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Climate Change Poses Risk of Local Extinction for Temperate Forest Species in Oaxaca, Mexico

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Abstract

Climate change is expected to drive significant shifts in species distributions, particularly in temperate forest ecosystems. Areas of long-term environmental stability, known as climatic refugia, may play a key role in preserving biodiversity under future climate scenarios. This study assessed the potential impact of climate change on the distribution of eleven temperate forest tree species in Oaxaca, Mexico. Species distribution models were developed for eleven tree-species of temperate forest using Random Forest, Generalized Additive Models, and Generalized Linear Models. Among these, Random Forest achieved the highest predictive performance. Future distributions were projected under two shared socioeconomic pathways (SSP126 and SSP585) for 2040 and 2100. Results indicate that under the SSP585 scenario, all species could lose over 90% of their current potential range by 2100. Although some are classified as "Least Concern" by the IUCN (2024), their local vulnerability is pronounced. Additionally, projections suggest declining representation within Natural Protected Areas, raising concerns about their long-term conservation capacity. These findings highlight the urgency of implementing adaptive conservation measures, including the identification and management of climatic refugia, promotion of assisted migration, and reduction of anthropogenic pressures to enhance species resilience.

Keywords: ecological niche, forest species distribution, *Pinus, Quercus*.

Introduction

Climate change (CC) has emerged as one of the main drivers of the transformation of terrestrial ecosystems globally (O'Neill et al., 2016). CC has modified the distribution patterns and resilience of forest ecosystems in several regions, including Mexico (Metcalfe et al., 2010; Rodríguez-Ramírez et al., 2015). For example, CC is causing changes in species distribution, modifying its altitudinal and latitudinal ranges (Dyderski et al., 2018), which can promote the local extinction of species (Cruz-Cárdenas et al., 2016; Mendoza-Ponce et al., 2020). In addition, CC alters the typical functioning of species and ecosystems due to changes in the annual growth, affecting the viability of seeds, reducing the vigour of plants and affecting the survival of new growth (Murga-Orrillo et al., 2021), among other alterations. Therefore, CC represents a challenge for the adaptive capacity of forest species, acting as an environmental filter (Moeslund et al., 2013).

Global Circulation Models (GCMs) seek to simulate the behaviour of the atmosphere at the global level and its influence on future climate (Rivera & Amador, 2008). Different authors, through ecological niche modeling, have sought to understand the effect of future climate on the distribution of species (Guisan & Zimmermann, 2000; Manzanilla-Quijada et al., 2020). Ecological niche modeling, also known as species distribution modeling, has been instrumental in representing the potential distribution of species and changes over time. This distribution is based on recognizing species-specific characteristics such as climatic preference, tolerance to disturbance and resource requirements (Peterson et al., 2012). Currently there is a wide range of tools that help for this purpose. Among the most widely used models, the following stand out: GARP (Stockwell, 1999), Maxent (Phillips et al., 2004) and Random Forest (Evans et al., 2011).

Mexico is recognized as the center of origin and diversification for the genus *Pinus*, harboring a high number of endemic species. It contains 41% of all known *Pinus* species (Govaerts et al., 1998) and 76% of all *Quercus* species, while 51% of all species worldwide are considered endemic to Mexico (Valencia, 2004). The wide geographic distribution of *Pinus* across the country enables its coexistence with other conifers such as *Abies, Cupressus, Pseudotsuga, Juniperus*, and various hardwoods (Mendoza-Ponce et al., 2018). The evolutionary history of *Pinus* and *Quercus* reveals distinct phylogenetic patterns shaped by climatic changes and genetic adaptations, suggesting a shared evolutionary trajectory between the two genera (Hao et al., 2015; Li et al., 2021; Zeb et al., 2022). During the early Holocene, the genus *Pinus* expanded into various regions of Mexico in response to global warming (Lozano-García et al., 2007; Ortega-Rosas et al., 2008). These environmental conditions promoted the diversification of numerous species and continue to play a critical role in the structure and function of temperate forest ecosystems (Gernandt & Pérez-de la Rosa, 2014). As a result, Mexico is considered a megadiverse country—not only due to its biological richness, but also its climatic heterogeneity.

At the subnational scale, the state of Oaxaca exhibits the highest biological diversity of temperate forest species in Mexico (Valencia, 2004; de Jesús Ordóñez & Rodríguez, 2008). However, this rich biodiversity is increasingly threatened by accelerated deforestation (Mendoza-Ponce et al., 2018), recurrent fires (Corona-Núñez et al., 2020), and the adverse effects of CC. Understanding the drivers and consequences of these threats is essential for developing effective conservation strategies (D'Amato & Palik, 2021), especially for species that are endangered and/or vulnerable (Trejo et al., 2011).

Although temperate forests in Oaxaca harbor high biodiversity and play a critical ecological role, few studies have quantitatively examined how CC may affect the distribution and persistence of key forest species in the region (Guzmán-Santiago, 2023). This knowledge gap limits the development of effective biodiversity management strategies under future CC scenarios. In response, this study evaluates the potential risk of range contractions and local extinctions among temperate forest tree species, with particular attention to their representation within Natural Protected Areas (NPAs) and the identification of climatic refugia as potential strongholds for long-term conservation.

Methods

Study area. The state of Oaxaca, located in southeastern Mexico (18°42'–15°39' N, 93°52'–98°32' W), reaches a maximum elevation of 3,750 m.a.s.l. and covers 95,354 km^2, ranking fifth nationally in area. It is divided into eight regions: *Cañada, Costa, Istmo, Mixteca, Papaloapan, Sierra Norte, Sierra Sur* and *Valles Centrales* (de Jesús Ordóñez, 2000). Each of these regions has distinct biodiversity shaped by unique biogeographic, bioclimatic, and biocultural conditions. Oaxaca encompasses both tropical and temperate biomes (Figure 1), with temperate forests accounting for over 50% of the state's forested area (Mendoza-Ponce et al., 2018).

Species inventory. Species location records were obtained from the National Forest Inventory (CONAFOR, 2012), iNaturalist (iNaturalist, 2025), Global Biodiversity Information Facility (GBIF) and San Juan Quiahije Forest Inventory (IF-SJQ) (Table S1). To avoid pseudo-replication, records were clustered by merging observations within a 1-km^2, resulting in 1,383 independent records for 11 tree species (Figure 1 and Table S1). The most abundant genus is *Quercus* with

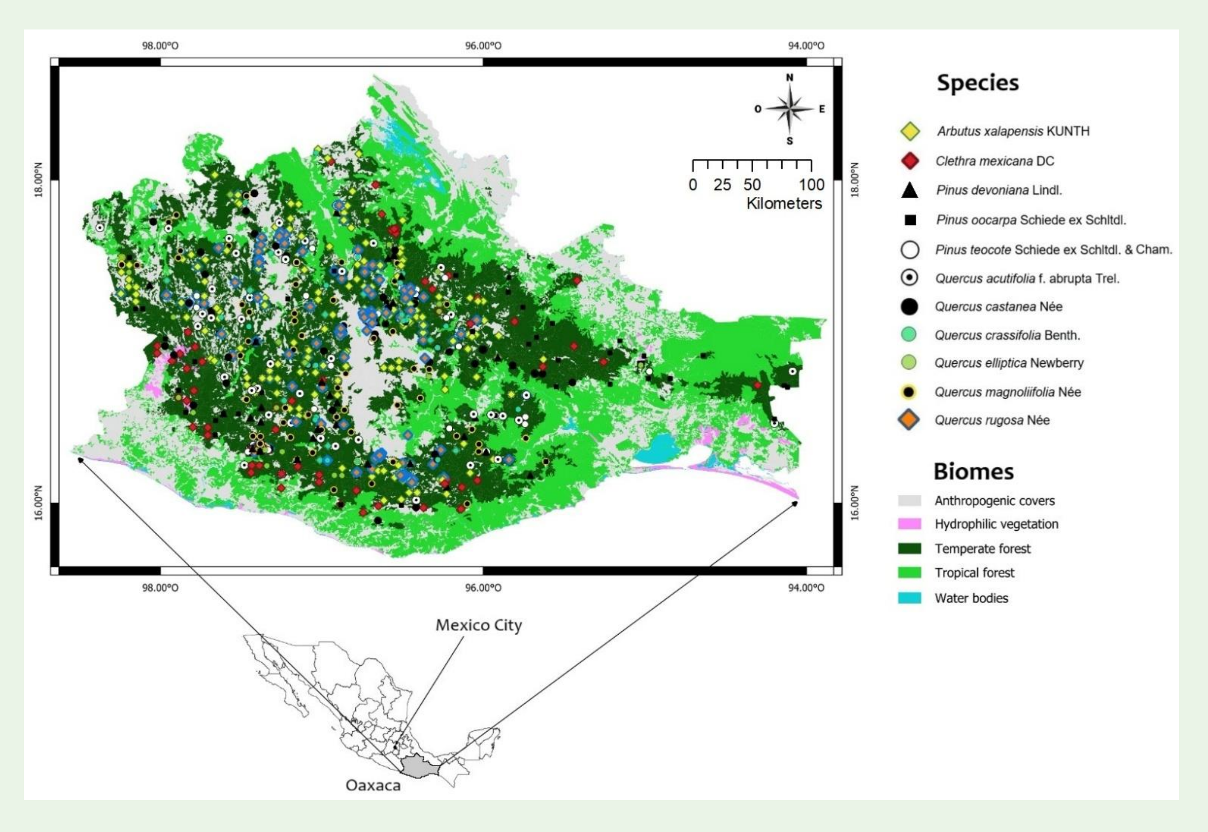

Figure 1. Study area showing the distribution of dominant biomes in the State of Oaxaca and the distribution of the evaluated species.

49.0% of the records, followed by *Arbutus* with 21.8% and *Pinus* with 21.4%. The species with the highest number of records was *Arbutus xalapensis* (21.8%) > *Pinus oocarpa* (12.4%) > *Quercus rugosa* (11.1%).

Bioclimatic variables. We used 19 bioclimatic variables from WorldClim v2.1 (Fick & Hijmans, 2017), representing both current (1970–2000) and future climate conditions (2021–2040 and 2081–2100), based on CMIP6 projections from the CNRM-CM6-1 global circulation model. CNRM-CM6-1 is a comprehensive Earth system model developed by CNRM/CERFACS for CMIP6, simulating climate dynamics and future scenarios using coupled atmosphere–ocean–land–ice components (Voldoire, 2023). These layers capture key climatic dimensions, including annual trends (e.g., mean annual temperature, annual precipitation), seasonality (e.g., temperature and precipitation ranges), and extreme or limiting environmental factors (e.g., temperature of the coldest and warmest month, precipitation of the wettest and driest quarters) (Table S2). All bioclimatic layers (Bio1–Bio19) were obtained from the WorldClim repository and have a spatial resolution of 30 arc-seconds (approximately 1 km² per pixel). To complement climatic predictors, we incorporated topographic variables: altitude (derived from SRTM data) and slope (calculated from the SRTM). The SRTM Digital Elevation Model is a near-global dataset of Earth's terrain elevation, captured by NASA's Shuttle Radar Topography Mission in 2000 (NASA-JPL, 2013). These layers were processed to match the resolution of the bioclimatic variables, ensuring spatial consistency across all environmental predictors.

Species distribution models. Species distribution models were calibrated using 80% of the occurrence data, with the remaining 20% reserved for independent blind validation to assess predictive performance. For each species, pseudo-absences were generated randomly at distances >1 km to ensure model contrast and reduce spatial autocorrelation. Distributions were modeled using three algorithms: Random Forest (RF), Generalized Additive Models (GAM), and Generalized Linear Models (GLM), selected for their demonstrated accuracy and ecological interpretability in ecological and species distribution modelling applications (Elith & Leathwick, 2009; Corona-Núñez et al., 2017). The models were evaluated using Receiver Operating Characteristic curves (ROC), True Skill

Statistic (TSS), and the Kappa index (Swets, 1988; Allouche et al., 2006). The best-performing algorithm per species was selected for subsequent analysis.

Distributional ranges were defined by selecting pixels with suitability scores >0.5, a threshold chosen to emphasize areas with a higher likelihood of species presence while reducing uncertainty in marginal zones. To evaluate model performance and identify optimal classification thresholds, we applied the Youden Index. The Youden Index is a widely used diagnostic metric in species distribution modeling that maximizes the sum of sensitivity and specificity, thereby balancing omission and commission errors. This index was selected for its robustness in threshold optimization, especially when presence–absence data are imbalanced or when both types of errors carry ecological consequences. We retained the >0.5 cutoff for spatial projections to ensure consistency across scenarios and facilitate ecological interpretation. This approach enhances model reliability and supports conservation-related decision-making by minimizing misclassification risks (Jiménez-Valverde & Lobo, 2007). This decision reflects a conservative approach that prioritizes ecological plausibility over statistical optimization, particularly in the context of future climate projections. Binary presence/absence maps were derived from these thresholds and used to estimate potential distributions under historical climate conditions (1970–2000) and two future periods: 2021–2040 (2040) and 2081–2100 (2100). Projections incorporated two contrasting Shared Socioeconomic Pathways (SSPs): SSP126 (optimistic) and SSP585 (pessimistic), representing divergent trajectories in global development and emissions.

Species at risk and changes in potential distribution. To assess the impact of CC on species distributions, we compared present and future projections across all scenarios and time periods. Distributional changes were classified as positive when species expanded their current distribution range, and negative when contractions occurred. To quantify these dynamics, we calculated three spatial metrics: loss (areas currently suitable but projected to become unsuitable), gain (areas unsuitable at present but projected to become suitable), and permanence (areas consistently suitable across time and scenarios, functioning as climate refugia). These metrics were derived from binary presence–absence maps generated using a standardized threshold, ensuring comparability across species and scenarios.

Climatic refugia were defined as zones of spatial overlap between present and future suitable habitats, indicative of climatic stability and ecological continuity. These areas are expected to remain within a species' environmental tolerance limits despite broader climatic shifts, and were identified using pixel-wise intersection across all scenario outputs. We then aggregated refugia across species to delineate multi-species refugial regions, which may act as buffers against local extinction and support long-term persistence.

To evaluate the conservation relevance of these refugial zones, we assessed their spatial congruence with existing Natural Protected Areas (NPAs), following approaches similar to others (Keppel et al., 2012; Morelli et al., 2016). This comparison allowed us to identify priority areas where current protection aligns with future climatic stability. Finally, to quantify conservation potential within NPAs, we calculated the average species richness across all future scenarios, providing a comparative measure of species density retained under projected climatic conditions.

To contextualize the conservation relevance of modeled species, we identified the threat statuses using the IUCN Red List (2024). All analyses were conducted in the RStudio environment (R-Core-Team, 2018), integrating outputs from species distribution models and CC scenarios.

Results

Model performance. For all species, the RF model showed the best performance, followed by GAM and finally GLM. On average RF resulted with a performance of 99.3%, GAM 93.1% and GLM 83.4%. The worst performance of GLM was with the Kappa < ROC < TSS metric. Specifically, for *Pinus teocote, Quercus elliptica* and *Q. castanea species* RF achieved a performance >98%, followed by GAM reaching values >86% (Table 1). The species sensitivity ranges from 0.62 to 0.99 with an average of 0.93±0.11 (Table S3).

Changes in species distribution. The Mixteca, Valles Centrales, Sierra Norte and Sierra Sur regions are where most of the species evaluated are concentrated (Figure 2). However, under CC scenarios all regions will show a reduction in their distribution, with low permanence in relation to their potential distribution. Gains in distribution are estimated to occur in the Sierra Sur and Costa (towards the south of the state), Mixteca (west), Valles Centrales (center) and Papaloapan (north).

Species exhibited diverse spatial responses to projected climate scenarios, reflecting varying degrees of resilience and sensitivity to environmental change (Table S4). Notably, *Pinus* species generally shifted upward in both altitude and latitude. In contrast, *Quercus* species displayed a divergent pattern, characterized by reductions in altitudinal range and increases in mean latitude. *Arbutus xalapensis* exhibited remarkable stability, with no detectable changes in altitude, latitude, or slope across all scenarios, suggesting strong resilience to climatic shifts. *Clethra mexicana* showed moderate latitudinal

Table 1. Validation metrics per species for each model. Kappa: Cohen's kappa statistic, ROC: area under the curve, TSS: true skill statistic, GAM: Generalized Additive Models, GLM: Generalized Linear Models, RF: Random Forest.

Species	Kappa			ROC			TSS		
	GAM	GLM	RF	GAM	GLM	RF	GAM	GLM	RF
Arbustus xalapensis	86.4	92.0	99.3	93.7	92.0	99.3	94.7	92.0	99.3
Clethra mexicana	90.7	82.4	99.1	94.4	82.4	99.1	94.4	82.4	99.1
Pinus devoniana	96.5	89.5	99.9	96.5	89.5	99.9	96.5	89.5	99.9
Pinus oocarpa	94.7	74.9	98.8	94.7	84.8	99.9	95.9	83.6	99.9
Pinus teocote	95.5	79.1	98.5	94.0	98.5	98.5	95.5	88.1	98.5
Quercus acutifolia	94.9	49.2	99.2	94.9	71.2	99.9	94.9	84.7	99.2
Quercus castanea	90.4	69.1	98.9	90.4	80.9	98.9	90.4	86.2	98.9
Quercus crassifolia	86.5	89.2	99.6	93.7	95.6	99.9	93.6	95.6	99.9
Quercus elliptica	96.3	74.1	98.8	96.3	75.3	98.8	96.3	77.8	98.8
Quercus magnoliifolia	86.0	79.1	99.2	89.9	85.3	99.2	90.7	85.3	99.2
Quercus rugosa	88.9	83.0	99.3	91.5	85.6	99.3	92.2	85.6	99.3

displacement and a notable decrease in altitude under SSP585-2100, indicating potential vulnerability to warming trends and habitat compression. Among *Pinus* species*, P. devoniana* exhibited gradual increases in altitude and latitude, with slight slope variability, indicating a shift toward higher terrain. In contrast, *P. oocarpa* and *P.* teocote both displayed a retreat to lower, flatter landscapes, particularly under SSP585-2100. Oak species responded more uniformly: *Quercus acutifolia*, *Q. castanea*, and *Q. crassifolia* demonstrated consistent declines in elevation and slope.

In the SSP126-2040 an average loss of 31.4±7.7% among all species is estimated, where *Pinus* would lose 39.2±8.3% and *Quercus* 29.9±5.3% (Figure 3 and Table S5), while for the year 2100 the average loss of the species amounts to 44.0±9.4%, *Pinus* would lose 53.9±9.8% and *Quercus* 42.0±6.7%. The species of greatest losses are *Pinus oocarpa, P. devoniana* and *Quercus rugosa* with 62.8%, 55.5% and 51.2%, respectively. The species with the lowest losses were *Q. castanea* with 32.9%, *Arbutus xalapensis* with 33.8% and *Q. magnolifolia* with 36.4%.

These same analyses for the SSP858-2040 scenario indicate that on average the species would lose 32.6±7.8% of their potential distribution, while by the year 2100 the losses are estimated to increase to 88.1±6.1% of their potential distribution (Figure 3 and Table S5). The *Pinus* genera will show a loss of 92.2±3.9 and *Quercus* of 88.0± 6.2%. The species *Pinus devoniana, P. oocarpa, Quercus acutifolia, Q. crassifolia* and *Q. elliptica* will have losses > 90%. While the species with the lowest losses are *Arbutus xalapensis* with 78.4% and *Quercus castanea* with 78.6%.

Although most of the anticipated changes in distribution are expected to result in a reduction of the species' current extent, these losses will be partly compensated by minor expansions into new regions where the species are currently absent (Figure 3 and Table S5). For example, when analysing the expansions the SSP126-2100 scenario, on average the species will increase their surface area by 12.7± 8.8%, where *Pinus* will be 23.3± 9.1% and *Quercus* 8.8±5.1. The species with the greatest expansion is *Pinus teocote* (33.7%), and those with the least gains are *Quercus acutifolia* (3.1%) and *Q. castanea* (5.0%). For the SSP585-2100 scenario the average expansion of all species is lower (8.5± 7.3%), where *Pinus* is expected to have a gain of 17.0± 3.6% and *Quercus* 6.7±5.9%. *Pinus oocarpa* will have the highest expansion of all *Pinus* species (20.5%). While those showing the lowest expansion capacity are *Quercus rugosa* (6.1%) > *Q. magnolifolia* (3.5%) > *Q. castanea* (2.3%) > *Q. acutifolia* (0.3%).

Climatic refugia and the importance of natural protected areas. Under CC scenarios, projected shifts in species distributions are not expected to align with their current spatial extent, including areas within NPAs. Our results indicate that in the SSP126-2100 scenario,

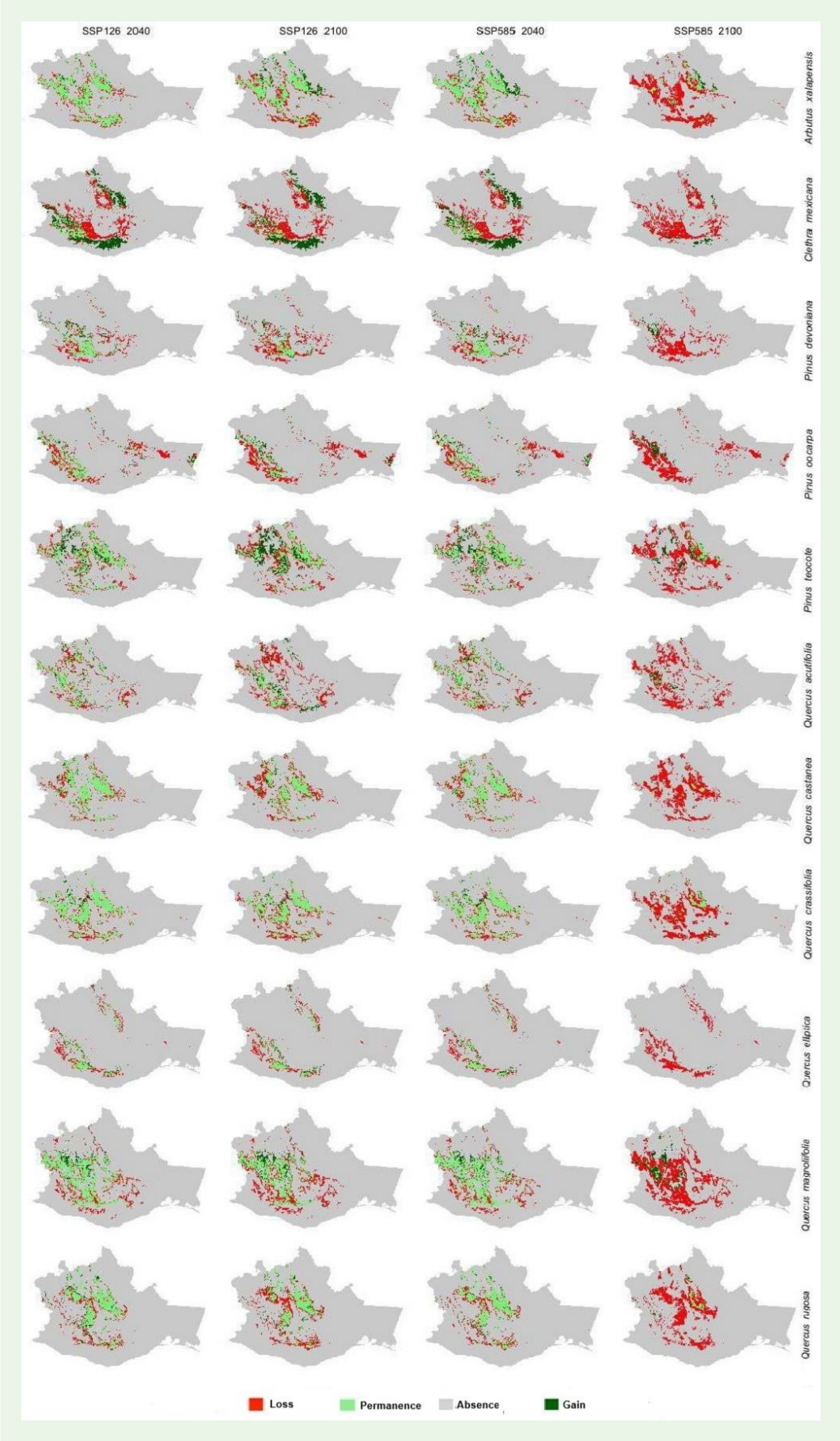

Figure 2. Changes in the distribution of species evaluated by period and climate change scenario.

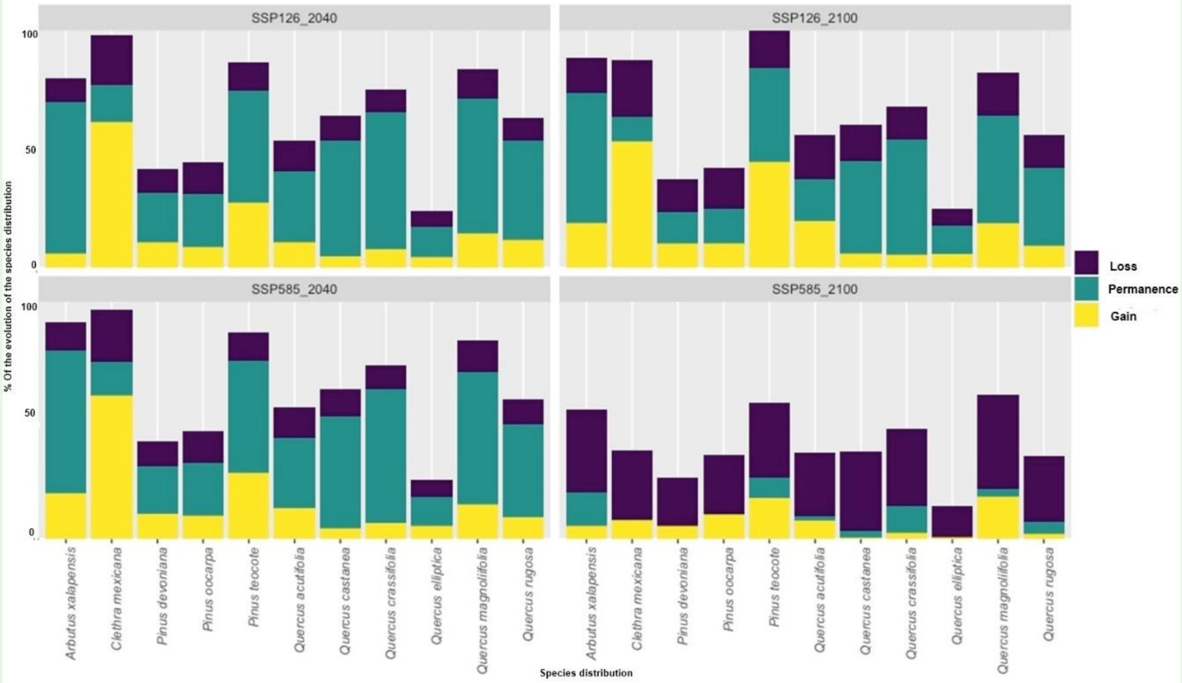

Figure 3. Bar graph of the distribution of species in different climatic scenarios.

the total extent of suitable habitat is projected to decline by 23.1%, while under the more severe SSP585-2100 scenario, this reduction could reach up to 81.0% (Figure 4). This contraction is accompanied by a decrease in species richness. Under SSP126-2100, up to seven species may be lost from areas where complete extinction is not recorded, while under SSP585-2100, this number increases to nine species (Figure 5). Consequently, NPAs will also experience a reduction in the extent of temperate forest they encompass, along with a diminished capacity to conserve forest species under future climate conditions.

Our study shows that NPAs conserve a maximum of 9 forest species of the 11 species evaluated for Oaxaca (Figure 4). However, under CC scenarios this number is reduced to a maximum of 8 and 6 for the SSP126 scenario for the years 2040 and 2100, respectively. For SSP585 the reduction is even more drastic, with a maximum of 7 and 5 for the same years. In addition, NPAs currently protect an average richness of 2.4±1.6 species per km^2. Under CC scenarios, this richness will also be affected. In the SSP126 scenario by the year 2100 this richness decreases to 1.7±1.8 species, and in SSP585 it is 0.4±1.0 species per km^2.

Discussion

Models performance. Among the modeling algorithms tested, RF demonstrated the highest performance, followed by GAM and GLM, consistent with previous findings (Evans et al., 2011; Barrio-Anta et al., 2020; Alegria et al., 2023). It is well established that both model choice and the quantity of calibration data significantly influence model accuracy (Corona-Núñez et al., 2017). Additionally, our results indicate that species-specific biological traits may impact model performance. Species with broad environmental tolerances tend to exhibit greater spatial heterogeneity, complicating accurate modeling. Conversely, species with narrow bioclimatic ranges are typically modeled with higher precision, corroborating earlier studies (Wisz et al., 2008; Guzmán-Santiago, 2023).

Changes in species distribution. Environmental change in temperate regions is driving *Pinus* species to higher elevations and more extreme latitudes, where conditions may offset precipitation deficits and offer more favourable temperatures (Castellanos-Acuña et al., 2014; Rehfeldt et al., 2014; Safaei et al., 2021; Mirhashemi et al., 2023). Interestingly, some *Quercus* species may reduce their altitudinal range while increasing their mean latitude, a pattern also observed by

Barradas et al. (2011). However, in addition to altitude, topographic slope has also been shown to constrain species distributions and development, consistent with the findings of this study (Moeslund et al., 2013; Cueva et al., 2019; Antúnez, 2021).

Pinus and *Quercus* species are particularly vulnerable to shifts in lower elevational limits, which may reduce available habitat and hinder growth rates (Castellanos-Acuña et al., 2015). Areas where species distributions remain stable under CC scenarios may function

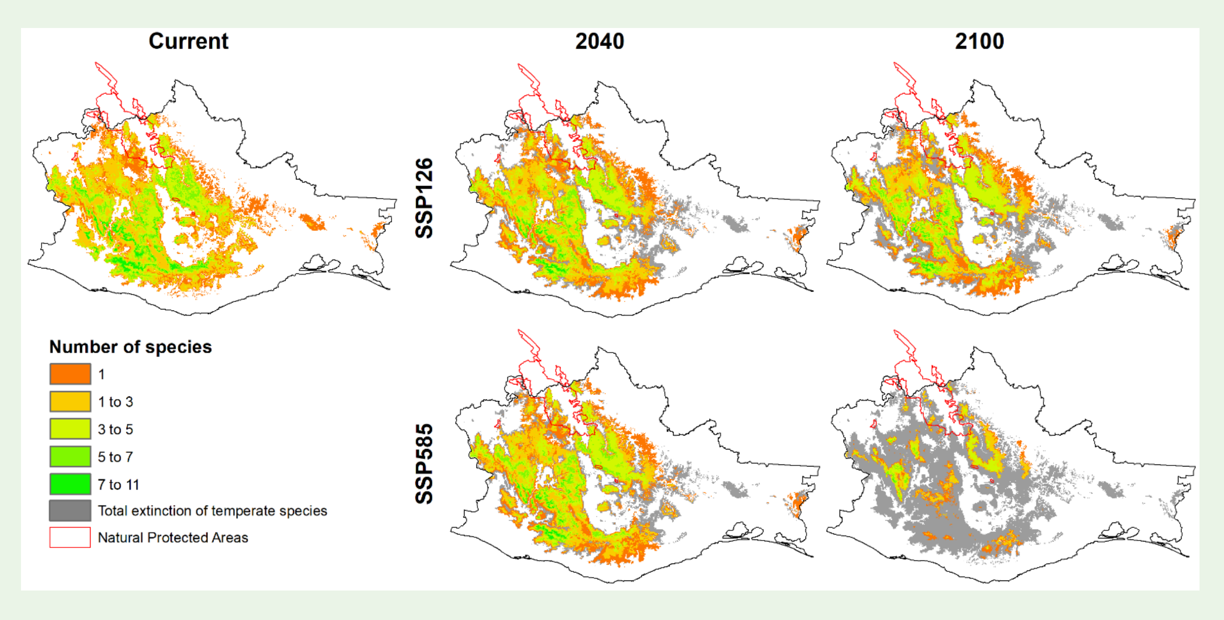

Figure 4. Species richness in temperate forests. Natural Protected Area polygons in the state of Oaxaca are highlighted in red.

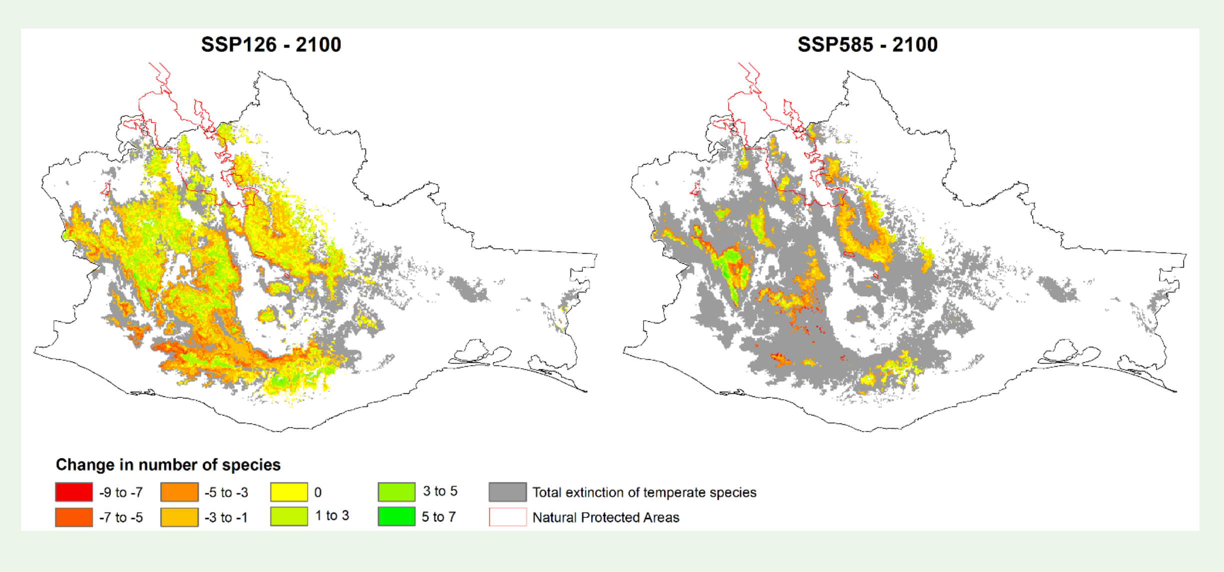

Figure 5. Changes in temperate forest species richness by the year 2100. Natural Protected Area polygons in the state of Oaxaca are highlighted in red.

as climatic refugia. These zones are essential for preserving genetic diversity and maintaining biotic interactions under reduced levels of disturbance. Similar patterns have been observed in studies of terrestrial vertebrates (Mendoza-Ponce et al., 2020). These refugia thus warrant targeted conservation efforts to mitigate pressures from deforestation and ecosystem degradation.

Species vulnerability. Our findings indicate that temperate species are projected to experience reductions in their potential distribution ranges. Although some may exhibit greater capacity to migrate into newly suitable areas, such shifts are insufficient to offset overall habitat loss. Consequently, localized extinctions are expected across various regions of Oaxaca. This vulnerability is further underscored by the fact that most of these species are currently classified as of "Least Concern" by the IUCN (2024), with *Quercus acutifolia* listed as "Vulnerable". Global conservation statuses may overlook region-specific threats, especially in fragile temperate ecosystems where climate-induced range reductions intensify conservation challenges

To reduce the vulnerability of these ecosystems, it is crucial to implement CC adaptation measures, including the establishment of NPAs within identified climate refugia. Additionally, landscape management should prioritize the reduction of anthropogenic pressures, such as forest land conversion (Mendoza-Ponce et al., 2020), and the prevention of fires (Corona-Núñez et al., 2020). Assisted migration strategies (Gray et al., 2011; Dumroese et al., 2015) may also play a complementary role by supporting species persistence within future suitable habitats. Collectively, these actions are essential for enhancing the resilience and long-term viability of temperate forest species under CC scenarios.

Importance of natural protected areas under climate change scenarios. NPAs were established globally to safeguard biodiversity. However, their initial designation did not account for their function as climate refugia, prompting recent concerns over their capacity to conserve species under changing climatic conditions (Dumroese et al., 2015). Our findings suggest that the representation of temperate forest species within NPAs will decline. This reduction affects not only total area but also species richness and the number of species each NPA conserves. Such shifts will compromise ecosystem functionality at multiple levels. Alterations in forest species composition and structure may disrupt trophic interactions by diminishing feeding, nesting, and sheltering sites (Gray et al., 2011; Millar & Stephenson, 2015). Additionally, changes in microclimates and biogeochemical cycles are expected, potentially undermining essential ecosystem services. To align with global goals such as the Kunming-Montreal Global Biodiversity Framework and the 2030 Agenda, it is critical to integrate climate refugia into conservation planning. Protecting these stable zones can enhance the resilience of NPAs and ensure the persistence of species in a changing climate (Keppel et al., 2024).

Conclusions

The results show that regardless of the algorithm used, and regardless of future CC scenarios, in all cases temperate forest species will show significant changes in their potential distribution, mainly with high losses of their potential extent, being SSP585-2100 where these changes will be more noticeable. Changes in species distributions expose the fragility of temperate forest ecosystems, through the modification of their species composition, and most likely of abundances. It is essential to establish adaptation strategies to CC that seek to conserve climatic refuges to conserve germplasm. Finally, it is important to evaluate the efficiency of NPAs as climatic refuges for biodiversity conservation.

Author contributions

ROCN, JCGS, and JCZC carried out data analysis and document writing. VEH, IFBM and WSG reviewed the wording.

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Supporting information

Table S1. Records of presence of the evaluated species.

Especies	IF_SJQ	INFyS Oaxaca	GBIF	iNaturalist	Records
Arbutus xalapensis KUNTH	14	144	57	87	302
Clethra mexicana DC	41	57	6	4	108
Pinus devoniana Lindl.	11	31	8	7	57
Piuns oocarpa Schiede ex Schltdl.	63	78	11	20	172
Pinus teocote Schiede *ex* Schltdl. & Cham.	24	23	0	20	67
Quercus acutifolia f. abrupta Trel.	47	51	11	9	118
Quercus castanea Née	13	32	25	24	94
Quercus crassifolia Benth.	17	61	0	24	102
Quercus elliptica Newberry	39	37	0	5	81
Quercus magnoliifolia Née	14	86	14	15	129
Quercus rugosa Née	13	54	24	62	153
Total	**296**	**654**	**156**	**277**	**1,383**

Table S2. Environmental variables used for modelling the potential distribution of species.

Key	Description (Unit)
Bio-1	Annual Mean Temperature (°C)
Bio-2	Mean Diurnal Range (Mean of monthly (max temp - min temp)) (°C)
Bio-3	Isothermality (BIO2/BIO7) (×100) (°C)
Bio-4	Temperature seasonality (standard deviation × 100) (°C)
Bio-5	Max Temperature of Warmest Month (°C)
Bio-6	Min Temperature of Coldest Month (°C)
Bio-7	Temperature Annual Range (BIO5-BIO6) (°C)
Bio-8	Mean Temperature of Wettest Quarter (°C)
Bio-9	Mean Temperature of Driest Quarter (°C)
Bio-10	Mean Temperature of Warmest Quarter (°C)
Bio-11	Mean Temperature of Coldest Quarter (°C)
Bio-12	Annual precipitation (mm)
Bio-13	Precipitation of Wettest Month (mm)
Bio-14	Precipitation of Driest Month (mm)
Bio-15	Precipitation Seasonality (Coefficient of Variation) (%)
Bio-16	Precipitation of Wettest Quarter (mm)
Bio-17	Precipitation of Driest Quarter (mm)
Bio-18	Precipitation of Warmest Quarter (mm)
Bio-19	Precipitation of Coldest Quarter (mm)

Table S3. Species adaptation threshold.

Species	Threshold	Accuracy	Sensitivity
Arbutus xalapensis	0.53	0.86	0.97
Clethra mexicana	0.42	0.81	0.62
Pinus devoniana	0.46	0.88	0.98
Pinus oocarpa	0.50	0.91	0.98
Pinus teocote	0.56	0.91	0.97
Quercus acutifolia	0.54	0.92	0.97
Quercus castanea	0.53	0.87	0.95
Quercus crassifolia	0.46	0.86	0.99
Quercus elliptica	0.54	0.96	0.95
Quercus magnoliifolia	0.64	0.92	0.89
Quercus rugosa	0.58	0.92	0.95

Table S4. Spatial attributes of studied species across climate change scenarios.

Species	Scenario	Altitude (m a.s.l.)	Latitude (°)	Slope (°)
Arbutus xalapensis	Current	1,107±824	16.967±0.637	5.8±4.7
	ssp126-2040	1,108±824	16.967±0.637	5.8±4.7
	ssp585-2040	1,108±824	16.967±0.637	5.8±4.7
	ssp126-2100	1,108±824	16.967±0.637	5.8±4.7
	ssp585-2100	1,108±824	16.967±0.637	5.8±4.7
Clethra mexicana	Current	939±685	17.342±1.030	7.2±5.3
	ssp126-2040	963±697	17.349±1.037	7.4±5.5
	ssp585-2040	982±694	17.346±1.036	7.2±5.4
	ssp126-2100	978±716	17.358±1.036	7.0±5.4
	ssp585-2100	979±885	17.393±1.044	7.0±4.6
Pinus devoniana	Current	897±770	17.346±1.047	6.4±5.1
	ssp126-2040	934±816	17.359±1.045	6.7 ±5.3
	ssp585-2040	924±808	17.359±1.046	6.8±5.3
	ssp126-2100	950±844	17.373±1.047	6.5±5.6
	ssp585-2100	989±827	17.398±1.045	6.0±5.1
Pinus oocarpa	Current	1,034±856	17.314±0.988	5.4±5.1
	ssp126-2040	977±921	17.321±1.000	5.0±5.1
	ssp585-2040	960±915	17.317±1.001	5.0±5.0
	ssp126-2100	870±922	17.321±1.003	4.6±4.9
	ssp585-2100	985±735	17.308±1.007	4.0±4.1
Pinus teocote	Current	1,123±952	17.364±1.030	5.7±4.9
	ssp126-2040	1,105±998	17.375±1.032	5.3±4.9
	ssp585-2040	1,079±985	17.374±1.033	5.3±4.9
	ssp126-2100	1,026±1012	17.380±1.035	4.7±4.8
	ssp585-2100	1,086±1057	17.400±1.045	4.0±3.8
Quercus acutifolia	Current	1,420±878	17.344±1.023	7.6±5.3
	ssp126-2040	1,350±924	17.359±1.034	8.0±5.8
	ssp585-2040	1,343±930	17.357±1.034	7.9±5.7
	ssp126-2100	1,303±969	17.367±1.037	7.8±5.7
	ssp585-2100	1,341±1,178	17.393±1.039	6.3±5.9
Quercus castanea	Current	1,444±1,002	17.347±1.011	6.0±4.7
	ssp126-2040	1,306±1,084	17.340±1.019	5.33±4.7
	ssp585-2040	1,199±1,085	17.335±1.023	5.0±4.6
	ssp126-2100	1,220±1,117	17.343±1.026	4.9±4.6
	ssp585-2100	1,187±1,061	17.374±1.041	3.0±3.4

Continue

Table S4. Continued

Quercus crassifolia	Current	1,642±947	17.352±1.003	7.5±4.9
	ssp126-2040	1,543±1,034	17.364±1.008	6.9±4.9
	ssp585-2040	1,493±1,054	17.368±1.006	6.8±4.9
	ssp126-2100	1,398±1,094	17.371±1.006	6.4±5.0
	ssp585-2100	1,496±1,119	17.391±1.016	5.1±5.0
Quercus elliptica	Current	1,056±749	17.364±1.032	8.3±5.5
	ssp126-2040	1,003±801	17.375±1.037	8.1±5.8
	ssp585-2040	994±783	17.373±1.036	7.9±5.7
	ssp126-2100	970±803	17.383±1.037	7.8±5.9
	ssp585-2100	908±835	17.405±1.038	6.5±6.8
Quercus magnoliifolia	Current	1,305±778	17.307±1.009	6.6±4.4
	ssp126-2040	1,221±871	17.310±1.013	6.1±4.6
	ssp585-2040	1,236±858	17.312±1.015	6.1±4.6
	ssp126-2100	1,183±904	17.319±1.017	5.7±4.6
	ssp585-2100	1,291±866	17.283±1.045	4.7±4.2
Quercus rugosa	Current	1,731±856	17.331±0.974	6.8±4.5
	ssp126-2040	1,615±976	17.354±0.980	6.6±4.6
	ssp585-2040	1,579±996	17.360±0.982	6.7±4.7
	ssp126-2100	1,417±1,067	17.372±0.983	6.4±4.8
	ssp585-2100	1,655±760	17.382±1.007	5.5±5.0

Table S5. Distribution percentages presented by forest species in Gain, Loss and Permanence (Per). Gain refers to the percentage increase in area with respect to the current potential distribution. The sum of Loss and Per corresponds to 100% in relation to the current potential distribution.

Species	**SSP126-2040**			**SSP126-2100**			**SSP585-2040**			**SSP585-2100**		
	Gain	**Loss**	**Per**	**Gain**	**Loss**	**Per**	**Gain**	**Loss**	**Per**	**Gain**	**Loss**	**Per**
Arbutus xalapensis	9.0	25.5	74.5	11.1	33.8	66.2	9.2	25.9	74.1	1.4	78.4	21.6
Clethra mexicana	6.2	22.2	77.8	5.4	36.7	63.3	5.8	24.2	75.8	1.6	85.9	14.1
Pinus devoniana	16.9	37.0	63.0	18.5	55.5	44.5	16.5	38.6	61.4	17.1	95.2	4.8
Pinus oocarpa	16.6	48.3	51.7	17.6	62.8	37.2	17.4	50.7	49.3	20.5	93.5	6.5
Pinus teocote	22.0	32.2	67.8	33.7	43.3	56.7	22.1	32.6	67.4	13.4	87.8	12.2
Quercus acutifolia	3.1	28.2	71.8	3.1	40.8	59.2	2.8	30.6	69.4	0.3	91.8	8.2
Quercus castanea	5.4	22.9	77.1	5.0	32.9	67.1	4.5	23.7	76.3	2.3	78.6	21.4
Quercus crassifolia	12.8	36.5	63.5	15.7	46.8	53.2	13.9	36.6	63.4	14.3	94.6	5.4
Quercus elliptica	10.0	30.5	69.5	13.3	43.6	56.4	10.0	32.1	67.9	13.5	93.2	6.8
Quercus magnoliifolia	11.0	26.0	74.0	10.6	36.4	63.6	9.2	28.0	72.0	3.5	84.1	15.9
Quercus rugosa	6.3	35.5	64.5	5.5	51.2	48.8	7.2	36.1	63.9	6.1	85.6	14.4