

PINUS LEIOPHYLLA SUITABLE HABITAT FOR 1961-1990 AND FUTURE CLIMATE

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Abstract: Our objectives were to predict and map the climatic niche for *Pinus leiophylla* for a period of normalization (years 1961-1990) and future (2030, 2060 and 2090) climates, and to suggest management strategies to accommodate climate changes, and discuss implications for conservation. A bioclimate model predicting the presence or absence of *P. leiophylla* (lumped with its putative variety *P. leiophylla* var. *chihuahuana*) was developed by using the Random Forests classification tree on Mexican and United States of America forest inventory data. The bioclimatic model had an average error of prediction of 4.6 %. The model used six predictor variables, dominated by precipitation variables. Projecting the 1961-1990 climate niche into future climates provided by three general circulation models and two greenhouse-effect gas emission scenarios, suggested that the area occupied by the niche should diminish rapidly over the course of the century: a decrease of 35 % by the decade surrounding 2030, 50 % for 2060, and 76 % for 2090. The most serious habitat reduction occurs at both latitudinal extremes of the species distribution: Chiricagua Mountains, Arizona, United States of America in the northern extreme, and at Oaxaca State, Mexico, in the southernmost extreme. There is no indication at all of expansion of suitable climatic habitat northwards. We urge establishing seed banks encompassing seed from provenances sampled from the largest part possible of the natural distribution, and start assisted migration tests, to realign the natural populations with the climate for which they are adapted and that will occur at higher altitudes.

Keywords: assisted migration, climate change impacts, Random Forests classification tree, responses to climate.

Resumen: Nuestros objetivos fueron predecir y mapear el nicho climático para *Pinus leiophylla*, para los climas del período 1961-1990 y del futuro (2030, 2060 y 2090), sugerir estrategias de manejo para adaptarse al cambio climático y discutir implicaciones para su conservación. Se desarrolló un modelo bioclimático que predice la presencia o ausencia de *P. leiophylla* (agrupado con su supuesta variedad *P. leiophylla* var. *chihuahuana*) utilizando la técnica de árboles de clasificación Random Forests, con datos del inventario forestal de México y Estados Unidos. El modelo bioclimático tuvo un error promedio de predicción de 4.6 %. El modelo utilizó seis variables de predicción, dominadas por variables de precipitación. La proyección del nicho climático 1961-1990 en climas futuros, a partir de tres modelos de circulación general y dos escenarios de emisiones de gases de efecto invernadero, sugieren que el área ocupada por el nicho disminuirá rápidamente durante el siglo: una disminución del 35 % en la década alrededor del 2030, del 50 % para 2060, y 76 % para 2090. La reducción más grave de hábitat se produce en los dos extremos latitudinales de la distribución de las especies: Montañas Chiricagua, Arizona, en Estados Unidos en el extremo norte y en el estado de Oaxaca, México, en el extremo sur; no hay indicio alguno de la expansión del hábitat climático propicio hacia el norte. Se sugiere el urgente establecimiento de bancos de semillas de procedencias colectadas en la mayor parte posible de su distribución natural, e iniciar ensayos de migración asistida, para realinear las poblaciones al clima para el cual están adaptadas, mismo que ocurrirá a mayores altitudes.

Palabras clave: árbol de clasificación Random Forests, impactos del cambio climático, migración asistida, respuestas al clima.

P*inus leiophylla* has an important ecological role as one of the primary component of the pine-oak and coniferous forests, mostly at the middle altitudes of the interior slopes of Sierra Madre Occidental (up to southern Arizona

and Nuevo México, USA), and at the Trans-Mexican Volcanic Belt, and Sierra Norte of Oaxaca (Perry, 1991; Farjon and Styles, 1997; Musálem and Martínez-García, 2003; Rehfeldt *et al.*, 2006). The species is usually heavily tapped for

resin production in Mexico, particularly in Michoacán state (Musálem and Martínez-García, 2003).

Vegetation models suggest that by the end of the current century, suitable climates for the conifer forests at the Sierra Madre Occidental and at the Trans-Mexican Volcanic Belt could be reduced by 85 % and 92 %, respectively, values obtained from the average impact of three general circulation models and two greenhouse gas emission scenarios (Rehfeldt *et al.*, 2012). These changes result from temperatures that are projected to increase by 3.7 °C and precipitation to decrease by 18 % by the end of the century in Mexico (Sáenz-Romero *et al.*, 2010). If the climate to which *Pinus leiophylla* populations are adapted shifts, it is likely that current forests are soon to exhibit decline.

Such decline or die-off of large masses of forest with causes related to climatic change is underway in many parts of the world: *e.g.* *Pinus edulis* at low altitudinal limits in south-western USA (Breshears *et al.*, 2005), *Populus tremuloides* in the Rocky Mountains, USA (Worrall *et al.*, 2008) and Canada (Hogg *et al.*, 2002), *Cedrus atlantica* in the Moyen Atlas mountain range, Morocco (Mátyás, 2010), and *Fagus sylvatica* in south-west Hungary (Mátyás *et al.*, 2010) and in northeast Spain (Peñuelas *et al.*, 2007).

We have observed trees with symptoms of declination (severe defoliation and some with upper crowns deads), likely induced by drought stress due to climatic change, of *Abies religiosa* at the Monarch Butterfly Biosphere Reserve (Michoacán state; Sáenz-Romero *et al.*, 2012), and of *Pinus leiophylla* and *P. pseudostrobus* at its respective lower altitudinal limit at the Puépecha Plateau at Michoacán state (personal observation). Severe defoliation of *A. religiosa* declining stands has been documented at the Trans-Mexican Volcanic Belt by Flores-Nieves *et al.* (2011).

Biogeographers view climate as the primary factor controlling the distribution of plants (Tukanan, 1980; Brown and Gibson, 1983; Woodward, 1987). Then, modeling the relationship between presence and absence of a species from climatic variables at the sites of occurrence or absence makes it possible to predict the geographic distribution of climatically suitable habitats for a species, that is, the realized climatic niche (Rehfeldt *et al.*, 2006; Iverson *et al.*, 2008). For simplicity, we call the ‘period of normalization 1961–1990 realized climate niche’ the ‘climate profile’. That modeling can be done using the Random Forests classification tree (Breiman, 2001), available in R (R Development Core Team, 2004; Liaw and Wiener, 2002), to predict the presence–absence of a species from climate variables; in other words, the resulting model predicts the potential distribution of a species (the set of locations with favorable climatic conditions, are these inhabited or not). That procedure has been employed to model the period of normalization 1961–1990 and future distributions of the climatic niche for Mexican endemic rare species, *Pinus chiapensis* (Sáenz-Romero *et al.*, 2010); *Picea chihuahuana*, *P. mexi-*

cana, and *P. martinezii* (Ledig *et al.*, 2010); the high altitude *Abies religiosa* (Sáenz-Romero *et al.*, 2012) and *Pinus leiophylla* on their portion of USA distribution (Rehfeldt *et al.*, 2006). The modeling require precise information of climate variables that occur at sites either of presence or absence, something that was solved by constructing a spline climatic model for México (Sáenz-Romero *et al.*, 2010) and for all North America (Rehfeldt *et al.*, 2012). Climate estimates from the climate model can be obtained from a web site (Crookston, 2011). Presence/absence data can be acquired from Mexican and USA Forest Inventory.

The objectives of this work were to: (1) define the period of normalization 1961–1990 realized climate niche for *Pinus leiophylla*, (2) predict and map 1961–1990 and future distribution of climatic suitable habitat for *P. leiophylla*, and (3) suggest management strategies for relocation of *P. leiophylla* populations to accommodate climatic changes.

Materials and methods

Considerations about presence data input. We constructed our database of presence observations from field presence observations of *Pinus leiophylla* (both 766 observations of *P. leiophylla* var. *leiophylla* and 752 observations of putative *P. leiophylla* var. *chihuahuana*), from a subset of 6,674 observations with presence of conifers mainly from the Mexican National Forest and Soil Inventory (MexFI), elaborated by the Mexican National Forest Commission (Comisión Nacional Forestal, CONAFOR). Observations were provided from the latest data base version on January 2010, that encompassed field observations before 2005. Mexican Inventory customarily establishes plots with four subplots which were combined for our analysis.

We considered *Pinus leiophylla* Schiede ex Schlechten-dal & Chamisso as a single species, lumping together putative varieties *P. leiophylla* var. *leiophylla* Schlechtdl. & Cham. and *P. leiophylla* var. *chihuahuana* (Engelm.) Shaw (Farjon and Styles, 1997).

We decided the lumping after the following considerations: (i) There are not taxonomic consensus about the existence of clearly separate *P. leiophylla* in two varieties, nor their separation in two species (*P. leiophylla* and *P. chihuahuana*). In the southern rank of its distribution both putative varieties merges, to such extent that it becomes very difficult to distinguish them as varieties (Farjon and Styles 1997), even for Martinez (1948), who suggested their separation as species. Populations with the most northern distribution that reaches southern New Mexico and Arizona, although considered *P. chihuahuana* by Perry (1991), it is considered as simply *P. leiophylla* by the USA Inventory data (see Rehfeldt *et al.*, 2006). (ii) Although presence observations of *P. leiophylla* var. *leiophylla* and *P. leiophylla* var. *chihuahuana* were coded as two different species in the Mexican Forest Inventory data (*P. leiophylla* and *P. chihuahuana*, due to for-

mat reasons in the MexFI), it turned out that CONAFOR actually consider those two taxa as *P. leiophylla* varieties and not as different species, based on the classification of Kral (1993), (R. Aldana-Barajas pers. comm.). Also, on CONAFOR's MexFI data, the typical and putative variety overlap in altitude (1,500 m to 2,900 m) and in a large extent in latitude (N 22° to N 31°, being putative *P. leiophylla* var. *chihuahuana* with the most northern distribution) and longitude (W 103.5° to W 109°). Also, there are observations in the MexFI of 71 sites where there is recorded both putative varieties. A possible explanation of the typical and putative variety overlapping in altitude on the MexFI is that if for taxonomists it is difficult to decide whether those two putative varieties should be kept as such, or as different species, or as the same species, then for CONAFOR field personnel it is even more difficult to distinguish them. So, likely in practice in the field, individuals of both putative varieties were recorded in either way. (iii) If it were an error to lump together those two putative varieties or species, the error likely will be minor, since they are undoubtedly phylogenetically closely related (Rodriguez-Banderas *et al.*, 2009), sharing unique traits that none other species share, like deciduous fascicle sheaths and (quite unique) three year cone development (Farjon and Styles, 1997).

After examining the Mexican inventory data, plotting altitude against latitude and longitude, reviewing bibliography available (Martinez, 1948; Perry, 1991; Farjon and Styles, 1997), and discussing the natural elevation observed by botanists and forest taxonomists and geneticist with extensive field and/or botanical collections experience on this species (personal observations and J.A. Pérez-de-la-Rosa, C. Flores-López, S. González-Elizondo and C. Wehenkel, pers. comm.), we decided to remove presence plots from the Mexican Inventory data with elevations recorded above 3,000 m and below 1,500 m a.s.l., since likely they are errors either of identification or of entering data. Those likely mistaken observations represented the 2.7 % of the presence data set. Then, we added 35 observations of *Pinus leiophylla* from their extreme Northern distribution, at Arizona and Nuevo México. Those populations were collected by Gerald E. Rehfeldt and were used in a climatic modeling of *P. leiophylla* (Rehfeldt *et al.*, 2006). Finally, we added 38 sites from the USA Forest Inventory (field data collected before year 2000), from also Arizona and New Mexico, but different than the locations sampled by Rehfeldt *et al.* (2006). Thus, we ended up with a revised presence data base for *P. leiophylla* of 1,475 observations.

Sampling of sites with absence. We sampled sites with absence of *Pinus leiophylla* from a subset of the MexFI data with ca. 14,000 plots with species other than conifers. To assure that our sample of absence observations was representative of the vegetation of Mexico, we also used a systematic sampling of point locations within the digitized map of the

Biotic Communities of North America (Brown *et al.*, 1998; Rehfeldt *et al.*, 2012). Technical procedures, described in detail in Rehfeldt *et al.* (2006) and used also by Ledig *et al.* (2010) involved the use of ARCMAP software to procure a systematic sample of point locations from each polygon on the map and assign an elevation to each point from the digitized elevation model of GLOBE Task Team (1999). Data points from all communities within which *P. leiophylla* can occur (Madrean Montane Conifer Forest, Transvolcanic - Guatemalan Conifer Forests, and Madrean-Transvolcanic Pine-Oak Woodland, biomes as defined by Rehfeldt *et al.* (2012), based on classification by Brown *et al.* (1998) were discarded in this step, and some biomes where there are no conifer tree species were explicitly included (Tamaulipan Thornscrub, Gulf Coastal Grassland, Savanna Grasslands, Western Alpine Tundra, California Valley Grassland, California Coastalscrub, Mohave Desertscreub, Pacific Coast Thornscrub, Sonoran Desertscreub, Great Basin Desertscreub, Chihuahuan Desertscreub, Semidesert Grassland, and Great Basin Shrub-Grassland). With this last step we aimed to include absence locations with clearly unfavorable conditions, similar of what suggested Chefaoui and Lobo (2008) or Jiménez-Valverde *et al.* (2008) for obtaining most constrained predictive distribution maps; with the difference that our climatically distant absence sites are not pseudo-absences, because those absence sites were actually visited on the ground by personnel of the Forest Inventory and absences can be inferred without doubt.

To assure that the highest and coldest sites in Mexico were represented among the data points that lack *Pinus leiophylla*, the digitized elevations of GLOBE (1999) were used to obtain a geographic sample of points on the flanks of Mexico's seven tallest volcanic peaks. This procedure produced a data set of 30 observations that, for instance, contained as many as seven data points for Iztaccíhuatl (ca. 19.18° N latitude, 98.64° W longitude) that ranged in elevation from 4,291 to 5,142 m.

The procedure provided ca. 145,000 data points, all of which were assumed to lack *Pinus leiophylla*. The climate of each was estimated from the spline climate surfaces of Saenz-Romero *et al.* (2010) for the period of normalization 1961-1990, available at URL <http://forest.moscowfsl.wsu.edu/climate/>. These climate surfaces predict monthly values of temperature and precipitation from which 18 variables of demonstrated importance in plant geography are derived. Additional variables involving the interaction of the 18 derived variables are used herein to produce 34 variables available for developing bioclimate models. Of the possible interactions, we concentrated on those involving temperature and precipitation. We view the period of normalization 1961-1990 as a climate for which the inventoried tree populations were adapted for and grown in, and not the current climate (decade 2000-2010 or so), that has already changed due to climatic change. In other words, the normalization

period 1961-1990 is our best estimate of the conditions that produced the semblance of equilibrium between plant distributions and climate that existed prior to anthropomorphic induced changes in climate began to accrue.

Bioclimatic model. Our statistical model for predicting the occurrence of climatically suitable habitats of *Pinus leiophylla* are built on the framework of Iverson and Prasad (1998), Iverson *et al.* (2008) and closely parallel to those of Rehfeldt *et al.* (2006). The approach uses the Random Forests classification tree (Breiman, 2001), available in R (R Development Core Team 2004, Liaw and Wiener 2002), to predict the presence-absence of *P. leiophylla* from climate variables.

For classification trees, Breiman (2001) recommends that the number of observations within classes should be reasonably balanced. We use the sampling protocol of Rehfeldt *et al.* (2009) to draw from our database ten datasets. In each dataset, 40 % of the observations were those for which *Pinus leiophylla* was present, weighted by a factor of two (*i.e.*, 2,950 observations for each dataset). An additional 40 % were drawn from the pool of observations lacking *P. leiophylla* that comprised an 18-variable hypervolume surrounding the climatic limits of *P. leiophylla*. Dimensions of the hypervolume were set at ± 1.25 standard deviations for each variable; the pool consisted of ca. 29,500 observations. The remaining 20 % of were selected from a pool of data points lacking *P. leiophylla* and lying outside the hypervolume (pool of approximately 14,750 observations). Observations were selected such that a broad range of climate variation was represented: a random sample of ca. 74 observations (1 % of the total) was drawn from each of ten uniform classes subtending each of the first and second principal components calculated from the 18-variable network for all observations in our database, using the software SAS (SAS 2004). That means: 74 observations by 20 classes = 1,480 observations, or about 20 % of the total in any one of the ten data sets.

This sampling procedure thus used all observations with of *Pinus leiophylla*, concentrated the remainder of the sample in those climates for which separating presence from absence would be the most difficult, but still represented the full range of variation among the plots. Weighting permitted a higher proportion of the total observations to be used in each forest.

Our analysis was initiated with ten forests of 100 trees using 34 climate variables to predict the presence of *Pinus leiophylla*. Each forest used one of our datasets. Variables were eliminated according to a stepwise procedure that culled the least important variable at each step, using the mean decrease in accuracy to judge variable importance (see Breiman and Cutler, 2004). The mean value of this statistic was calculated across the ten forests at each iteration to determine which variable should be eliminated.

The best model was chosen according to the out-of-bag errors which take into account errors of omission and er-

rors of commission (see Breiman, 2001). When out-of-bag errors began increasing consistently, we assumed that the corresponding model was of reasonable parsimony (see Rehfeldt *et al.*, 2009). This model was used to derive the bioclimate climate model from ten forests and 100 trees.

Mapping realized 1961-1990 climate niche. Pixels of $\sim 1 \text{ km}^2$ (0.0083 decimal degrees) resolution comprises the terrestrial portion of our geographic window defined as: N 47° , N $13^\circ 54'$; W 117° , W 86° . By using the digitized elevations of GLOBE Task Team (1999), we estimated the climate of each pixel from the spline surfaces of Sáenz-Romero *et al.* (2010) and Rehfeldt *et al.* (2012). The climate of each pixel was then run through the bioclimate model using a R program (modules random Forest and yaImpute), with each tree of each forest providing a vote as to whether a pixel fell within the realized climate niche of *Pinus leiophylla*; a pixel was assumed to have a suitable climate when receiving a majority (> 0.5) of favorable votes.

Prediction of future suitable habitats. We projected the 1961-1990 climate niche into future climate space for decades surrounding 2030, 2060, and 2090, using climate grids (available in <http://forest.moscowfsl.wsu.edu/climate/> consulted 3 January 2010), for three General Circulation Models (GCM) and two scenarios: (1) Canadian Center for Climate Modeling and Analysis, using the CGCM3 (T63 resolution) model, SRES A2 and B1 scenarios; (2) Met Office, Hadley Centre, using the HadCM3 model, SRES A2 and B2 scenarios; and (3) Geophysical Fluid Dynamics Laboratory, using the CM2.1 model, SRES A2 and B1 scenarios. Data, their descriptions, and explanation of the scenarios are available from the Intergovernmental Panel on Climate Change Data Distribution Center <http://www.ipcc-data.org/> (consulted 3 January 2010). See Rehfeldt *et al.* (2006) and Sáenz-Romero *et al.* (2010) for a description of downscaling techniques and grid development.

In mapping projections, we adopt the view that disagreement among the projections reflects uncertainty for the future (see also Hansen *et al.*, 2001). Maps of suitable climate are presented according to the consensus among six projections for the decades centered on years 2030, 2060 and 2090. When only three or fewer projections agree (with each projection receiving a majority of favorable votes, > 0.5), we assume that uncertainty is high. Using this threshold means that a confident prediction would require an agreement between the disparate A and B scenarios, with at least four of the total of six projections in agreement.

Results

Bioclimate model. The 34-variable model produced a classification error that averaged 4.6 % across the ten 'forests'. As variables were eliminated in the stepwise procedure,

this error fluctuated between 4.5 % (for 31 variables in the model) and 5.2 % (for 3 variables in the model). Errors for the 2-variable model increased to 6.1 % and to 20.1 % for one-variable model. The lowest error with a small number of variables was for the 6-variable model which, when run anew to produce the bioclimate model, had an error of 4.6 %, with errors caused by predicting *Pinus leiophylla* to be present when absent averaging 7.2 % while those caused from predicting *P. leiophylla* to be absent when present were nill (0.79 %). The six climatic variables, listed in order of importance, were: SUMP, GSDD5, SPRP, MTCMMAP, WINP, and MAPDD5 (Table 1).

As measured by the overall classification error, the fit of our bioclimate model using 6 predictors is among the intermediate of those for 74 western USA species for which the same methods have been used (Crookston *et al.*, 2010). For the latter group, classification errors ranged from 1.4 to 11.0 %. For conifers of Mexico, errors were 4.5 % for *Picea* spp. (Ledig *et al.*, 2010) and 4.7 % for *Pinus chiapensis* (Sáenz-Romero *et al.*, 2010).

In bioclimate modeling, the most serious errors are in predicting the absence of a species when it was present, that is, the errors of omission. While many ecologically sound reasons may prevent a species from occurring in climates for which it is well suited, the most likely source of the er-

Table 1. Acronyms, derivation, and ranking of climatic variables of greatest relevance to the climate profile of *Pinus leiophylla*.

Acronym	Definition	Importance ranking
MAT	Mean annual temperature (°C)	-
MAP	Mean annual precipitation (mm)	-
DD5	Degree-days > 5 °C	-
ADI	Annual Dryness Index: (DD50.5)/MAP	-
GSP	April-September precipitation	-
GSDD5	Degree-days > 5 °C summed between the last freeze of spring and the first freeze of autumn; that is, between SDAY and FDAY	-
MTCM	Mean temperature of the coldest month	-
SDAY	Julian date of the last freezing date of Spring	-
FDAY	Julian date of the first freezing date of Autumn	-
SUMP	Summer precipitation: Sum of precipitation of July and August	1
GSDD5	Degree-days > 5 °C summed between the last freeze of spring and the first freeze of autumn; that is, between SDAY and FDAY	2
SPRP	Spring precipitation: Sum of precipitation of April and May	3
MTCMMAP	MTCM/MAP	4
WINP	Winter precipitation: Sum of precipitation of November, December, January and February	5
MAPDD5	(MAP × DD5)/1000	6

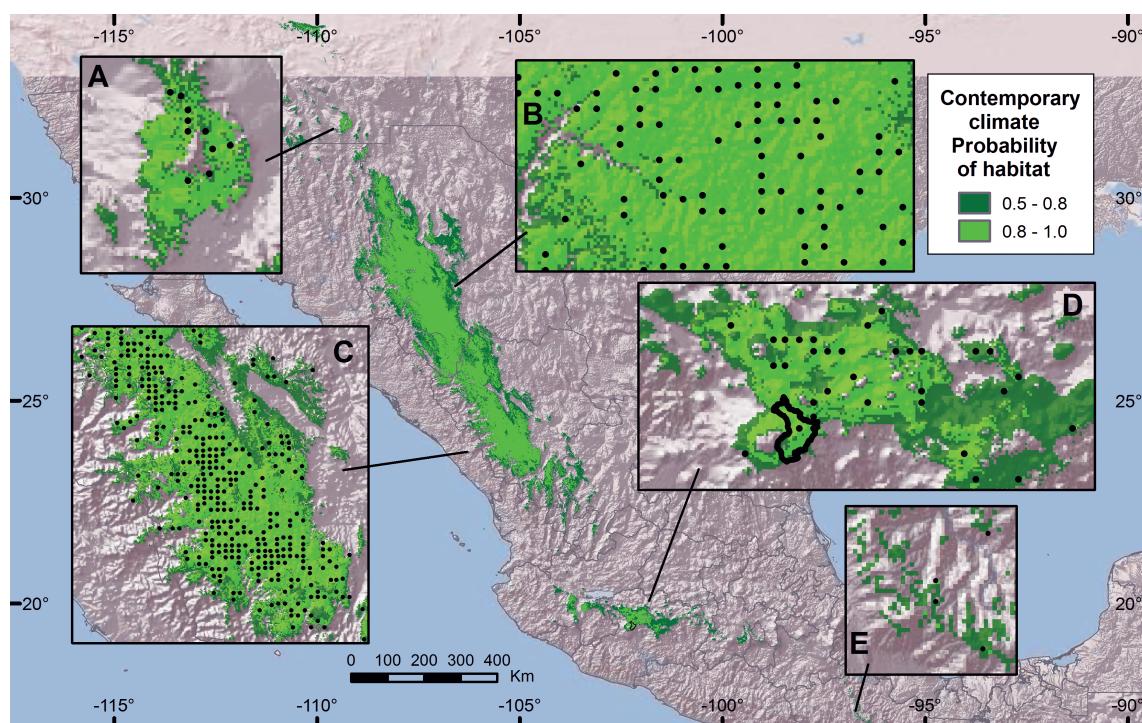


Figure 1. Mapped locations of areas predicted by the bioclimate model to lie within the period of normalization 1961-1990 climate niche of *Pinus leiophylla*. Likelihood that the climate is suitable is indicated (from 0.5 to 0.8, dark green; 0.8 to 1.0, light green). Symbols (black circles) locate existing populations as recorded by the Mexican or USA forest inventory. Panels show distribution areas in: (A) Chiricahua mountains, Arizona, USA; interior slopes of Sierra Madre Occidental at (B) southern Chihuahua state and (C) southern Durango state; (D) Pico de Tancitaro Natural Protected Area and forest of the Native Indian Community of Nuevo San Juan Parangaricutiro (black contour), Michoacán state; (E) northern Oaxaca state.

Table 2. Predicted area of suitable climate for *Pinus leiophylla* for the period of normalization 1961-1990 and for decades centered in years 2030, 2060 and 2090 (only when consensus of majority of model-scenarios -at least 4 of 6). Future predicted area expressed as projected km² (one pixel \approx 1 km²), and as % of change in area in comparison to contemporary area.

1961-1990 suitable climate		Future predicted area (projected km ² and % change of present)					
km ²	km ²	2030	2060	2090	km ²	km ²	%
184,625	120,717	-34.6	92,525	-49.9	45,197	45,197	-75.5

rors of omission are in the model fitting process (see, for instance, Rehfeldt *et al.*, 2009). In our analyses, like those of many western USA species (see Crookston *et al.*, 2010), errors of omission were essentially nonexistent, a result directly linked to the sampling protocol which weights by a factor of two those observations in which the species of interest was present (see Rehfeldt *et al.*, 2009).

Mapped 1961-1990 climate profile. The precision of the bioclimate model is further apparent by superimposing the locations inhabited by *Pinus leiophylla* on climate profile (Figure 1). Nearly all data points occur in grid cells for

which the likelihood was high that the climate would be suited for the species.

Predicted distribution of the suitable climatic habitat well represents the actual distribution mainly along the interior slopes of the Sierra Madre Occidental (Figure 1B, C), along an area of transition between the high altitude colder and moister conifer forest of the Sierra Madre Occidental and the warmer and dryer pinyon-pine forest at the lower part of the slopes of the Sierra. The extreme northern distribution that reaches Arizona, USA, is well represented at the Chiricahua mountains (Figure 1A). On the Trans-Mexican Volcanic Belt, their predicted distribution appears with lower probability of occurrence (mostly between 0.5 and 0.8; Figure 1D), which is congruent with our direct observation that in that area, *Pinus leiophylla* in general does not conform pure stands; almost always is in mixed stands. Even more marginal is the extreme southern distribution at the northern of Oaxaca state, where fragmented climate habitat has a probability between 0.5 and 0.8 (Figure 1E). The extent of predicted distribution area (probability > 0.5) for the species in México and in USA is shown in Table 2.

Future suitable habitat for *Pinus leiophylla*. Predicted suitable habitat for *P. leiophylla* for the decades centered around

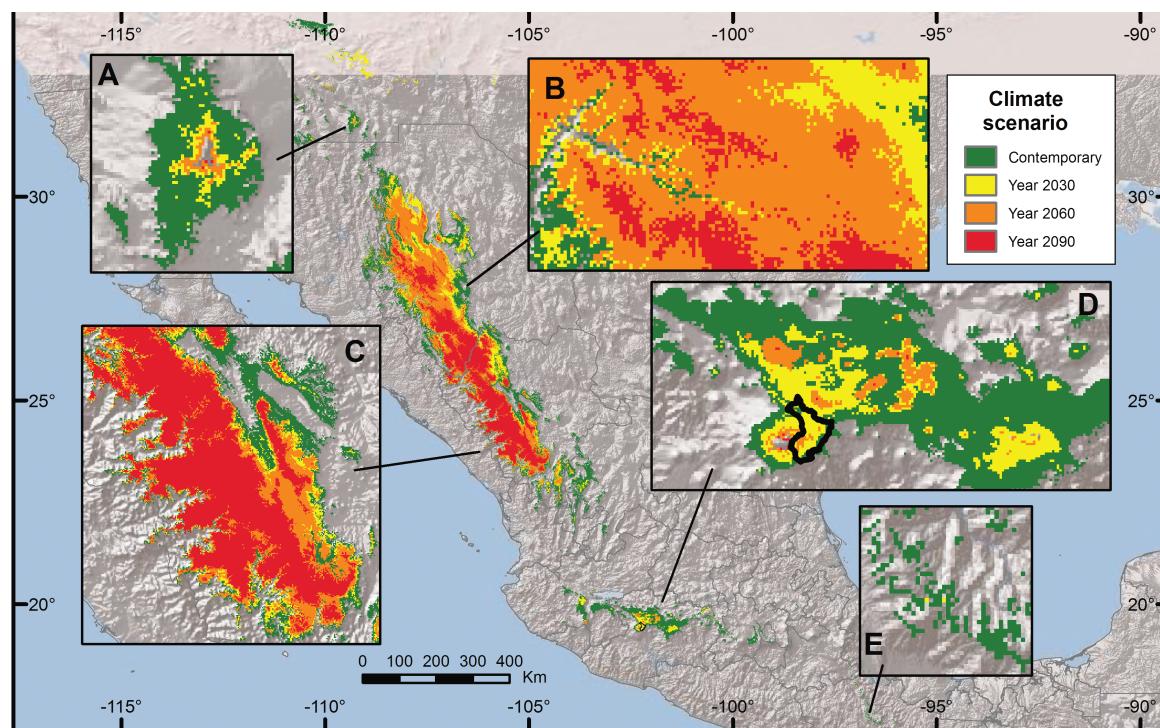


Figure 2. Mapped locations of areas predicted by the bioclimate model to lie within the climate niche of *Pinus leiophylla* for four time frames (period of normalization 1961-1990 and decades surrounding 2030, 2060, and 2090). For 1961-1990 climate, grid cells colored green indicate the likelihood that the climate is suitable (votes > 0.5 , Figure 1); for future climates, colors indicate the consensus of six projections that predict suitable climate (at least four of six, each one with votes > 0.5). Panels show distribution areas in: (A) Chiricahua mountains, Arizona, USA; interior slopes of Sierra Madre Occidental at (B) southern Chihuahua state and (C) southern Durango state; (D) Pico de Tancítaro Natural Protected Area and forest of the Native Indian Community of Nuevo San Juan Parangaricutiro (black contour), Michoacán state; (E) northern Oaxaca state.

2030, 2060, and 2090 (Figure 2) is based on the consensus of six projections. In this figure, current area is determined by > 50 % of the votes from the classification tree, but future predictions require agreement of at least four of the six projections before being accepted as a likely prediction. The figure suggests a reduction of the climatically suitable habitat for *Pinus leiophylla*, by 35 % in relation to the period of normalization 1961-1990 area by 2030, 50 % by 2060, and by 76 % by 2090 (Table 2).

In general, as the century advances, suitable habitat for *Pinus leiophylla* is predicted to occur at higher altitudes along the Sierra Madre Occidental and Mexican Transvolcanic Belt. The region around the border between northwest of Durango and southwest Chihuahua states retain in the future most of the 1961-1990 distribution (main Figure 1), as well as the high elevations of the Sierra Madre Occidental along western Durango (Figure 1C). However, the central and northern distribution of suitable climate for *P. leiophylla* inside Chihuahua state is severely reduced by 2090 (Figure 1B).

Suitable climatic habitat reduction is more dramatic at both northern and southern latitudinal extremes of the 1961-1990 distribution. At northern limits, suitable climatic habitat increase in altitude at the Chiricagua Mountains, Arizona, but almost disappear by 2090 (Figure 1A; notice almost complete lack of 2090 red pixels -it remains only four). Likewise, at the Trans-Mexican Volcanic Belt, on the Pico de Tancítaro and Nuevo San Juan Parangaricutiro region, Michoacán state, suitable climatic habitat increase in altitude but almost disappear by 2090 (Figure 1D, only 15 red pixels for 2090 remains). The extreme southern 1961-1990 distribution, at northern Oaxaca state, almost disappear since 2030 (only two yellow pixels remains for 2030, Figure 2E) and suitable climate habitat is completely gone by 2060 and 2090 (none orange or red pixels, respectively, on Figure 2E).

Discussion

The prediction of 1961-1990 distribution in general is in agreement of maps developed by Perry (1991), Farjon and Styles (1997), Rodríguez-Banderas *et al.* (2009) and Rehfeldt *et al.* (2009). The area where the 1961-1990 climate is predicted to be suitable for *Pinus leiophylla* is greater than the actual distribution. This result is to be expected when habitat suitability is predicted on the basis of climate alone. Many other factors may restrict where a species actually occurs, *e.g.*, substrate, interactions with other species, or restrictions on seed dispersal (see Pearson and Dawson, 2003, van Zonneveld *et al.*, 2009). In addition, using the majority of votes (> 0.5) to predict presence or absence prevents identification of locations where the climate may approach suitability (*e.g.*, with: $0.25 < \text{votes} < 0.50$). Nonetheless, a portion of the classification error results from cor-

rectly predicting suitable niche space that is, by chance, not occupied.

Perhaps it is not surprising the future disappear of suitable climatic habitat at the extreme southern distribution limit (northern Oaxaca, Figure 2E), if we view it as “rear end” populations, when the faith of low altitudinal limit or extreme southern limit populations at Northern Hemisphere seems to be extirpation (Aitken *et al.*, 2008, Fettig *et al.*, 2013). However, future projections do not indicate at all an expansion of the suitable climatic northwards (Figure 2); on the contrary, extreme northern populations will see its suitable climatic habitat disappear (like the ones at Chiricagua Mountains, Figure 2A).

Implications for management and conservation. Maps such as Figure 2 showing projected climate profiles of the future do not necessarily predict that the tree populations will actually occupy the future locations of their climatic niches. Although there are well documented examples of populations that are migrating to and colonizing altitudes higher than those they occur in today as an apparent response to the ongoing climatic change (Lenoir *et al.*, 2008), the speed at which migration is occurring is much slower than that needed for tracking the changing climatic. For example, an examination of the altitudinal distribution of 171 forest plant species (woody and non-woody) in West Europe, indicates that on average there has been an altitudinal upward shift of 65 m, when, in fact, a shift of 150 m would be required to compensate for the increase in average temperature that already has occurred (Lenoir *et al.*, 2008). In the case of four pine species distributed in the Trans-Mexican Volcanic Belt, an upward migration of 300-400 m would be required to compensate for the change in climate expected for year 2030 as predicted, for instance, by the A2 scenario of the Canadian GCM (Sáenz-Romero *et al.*, 2010).

Thus, an inescapable conclusion is that human assistance will be needed to realign natural populations to the climate for which they are adapted. Assisted migration by means of massive reforestation programs, where seed are collected at contemporary populations but seedlings should be planted at sites where it is predicted that will happen their suitable climatic habitat, perhaps by 2030 or by 2060 (Rehfeldt *et al.*, 2002, Tchevakova *et al.*, 2005, Rehfeldt and Jaquish, 2010, Joyce and Rehfeldt, 2013). It is indispensable to avoid to plant on a site where climate will occur in a too far away horizon, because at present seedlings might be killed by frost damage (Sáenz-Romero and Tapia-Olivares, 2008).

It is needed to remark that planning to collect seeds from contemporary populations and to plant the nursery-produced seedlings on the predicted areas of suitable climate for 2030 or 2060, does consider the climate niche for the species, but lacks any subdivision due to genetic differentiation among populations. An approach of subdividing the species niche

in climatypes (set of populations genetically differentiated to other sets of populations, due to selection imposed by environmental variables, where such differences were demonstrated on field and/or common garden provenance trials; climatype definition *sensu* Rehfeldt and Jaquish (2010), would be highly needed for *Pinus leiophylla*. Such climatype approach has been detailed suggested for *Larix occidentalis* (Rehfeldt and Jaquish, 2010) and for *P. strobus* (Joyce and Rehfeldt, 2013).

One limitation is the scarcity of *Pinus leiophylla* provenance tests. Some unpublished data for provenances collected at Chiricagua mountains, a nursery provenance tests (Castellanos-Acuña *et al.*, 2013) and field common garden tests (Castellanos-Acuña *et al.*, 2015), indicate very limited genetic differentiation among *P. leiophylla* populations. That, in fact, would simplify the rules for seed and seedling movement, making those movements more liberal.

Despite the very extensive distribution of the species, two factors might contribute significantly on endangering the persistence of the natural populations on future climatic change scenarios: The extensive tapping of *Pinus leiophylla* individuals for resin production, and the (very rare) three year cycle cone development (Farjon and Styles, 1997). Undoubtedly heavy tapping weak the possibility of a tree to unfold its natural defenses (like ejection of incoming pine beetles). One typical symptom of a drought stressed tree is to decrease the cone production; with a 3-year-cycle, the decreasing of seed production would create an even larger lag on seed production. Thus, the interaction of climatic change inducing drought stress, heavy tapping weakening the trees, and a long 3-year-cycle for cone production, highlights the need of the urgent establishing of seed banks encompassing seed from provenances sampled from the largest part possible of the wide natural distribution, as well as starting experimental assisted migration test, to realign the natural populations with the climate for which they are adapted.

Conclusions

Projecting future suitable climatic habitat for *Pinus leiophylla* under climate change scenarios suggest that the area occupied by the niche should diminish rapidly, with a decrease of 35 % by the decade surrounding 2090. The most serious future habitat reduction occurs at both northernmost and southernmost latitudinal extremes of the 1961-1990 species distribution: Chiricagua Mountains, Arizona, USA and Oaxaca state, Mexico, respectively. There is no indication at all of expansion of suitable climatic habitat northwards. Extensive seed collections and assisted migration plantations at higher altitude than the seed sources, to realign the populations to the climate for which they are adapted, is highly needed to conserve this species in a future warmer and dryer climate.

Acknowledgements

Financial support to CSR was provided by a grant from Mexican Commission for the Study and Use of the Biodiversity (CONABIO, project JM036), the Coordination for Scientific Research of the University of Michoacán (CIC, UMSNH), and the Mexican Integral Program for Institutional Strengthening Fund (PIFI-2012). We thank Miriam Vargas-Llamas, Rigoberto Palafox-Rivas, and Octavio Magaña-Torres, Mexican National Forestry Commission (CONAFOR) for providing Mexican forest inventory data; Nicholas Crookston (USDA-Forest Service, Moscow, Idaho, for technical support; Jorge Alberto Pérez-de-la-Rosa (Universidad de Guadalajara), Rebeca Aldana-Barajas (CONAFOR), Celestino Flores-López (Universidad Autónoma Agraria Antonio Narro), Christian Wehenkel (Universidad Juárez del Estado de Durango), Socorro Gonzales-Elizondo (CIIDIR-Durango, Instituto Politécnico Nacional), Javier López-Upton (Colegio de Postgraduados) and Antonio Plancarte-Barrera (Ailen México), for valuable comments about quality of data input, taxonomic status and preliminary maps. Two anonymous reviewers made valuable comments that helped to improve the manuscript.

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Received: March 20th, 2014

Accepted : August 14th, 2014