *et al*. 2007; Villanueva *et al*. 2013; Stahle *et al*. 2016). Given that the response of the species expressed in radial increase took place one to two years after the event (Herrera *et al*. 2002; Kwiaton and Wang 2015; Rohner *et al*. 2016), it is possible that both factors, namely selective logging of oak trees and high rainfall, could have influenced the increase in ring width.

Turning now to suppressions, one of the most conspicuous events of this type occurred in 1924, which points to the slow growth of juveniles in the understory (Crawley 1997), probably because of a closed canopy. The data obtained by Ortiz-Quijano *et al*. (2015) confirm this supposition. Before the agrarian reform and land distribution of 1939, tree density was high in Chicamole and Tutotepec, which are adjacent to Medio Monte. Subsequently, clearing of the forest began and illegal logging increased.

Analysis of suppressions and releases after the 1939 land reform showed no evidence that the *Fagus* population was affected by clearing or logging, perhaps because the forest sites are located in rugged terrain on steep slopes and are surrounded or insulated by oak and pine forests, which would function as natural buffer areas (CONABIO 2008). The suppression observed in the 1950s and 1960s, may have the same explanation as that of 1924, when Miranda and Sharp (1950) noted that in the 1950s the beech forests were dense, with canopies almost exclusively dominated by *Fagus*. Moreover, they were isolated on steep slopes and surrounded by oak forests. In addition, drought conditions that predominated during the 1950s may have had a strong influence on reducing radial growth (Stahle *et al.* 2016).

There was a marked period of suppression in the Mojonera (1929–1942). The climate instability that occurred in the region before and during this period, which consisted of pronounced drought (1928–1934), a wet episode (1935–1938) and a moderate drought (1939–1940), likely caused this growth behavior. The most obvious period of release in growth in El Gosco (1918–1920) was preceded by a wet period (1913–1915) and a period of moderate drought in 1916–1918 (Stahle *et al*. 2016), which did not affect the development of beech trees at the local level. The other release event in 1997 was set in motion by two factors that occurred at the local level, namely the introduction of chainsaws, which accelerated logging of pine and oak (Ortiz-Quijano *et al.* 2015), and an increase in human population, which rose by 100 inhabitants that year (INEGI 2010).

The population structure in the beech forests at El Mojonera and Medio Monte is dominated by young individuals, suggesting that the forests have sufficient natural recruitment for preservation of the species (Ortiz-Quijano *et al.* 2016), stimulated by a mosaic of clearings in various stages of recovery. The floristic composition and structure at both sites are typical of mature beech forests in North America and Europe with little to moderate disturbance (Peters 1997; Williams-Linera *et al.* 2003; Brunet *et al*. 2010).

The amount of land area covered by beech forest in the state of Hidalgo has remained constant for several decades. No evidence has been found in these forests of large-scale disturbances, whether of natural or of human origin, at least within the past 150 years (Ortiz-Quijano *et al.* 2015). These forests are located on steep slopes in rugged terrain and are not regularly visited by people, except during seed collection every 4–7 years (Godínez-Ibarra *et al*. 2007; Rodriguez-Ramirez *et al*. 2013). The exception is El Gosco, where excessive logging of oak and beech during the last five years has put the continuity of the beech forest at high risk.

The history of an area's disturbance regime must be taken into consideration when developing biological conservation practices and natural resource management plans (Landres *et al*. 1999). The release and suppression periods observed in this study suggest that the beech forests have a natural dynamic of disturbance that is impacted very little by human activity, and also indicate that climate changes in the recent past have not had an obvious effect on tree growth, perhaps partly because of a buffering effect caused by the particular physiography (exposure, slope, topography, soil type) and surrounding vegetation at the sites where these forests are located (Williams-Linera *et al.* 2000).

In recent years, people living in the villages nearest to the beech forests of La Mojonera and Medio Monte have developed a better appreciation for the beech forests and their ecological importance as they learn about the biology, natural history, and extinction risk category of the species (Ortiz-Quijano *et al.* 2015), which will probably contribute to the conservation of these forests, at least in the short term. However, evidence indicates that global climate change has altered the phenology and distribution of many plant species (Jump *et al.* 2007). Téllez-Valdés *et al.* (2006) state that the geographical distribution of *Fagus grandifolia* subsp. *mexicana* could decline drastically in the near future, even under a hypothetical scenario of moderate climate change.

The growth of *Fagus sylvatica* is limited by low rainfall in the spring, but from 1980 to the present, an unusual reduction has been reported in annual radial growth of individuals of this species in various regions of Europe caused by increased frequency and intensity of heat waves and drought during the growing season (Jump *et al.* 2007; Zimmermann *et al.* 2015; Hacket-Pain *et al.* 2016; Latte *et al.* 2016; Rohner *et al.* 2016). In the present study a similar trend was observed. Prior to 1982, fluctuations in ring width were associated mainly with local events, but in the period 1982–2004, the correlation between climate (temperature and moisture) and radial growth (ring width index) was significant.

Seasonal climate differences are not strongly expressed in the Sierra Madre Oriental mountain range of Mexico, where *Fagus grandifolia* subsp. *mexicana* populations grow, but the first half of the year is generally the dry season and the second half of the year is the rainy season with more rainfall, especially in the summer (García 1988). This rainfall pattern could explain the relationship observed between ring-width indices and seasonal rainfall from January to June (namely, water stress influences growth during the early growing season). This confirms that environmental factors (seasonal droughts) that limit radial growth in *Fagus* species are similar in different parts of the world (Tardif *et al.* 2001; Čufar *et al.* 2008; Kwiaton and Wang 2015; Zimmermann *et al.* 2015; Latte *et al.* 2016; Rohner *et al.* 2016).

Among all forests dominated by some species of *Fagus*, those of Mexico, located at 21°N, are the southernmost in the world (Pignatti *et al.* 2006). Their geographical distribution is therefore marginal, and they may as a result be more sensitive to climate change. Tardif *et al.* (2001) and Kwiaton and Wang (2015) suggest that the climate is less limiting to growth of *Fagus grandifolia* in northeastern North America than in southwestern North America. However, the Mexican beech grows under a variety of local "relict climate" conditions (*sensu* Cavin and Jump 2016) whose interaction up to now has mitigated changes in the overall climate in the region (Hacket-Pain *et al.* 2016; Stahle *et al.* 2016).

CONCLUSIONS

The dendrochronological analysis was able to identify several factors that have influenced annual radial growth of *Fagus grandifolia* subsp. *mexicana* during the last century. The multiple release and suppression pattern found for individuals of the species was attributed to ecological processes occurring at the stand level (disturbances of natural origin producing a mosaic of openings in mature beech stands) and to a lesser extent to climate variability (dry and wet years), land-use changes, and large-scale disturbances. The climate sensitivity of the species derived from the ARSTAN program showed low to medium values, which suggested a weak relationship between ring-width indices and climate variables. However, during the most recent decades, particularly in the period 1884–2004, the correlation was positive and significant with seasonal January–June precipitation, probably caused by climate change and the decline in indirect protection from surrounding pine-oak forest associated with the beech forest related to changes in land use.

ACKNOWLEDGMENTS

This study received financial support from the Consejo Nacional de Ciencia y Tecnología, Ciencia Básica project: "Estructura, diversidad de especies vegetales y distribución actual de los bosques de haya (*Fagus grandifolia* subsp. *mexicana*) en el estado de Hidalgo, México", No. CB-2011/169141, and through postgraduate scholarship No. 336759. We thank all the people who kindly provided information used in this study, most notably Yesenia Vital Cornejo, Esperanza García Lucio and Valentín Gómez García. We thank Miguel Campos Bustos for mapping the study area. The authors acknowledge the comments and suggestions of two anonymous reviewers, which contributed to substantially improving this article.

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Received 17 October 2016; accepted 12 April 2017.