

Tomicus species (Coleoptera: Curculionidae: Scolytinae) as Invasive Forest Pest to Mexico with Ecological Niche Modeling

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ABSTRACT

Scolytine bark beetles of the genus *Tomicus* (Coleoptera: Curculionidae: Scolytinae) include some forestry pests of major importance worldwide, with the capacity for invading new habitats and threatening native forest populations and are considered as exotic species for America. However, *Tomicus piniperda* L. the common pine shoot beetle has invaded North America recently and specimens of *T. minor* Hart have been intercepted in the United States. The possibility for an invasion of Mexico grows day by day. A preventive strategy to evaluate the invasion by exotic species is ecological niche modeling. Using bioclimatic variables, distributional data, entropy algorithm, and modeling software, the ecological niche of three *Tomicus* species was calculated and projected to Mexico. Results of this analysis showed potential environmental suitability in Mexico for *T. destruens* (small and dispersed areas in the Altiplano Norte biogeographic province and an isolated area in the Tamaulipeca biogeographic province) and *T. minor* (high suitability in the biogeographical provinces of Baja California, California, Sonorensis, Altiplano Norte and Altiplano Sur, Tamaulipeca and small areas in eastern Eje Volcánico.). For *T. piniperda*, no environmental suitability was projected in Mexico. Additional ecological requirements, host preferences, and local fauna competition, as factors influencing the potential invasion of *T. minor* in Mexico, are discussed. Our work has an important impact because Mexico is one of the most important countries with high pine diversity in the world and shows an important impact on pine's hot spots.

Keywords: Invasive species, Ecological niche, Pine shoot beetles, Mexican biogeographic provinces.

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INTRODUCTION

Mexico is considered a megadiverse country [1] its plant composition, abundance, and distribution are favored by the combination of neotropical/Nearctic elements [2]. Furthermore, the time and formation of the mountainous systems, help to disperse forests across the country [3].

Pinaceae found in Mexico space, geographic complexity, and weather for evolution, i.e., is a *Pinus* diversity and radiation center [4], with at

least 23 endemic species [5, 6]. 49 species of the genus are recorded for the country, distributed in its entire surface, except tropical lowlands of Tabasco and Yucatan [5]. However, forest cover in Mexico is reduced annually by economic (poverty), social (population growth, migration), political (governmental programs), and climatic factors (drought, climatic changes) [7, 8]. As consequence, populations of 21 species are under threat or special protection [5, 9].

In the case of coniferous forests, to this set of adverse factors, an additional threat is invasive

species, mainly by insect pests [10]. Of this group of arthropods, some species of the genus *Tomicus* (Coleoptera: Curculionidae: Scolytinae) have gained prominence for invading new habitats and for threatening native forest populations by direct and/or indirect damages. *Tomicus* species live in Pinaceae (mainly *Pinus*) [11] and are classified into eight species [*T. armandii* Li & Zhang, *T. brevipilosus* Eggers, *T. destruens* Woll., *T. minor* Hart., *T. piniperda* L., *T. puellus* Reitter, *T. pilifer* Spessivtsev and *T. yunnanensis* (Kirkendall & Faccoli)], considered as pests in several regions of the world [11]. *Tomicus armandii*, *T. brevipilosus*, *T. pilifer*, *T. puellus*, and *T. yunnanensis* are distributed in central, southwestern, and eastern China [11] but *T. destruens*, *T. minor*, and *T. piniperda* have a wider distribution, with major forestry importance [11].

Tomicus piniperda, the common pine shoot beetle, is considered a major scolytinae pest, with a widely Euroasian distribution, and established in North America [12], infesting Christmas tree plantations [13]. *Tomicus piniperda* is showing an incredible adaptation and wider distribution in Canada and the United States [14]. In its natural range, *T. piniperda* frequently is associated with the lesser pine shoot beetle, *T. minor*, combined attack of both species breaks natural tree resistance [15]. Interception records for *T. minor* for the USA from countries outside their original distribution pattern have been reported [16]. For some authors is considered as a secondary pest, but *T. minor* threatens *Pinus* species in China [17]. *Tomicus destruens* occurs only in Mediterranean Basin and Macaronesian Islands [17, 18] and has been considered as an injurious pest for Mediterranean pine forests [19]. In general, *Tomicus* species infest *Pinus* trunk and branches, inducing foliage malformations and reducing their commercial value, trees can be destroyed by massive infestation or favoring secondary infestations killing the host by stress

Mexico is an importer of Christmas pines from the USA and Canada, 25,859 metric tons were imported in 2014 [20] movement of plant material favors the entry of harmful fauna to native flora and could threaten the local wood market. Locally, *Pinus* contributes 75.1 % of annual wood production [21].

With this perspective, in this manuscript, we used ecological niche modeling, as a strategy to calculate as far as possible, the climate

compatibility for three *Tomicus* (Coleoptera: Curculionidae: Scolytinae) species considered invasives in other regions of the world. The finality is to provide data that Mexican phytosanitary agencies could use to make better management choices [22], or for the establishment of areas for sampling/monitoring or implementing preventive management tactics.

MATERIALS AND METHODS

Distribution record of Tomicus spp. and Pinus spp
Distribution data of three *Tomicus* species (*T. destruens*, *T. minor* and *T. piniperda*) were compiled from scientific literature and the database Global Biodiversity Information Facility (GBIF) [14, 15, 17, 19, 23-27].

Model calibration

Good practices for working with distributional data were used, duplicated points were removed, and for reducing spatial correlation, points with a minor distance of 10 km between them were erased with the package 'spThin' in Rstudio® ver. 3.3. The original database for *T. minor* was integrated by 3,825 points, after depuration, the final compilation consisted of 747 points, 561 used for training model (75 %), and 186 for model evaluation (25 %). For *T. piniperda*, from 5,504 initial points, the final database was integrated with 1,357 points, 1,018 used for training (75%), and 339 for model evaluation. In the case of *T. destruens*, the initial data was integrated by 237 points (25 %), and after the good practices were applied, the final database was integrated by 145 points, 109 (75%) used for training, and 36 (25 %) for model evaluation.

The accessible area for each species (M), defined as the origin areas according to its dispersion capacity [28], according to the BAM diagram (M= Species accessibility, B = Biotic variables, A= Abiotic variables) [28]. Areas were delimited with the world biogeographic ecoregions [29] in Qgis ver. 3.16.11®. 19 bioclimatic variables were downloaded from www.worldclim.org with a spatial resolution of 2.5 minutes, but bioclimatic variables 8, 9, 18, and 19 were discarded due to problems with some pixel values (**Table 1**) [18].

Table 1. Bioclimatic variables were used for the ecological niche model calculation of three *Tomicus* species (Coleoptera: Curculionidae: Scolytinae).

Bioclimatic variable

BIO1 = Annual Mean Temperature
BIO2 = Mean Diurnal Range (Mean of monthly (max temp - min temp))
BIO3 = Isothermality (BIO2/BIO7) (×100)
BIO4 = Temperature Seasonality (standard deviation ×100)
BIO5 = Max Temperature of Warmest Month
BIO6 = Min Temperature of Coldest Month
BIO7 = Temperature Annual Range (BIO5-BIO6)
BIO10 = Mean Temperature of Warmest Quarter
BIO11 = Mean Temperature of Coldest Quarter
BIO12 = Annual Precipitation
BIO13 = Precipitation of Wettest Month
BIO14 = Precipitation of Driest Month
BIO15 = Precipitation Seasonality (Coefficient of Variation)
BIO16 = Precipitation of Wettest Quarter
BIO17 = Precipitation of Driest Quarter

A Spearman correlation with the environmental data was performed NicheToolBox (<http://shiny.conabio.gob.mx:3838/nichetoolb2/>), a tool for exploratory data analysis in ecological niche modeling (ENM) for the elimination of correlated variables (MNE) [30]. Variables without correlation were used to build two sets of variables. Model candidates were designed with Rstudio® ver. 3.3 and the package kuenm, this is a tool to perform detailed development of ecological niche models using Maxent [31]. 310 candidate models were created with the function kuenm_cal of the 'kuenm' package, this function creates candidate models with multiple regularization multiplier combinations, entity classes, and sets of environmental predictors. For each combination, Maxent builds a model with the occurrences set points and another model with the training occurrence data [32]. The combination of

features classes was linear (L), quadratic (Q), product (P), threshold (T), hinge (H), and for multipliers, regularization were 0.5, 1, 2, 3, and 4. Each model quantifies the environmental suitability for the species of interest, as a function of the variables studied.

Evaluation of ecological niche models

Candidate models were evaluated with the function kuenm_ceval of the 'Kuenm' package in Rstudio® ver. 3.3, this evaluation selects one or two best models, categorized by their prediction capacity and complexity, selecting those models with statistical significance [33]. Partial roc was used to choose models that are significantly better than randomly null expectative [33]. Then, the omission rate criterion was applied to these models. In the end, those significative, low omission rates, and delta AICc with lower values of 2, were selected [32].

RESULTS AND DISCUSSION

Models' quality

Ecological niche modeling for invasive species studies "use occurrence records of the species in one region to calibrate models, and to then project those models into other regions, where the species may or may not be invasive at present" [28]. For supporting the hypothesis of environmental suitability, we selected models with statistical robustness (**Table 2**), with omission rates ≤ 5%, and delta AICc values ≤ 2 [28, 32].

Table 2. *Tomicus* (Coleoptera: Curculionidae: Scolytinae) species best models evaluated statistically and used for modeling their ecological niche.

Species	Model	Partial ROC	Omission the rate at 5%	AICc	Delta AICc	W_AICc	Number of parameters
<i>T. minor</i>	M_4_F_pt_Set_02	0.02	0.049	17450.033	0	0.99996812	16
<i>T. piniperda</i>	M_1_F_lqpt_Set_01	0	0.024	32079.290	0	0.38921386	96
<i>T. destruens</i>	M_1_F_lq_Set_01	0	0.029	2787.7524	0	0.99934317	10

Bioclimatic variables for modeling ecological niches

Models for the species studied here were determined by a particular set of bioclimatic variables (**Table 3**), reflecting different environmental requirements, related to their natural geographic distribution. In terms of world biogeographic regions [34], *T. destruens* has an Oriental region distribution, expanding to the Palearctic and until the Saharo-Arabian

transition zone, their southernmost distribution habitat [11]. Both *T. piniperda* and *T. minor* follow a similar distribution pattern, from the Chinese transition zone, along with to the Oriental region for a natural wide expansion through the Palearctic region [11]. However, *T. piniperda* needs a wider set of bioclimatic variables in comparison to *T. minor*.

Ecological models were defined mainly by three-four bioclimatic variables, contributing with

71.9, 97.1, 78.3 % for *T. destruens*, *T. minor*, and *T. piniperda*, respectively (**Table 3**). For *T. destruens*, variables related to precipitation and temperature seem to define their ecological niche: bio14 (Precipitation of the driest month, indicates the month with the lowest cumulative precipitation total in their origin site), bio15 (precipitation seasonality), and bio2 (annual mean diurnal range). By another hand, *T. minor*

showed more precipitation variables for defining their ecological niche, with bio1 (annual mean temperature), bio 7 (Annual temperature range), and bio 16 (Precipitation of wettest quarter) as the main bioclimatic variables. *Tomiscus piniperda* was defined by bio1 (annual mean temperature), bio5 (max temperature of the warmest month), and bio 4 (temperature seasonality, a measure of temperature changes annually).

Table 3. Bioclimatic variables were used in the final modeling of the ecological niche of three *Tomiscus* species (Coleoptera: Curculionidae: Scolytinae) species.

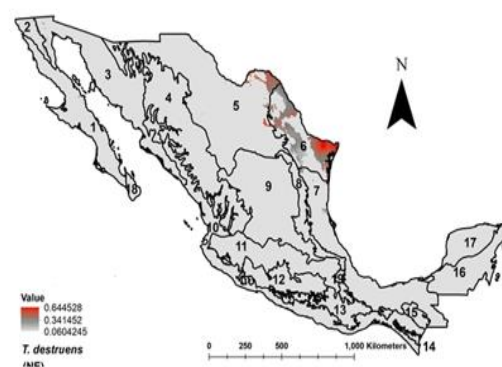
<i>T. destruens</i>		<i>T. minor</i>		<i>T. piniperda</i>	
Bioclimatic variable	Percent contribution	Bioclimatic variable	Percent contribution	Bioclimatic variable	Percent contribution
Bio 14	30.9	Bio 1	49.4	Bio 1	19.8
Bio 15	22.0	Bio 7	33.9	Bio 5	28.6
Bio 2	19.0	Bio 16	13.8	Bio 4	14.6
Bio 4	15.0	Bio 15	2.9	Bio 2	15.3
Bio 1	5.2			Bio 3	9.8
Bio 5	3.5			Bio 12	7.0
Bio 12	3.4			Bio 15	4.8
Bio 3	1.0				

Environmental suitability

The environmental availability calculated varied among the three species studied and varied as an effect of the software configuration. Maxent has three distinct options for extrapolation: free extrapolation, no extrapolation, and extrapolation with clamping. Here we did not use the free extrapolation option because “it can project an unlimited extrapolation into the study area”. Under the no extrapolation setting, the response is set to zero if the environments in transfer areas are extremer than those in areas across which the models were calibrated” [32]. In this sense, only *T. destruens* and *T. minor* found environmental availability in Mexico, while for *T. piniperda* it was not possible to extrapolate environmental information. This does not necessarily mean that Mexico did not have environmental suitability for this species, probably the increase of geographical data in the future could improve the model resolution.

With the extrapolation and clamping setting, the response in areas with environments distinct from those in the calibration area is clamped to levels presented at the periphery of the calibration region in environmental space [32]. Under this premise, all the three species found in Mexico's environmental conditions would allow them a probable temporary permanence.

According to the no extrapolation setting in Maxent, *T. destruens* model shows an optime environmental suitability in a limited area in northeastern Mexico, in small and dispersed areas in the Altiplano Norte biogeographic province, and an isolated area in the Tamaulipeca biogeographic province (**Figure 1a**). Medium to lower environmental suitability was projected in the biogeographic provinces lasted mentioned, but mainly in the Tamaulipeca (**Figure 1a**).



a)

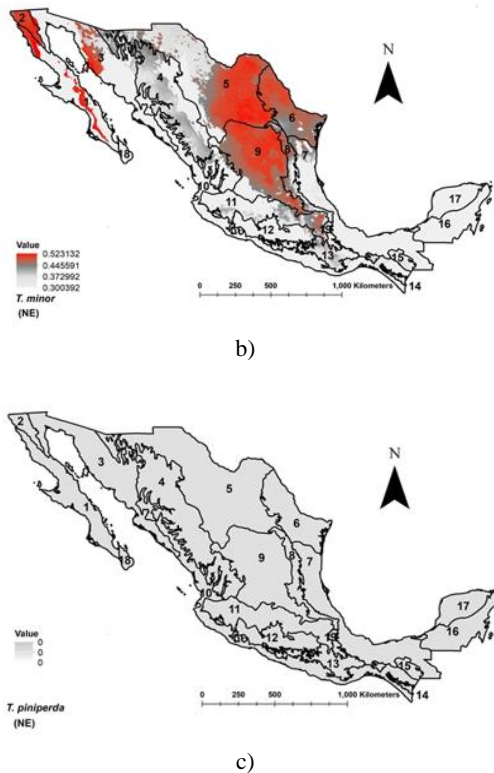


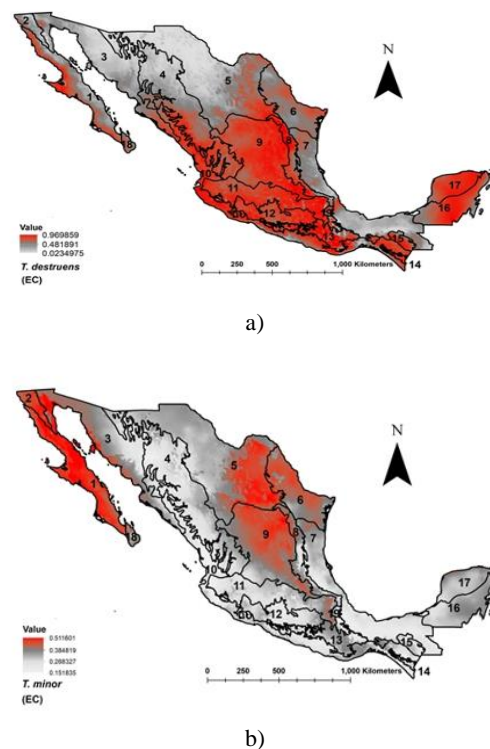
Figure 1. Ecological niche model of three *Tomicus* species (Coleoptera: Curculionidae: Scolytinae) projected on the Mexican biogeographic provinces [35], using Maxent no Extrapolation setting. a) *Tomicus destruens*, b) *T. minor* and c) *T. piniperda*. 1. Baja California, 2. California, 3. Sonorensis, 4. Sierra Madre Occidental, 5. Altiplano Norte, 6. Tamaulipeca, 7. Golfo de México, 8. Sierra Madre Oriental, 9. Altiplano Sur, 10. Costa del Pacífico, 11. Eje Volcánico, 12. Depresión del Balsas, 13. Sierra Madre del Sur, 14. Soconusco, 15. Los Altos de Chiapas, 16. Peten, 17. Yucatán, 18. Del Cabo, 19. Oaxaca.

Tomicus minor showed the most surface in Mexico with environmental suitability in the present study (**Figure 1b**), with areas projected along with the biogeographic province Baja California, all the biogeographic province of California, northwestern of Sonorensis, central areas of Altiplano Norte and Altiplano Sur, northwestern of Tamaulipeca and small areas in eastern Eje Volcánico. Minor suitability was calculated in the biogeographical provinces of Sierra Madre Occidental, Altiplano Norte and Altiplano Sur, Eje Volcánico, Sierra Madre Oriental, Sierra Madre del Sur, Sonorensis and northern Golfo de México.

For *T. piniperda* it was not possible to calculate environmental suitability for the country (**Figure 1c**).

By expanding the model exploration options with the extrapolation-clamping setting, the environmental availability of *T. destruens* expands enormously in the central region of the country (**Figure 2a**). Environmental suitability was projected now into the biogeographic provinces of Baja California, Los Cabos, southern Sonorensis, along Costa del Pacífico, southern Sierra Madre Occidental, most of the Eje Volcánico, Altiplano Sur, Depresión del Balsas, Sierra Madre del Sur, eastern Altiplano Norte, isolated areas in the Tamaulipeca and Golfo de México, most of the Yucatán and Peten, Soconusco and Altos de Chiapas.

The projection for *T. minor* was quite similar in both model configuration designs (**Figures 1b and 2b**), but with the following changes: expanded their suitability into full covering the Baja California biogeographic province. By another hand, a contraction in the surface projected in the Altiplano Norte, Altiplano Sur, and Tamaulipeca biogeographic provinces. Areas with environmental suitability were calculated in northern Golfo de México and conserved areas in the Eje Volcánico. In the Sonorensis biogeographic province, the regions calculated were reshaped, contracting, and stretching at the eastern of the province, and increasing in the limits with the California biogeographic province (**Figures 2a and 2b**).



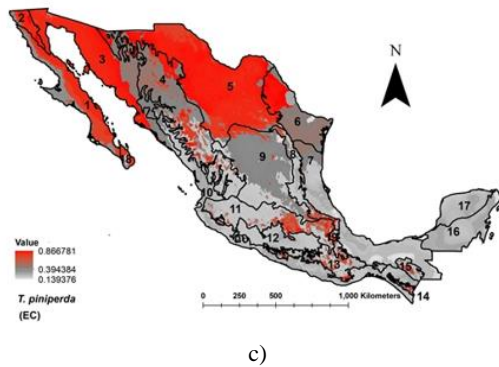


Figure 2. Ecological niche model of three *Tomicus* species (Coleoptera: Curculionidae: Scolytinae) projected on the Mexican biogeographic provinces [35], using Maxent Extrapolation-Clamping setting. a) *Tomicus destruens*, b) *T. minor* and c) *T. piniperda*. 1. Baja California, 2. California, 3. Sonorensis, 4. Sierra Madre Occidental, 5. Altiplano Norte, 6. Tamaulipeca, 7. Golfo de México, 8. Sierra Madre Oriental, 9. Altiplano Sur, 10. Costa del Pacífico, 11. Eje Volcánico, 12. Depresión del Balsas, 13. Sierra Madre del Sur, 14. Soconusco, 15. Los Altos de Chiapas, 16. Peten, 17. Yucatán, 18. Del Cabo, 19. Oaxaca.

Environmental suitability for *T. piniperda* with Extrapolation plus Clamping setting changes drastically its projection into Mexico: from zero (**Figure 1c**) to cover biogeographic provinces northern the country and some central and southern biogeographic provinces (**Figure 2c**). Most of the Altiplano Norte, Baja California, California, and Los Cabos; and Sonorensis are now with environmental suitability. Other areas were calculated western Tamaulipeca, disperse spots in Sierra Madre Occidental, northern Altiplano Sur, Sierra Madre Oriental, Eje Volcánico, Sierra Madre del Sur, Oaxaca, with projection in Soconusco and Altos de Chiapas biogeographic provinces (**Figure 2c**).

The great variation showed with the Extrapolation plus Clamping setting, increasing drastically from zero to calculate wider areas for *T. piniperda*; and expanding the environmental suitability several times for *T. destruens* indicated to us be careful with interpretation derived from those models. As to be noted before, extrapolation and clamping settings take into account the environmental conditions in the calibration area periphery, and if two geographical areas are so contrasting environmental conditions so distant to the calibration area are given [28, 32]. For this reason, we considered the results obtained from

the No extrapolation as more adequate and this will be used in the rest of the manuscript.

Ecological niche and *Pinus* distribution in Mexico
Although *T. destruens* is projected punctually in northeastern Mexico, this is probably no concern for the Mexican *Pinus* diversity (**Figure 3a**). Tamaulipeca biogeographic province did not show abundant *Pinus* records. *Pinus* diversity and abundance increase gradually in the Altiplano Norte-Tamaulipeca limits, where scarce environmental suitability is calculated. *Tomicus destruens* is a univoltine species and choices *Pinus* from the Mediterranean ecosystem, as *P. brutia* Ten., *P. canariensis* C. Sm., *P. halepensis* Miller, *P. nigra* J.F. Arnold, *P. pinaster* Aiton, *P. pinea* L., and *P. radiata* D. Don [11, 20]. The number and amount of monoterpenes have been cited as the main factor in the host selection for this scolytine in its natural distribution range [19]. This opens an opportunity to explore the composition, concentration, and distribution of monoterpenes in *Pinus* from Mexico, as a preventive strategy to known potential or susceptible host species.

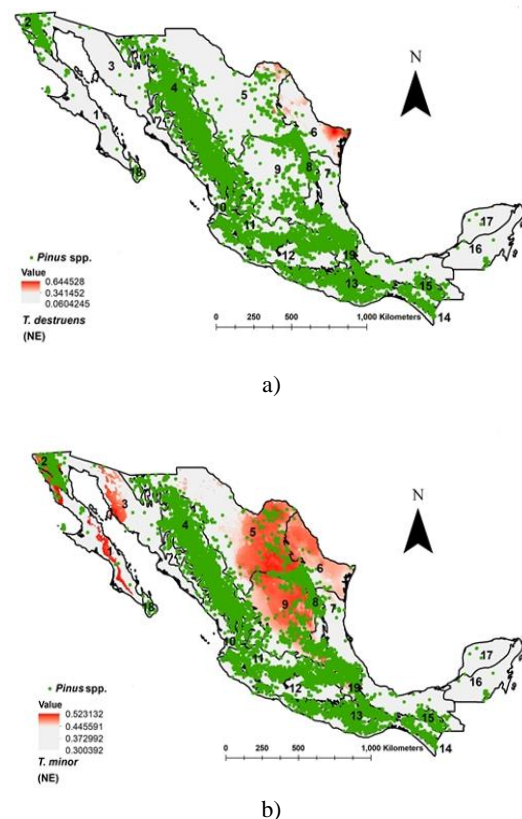


Figure 3. Ecological niche model of *Tomicus destruens* (a) and *T. minor* (b) (Coleoptera: Curculionidae: Scolytinae) projected on the Mexican

biogeographic provinces [35], using Maxent No Extrapolation setting, and *Pinus* distribution data. a) *Tomicus destruens*, and b) *T. minor*. 1. Baja California, 2. California, 3. Sonorensis, 4. Sierra Madre Occidental, 5. Altiplano Norte, 6. Tamaulipeca, 7. Golfo de México, 8. Sierra Madre Oriental, 9. Altiplano Sur, 10. Costa del Pacífico, 11. Eje Volcánico, 12. Depresión del Balsas, 13. Sierra Madre del Sur, 14. Soconusco, 15. Los Altos de Chiapas, 16. Peten, 17. Yucatán, 18. Del Cabo, 19. Oaxaca.

A different panoramic was shown for *T. minor*. This scolytine has the wider environmental suitability of the *Tomicus* species studied, increasing their possibilities to match with coniferous species (**Figure 3b**). However, our findings must be taken care of for the following three reasons: a) *T. minor* ecology, b) *T. minor* host preferences, and c) local pine shoot fauna. *Tomicus minor* is considered a less aggressive pine shoot beetle [36] is a secondary colonizer following *T. piniperda* infestation, with fragmented distribution [11], and selecting stressed trees [i.e. small or larger individuals with around 80 % needle loss [37]. In its original distribution areas, this species attacks *P. brutia*, *P. cembra* L., *P. densiflora* Siebold & Zucc., *P. halepensis*, *P. koraiensis* Siebold & Zucc., *P. leucodermis* Antoine, *P. mugo* Turra, *P. nigra*, *P. pallasiana* Lamb., *P. pinaster*, *P. pinea*, *P. pythiussa* Friwald ex Nyman, *P. rotundata* Link, *P. strobus* L., *P. sylvestris* L., *P. tabuliformis* Carrière, *P. thunbergiana* Franco and *P. yunnanensis* Franch. [11]. However, these species are not present in Mexico [6]. This sounds like good news for Mexican *Pinus* diversity, but, if *T. minor* invades the country, there are a lot of host options for a potential ecological change in its host preferences. Scolytines have the potential to infest and complete their cycle of life in a new host but related with their ancestral host, i.e. *Xyleborus glabratus* feeding in new Lauraceae species in North America [38]. Host resource competition with local fauna, as Lepidopteran species [i.e. *Eucosma sonomana* Kearfoot, and *Rhyacionia neomexicana* (Dyar) (Tortricidae)] who are considered several pine shoot pests, with several hosts, and widely distributed across the country [39]. This competition could reduce host options for *Tomicus* species and possibly represent an ecological barrier to overcome. For a successful invasion of *T. minor* in Mexico, environmental suitability is not sufficient, and

probably requires two initial conditions: host stress and *T. piniperda* infestation. By now, the first condition is being fulfilled, severe drought conditions started in northern Mexico in 1994 [40], affecting survival rates of *Pinus* species in Mexico [41]. Drought stress facilitates invasion of xylophagous beetles [41]. The second condition is missing, for *T. piniperda* Mexico means an unfavorable place at this point.

According to our results, *T. piniperda* is the less potential invasive species here analyzed. Even if prefer high altitude and wetter locations [42], or it has a wider host range [*P. brutia*, *P. cembra*, *P. densiflora*, *P. funebris* Kom., *P. halepensis*, *P. koraiensis*, *P. leucodermis*, *P. mugo*, *P. nigra*, *P. pentaphylla* Mayr, *P. peuce* Griseb., *P. pinaster*, *P. pinea*, *P. pythiussa*, *P. radiata*, *P. strobus*, *P. sylvestris*, *P. thunbergiana*, and *P. tubaeformis* (Jacq.) Cass.] [11, 39]. As mentioned before, the potential success of *T. minor* depends on the *T. piniperda* success, but according to results *T. piniperda* fails to find areas with environmental suitability and this affects the potential invasion of *T. minor*.

Analysis of environmental suitability for exotic forest pests is still growing, even with local phytosanitary issues, but is necessary to analyze data to calculate potential areas with environmental suitability. In the immediate future, several management tactics must be implemented to limit invasion and colonization of these pine shoot beetles, including monitoring drought conditions and their impact in *Pinus* populations [43], adult monitoring for *T. piniperda* and *T. minor* [23], and implement quarantine inspections in international borders [44].

CONCLUSION

The ecological niche model for three *Tomicus* species (Coleoptera: Curculionidae: Scolytinae) was calculated and projected in Mexican biogeographic provinces. It was possible to calculate with no extrapolation setting environmental suitability for two species: *Tomicus destruens* and *T. minor*, no areas were calculated for *T. piniperda*. The diversity of *Pinus* (Pinaceae) in Mexico seems to be safe in case of a potential invasion of these beetles.

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REFERENCES

- Rodríguez P, López L. Modeling the distribution of Mexican plants: knowledge and challenges in the face of biodiversity loss. *Bot Sci.* 2016;94(1):1-4. doi:10.17129/botsci.679
- Morrone JJ. Biogeographic regionalization and biotic evolution of Mexico: biodiversity's crossroads of the New World. *Rev Mex Biod.* 2019;90:e902980. doi:10.22201/ib.20078706e.2019.90.2980
- Wei J, Gernandt DS, Wehenkel C, Xiao X, Xiao W, Xiao W. Phylogenomic and ecological analyses reveal the spatiotemporal evolution of global pines. *PNAS.* 2021;118(20):e2022302118. doi:10.1073/pnas.2022302118
- Pérez R, Romero ME, González A, Rosales S, Moreno F, Arriola VJ. Modelado de la distribución actual y bajo cambio climático de pinos piñoneros endémicos de México. *Rev. Mex cienc. Forestales.* 2019;10(56):1-21. doi:10.1073/pnas.2022302118
- Gernandt DS, Pérez JA. Biodiversidad de Pinophyta (coníferas) en México. *Rev Mex Biodivers.* 2014;85:126-33. doi:10.7550/rmb.32195.
- Pérez JA, Gernandt DS. *Pinus vallartensis* (Pinaceae), a new species from western Jalisco, Mexico. *Phytotaxa.* 2017;331(2):233-42. doi:10.11646/phytotaxa.331.2
- Ellis EA, Navarro A, García M. Drivers of forest cover transitions in the Selva Maya, Mexico: integrating regional and community scales for landscape assessment. *Land Degrad Dev.* 2021;32(10):3122-41. doi:10.1002/ldr.3972
- Gómez JA, Brast K, Degener J, Krömer T, Ellis E, Heitkamp F, et al. Long-term changes in forest cover in Central Veracruz, Mexico (1993-2014). *Trop Conserv Sci.* 2018;11:1-12. doi:10.1177/1940082918771089
- Romero ME, Pérez R, González A, Velasco MV, Velasco E, Flores A. Current and potential spatial distribution of six endangered pine species of Mexico: towards a conservation strategy. *Forest.* 2018;9(12):767. doi:10.3390/f9120767
- Garonna AP, Foscari A, Russo E, Jesu G, Somma S, Cascone P, et al. The spread of the non-native pine tortoise scale *Toumeyella parvicornis* (Hemiptera Coccidae) in Europe: a major threat to *Pinus pinea* in Southern Italy. *iForest* 2018;11(5):628-34. doi:10.3832/ifer2864-011
- Vega FE, Hofstetter RW. *Bark Beetle Biology and ecology of native and invasive species.* London, UK; 2015. 620p.
- Bogdanski BEC, Corbett L, Dyk A, Grypma D. Pine shoot beetle, *Tomicus piniperda* (Linnaeus): analysis of regulatory options for Canada. Victoria, Canada: Canadian Forest Service; 2018. 26 p.
- Virginia Register of Regulations. Regulations Governing Pine Shoot Beetle. Richmond, Virginia, USA: Department of Agriculture and Consumer Services; 2021 August 18 [cited 2021 Dec 18]. Available from: <http://register.dls.virginia.gov/details.aspx?id=9687>
- Sánchez FJ, Galián J, Gallego D. Distribution of *Tomicus destruens* (Coleoptera: Scolytinidae) mitochondrial lineages: phylogeographic insights and niche modeling. *Org Divers Evol.* 2014;15(1):101-13. doi:10.1007/s13127-014-0186-2
- Borkowski A. Spatial distribution of losses in growth of trees caused by the feeding of pine shoot beetles *Tomicus piniperda* and *T. minor* (Col., Scolytidae) in Scots pine stands growing within range of the influence of a timber yard in southern Poland. *J For Sci.* 2006;52(3):130-5. doi:10.3390/f12101336
- Rabaglia RJ, Cognato AI, Hoebeke ER, Johnson CW, Labonte JR, Carter ME, et al. Early detection and rapid response. A 10-year summary of the USDA Forest Service Program of Surveillance for Non-native bark and ambrosia beetles. *Amer Entomol.* 2019;65(1):29-42. doi:10.1093/ae/tmz015
- Lu RC, Wang HB, Zhang Z, Byers JA, Jin YJ, Wen HF, et al. Coexistence and competition between *Tomicus yunnanensis* and *T. minor* (Coleoptera: Scolytinae) in Yunnan Pine. *Psyche.* 2012;2012:185312. doi:10.1155/2012/185312
- Escobar LE, Lira A, Medina G, Peterson AT. Potential for spread of the white-nose fungus (*Pseudogymnoascus destructans*) in the

- Americas: use of Maxent and NicheA to assure strict model transference. *Geospat Health*. 2014;9(1):221-9. doi:10.4081/gh.2014.19
19. Davi H, Durand M, Damesin C, Delzon S, Petit C, Rozenberg P, et al. Distribution of endemic bark beetle attacks and their physiological consequences on *Pinus halapensis*. *For Ecol Manag*. 2020;469:118187. doi:10.1016/j.foreco.2020.118187
 20. USDA Foreign Agricultural Service. Christmas trees in Mexico-importers say bah humbug to tough season. USDA Foreign Agricultural Service: Washington D. C., USA: USDA Foreign Agricultural Service; 2015. 4p. Report No. MX5058.
 21. Moctezuma G, Flores A. Importancia económica del pino (*Pinus* spp.) como recurso natural en México. *Rev Mex de Cienc Forestales*. 2020;11(60):162-85. doi:10.29298/rmcf.v11i60.720
 22. Barzman M, Bàrberi P, Birch NE, Boonekamp P, Dachbrodt-Saaydeh S, Graf B, et al. Eight principles of integrated pest management. *Agron Sustain Dev*. 2015;35(4):1199-215.
 23. Hui Y, Sue D. Impacts of *Tomicus minor* on distribution and reproduction of *Tomicus piniperda* (Col., Scolytidae) on the trunk of the living *Pinus yunnanensis* trees. *J Appl Ent*. 2001;123(6):329-33. doi:10.1046/j.1439-0418.1999.00353.x
 24. Wang J, Zhang Z, Kong X, Wang H, Zhang S. Intraspecific and interspecific attraction of three *Tomicus* beetle species during the shoot-feeding phase. *Bull Entomol Res*. 2015;105(20):225-33. doi:10.1017/S0007485315000048
 25. Vasconcelos T, Horn A, Lieutier F, Branco M, Kerdelhue C. Distribution and population genetic structure of the Mediterranean pine shoot beetle *Tomicus destruens* in the Iberian Peninsula and Southern France. *Agric For Entomol*. 2006;8(2):103-11. doi:10.1111/j.1461-9563.2006.00292.x
 26. Wang HM, Wang Z, Liu F, Wu CX, Zhang SF, Kong XB, et al. Differential patterns of ophiostomatoid fungal communities associated with three sympatric *Tomicus* species infesting pines in south-western China, with a description of four new species. *MycKeys*. 2019;50:93-133. doi:10.3897/mycokeys.50.32653
 27. Faccoli M, Pisedda A, Salvato P, Simonato M, Masutti L, Battisti A. Genetic structure and phylogeography of pine shoot beetle populations (*Tomicus destruens* and *T. piniperda*, Coleoptera Scolytidae) in Italy. *Ann For Sci*. 2005;62(4):361-8. doi:10.1051/forest:2005031
 28. Simões M, Romero D, Núñez C, Jiménez L, Cobos ME. General theory and good practices in ecological niche modeling: a basic guide. *Biodivers Inform*. 2020;15(2):67-8. doi:10.17161/bi.v15i2.1337
 29. Olson DM, Dinerstein E, Wikramanayake ED, Burgess ND, Powell GVN, Underwood EC, et al. Terrestrial ecoregions of the world: a new map of life on Earth: A new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity. *Bioscience*. 2001;51(11):933-8. doi:10.1641/00063568(2001)051[0933:TEOTWA]2.0.CO;2
 30. Osorio L, Lira A, Soberón J, Peterson AT, Falconi M, Contreras RG, et al. NTBOX: An R package with graphical user interface for modeling and evaluating multidimensional ecological niches. *Methods Ecol Evol*. 2020;11(10):1199-206. doi:10.1111/2041-210X.13452
 31. Phillips SJ, Anderson RP, Dudík M, Schapire RE, Blair ME. Opening the black box: An open-source release of Maxent. *Ecography*. 2017;40(7):887-93. doi:10.1111/ecog.03049
 32. Cobos ME, Peterson AT, Barve N, Osorio L. Kuenm: An R package for detailed development of ecological niche models using Maxent. *PeerJ*. 2019;7:e6281. doi:10.7717/peerj.6281
 33. Machado F, Cobos ME, Peterson AT. A simulation-based method for selecting calibration areas for ecological niche models and species distribution models. *Front Biogeogr*. 2021;13(4):e48814. doi:10.21425/F5FBG48814
 34. Morrone JJ. Biogeographical regionalization of the world: a reappraisal. *Aust Syst Bot*. 2015;28(3):81-90. doi:10.1071/SB14042
 35. Conabio. Portal de Geoinformación 2021. Ciudad de México, México: CONABIO; 2021 Mar [cited 2021 Sep 10]. Available from: <http://www.conabio.gob.mx/informacion/gis/>

36. Borkowski A. Resource partitioning of Scots pine (*Pinus sylvestris* L.) by pine shoot beetles in stands under stress conditions. *Forests*. 2021;12(10):1336. doi:10.3390/f12101336
37. Wemeling B, Gossner MM, Mathis DS, Trummer D, Rigling A. Einfluss von klima und baumvitalität auf den Befall von waldföhren durch rindenbrütende insekten. *Schweis Z Forstwes*. 2018;169(5):251-9. doi:10.3188/szf.2018.0251
38. Morgan AR, Graham K, Green C, Smith-Herron AJ. Distribution of the invasive redbay ambrosia beetle *Xyleborus glabratus* in southeastern Texas. *Southwest Nat*. 2017;62(4):300-2. doi:10.1894/0038-4909-62.4.300
39. Cervantes JF, Huacuja AH. Guía de los ácaros e insectos hérvivoros de México. Coyoacan, Ciudad de México, México: Universidad Autónoma Metropolitana; 2017. 719p.
40. Stahle DW, Cook ER, Burnette DJ, Villanueva J, Cerano J, Burns JN, et al. The Mexican drought atlas: Tree-ring reconstructions of the soil moisture balance during the late pre-Hispanic, colonial, and modern eras. *Quat Sci Rev*. 2016;149:34-60. doi:10.1016/j.quascirev.2016.06.018
41. García JF, Jurado E. Is drought altering plant populations in the mountainous region of Northeastern Mexico? *Acta Bot Croat*. 2015;74(1):95-108.
42. Vose JM, Peterson DL, Luce CH, Patel-Weynand (editors). Effects of drought on forests and rangelands in the United States: Translating science into management responses. Washington, D.C., USA. U.S. Department of Agriculture, Forest Service; 2019. 227 p.
43. Pompa-García M, González-Cásares M, Acosta-Hernández AC, Camarero JJ, Rodríguez-Catón M. Drought influence over radial growth of Mexican conifers inhabiting mesic and xeric sites. *Forests* 2017;8:175. doi:10.3390/f8050175
44. Zhao J, Hu K, Chen H, Shi J. Quarantine supervision of wood packaging materials (WPM) at Chinese ports of entry from 2003 to 2016. *PLoS ONE*. 2021;16(8):e0255762. doi:10.1371/journal.pone.0255762