Conservation Gap Analysis of Native

Mesoamerican Oaks

Kate Good, Allen J. Coombes, Susana Valencia-A,
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Global Conservation Consortium Oak
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Cover photos
Front cover: *Quercus hirtifolia* in habitat. *Quercus hirtifolia* is an endangered species that only occurs in the montane humid and temperate forests of the Sierra Madre Oriental in Mexico. Oaks are key species for water protection in cloud forests across Mesoamerica (photo credit: Maricela Rodríguez-Acosta)
Back cover: *Quercus ajoensis* acorns (photo credit: Mimi Kamp)

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Quercus grisea forest, Nuevo Léon, Mexico (The Morton Arboretum)

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ACRONYMS

AOO	Area of Occupancy
BGCI	Botanic Gardens Conservation International
BIEN	Botanical Information and Ecology Network
CONABIO	Comisión Nacional para el Conocimiento y Uso de la Biodiversidad
EOO	Extent of Occurrence
ERS	Ecological Representativeness Score
ESA	Endangered Species Act
FCS	Final Conservation Score
GBIF	Global Biodiversity Information Facility
GCCO	Global Conservation Consortium for Oak
GRS	Geographical Representativeness Score
IOS	International Oak Society
IUCN	International Union for Conservation of Nature
KBA	Key Biodiversity Area
NGO	Non-governmental Organization
SRS	Sampling Representativeness Score
SSC	Species Survival Commission
WDPA	World Database on Protected Areas

IUCN RED LIST THREAT CATEGORIES

CR	Critically Endangered
EN	Endangered
VU	Vulnerable
NT	Near Threatened
LC	Least Concern
DD	Data Deficient

Quercus grisea in Nuevo Léon, Mexico (The Morton Arboretum)

CONTENTS

Quercus cualensis (M.C. Luz María González Villarreal)

EXECUTIVE SUMMARY

Mesoamerica is a global center for oak (genus *Quercus*) biodiversity, with more than 160 species in Mexico alone. Despite this incredible diversity, for many species, little is known regarding population size, distribution, or threats. There is an urgent need to coordinate and prioritize conservation actions for both wild populations and living collections in botanic gardens. To this end, we conducted a conservation gap analysis of 59 threatened and Data Deficient species of Mesoamerican oaks, which we present here. We define Mesoamerica as the region extending from the United States-Mexico border through Panama. As part of this analysis we created a curated dataset of over 4,400 *in situ* occurrence points, assessed the geographic and ecological representation of species in ex *situ* collections, identified priority conservation areas for oaks in the region, and determined conservation needs, with a particular focus on representation in living collections. In addition to the main report, which summarizes results across species and subregions, we also created an in-depth profile for each threatened species. These Species Profiles are stand-alone documents prepared and reviewed by taxonomic experts. Each highlights the most urgently needed conservation activities for that species, with the purpose of serving as a guiding tool for conservation practitioners, land managers, and researchers.

Between 2017 and 2022 we requested collections data from *ex situ* institutions with *Quercus* accessions. There were 197 institutions that reported living collections of at least one Mesoamerican oak, a majority of which are in the United States (49%) and Europe (32%). Only nine (5%) institutions in Mesoamerica reported having one or more species of Mesoamerican oak in their collection. We identified 22 of our target species that are not held in any *ex situ* collections, anywhere in the world. Through spatial analyses, we found only three species have *ex situ* collections representing more than 50% of the species' geographic range (i.e., the proportion of a species' native range that is represented in collections), and 19 species have an ecological coverage greater than 50% (i.e., the proportion of ecoregions represented in collections).

For each threatened species, we performed an extensive literature review and interviewed regional species experts to identify the most urgent threats, as well as current conservation activities. The most commonly reported threats were climate change (100% of species), agriculture (72%), and residential/commercial development (69%). The most frequently reported conservation activities were wild collection of living material and/or representation in *ex situ* collections (84% of species) and research (66%). Approximately one quarter (16 of 59) of the target species have less than 10% of their native range within protected areas. We also asked regional *Quercus* experts to identify which conservation activity should be the priority for each species. The most commonly reported priorities were education/outreach (14 species), research (13), and propagation/breeding programs (13).

This gap analysis relies on methodology developed by The Morton Arboretum, in partnership with Botanic Gardens Conservation International-US (BGCI-US). The methodology is designed to be flexible and can be adapted to fit the needs of specific target taxa and geographic regions. In addition to incorporating well established gap analysis methods, we have also developed several novel methods in order to meet the unique needs associated with conserving rare and oftentimes under-studied oaks in Mesoamerica. Notably, we: 1) developed a new methodology for quantifying climate change vulnerability, 2) incorporated the Holdridge life zone classification system in our assessment of ecological coverage, and 3) prioritized the use of Key Biodiversity Areas as a tool for *in situ* conservation.

Significant progress has been made in recent decades to better understand the rich diversity of oaks in Mesoamerica. However, important knowledge gaps remain, and scientific inquiries have not always translated into effective conservation actions. Efficient collaboration between a broad array of institutions and sectors is crucial in furthering this progress and preventing further biodiversity loss within the region. This gap analysis can be used to identify potential areas for collaboration and set priorities. Our results highlight the urgent need for expanding survey and exploration work, increasing representation of oak species in botanic gardens and arboreta (particularly in Mexico and Central America) and identifying priority regions, species, and activities to focus both *in situ* and *ex situ* conservation efforts.

INTRODUCTION AND OBJECTIVES

New coffee plantation showing cloud forest destruction in Costa Rica (The Morton Arboretum)

Mesoamerica (defined here as the region comprising Mexico and Central America) is one of the most floristically diverse regions in the world. Containing nearly 8% of the world's biodiversity, it is recognized as the third largest biodiversity hotspot (Suzart de Albuquerque et al., 2015). Mexico alone has over 23,000 species of vascular plants, approximately 11,000 of which are endemic (Villaseñor, 2016). Mexico is within the top ten countries with the most tree species at 3,364, with *Quercus* being the most species-rich tree (Beech et al., 2017; Tellez et al., 2020). There are an estimated 164 species of oaks in Mexico, making it the center of oak diversity globally. Oaks inhabit most vegetation types within the region, where they are often keystone species that shape ecological relationships and provide multiple ecosystem services and economic benefits (Valencia-A, 2010).

The oak forests of Mesoamerica have experienced rapid changes within the last several decades, and the forests within this geographic region are among the most endangered of all tropical ecosystems. Globally, this region is one of the top three biodiversity hotspots experiencing the greatest recent loss of forest area (Hu et al., 2020). The Red List of Oaks revealed that Mexico is second only to China in terms of the number of threatened oak species in the world, with 20% of species threatened with extinction (Carrero et al., 2020). Thirty-two species have been categorized as Data Deficient, meaning that there is inadequate information to assess their extinction risk. Oaks face a variety of threats, including urban and rural development, agriculture, climate change, invasive species, and pests. Despite the urgent threats facing Mesoamerican oaks, for many species very little is known regarding their population size and trends, distribution, or ecology. This lack of knowledge makes planning and implementing appropriate conservation activities extremely challenging.

The IUCN Species Survival Commission relies on the Species Conservation Cycle of "Assess, Plan, Act" as a framework to guide conservation activities. An important aspect of the "Assess" component is Red Listing. The recently published Red List of Oaks made crucial contributions to our understanding of the current status of oaks worldwide, including Mesoamerica (Carrero et al., 2020). Still, questions remain regarding how best to prioritize species and regions for conservation. One approach to identify and address these knowledge gaps is through a conservation gap analysis. A conservation gap analysis is a comprehensive evaluation of the successes and needs of both the *in situ* (wild, within native habitat) and *ex situ* (within living collections or seed banks) populations. The only known conservation gap analysis for oaks was produced in 2019 by Beckman et al. for species native to the United States. Despite its status as the region with the greatest number of oak species, this type of analysis has never been performed for oaks in Mesoamerica.

Quercus brandegeei (The Morton Arboretum)

Oak-*Pinus* forests, Nuevo Léon, Mexico
(The Morton Arboretum)

There are several challenges to conservation of oaks that necessitate their existence in *ex situ* collections and strategic collaboration among stakeholders. First, they are recalcitrant species, meaning that acorns cannot survive the drying and freezing conditions typical of conventional seed banking. Oaks therefore need alternative methods such as cryopreservation (Ballesteros and Pritchard, 2020), tissue culture (Meyad et al., 2023), or living *ex situ* collections. Although protecting species in their native habitat is ideal, there is a growing recognition of the conservation value of high-quality living collections (Cavender et al., 2015; Westwood et al., 2021). Second, oaks are notorious for their ability to hybridize within the same section. Hybrids typically do not form large groups, but rather are sporadic and isolated among parents (Valencia-A, 2010). Hybrids may present a mosaic of intermediate characteristics, or they may favor the resemblance of one parent over the other, making species identification challenging in the field. Further challenges related to the recognition of Mesoamerican oaks include high morphological variation within a single species and original descriptions that lack sufficient information on this variation (Valencia-A, 2010). Collaboration among researchers focusing on topics such as population genetics, taxonomy, and phylogenetics is needed to better understand and protect this challenging genus. Finally, because oaks can be long lived and large, they require a significant amount of physical space to grow. Metacollections involving multiple institutions working together are oftentimes needed in order to achieve an appropriate number of individuals in collections. Close collaboration among different stakeholders as well as effective *in situ* and *ex situ* conservation is necessary to address these challenges.

Here, we present a comprehensive gap analysis of Mesoamerican oaks, which we conducted to better understand the conservation needs and opportunities for all threatened and Data Deficient species in the region. For each of our target species, we characterized the following:

- Native distribution
- Protected area coverage
- Conservation value of *ex situ* collections based on geographic and ecological representation of wild populations
- Past, present, and future threats and conservation activities

In addition to a summary of results for all 59 target species, this gap analysis also includes in-depth Species Profiles for all 32 threatened species that summarize distribution and threats, as well as *ex situ* and *in situ* conservation status and needs (Appendix G). A similar abridged profile is provided for all 27 Data Deficient species. These Species Profiles build on Red List assessments by providing the most up-to-date status for each species, as well as prioritizing conservation activities. This analysis relied on the input of dozens of species experts from Mexico and Central America who vetted occurrence points and provided input on the current threats and conservation needs of each species. These species experts are members of the Global Conservation Consortium for Oak (GCCO) and represent a variety of sectors, including academia, government, botanic gardens, arboreta, herbariums, and NGOs.

The goal of this gap analysis is to help prioritize and coordinate conservation activities between relevant stakeholders in their effort to both effectively and efficiently conserve Mesoamerican oaks. We encourage participatory conservation action and projects that support local livelihoods and respect local knowledge. Because we hope this document will be useful to a wide audience, we have published it in English and Spanish, and provide both digital and printed formats of the main report. The Species Profiles serve as stand-alone technical guides that can be used by academics, students, or conservation practitioners interested in working with one or more of the priority species.

Quercus macdougallii (Nelly Pacheco)

Quercus engelmannii (Dave Muffly)

CONSERVATION GAP ANALYSIS METHODOLOGY

The Morton Arboretum, in partnership with Botanic Gardens Conservation International-US (BGCI-US), began developing a conservation gap analysis methodology in 2016 with the goal of identifying gaps and providing conservation recommendations for *ex situ* and *in situ* populations of woody plants. Oaks native to the United States were used as a pilot group to test the methodology (Beckman et al., 2019), which incorporated methods developed by Khoury et al. (2020) to assess conservation priorities for crop wild relatives. Since 2016, the methodology has continued to be developed and additional gap analyses have been published that expand on the workflow developed by The Morton Arboretum, including *Acer* (Crowley, 2019), nine priority genera in the United States (American beech, hickories, Kentucky coffee tree, pines, selected laurels, walnuts, and yews; Beckman et al., 2021), *Magnolia* (Linskey et al., 2022a; 2022b), and ten fruit and nut tree crop wild relative genera in North America (*Asimina, Carya, Castanea, Corylus, Diospyros, Juglans, Malus, Persea, Pistacia*, and *Prunus*; Beckman Bruns et al., 2023a). This gap analysis of Mesoamerican oaks is the most recent example of implementing the conservation gap analysis methodology. See Beckman Bruns (2023) for gap analysis documentation and training materials.

STUDY REGION

We defined Mesoamerica as the region comprising the countries of Mexico, Guatemala, Belize, El Salvador, Honduras, Nicaragua, Costa Rica, and Panama. Several species native to Mexico have the northernmost portion of their range in the United States, specifically the states of California, Arizona, New Mexico, and Texas. While the focus of this study is on the status of oaks within Mesoamerica, we also considered the full range of these cross-border species in all analyses. There is one species of oak in South America: *Q. humboldtii* in Colombia. This species is assessed as Least Concern, and was therefore not a target of our analysis. In addition, *Q. sagraeana* is the only species of oak native to the Caribbean, in Cuba. Because it is outside of the study region, we did not include it in our list of target taxa.

TARGET SPECIES

We first identified 177 Mesoamerican oak species and their synonyms based on a species list supplied by the GCCO Mexico and Central America. We then refined our species list to include only those assessed by the IUCN Red List as Critically Endangered, Endangered, Vulnerable, or Data Deficient (IUCN, 2023). After further review of our target species list we removed two Data Deficient species: *Q. edwardsiae* as a synonym of *Q. monterreyensis* and *Q. alpescens* as a synonym of *Q. greggii*. We also removed one Vulnerable species, *Q. furfuracea*, as a synonym of *Q. sartorii*. In addition, three species (*Q. tardifolia, Q. robusta*, and *Q. hinckleyi*) have no known records in Mesoamerica and their presence outside of Texas is uncertain. We did not include these three species in the gap analysis. However, they should be a target of future survey work to the Mexican states of Chihuahua and Coahuila in order to potentially identify additional populations outside of the United States. Finally, it should be noted that there are several species of Mesoamerican oak that are not well defined, and experts disagree on their taxonomic status. These species include *Q. aerea, Q. carmenensis, Q. cupreata, Q. diversifolia, Q. graciliformis, Q. ignaciensis, Q. perpallida, Q. rekonis, Q. runcinatifolia, Q. verde*, and *Q. vicentensis* (Susana Valencia-A and Andrew Hipp, personal communication, 2024). Although we have included these species in the gap analysis, we recognize that they deserve further taxonomic review. Our final target species list includes 32 threatened species and 27 Data Deficient species, for a total of 59 species (Table 1).

Oak habitat in Costa Rica (The Morton Arboretum)

Quercus insignis acorn (Diego Gomez Hoyos)

Table 1. List of 59 target species along with their Red List category, assessment criteria, and assessment year. Definitions of IUCN Red List criteria can be found at www.iucnredlist.org/resources/categories-and-criteria. NA = not applicable.

Species Name	IUCN Red List Category	IUCN Red List Criteria	Assessment Year
Quercus graciliformis	Critically Endangered	C2a(ii)	2016
Quercus mulleri	Critically Endangered	B1ab(iii,v)+2ab(iii,v); C2a(ii)	2015
Quercus brandegeei	Endangered	B1ab(iii,v)c(iv)+2ab(iii,v)c(iv)	2016
Quercus carmenensis	Endangered	B1ab(iv)	2015
Quercus cualensis	Endangered	B1ab(iii)	2016
Quercus cupreata	Endangered	B1ab(iii)+2ab(iii)	2017
Quercus delgadoana	Endangered	B2ab(iii)	2018
Quercus devia	Endangered	B1ab(iii)+2ab(iii)	2018
Quercus diversifolia	Endangered	B2ab(iii)	2017
Quercus dumosa	Endangered	B2ab(ii,iii,iv,v)	2016
Quercus engelmannii	Endangered	A3c	2016
Quercus flocculenta	Endangered	B1ab(iii)+2ab(iii)	2017
Quercus galeanensis	Endangered	B2ab(iii)	2018
Quercus hintonii	Endangered	B1ab(i,ii,iii)+2ab(i,ii,iii)	2017
Quercus hirtifolia	Endangered	B1ab(iii)+2ab(iii)	2017
Quercus insignis	Endangered	B2ab(iii)	2017
Quercus macdougallii	Endangered	B1ab(iii)+2ab(iii)	2018
Quercus miquihuanensis	Endangered	B1ab(iii)+2ab(iii)	2018
Quercus nixoniana	Endangered	B2ab(iii)	2019
Quercus radiata	Endangered	B2ab(iii)	2018
Quercus runcinatifolia	Endangered	B1ab(iii)+2ab(iii)	2018
Quercus tomentella	Endangered	B2ab(i,ii,iv,v)	2016
Quercus acutifolia	Vulnerable	A3bc	2015
Quercus ajoensis	Vulnerable	B2ab(iii)	2017
Quercus cedrosensis	Vulnerable	B2ab(ii,iii,iv)	2016
Quercus costaricensis	Vulnerable	A2cd; B1ab(ii,iii)+2ab(ii,iii)	2019
Quercus gulielmi-treleasei	Vulnerable	B1ab(iii)+2ab(iii)	2018
Quercus hintoniorum	Vulnerable	B2ab(iii)	2018
Quercus meavei	Vulnerable	B1ab(iii)+2ab(iii)	2019
Quercus rubramenta	Vulnerable	B1ab(iii)+2ab(iii)	2017
Quercus tuitensis	Vulnerable	D2	2018
Quercus vicentensis	Vulnerable	A2bc	2019

Species Name	IUCN Red List Category	IUCN Red List Criteria	Assessment Year
Quercus acherdophylla	Data Deficient	NA	2018
Quercus aerea	Data Deficient	NA	2019
Quercus barrancana	Data Deficient	NA	2015
Quercus breedloveana	Data Deficient	NA	2020
Quercus centenaria	Data Deficient	NA	2020
Quercus coahuilensis	Data Deficient	NA	2019
Quercus coffeicolor	Data Deficient	NA	2019
Quercus deliquescens	Data Deficient	NA	2018
Quercus ghiesbreghtii	Data Deficient	NA	2019
Quercus gracilior	Data Deficient	NA	2020
Quercus grahamii	Data Deficient	NA	2018
Quercus ignaciensis	Data Deficient	NA	2019
Quercus melissae	Data Deficient	NA	2020
Quercus mexiae	Data Deficient	NA	2020
Quercus opaca	Data Deficient	NA	2018
Quercus paxtalensis	Data Deficient	NA	2018
Quercus perpallida	Data Deficient	NA	2019
Quercus porphyrogenita	Data Deficient	NA	2020
Quercus rekonis	Data Deficient	NA	2019
Quercus sarahmariae	Data Deficient	NA	2020
Quercus supranitida	Data Deficient	NA	2018
Quercus tinkhamii	Data Deficient	NA	2019
Quercus toumeyi	Data Deficient	NA	2017
Quercus toxicodendrifolia	Data Deficient	NA	2017
Quercus trinitatis	Data Deficient	NA	2018
Quercus undata	Data Deficient	NA	2020
Quercus verde	Data Deficient	NA	2019

Quercus costaricensis (Fancisco Garin)

Quercus engelmannii (Dave Muffly)

EX SITU COLLECTION DATA

Once per year between 2017 and 2022, Quercus accessions data as well as associated wild provenance details were requested from *ex situ* collections globally. We targeted institutions that reported holding native United States and Mesoamerican oak species to the BGCI PlantSearch database (BGCI, 2022), GCCO members, as well as our professional networks. See Appendix B for a detailed description of the data requested per survey year. All submitted accessions' data was compiled, standardized, and filtered in R (Version 4.2.0; R Core Team, 2022) using scripts adapted from Beckman Bruns et al. (2023b). We further refined our dataset to include species records only, excluding hybrids and cultivars. When coordinates were not provided, we manually geolocated points using the locality description. We did not attempt to geolocate points that included a general locality description at the state-level or higher. When institutions did not report the number of individuals representing each accession, we assumed the accession consisted of a single individual. As such, the number of plants reported in ex *situ* collections is an estimate based on available data, and represents the minimum number of plants in ex *situ* collections.

Quercus macdougallii (Nelly Pacheco)

IN SITU DATA SOURCES

To create a curated set of data points representing the known native distribution of each target species, we first compiled and standardized a variety of spatial point datasets in R. Raw spatial point data sources for the 59 target species include:

- **Global Biodiversity Information Facility (GBIF)**; downloaded January 2023 (GBIF.org)
- **Herbaria consortiums**, downloaded January 2023 via SEINet Portal Network (https://symbiota.org/seinet/)
- **Regional herbaria**, including:
  - Universidad de San Carlos de Guatemala (USCG), downloaded February 2023
  - Universidad Nacional Autónoma de Honduras (TEFH), downloaded June 2023
  - Herbario del Jardín Botánico Universitario BUAP (HUAP), downloaded March 2023
  - Museo Nacional de Costa Rica (CR), downloaded February 2023
  - Universidad de Panamá (PMA), downloaded February 2023
  - Colegio de la Frontera Sur Herbarium (CH), downloaded February 2022
  - Instituto Nacional de Estadística Geografia e Informática Herbario (INEGI), downloaded July 2021.
  - Herbario Instituto de Ecología, A.C. (XAL), downloaded February 2022
  - Herbario Isidro Palacios (SLPM) Universidad Autónoma de San Luis Potosí, downloaded December 2021
  - Escuela Agrícola Panamericana (EAP), downloaded March 2022
  - Museo de Historia Natural de El Salvador (MHES), downloaded September 2022
  - SERBO, A.C., downloaded March 2022
- **DigBio Integrated Digitized Biocollections**; downloaded January 2023 (idigbio.org)
- **The national network of forest survey plots** managed by the Forest Inventory and Analysis Program (FIA) of the USDA Forest Service; downloaded January 2023 (fia.fs.fed.us/tools-data)
- **Tropicos**; downloaded February 2023 (https://www.tropicos.org/home)
- **IUCN Red List**; downloaded January 2023 (https://www.iucnredlist.org/)
- **Botanical Information and Ecology Network (BIEN)**; downloaded January 2023 (https://bien.nceas.ucsb.edu/bien/)
- **Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO)**; downloaded March 2023 (https://www.gob.mx/conabio)

- **California Natural Diversity Database (CNDDB)**; downloaded June 2023
- **Genesys**; downloaded November 2022 (https://www.genesys-pgr.org/)
- **FAO's World Information and Early Warning System** (WIEWS) on plant genetic resources for food and agriculture; downloaded December 2022
- **Published papers**
- **Communication with experts**, including records from collection trips and research projects
- **Geolocated wild provenance localities** of the accessions from the 2017, 2018, 2019, 2020, 2021, and 2022 *ex situ* collections surveys

CURATION OF OCCURRENCE DATA

All datasets were combined, and occurrence data for the target species were mapped using R statistical software and the 'leaflet' package (Graul, 2016). Points were initially flagged for further review using the R package 'CoordinateCleaner' (Zizka et al., 2019) and if necessary removed from the dataset based on the following conditions: 1) records within 500 m of a country or state centroid, 2) records within 100 m of biodiversity institutions, 3) records outside of the species native range as reported by the IUCN Red List and GlobalTreeSearch (BGCI, 2023), and/or 4) records in countries reported in the IUCN Red List as part of the species "introduced" range. We also removed spatial duplicates by rounding the latitude and longitude to two digits after the decimal point, which removes points less than approximately 1 km apart. In addition, we performed a literature review and consulted with experts to identify an elevation range for each species, and removed points that fell well outside of that range. Each species' occurrence map was reviewed either in person or virtually by a minimum of two regional *Quercus* taxonomic experts to further curate the dataset. For species that cross the border into the United States, we had experts within the United States review that portion of the species' range.

Quercus gulielmi-treleasei in Panama (Roderick Cameron)

Records from GBIF include iNaturalist research-grade observations. For threatened species, iNaturalist coordinates are obscured with an uncertainty of approximately 500 km^2 to protect the exact location of the specimen. Following iNaturalist's protocol, we contacted the observers of our target species with a request to share their unobscured data. If we did not receive the unobscured coordinates, we removed the record from our dataset. If we did obtain the unobscured coordinates, the iNaturalist photos used to identify the species were reviewed by a regional *Quercus* expert. If they agreed with the identification, we included the record in our dataset. If they believed that the identification was incorrect or it could not be made with certainty based on the photos alone, we removed the record from our dataset. Our final, curated dataset contained 4,424 records.

SPATIAL ANALYSES

For each target species, we used *in situ* occurrence points as well as geolocated wild occurrence provenance records from the *ex situ* surveys to calculate the geographic and ecological coverage of *ex situ* collections. Geographic coverage is the proportion of a species native range that is represented in collections, whereas ecological coverage represents the proportion of life zones or ecoregions that are represented in collections. For species without population-level genetic data, these are useful proxies to estimate the genetic representation of ex *situ* collections (Hoban et al., 2018; Di Santo and Hamilton, 2020). We approximated the native range of a species by placing circular buffers with a radius of 20 km around each occurrence point. Buffers were cropped to land when necessary. Previous gap analyses have assessed native range through the use of Species Distribution Models (SDM; Khoury et al., 2019), 20 km buffers (Linsky et al., 2022a; 2022b), or 50 km buffers (Beckman et al., 2019). Due to the limited range and habitat specificity of many of our target species, we determined the 20 km buffer method to be most appropriate and informative.

Quercus engelmannii (Dave Muffly)

Geographic coverage of *ex situ* collections was estimated by dividing the total buffer area around *ex situ* wild provenance collection points by the total buffer area around all *in situ* points. The results of this analysis are used as an indicator of how well the *ex situ* collections represent the geographical range of the native population. Ecological coverage was calculated by dividing the total number of ecoregions under the *ex situ* buffer area by the total number of ecoregions under the *in situ* buffer area. The results of this analysis are used as an indicator of how well *ex situ* collections represent the ecological range of the native population. An innovative aspect of this gap analysis relative to previous reports is the use of the Holdridge life zone classification system to define ecoregions. First developed by Leslie Holdridge in 1967 for use in the tropics, this ecosystem mapping tool has since been widely adapted across the globe (Khatun et al., 2013; Missanjo et al., 2019; Derguy et al., 2022). The Holdridge life zone system classifies land areas based on the variables of precipitation, biotemperature, evapotranspiration ratio, latitude, and longitude. Life zones are not meant to replace micro environments and ecosystems in which these species are found, but rather are general guidelines based on the aforementioned predictor variables. There are 38 potential life zones globally, ranging from polar deserts to tropical rainforests. We mapped the Holdridge life zones of our study region using WorldClim Version 2.1 bioclimatic data from 1970–2000 at 30 second resolution (approximately 1 km^2; Fick and Hijmans, 2017). To calculate Holdridge life zones and generate maps we used an R script developed by Isabel Trejo and Angela Cuervo of the Universidad Nacional Autónoma de México, Mexico City (Trejo and Cuervo, 2016).

SPECIES RICHNESS AT THREE SPATIAL RESOLUTIONS

We analyzed species richness at three different spatial resolutions: 1) country level, 2) state level, and 3) a 50 x 50 km grid. Data on the native country for each of the 177 species of Mesoamerican oaks was obtained from the IUCN Red List and BGCI GlobalTreeSearch (BGCI, 2023), and country-level heat maps were generated based on these results. We also generated heat maps at the state-level for our target species only. We mapped target species occurrence data, counted the number of species within each state, and created a heat map based on those values. To achieve a finer resolution, we overlaid occurrence data with a grid of 50 km x 50 km cells placed over the entire study region, and counted the number of species within each cell. Country and state level heat maps were generated in R using the 'leaflet' package, and the grid cell map was generated in QGIS (Version 3.28.3-Firenze).

CLIMATE CHANGE VULNERABILITY

Previous gap analyses have relied on literature review to classify climate change as a high, moderate, or low impact threat for each species (Beckman et al., 2019). Here, we present a novel approach to quantitatively assessing climate change vulnerability for each target species using the Holdridge life zone classification system. In addition to mapping Holdridge life zones using bioclimatic data from 1970–2000, we also mapped life zones using precipitation and temperature data predicted from ten different climate change models for the years 2061–2080 (WorldClim, 2022; Table 2). We selected the climate models based on those that were available on WorldClim Version 2.1 at 30 second spatial resolution and had data for the Shared Socioeconomic Pathway (SSP) 245. The SSP245 pathway is considered the "middle of the road" scenario, with moderate future greenhouse gas emissions and an additional radiative forcing of 4.5 W/m^2 by 2100 (Hausfather, 2019).

We first generated the life zone map using the 1970–2000 bioclimatic variables as a reference point. We overlaid occurrence data on this map and added a 20 km buffer around each point to represent the species' inferred native range. We then determined the species "preferred" Holdridge life zone by identifying the life zone in which the greatest number of occurrence points were found. We calculated the area in square kilometers of the preferred life zone within the species' inferred native range. This represents the current area of preferred habitat for each species under reference conditions. We then repeated this process for each life zone map generated using data from one of the ten climate models. We calculated the percentage difference between the area of the preferred life zone under reference conditions and the life zone area under climate change conditions. Finally, we calculated the average percentage difference across all ten climate models for each species. A positive percentage difference indicates that the area of the preferred life zone is predicted to increase under future climate scenarios, and a negative percentage difference indicates a predicted decrease in life zone area. It should be noted that a decrease in preferred life zone area does not necessarily mean that the species will no longer be able to survive in the new environment. Additional mechanisms for quantifying climate change vulnerability, such as ecological niche modeling, should also be explored.

Table 2. Climate change models that were used to generate Holdridge life zone maps with downscaled bioclimatic data predicted for years 2061–2080 (WorldClim, 2022).

Model Name	Modelling Center	Reference
ACCESS-CM2	Australian Community Climate and Earth System Simulator	Dix et al. (2019)
CMCC-ESM2	Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici	Peano et al. (2020)
EC-Earth3-Veg	EC-Earth-Consortium	EC-Earth Consortium (2019)
GISS-E2-1-G	National Aeronautics and Space Administration	NASA Goddard Institute for Space Studies (2018)
INM-CM5-0	Russian Academy of Science	Volodin et al. (2019)
IPSL-CM6A-LR	Institute Pierre Simon Laplace	Boucher et al. (2018)
MIROC6	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute, University of Tokyo, National Institute for Environmental Studies, RIKEN Center for Computational Science	Shiogama et al. (2019)
MPI-ESM1-2-HR	Max Planck Institute for Meteorology	von Storch et al. (2017)
MRI-ESM2-0	Meteorological Research Institute	Yukimoto et al. (2019)
UKESM1-0-LL	The UK Earth System Modelling project	Tang et al. (2019)

KEY BIODIVERSITY AREAS

Key Biodiversity Areas (KBAs) are sites that have been identified as contributing significantly to the persistence of global biodiversity across taxonomic groups and ecosystems. Originally adopted by the IUCN in 2016, KBAs act as a standardized, science-based framework for identifying the most important terrestrial, marine, and freshwater sites to conserve on the planet (IUCN, 2016). To date, over 16,300 KBAs have been mapped globally. These maps and their associated data help to guide expansion of protected areas, inform the implementation and monitoring of international environmental agreements, focus conservation efforts on areas with the biggest potential impact, and inform private sector project implementation, design, and development. In order to be designated as a KBA, a site must meet a specific set of criteria in one of five categories designed to capture biodiversity at the genetic, species, and ecosystem scale: 1) threatened biodiversity, 2) geographically restricted biodiversity, 3) ecological integrity, 4) biological processes, or 5) irreplaceability. These criteria are primarily based on the presence of one or more "trigger species". These are species that identify a KBA by triggering either the threatened biodiversity or irreplaceability criterion. A site can be designated as a KBA if it contains >0.5% of global population size and >5 reproductive units (RU) of a Critically Endangered or Endangered species (IUCN, 2016). Vulnerable species can also be used to trigger a KBA if the site contains >1% of the global population size and >10 RU of said species.

There are currently 280 KBAs in Mexico alone, with 541 trigger species used to designate these KBAs (KBA, 2023). To date, there have been no oaks used as trigger species for KBAs within Mesoamerica. We mapped the wild occurrence points of all threatened oak species in Mesoamerica overlaid with a map of KBAs to identify species that could potentially be added as triggers to existing KBAs, as well as species that could be used to designate new KBAs.

THREATS AND CONSERVATION ACTIVITIES

This section builds upon the threats identified in the Red List of Oaks 2020 (Carrero et al., 2020). In addition to the threats identified there for each species, we conducted an additional literature review and interviewed regional species experts. Based on this information we identified the most urgent threats facing each of the 32 species listed as Critically Endangered, Endangered, or Vulnerable on the IUCN Red List. Because there is very little information regarding threats facing Data Deficient species, we focused our analysis on those currently assessed as threatened. We classified threats into one of ten categories based on the

Quercus macdougallii (Francisco Garin)

Threats Classification Scheme (Version 3.2) of the IUCN Red List (Conservation Measures Partnership, 2016) and the Conservation Gap Analysis of Native U.S. Oaks (Beckman et al., 2019):

- Human use of species: wild harvesting
- Human use of landscape: agriculture, silviculture, ranching, grazing
- Human use of landscape: residential/commercial development, mining, roads
- Human use of landscape: tourism, recreation
- Human modification of natural systems: altered fire regimes, pollution, eradication
- Human modification of natural systems: invasive species competition/disturbance
- Climate change: habitat shifting, drought, temperature extremes, flooding
- Genetic material loss: inbreeding, introgression
- Pests/pathogens
- Extremely small/restricted populations

We also identified conservation activities currently underway for each threatened species based on the categories outlined in Beckman et al. (2019). We considered land protection to be a conservation activity if at least 30% of the species' inferred native range was covered by protected areas. For cross-border species, conservation activities were considered to be implemented for the species if they occurred anywhere in the species' range. For each species, we also asked regional experts which activity/activities they consider to be the most urgent conservation priority.

- Land protection
- Sustainable management of land
- Population monitoring/occurrence surveys
- Wild collecting/*ex situ* curation
- Propagation/breeding programs
- Reintroduction/reinforcement/translocation
- Research
- Education/outreach/training
- Species protection policies

CONSERVATION ACTION SCORE

With so many species in need of conservation action and in the face of limited time and resources, it is necessary to prioritize species based on the most urgent need. There are many different methods that have been proposed to set conservation priorities. Prioritization methods at the species level typically fall into one of three categories: point-scoring methods, rule-based methods, or conservation status rank methods (Mace et al., 2006; Le Berre et al., 2019). In point-scoring methods, a score is assigned to each species based on a set of quantitative criteria for different parameters. The scores are typically summed, and the species are ranked based on their final score. One example of a point-scoring method is the Conservation Action Score (Khoury et al., 2020). The Conservation Action Score categorizes taxa for further conservation action based on three parameters focused on protected area coverage (*in situ* scores) and three parameters focused on geographic/ecological representation of *ex situ* collections (*ex situ* scores). When considered in conjunction with the threat data from IUCN Red List assessments, the Conservation Action Score is a valuable tool in directing and prioritizing conservation efforts.

Quercus dumosa (Maricela Rodríguez-Acosta)

For each target species, we calculated a Conservation Action Score to prioritize species for *ex situ* and *in situ* conservation efforts by adapting methods outlined in Khoury et al. (2020). Scores were divided into two categories: those related to *in situ* populations and those related to *ex situ* populations. *In situ* scores provide geographic and ecological measurements of the proportion of a species' range that is conserved in protected areas. *Ex situ* scores provide geographic and ecological measurements of the proportion of a species' range that is conserved in *ex situ* collections. All scores range from 0–100, with a score of 100 indicating complete conservation, and a score of 0 indicating extremely poor conservation. A combined final conservation score was then calculated by taking the average of the final conservation score *in situ* and the final conservation score *ex situ* for each species.

In Situ Scores

- **Sampling Representativeness Score *In Situ* (SRS *In Situ*)**: The number of occurrence points that fall within protected areas divided by the total number of occurrence points.
- **Geographical Representativeness Score *In Situ* (GRS *In Situ*)**: The area of a species' inferred native range that is covered by protected areas divided by the total area of a species' inferred native range.
- **Ecological Representativeness Score *In Situ* (ERS *In Situ*)**: The number of Holdridge life zones within a species' inferred native range that are located inside protected areas divided by the number of Holdridge life zones within the species' inferred native range.
- **Final Conservation Score *In Situ* (FCS *In Situ*)**: The mean of all *In Situ* scores.

Ex Situ Scores

- **Sampling Representativeness Score *Ex Situ* (SRS *Ex Situ*)**: The number of *ex situ* institutions that hold at least one accession of wild provenance of the target species, up to a maximum of 10. Final SRS *Ex Situ* scores were multiplied by 10 to achieve a scale of 0–100.
- **Geographical Representativeness Score *Ex Situ* (GRS *Ex Situ*)**: The area of the buffer surrounding all *ex situ* points divided by the area of the species' inferred native range.
- **Ecological Representativeness Score *Ex Situ* (ERS *Ex Situ*)**: The number of Holdridge life zones in the buffer surrounding all *ex situ* points divided by the number of Holdridge life zones in the species' inferred native range.
- **Final Conservation Score *Ex Situ* (FCS *Ex Situ*)**: The mean of all *Ex Situ* scores.

RESULTS AND ANALYSIS

Quercus agrifolia (Jesús Serrano)

SPECIES RICHNESS AT THREE SPATIAL RESOLUTIONS

Mexico is the center of oak biodiversity in Mesoamerica, with an estimated 164 species (Figure 1). In general, oak diversity decreases as you move southeast from Mexico into Central America. Guatemala has the second highest number of oak species at 28, followed by Honduras (22), El Salvador (18), Costa Rica (14), Nicaragua (13), Belize (12) and Panama (12). Although outside of our study range, it is important to note that there is also one species of oak in Colombia (*Q. humboldtii*), which is the only species of oak in South America and is currently assessed as Least Concern. This species also occurs in Panama.

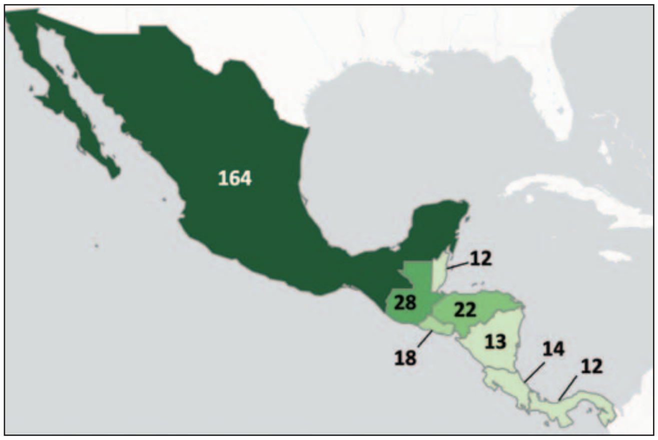


Figure 1. Species richness of native Mesoamerica oaks by country.

The two states in Mexico with the greatest richness of target species (threatened and Data Deficient) are Puebla and Nuevo León with 12 each, followed by five states that have 10 target species: Tamaulipas, Veracruz, Hidalgo, Oaxaca, and Jalisco (Figure 2A). In the remaining Mesoamerican countries, all states have 0–4 target species, the exception being Huehuetenango and Baja Verapaz states in Guatemala, which each have five (Figures 2B-H). See Appendix C for a list of target species by state for each country.

Quercus macdougallii habitat (Nelly Pacheco)

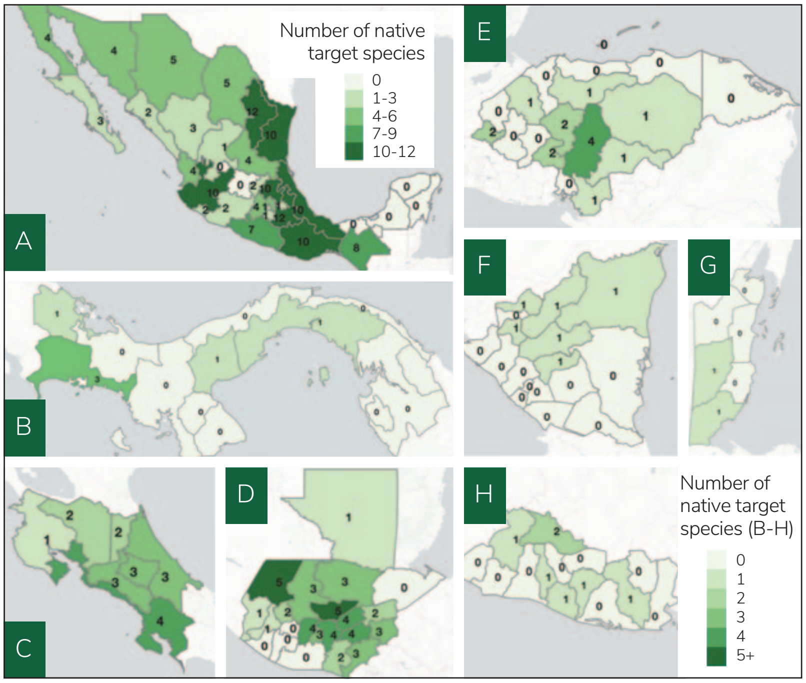


Figure 2. State-level richness of 59 target species in A) Mexico, B) Panama, C) Costa Rica, D) Guatemala, E) Honduras, F) Nicaragua, G) Belize, and H) El Salvador. Target species refers to species that are assessed as either threatened or Data Deficient.

Quercus cualensis
(M.C. Luz María González Villarreal)

Of our target species, 71% (42 of 59) are endemic to Mexico: one Critically Endangered species (*Q. mulleri*), 14 Endangered species (*Q. brandegeei*, *Q. cualensis*, *Q. delgadoana*, *Q. devia*, *Q. diversifolia*, *Q. flocculenta*, *Q. galeanensis*, *Q. hintonii*, *Q. hirtifolia*, *Q. macdougallii*, *Q. miquihuanensis*, *Q. nixoniana*, *Q. radiata*, and *Q. runcinatifolia*), five Vulnerable species (*Q. hintoniorum*, *Q. meavei*, *Q. rubramenta*, *Q. tuitensis*, and *Q. verde*), and 22 Data Deficient species (*Q. acherdophylla*, *Q. aerea*, *Q. barrancana*, *Q. breedloveana*, *Q. centenaria*, *Q. coahuilensis*, *Q. coffeicolor*, *Q. deliquescens*, *Q. ghiesbreghtii*, *Q. grahamii*, *Q. ignaciensis*, *Q. mexiae*, *Q. opaca*, *Q. perpallida*, *Q. porphyrogenita*, *Q. rekonis*, *Q. supranitida*, *Q. tinkhamii*, *Q. toxicodendrifolia*, *Q. trinitatis*, *Q. undata, and Q. verde*). Only three of our target species are endemic to Central America: *Q. costaricensis*, *Q. sarahmariae*, and *Q. gracilior*. There are eight species that occur in both the United States and Mexico: *Q. ajoensis*, *Q. carmenensis*, *Q. cedrosensis*, *Q. dumosa*, *Q. engelmannii*, *Q. graciliformis*, *Q*, *tomentella*, and *Q. toumeyi*.

Quercus dumosa (Roderick Cameron)

We further divided the study region by 50 km^2 cells to quantify species richness on a finer scale. The region with the greatest concentration of threatened and Data Deficient oaks is the Sierra Madre Oriental (21 species, 36%), followed by the Trans-Mexican Volcanic Belt (16 species, 27%; Figure 3). The Sierra Madre Oriental has been recognized as the most diverse region of oaks in Mexico for both threatened and non-threatened species (Valencia-A, 2010). In this mountain range, many different oak species can be found within a relatively small area. For example, 20% of our target species occur within one 50 km^2 area in northern Sierra Madre Oriental approximately 100 km south of Monterrey. The remarkable diversity of this region likely results from a combination of its geological history, ecological opportunity, and landscape heterogeneity, which can support many niches and promote diversification (Althaus et al., in prep; Hipp et al., 2018).

EX SITU COLLECTIONS

A total of 273 institutions from 32 countries submitted accessions data for *Quercus* in response to our *ex situ* collections surveys from 2017 to 2022. Of these, 197 institutions (72%) in 27 countries reported accessions of at least one species of native Mesoamerican oak (Figure 4). Surprisingly, there are only nine (5%) institutions located within Mesoamerica that reported having one or more species of Mesoamerican oak in their collection. A majority of institutions reporting Mesoamerican oaks are in the United States (96 institutions, 49%) and Europe (63, 32%). Results are similar for threatened and Data Deficient Mesoamerican oaks, with a majority of the collections for these species being held in the United States and Europe (Figure 5). The two target species with the greatest representation in *ex situ* collections within Mesoamerica are *Q. insignis* and *Q. brandegeei* (four institutions each), followed by *Q. acutifolia* (three institutions). Only 29% (17 of 59) of target species are held in *ex situ* collections within their native country (Table 3), therefore there is an urgent need to increase *ex situ* representation of rare and threatened Mesoamerican oak species among living collections in the region. This is particularly important considering that oaks cannot be seedbanked or preserved by conventional methods. This is one of the goals of the GCCO. *Quercus insignis* and *Q. brandegeei* are two of the target species for which the GCCO has promoted *ex situ* conservation, with additional species planned for the future (see Case Study 1, page 31).

Quercus brandegeei seedlings at a home nursery in Santiago, Baja California Sur, Mexico (The Morton Arboretum)

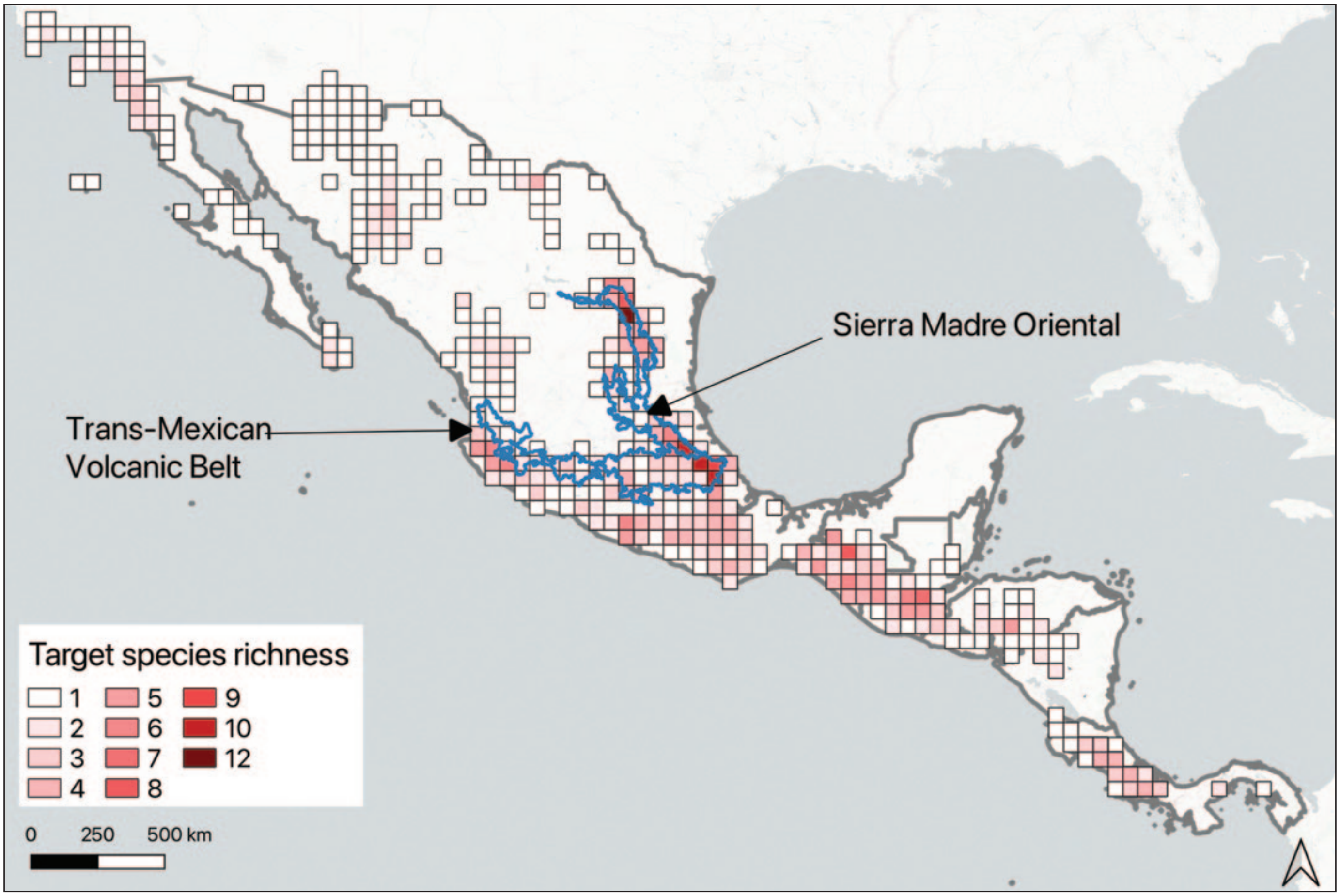


Figure 3. Target species richness per 50 km^2. Delineations of the Sierra Madre Oriental and Trans-Mexican Volcanic Belt are outlined in blue (Morrone et al., 2017).

Figure 4. Institutions that responded to our *ex situ* survey and reported having accessions of at least one Mesoamerican oak species.

Although most collections are held outside of the native range of the species, threatened and Data Deficient Mesoamerican oak species are represented by at least 3,875 plants living in *ex situ* collections globally. The species with the most plants living in *ex situ* collections are *Q. engelmannii* (2,604 individuals), *Q. dumosa* (359), and *Q. graciliformis* (189; Figure 6). A vast majority of threatened or Data Deficient oaks are represented by fewer than 100 plants in *ex situ* collections (56 species, 95%). Of the 34 species that are in *ex situ* collections with wild provenance, 62% are held in collections of 10 or fewer individuals. For a majority of plants in *ex situ* collections, the origin was either unknown or not provided (1,606 individuals, 41%). Only 26% of plants are documented as wild origin, and approximately 24% of these either have no source information or could not be geolocated. Provenance information is crucial in order to evaluate the genetic representation of the collection and in case plants need to be used as germplasm sources in the future (Wood et al., 2020). There are 22 target Mesoamerican oak species that are not found in any *ex situ* institutions anywhere in the world, according to the results of our 2017–2022 *ex situ* surveys. These include six threatened species (*Q. devia*, *Q. mulleri*, *Q. nixoniana*, *Q. radiata*, *Q. rubramenta*, *Q. tuitensis*) and 16 Data Deficient species (*Q. aerea*, *Q. breedloveana*, *Q. centenaria*, *Q. coahuilensis*, *Q. ghiesbreghtii*, *Q. gracilior*, *Q. ignaciensis*, *Q. melissae*, *Q. mexiae*, *Q. paxtalensis*, *Q. perpallida*, *Q. rekonis*, *Q. sarahmariae*, *Q. supranitida*, *Q. undata*, *Q. verde*). It should be noted that we know of two species that were added to *ex situ* collections in 2023. Because these events occurred after our last *ex situ* survey, they are not reflected in the results.

Quercus paxtalensis was added to the Jardín Botánico Universitario de la Benemérita Universidad Autónoma de Puebla (JBU-BUAP) satellite collection in Teziutlan, Puebla in 2023. In addition, within the last year *Q. rubramenta* has been the focus of a large wild collecting effort by Profauna Region Norte, International Oak Society (IOS), and JBU-BUAP, with plans to distribute this species to *ex situ* collections within Mexico as well as reintroduce it to the wild. See Case Study 4 (page 45) for more information on *Q. rubramenta*.

Quercus engelmannii seedlings at the San Diego Zoo (The Morton Arboretum)

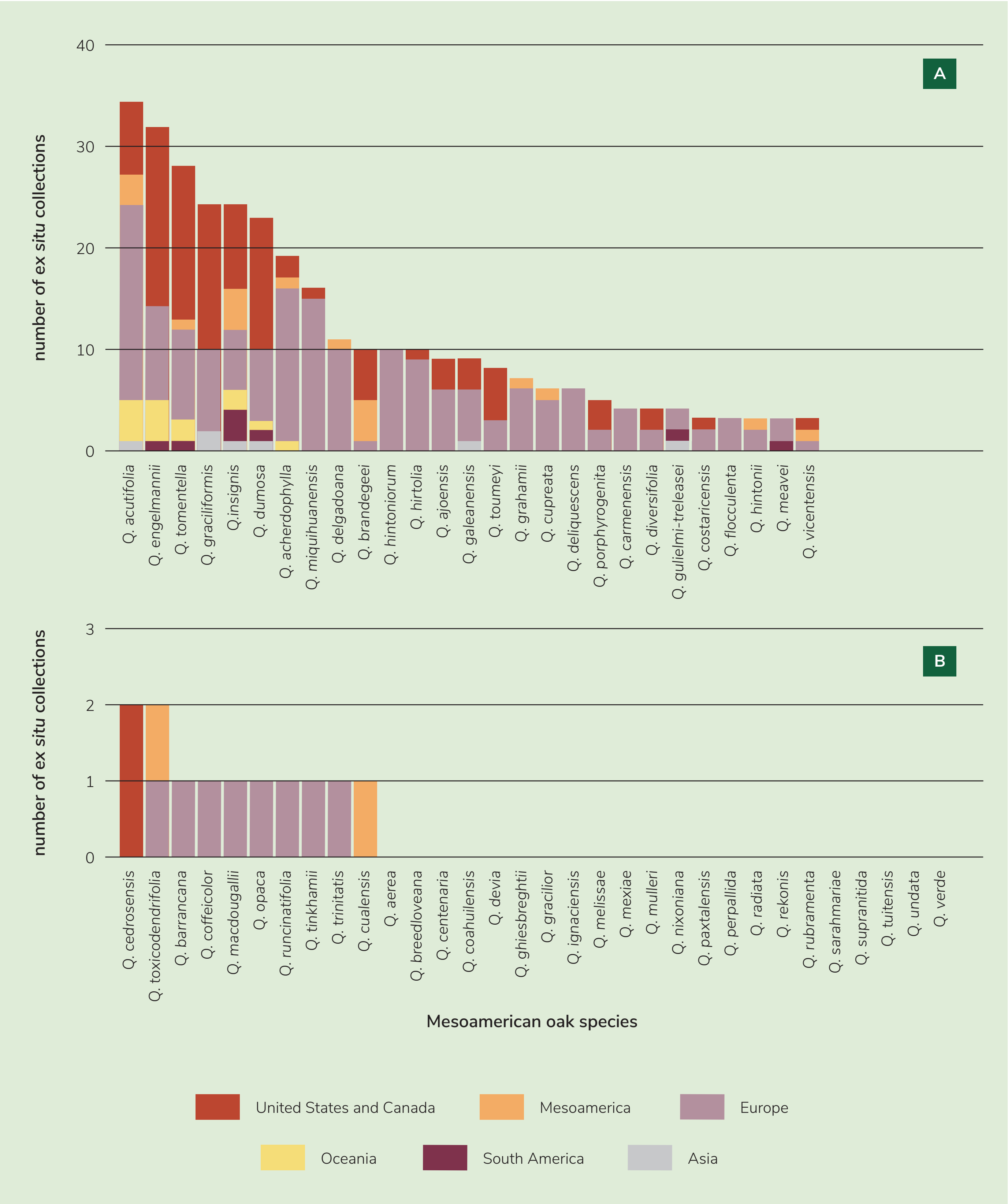


Figure 5. Number of *ex situ* collections for target Mesoamerican oak species, categorized by *ex situ* collection location for A) species in 3 or more *ex situ* collections and B) species in two or fewer ex situ collections. "*Ex situ* collections" is used as an equivalent to "living collections". Note change in Y-axis.

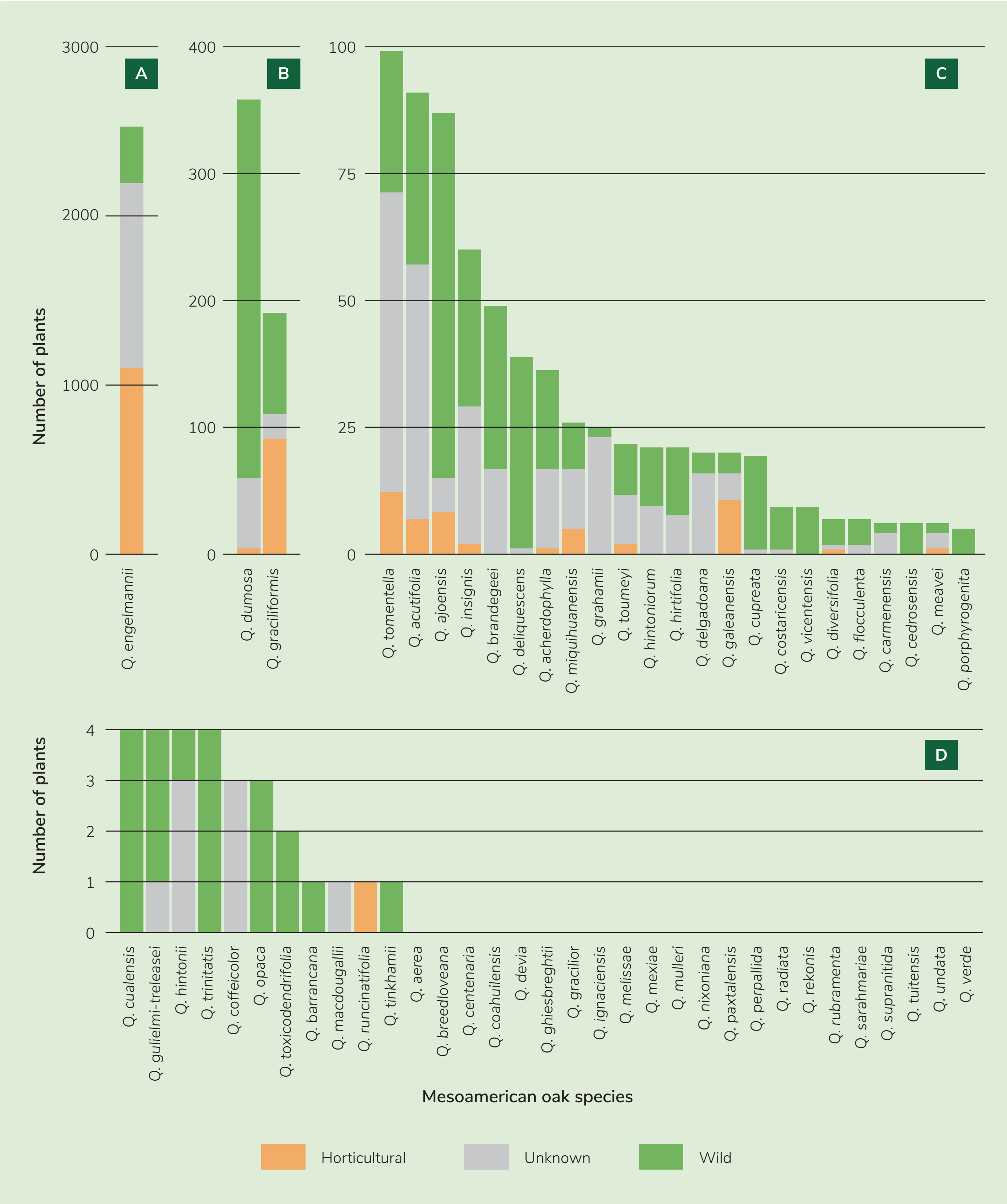


Figure 6. *Ex situ* collections survey results for target Mesoamerican species: number of plants per species in *ex situ* collections, categorized by provenance type for (A, B, & C) species with more than four plants in *ex situ* collections, and D) species with four or fewer plants in *ex situ* collections. Note change in Y-axis. See Appendix E for exact numbers of plants in *ex situ* collections.

Table 3. Native country for each target species, and the number of institutions holding living collections of the species both inside and outside of the native country.

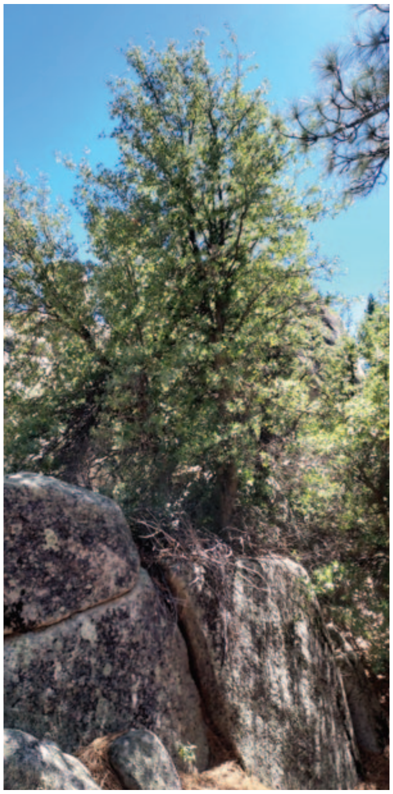
Species	Native country	Number of ex *situ* institutions	
		in native country	not in native country
Q. engelmannii	MX; US	18	14
Q. tomentella	MX; US	16	12
Q. graciliformis	MX; US	14	10
Q. dumosa	MX; US	13	10
Q. toumeyi	MX; US	5	3
Q. insignis	BZ; CR; SV; GA; HA; MX; NI; PA	4	20
Q. brandegeei	MX	4	6
Q. acutifolia	BZ; GA; HA; MX	3	31
Q. ajoensis	MX; US	3	6
Q. cedrosensis	MX; US	2	1
Q. delgadoana	MX	1	10
Q. grahamii	MX	1	6
Q. cupreata	MX	1	5
Q. hintonii	MX	1	2
Q. vicentensis	SV; MX	1	2
Q. toxicodendrifolia	MX	1	1
Q. cualensis	MX	1	0
Q. acherdophylla	MX	0	19
Q. miquihuanensis	MX	0	16
Q. hintoniorum	MX	0	10
Q. hirtifolia	MX	0	10
Q. galeanensis	MX	0	9
Q. deliquescens	MX	0	6
Q. carmenensis	MX; US	0	4
Q. diversifolia	MX	0	4
Q. gulielmi-treleasei	MX; CR; PA	0	4
Q. porphyrogenita	MX	0	4
Q. costaricensis	CR; PA	0	3
Q. flocculenta	MX	0	3
Q. meavei	MX	0	3
Q. barrancana	MX	0	1
Q. coffeicolor	MX	0	1
Q. macdougallii	MX	0	1
Q. opaca	MX	0	1
Q. runcinatifolia	MX	0	1
Q. tinkhamii	MX	0	1
Q. trinitatis	SV; MX	0	1
Q. aerea	MX	0	0
Q. breedloveana	MX	0	0
Q. centenaria	MX	0	0

Oak seedlings ready for *in situ* and ex *situ* conservation efforts at a greenhouse in Puebla University Botanic Garden (The Morton Arboretum)

New growth on a *Quercus insignis* seedling, around two years of age (The Morton Arboretum)

Table 3: continued

Species	Native country	Number of *ex situ* institutions	
		in native country	not in native country
Q. coahuilensis	MX	0	0
Q. devia	MX	0	0
Q. ghiesbreghtii	MX	0	0
Q. gracilior	HA; NI	0	0
Q. ignaciensis	MX	0	0
Q. melissae	GA; MX	0	0
Q. mexiae	MX	0	0
Q. mulleri	MX	0	0
Q. nixoniana	MX	0	0
Q. paxtalensis	MX	0	0
Q. perpallida	MX	0	0
Q. radiata	MX	0	0
Q. rekonis	MX	0	0
Q. rubramenta	MX	0	0
Q. sarahmariae	CR; PA	0	0
Q. supranitida	MX	0	0
Q. tuitensis	MX	0	0
Q. undata	MX	0	0
Q. verde	MX	0	0



Quercus peninsularis in Baja California, Mexico (Roderick Cameron)

EX SITU SPATIAL ANALYSES

Safeguarding threatened species in living *ex situ* collections is increasingly recognized as a crucial tool to prevent biodiversity loss, especially in the face of growing threats from climate change and habitat degradation (Westwood et al., 2021). The conservation value of living collections is highly dependent on the amount of genetic diversity captured within said collections. However, the detailed molecular studies necessary to determine if the genetic diversity of a collection is representative of the wild population is often lacking for rare species, especially in under-studied regions like Mesoamerica. In the absence of genetic data, we used two proxies to identify the degree to which *ex situ* collections represent genetic diversity in the wild: geographic and ecological coverage. These proxies assume that in order to capture the full spectrum of a species' genetic diversity, one must sample across the entire range of a species' native distribution, as well as within all ecoregions in which the species is found. Here we use 20 km buffers around each occurrence point to represent a species' native range, but this is just an estimate that should be interpreted with caution. Genetic diversity is distributed differently across space depending on many factors, such as life history traits, the historic range of the species, and environmental variables (Hoban et al., 2022). In addition, it should be noted that our *ex situ* collection points could represent a collection composed of hundreds of plants or just one individual living in an *ex situ* collection. Recent studies have shown that sampling seed from hundreds to upwards of a thousand individuals across a species' entire range may be necessary in order to preserve genetic diversity and evolutionary potential (Hoban, 2019). Nevertheless, spatial analyses presented here provide an effective tool to prioritize species, geographic regions, and ecoregions for future collection work. Take the example of *Q. hintoniorum* (Figure 7). Living collections of this species have been sourced from four locations in the northern portion of this species' range (represented by the black triangles on the map in Figure 7). This results in a geographic coverage of 23%. There are five Holdridge life zones in the species' estimated native distribution, and all five life zones are represented in *ex situ* collections. This results in an ecological coverage of 100%. Future wild collecting efforts for *Q. hintoniorum* would ideally be focused toward the southern portion of this species' range.

A species' representation in ex situ collections can derive from many factors including the range size, the species phenology, and the relative abundance of the species (BGCI, 2014). We found that twenty species of Mesoamerican oak have a geographic coverage of less than 25% and only three species were estimated to have *ex situ* collections that represent over 50% of the species' full geographic range: *Q. brandegeei* (63%), *Q. tomentella* (61%), and *Q. cualensis* (57%). Within the United States, *Q. tomentella* is found on four islands off of the coast of southern California, and there are living individuals in *ex situ* collections that originate from three out of four of those islands. There are unverified reports of *ex situ* collections originating from Guadalupe Island in Mexico, but this data was not captured in our *ex situ* surveys and is not reflected in our results. *Quercus brandegeei* has a very narrow distribution in the Cape Region at the southern tip of the Baja California peninsula, Mexico. This species has been collected from seven different locations within this region, and there are currently 10 *ex situ* institutions reporting collections of this species (Morton Arboretum, 2023). *Quercus cualensis* has an even more restricted geographic range than *Q. brandegeei*, and as such a single collection from the center of this species' range results in a relatively high percentage of the species' range reflected in a collection.

For all 59 target species, with two exceptions, ecological coverage is greater than geographic coverage. One exception is *Q. tomentella*, which has an ecological coverage of only 20% (compared to a geographic coverage of 61%; see Figure 4 in Species Profile, Appendix G). This is due to the fact that all of the islands from which there are *ex situ* collections are in the same life zone: warm temperate thorn scrub. There are currently no collections from San Clemente Island, California or Guadalupe Island, Mexico, and therefore the unique life zones on these islands are not conserved. The second exception is *Q. cualensis*, with an ecological coverage of 50% (compared to a geographic coverage of 57%; see Figure 4 in Species Profile, Appendix G). Two out of the four life zones within this species' inferred native range are not represented in *ex situ* collections. However, these two life zones are on the very edge of the species' range near the coast, and may not accurately reflect the habitat in which this species is actually found. Of the 37 species that are held in *ex situ* collections, there are eight that have an ecological coverage of less than 50%. These tend to be species with very wide distribution that inhabit many different life zones (e.g., *Q. acutifolia*, 47% ecological coverage), or underrepresented species *ex situ* that inhabit mountainous regions in which several different life zones are found within a small area (e.g., *Q. meavei*, 45% ecological coverage).

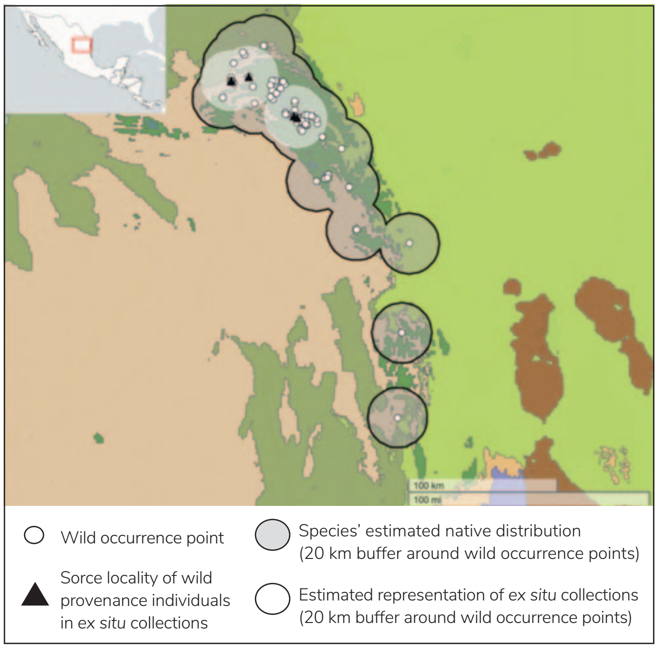


Figure 7. *Quercus hintoniorum* wild occurrence points and *ex situ* collection source localities. Colored regions are Holdridge life zones. All *ex situ* collection source localities are also wild occurrence points. See Appendix D for Holdridge life zone key

There are five species that have 100% ecological coverage: *Q. hintoniorum*, *Q. engelmannii*, *Q. deliquescens*, *Q. carmenensis*, and *Q. brandegeei*. *Quercus engelmannii* has been sampled from several different locations throughout the species range in California. Despite no *ex situ* collections originating from Mexico, the Mexican population occurs within the warm temperate thorn scrub, which is represented in *ex situ* collections from samples originating in California. Similarly, *Q. brandegeei* has been collected from several locations throughout its range in southern Baja California Sur, and all ecoregions are represented *ex situ*. *Quercus deliquescens* and *Q. carmenensis* are both found primarily in the warm temperate thorn scrub life zone, which is one of the largest life zones by total area in Mesoamerica (Appendix D). Because this life zone is so large, one can collect from relatively few locations and still achieve 100% ecological coverage. Finally, although *Q. hintoniorum* has only been collected from the northern portion of its range, all five life zones within the total range are represented in this small area, resulting in 100% ecological coverage. In summary, ecological coverage representation is dependent on the number of ecoregions that the species inhabits as well as the overall area of the ecoregion. Sampling within all ecoregions in which a species is found is one way to attempt to represent the full spectrum of geographic diversity in *ex situ* collections. However, it should be noted that this may not fully capture local adaptations to microclimate differences within an ecoregion.

Table 4. The total number of protected areas and the percentage of protected area coverage for each country in Mesoamerica.

	Belize	Panama	Costa Rica	Honduras	Nicaragua	Guatemala	Mexico	El Salvador
Total number of protected areas *	120	114	167	118	84	352	1185	202
Percent coverage of protected areas	37.55%	31.37%	26.59%	23.45%	21.35%	20.12%	14.60%	8.64%

* Note: according to the World Database on Protected Areas (WDPA), "Some geographic locations are designated more than once, e.g., as both a National Park (a national designation) and a World Heritage Site (an international designation). In the WDPA, these designations are counted as separate protected areas, meaning this number might appear higher than expected." (UNEP-WCMC and IUCN, 2023)

IN SITU SPATIAL ANALYSES

In order to characterize the degree of *in situ* conservation efforts for each target species, we estimated the percentage of a species' inferred native range that is covered by protected areas. It has been recommended that at least 10% of a species' distribution occur within protected areas (Salinas-Rodriguez et al., 2018; Zeng et al., 2023). This target is only applicable for species with very large ranges (>250,000 km^2; Rodriguez et al., 2004). Ideally species with much smaller ranges, as is the case with many threatened Mesoamerican oaks, would have virtually all of their habitat protected. We found that 73% (43 of 59) of our target species have greater than 10% of their range protected. The remaining 16 species should be prioritized for additional *in situ* conservation. In particular, we have identified three species that have 0% of their inferred native range protected: *Q. cualensis*, *Q. tuitensis*, and *Q. ignaciensis*. *Quercus cualensis* and *Q. tuitensis* are microendemic species located in Jalisco, Mexico just southeast of Puerto Vallarta. In addition to being near a popular tourist destination, there is active mining activity within these species' native range (Wenzell et al., 2020). *Quercus ignaciensis* is a Data Deficient species that is known from only one occurrence point in Sinaloa, Mexico. If future survey work is performed to locate additional occurrences of this species, it is possible that it may be found in nearby protected areas.

In contrast, there are three species that have over 80% of their inferred native range protected: *Q. tomentella* (84%), *Q. costaricensis* (91%), and *Q. carmenensis* (98%). *Quercus tomentella* is found on the Channel Islands off of the coast of California in the United States as well as Guadalupe Island in Mexico. Guadalupe Island is a protected biosphere reserve and is managed by the nonprofit organization Conservación de Islas. The only island in California that does not have a formal protection area established is San Clemente Island. However, this island is managed by the US Navy which has an Integrated Natural Resources Management plan and a long history of collaborative conservation efforts with the U.S. Fish and Wildlife Service (USFWS, 2023). Nearly 100% of wild occurrence points of *Q. costaricensis* are found within two protected areas in Costa Rica: Cordillera Volcánica Central (UNESCO-MAB Biosphere Reserve) and Parque Internacional de la Amistad (National Park). Finally, all known occurrence points of *Q. carmenensis* are within two protected areas: the Maderas del Carmen in Mexico (UNESCO-MAB Biosphere Reserve) and Big Bend National Park in Texas, United States.

Of all of the countries in Mesoamerica, Belize has the greatest percentage of its county covered by protected areas at 37.55%. El Salvador has the least, at 8.64% (Table 4). Within Mexico, the two most common protected area designations are Voluntary Conservation Areas (VCA) and Ramsar Sites, Wetlands of International Importance (UNEP-WCMC and IUCN, 2023). VCAs represent a bottom-up approach to the establishment of protected areas, in which people and communities propose their land for conservation. They tend to be very small in area. Ramsar Sites are areas that have been designated as containing rare, representative, or unique wetlands as part of an international agreement commonly known as the Ramsar Convention. There are 168 member countries that are part of this global treaty, including every country within Mesoamerica (The Convention on Wetlands, 2023).

Protected areas in Mexico are not distributed evenly, with some states having a significantly greater proportion of their land protected than others. The Mexican states with the greatest percentage of land covered by protected areas are Baja California Sur (49%), Baja California (43%), México (39%), and Nayarit (35%). Although Baja California has over 40% protected area coverage, almost all of the protected areas are in the southern half of the state in one large Terrestrial and Inland Waters Protected Area called Valle de los Cirios. The target species that occur within mainland Baja California (*Q. dumosa*, *Q. cedrosensis*, and *Q. engelmannii*) all occur north of this protected area, and as a result a majority of their range in Mexico is not protected.

There are 13 Mexican states that have less than 10% of their land covered by protected areas: Puebla (9.8%) Tlaxcala (9.7%), Sinaloa (8.0%), Zacatecas (8.0%), Colima (7.7%), Nuevo León (7.5%), Veracruz (7.4%), Durango (7.4%), Hidalgo (7.2%), Chihuahua (6.7%), Michoacán (5.9%), Oaxaca (5.7%) and Guerrero (1.3%). The two states (Puebla and Nuevo León) that have the greatest number of threatened and Data Deficient oaks both have less than 10% protected area coverage. Further work is needed within these two states to explore the creation of protected areas in order to ensure the conservation of threatened oaks within the region.

The Sierra Madre Oriental is a hotspot for diversity of threatened oaks in Mexico. Twenty-eight percent of this biogeographic province, as delimited in Morrone et al. (2017), is covered by protected areas (Figure 8). The

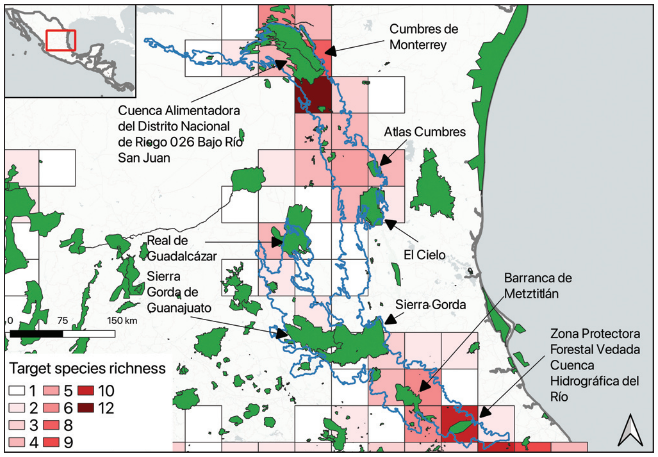


Figure 8. Richness of target species per 50 km^2 with major protected areas labeled. The Sierra Madre Oriental is outlined in blue. Protected areas are from Protected Planet (UNEP-WCMC and IUCN, 2023).

Cumbres de Monterrey and Cuenca Alimentadora del Distrito Nacional de Riego 026 Bajo Río San Juan are two protected areas in the Sierra Madre Oriental that are especially rich in threatened and Data Deficient oak species. There are nine target species that can be found within the borders of these two protected areas alone. It should be noted, however, that this result may be biased by higher exploration and collection work conducted within the protected area. In general, further survey work is needed in regions where high diversity is expected but where less exploration has taken place due to inaccessibility issues (e.g., Guerrero State).

KEY BIODIVERSITY AREAS

The Convention on Biological Diversity under the The Kunming-Montreal Global Biodiversity Framework has identified 23 global targets in need of urgent action by the year 2030. A core target within this framework is to "ensure and enable that by 2030 at least 30 percent of terrestrial and inland water areas, and of marine and coastal areas, especially areas of particular importance for biodiversity and ecosystem functions and services, are effectively conserved and managed through ecologically representative, well-connected and equitably governed systems of protected areas and other effective area-based conservation measures..." (Convention on Biological Diversity, 2024.). The so-called 30x30 initiative relies on the timely identification and prioritization of protected areas. Key Biodiversity Areas (KBAs) have emerged as one of the most widely used approaches to identify areas in need of protection. KBAs aim to identify and delineate areas of global importance to the persistence of biodiversity, based on "trigger species". A trigger species is used to identify a KBA by triggering either the threatened biodiversity or irreplaceability criterion. It is important to note that 1) KBAs cannot overlap each other, 2) new trigger species can be added to an existing KBA, and 3) although an important tool for prioritization of conservation areas, KBAs do not represent legal protection per se.

In Mesoamerica, 795 trigger species have been used to delineate KBAs, 63% of which are birds. Plants make up 7.7% of all trigger species in Mesoamerica, none of which are oaks. Comprehensively identifying KBAs for all taxa and ecosystems has been identified as an urgent priority within the coming decade (Visconti et al., 2019). We propose that including oaks as trigger species to Mesoamerican KBAs is a prime opportunity for tree conservation leaders within the region to highlight these rare, endemic, and often under-appreciated species.

We identified nine oak species that meet at least one criteria for delineating a KBA. For seven of these species, a majority of the known wild occurrences are within a currently established KBA, making them ideal candidates to add to the list of existing trigger species. One species, Q. *macdougallii*, meets criteria A1e for designation as a KBA. This criterion relates to a region that holds effectively the entire population size of a Critically Endangered or Endangered species. *Quercus macdougallii* is Endangered, and all known occurrences occur within the Sierra Norte de Oaxaca KBA (Figure 9D).

Four species meet criteria A1a for designation as a Key Biodiversity Area: Q. *cualensis*, Q. *devia*, Q. *brandegeei*, and Q. *carmenensis*. Criteria A1a designates a region with >0.5% of the total population size and >5 reproductive units of a Critically Endangered or Endangered species as a KBA. Eighty-four percent of the known occurrences of Q. *cualensis*, an Endangered species, are within the boundaries of the West of Talpa de Allende KBA (Figure 9A). *Quercus devia* and Q. *brandegeei* are also Endangered species, and 85% and 19% of known occurrences of these two species, respectively, are within the Sierra de La Laguna KBA (Figure 9B). Finally, 57% of the known occurrence points of Q. *carmenensis*, another Endangered species, are within the Sierra Maderas del Carmen KBA (Figure 9F). Each of the above listed species have a population size of more than five individuals within the KBA.

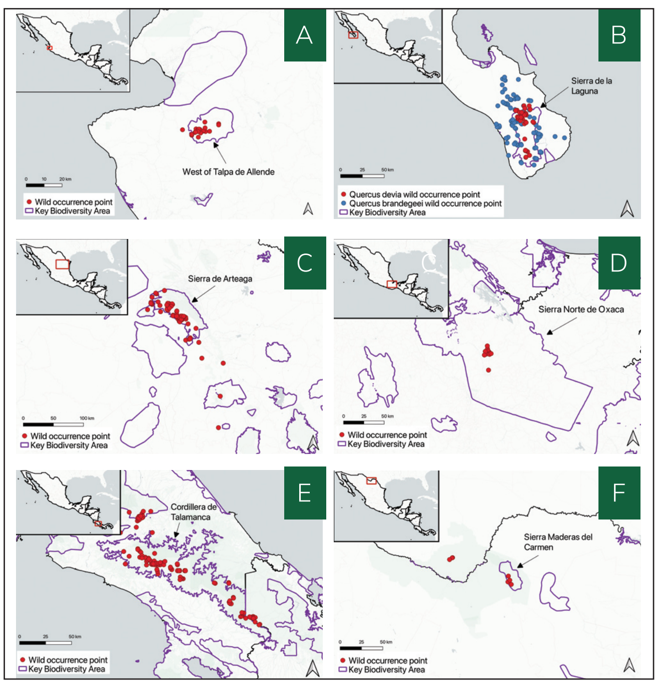


Figure 9. Wild occurrence points of A) *Quercus cualensis*, B) Q. *devia* and Q. *brandegeei*, C) Q. *hintoniorum*, D) Q. *macdougallii*, E) Q. *costaricensis*, and F) Q. *carmenensis* in relation to Key Biodiversity Areas.

An additional two species meet criteria A1b, which is a region with >1.0% of the total population size and >10 reproductive units of a Vulnerable species: Q. *costaricensis* and Q. *hintoniorum*. Over 50% of known wild occurrences of Q. *costaricensis*, a Vulnerable species, are in the Cordillera de Talamanca KBA (Figure 9E). Over 70% of Q. *hintoniorum* occurrences, another Vulnerable species, are within the Sierra de Arteaga KBA (Figure 9C).

We identified two threatened oak species that are not currently found within an existing KBA, but could potentially meet the criteria to establish a new KBA: Q. *tuitensis* and Q. *hintonii*. *Quercus tuitensis* is found in a very similar range to Q. *cualensis*. However, a majority of the known occurrences of this species are just outside of the West of Talpa de Allende KBA (Figure 10A). All known wild occurrences of Q. *hintonii* are found just to the west of an existing KBA, the Sierra de Taxco - Nevado de Toluca (Figure 10B). One key component in delineating the geographic boundaries of a KBA is that it must be manageable as a unit, and therefore boundaries need to be drawn that take into account not only ecological considerations, but socio-economic considerations as well (e.g., land tenure and political boundaries; IUCN 2016). For example, a KBA should not cut through private land. Therefore, the next step after identifying species that meet the criteria for delineating a KBA is to identify appropriate boundaries.

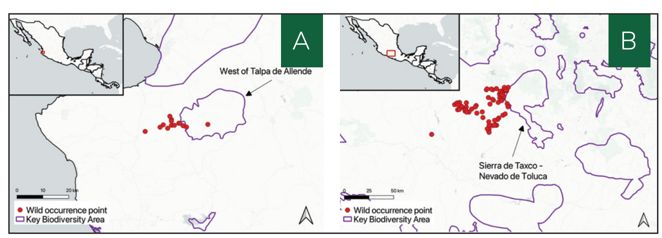


Figure 10. Wild occurrence points of A) *Quercus tuitensis* and B) Q. *hintonii* in relation to Key Biodiversity Areas.

One potential challenge to both delineating a new KBA and adding threatened oaks as trigger species to an existing KBA is the age of data used to confirm that a threshold is met. Ideally, data should be collected within the last 12 years (IUCN, 2016). Occurrence data for oaks, especially rare and under-studied species such as those in Mesoamerica, is often several decades old. Depending on the age of the data, additional survey work may be needed before a species can be considered as part of a KBA. It should also be noted that this is not an exhaustive list of species that can be used to either update or establish a new KBA. As additional survey work is completed and occurrence maps are updated, species should be mapped against existing KBAs to determine if they could potentially be used to update or delineate a new KBA.

HOLDRIDGE LIFE ZONES

Oaks inhabit most vegetation types within Mesoamerica, and many species have very specific habitat requirements. For example, *Q. acherdophylla* is restricted to humid ravines in cloud forests in the Sierra Madre Oriental at elevations 1,800–2,500 m asl (González-Espinosa et al., 2011; Jerome, 2018a). At the other extreme is *Q. dumosa*, which is found only in chaparral habitat in low hills typically near the coast. Both of these species at opposite ends of the habitat spectrum highlight the importance of elevation, temperature, and precipitation in determining where any one species of oak can survive. The Holdridge life zone classification system relies on these three parameters, as well as evapotranspiration ratio, in distinguishing local ecosystems (Figure 11). This classification system has been shown to be ideally suited for the tropics, especially alpine areas, where it was first developed (Khatun et al., 2013; Derguy et al., 2022).

We found that Holdridge life zones have the potential to be a useful tool in identifying suitable habitat for Mesoamerican oaks. Many target species showed a strong preference for one life zone: twenty-two of our target species had 75% or more of all occurrence points in a single life zone. For example, 90% of geolocated wild occurrence points for *Q. cualensis* occur within the warm temperate moist forest (Figure 12). This ecoregion is within the lower montane altitudinal belt and is characterized by an annual average precipitation of 1,000–2,000 mm, a biotemperature of 12–18°C, and a potential evapotranspiration ratio of 0.5–1. There is a large area of warm temperate moist forest within Jalisco just to the east of all known occurrences of *Q. cualensis*. Identifying where this ecoregion is found within the native range of *Q. cualensis* has the potential to direct future surveys in search of this rare and threatened species.

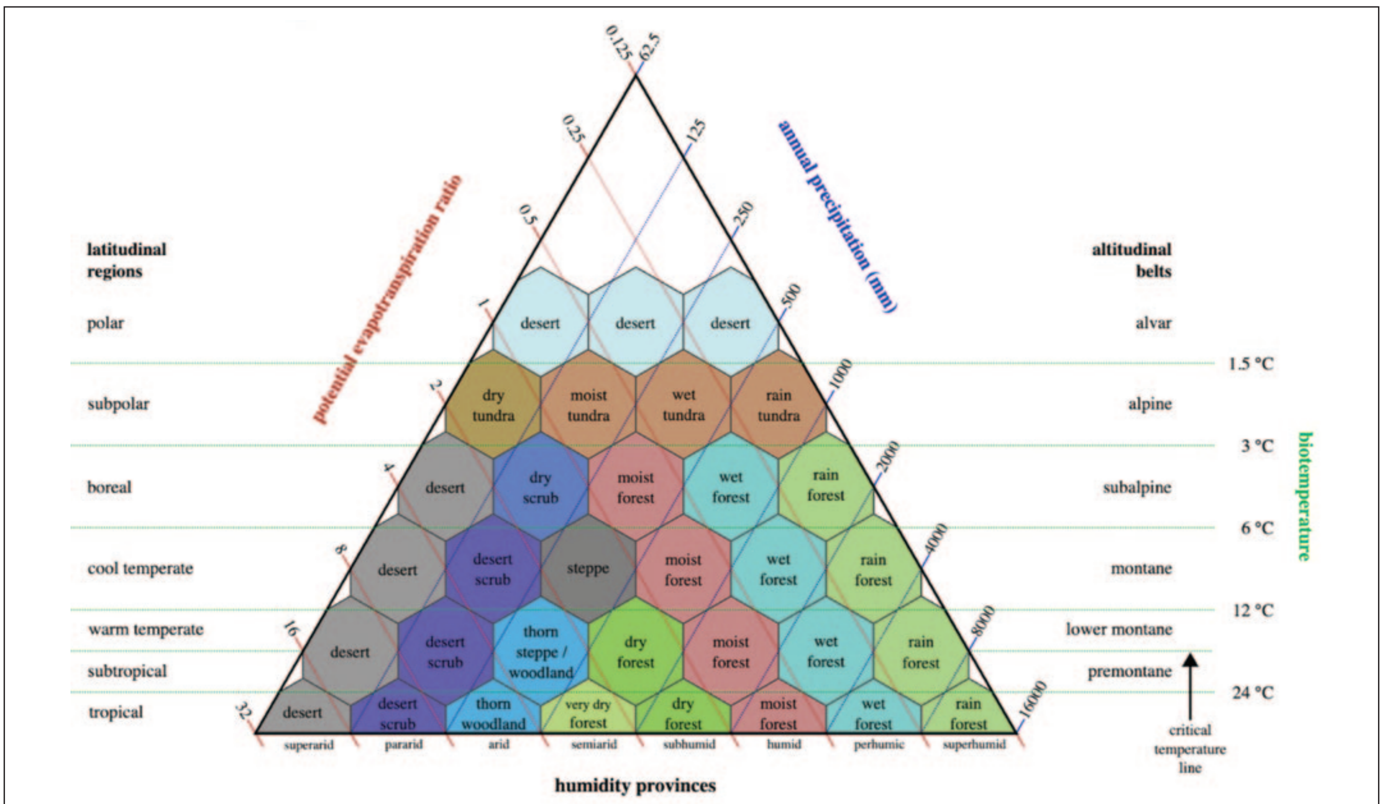


Figure 11. Holdridge life zone classification system (Holdridge, 1967). Image by Peter Halasz/ Creative Commons Attribution-Share Alike 2.5.

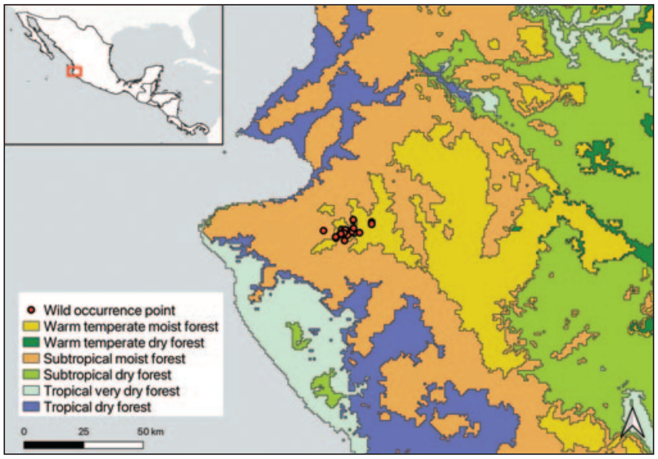


Figure 12. Wild occurrence points of *Quercus cualensis*. Colored regions are Holdridge life zones. A majority of occurrence points for *Q. cualensis* are in the warm temperate moist forest.

Within Mesoamerica, there are 34 Holdridge life zones, 21 of which contain a threatened or Data Deficient species of oak (Figure 13; Appendix D). A majority of target species (58%) occur within the warm temperate dry forest. This life zone is characterized by a biotemperature of 12–18°C, an annual precipitation of 500–1,000 mm and a potential evapotranspiration ratio of 1.0–2.0. Nine percent of Mesoamerica is covered by warm temperate dry forest, making this the sixth largest life zone within the region. The largest life zone is the subtropical moist forest, which covers 16% of Mesoamerica. This life zone is also an important ecoregion for oaks, containing 42% (25 of 59) of target species

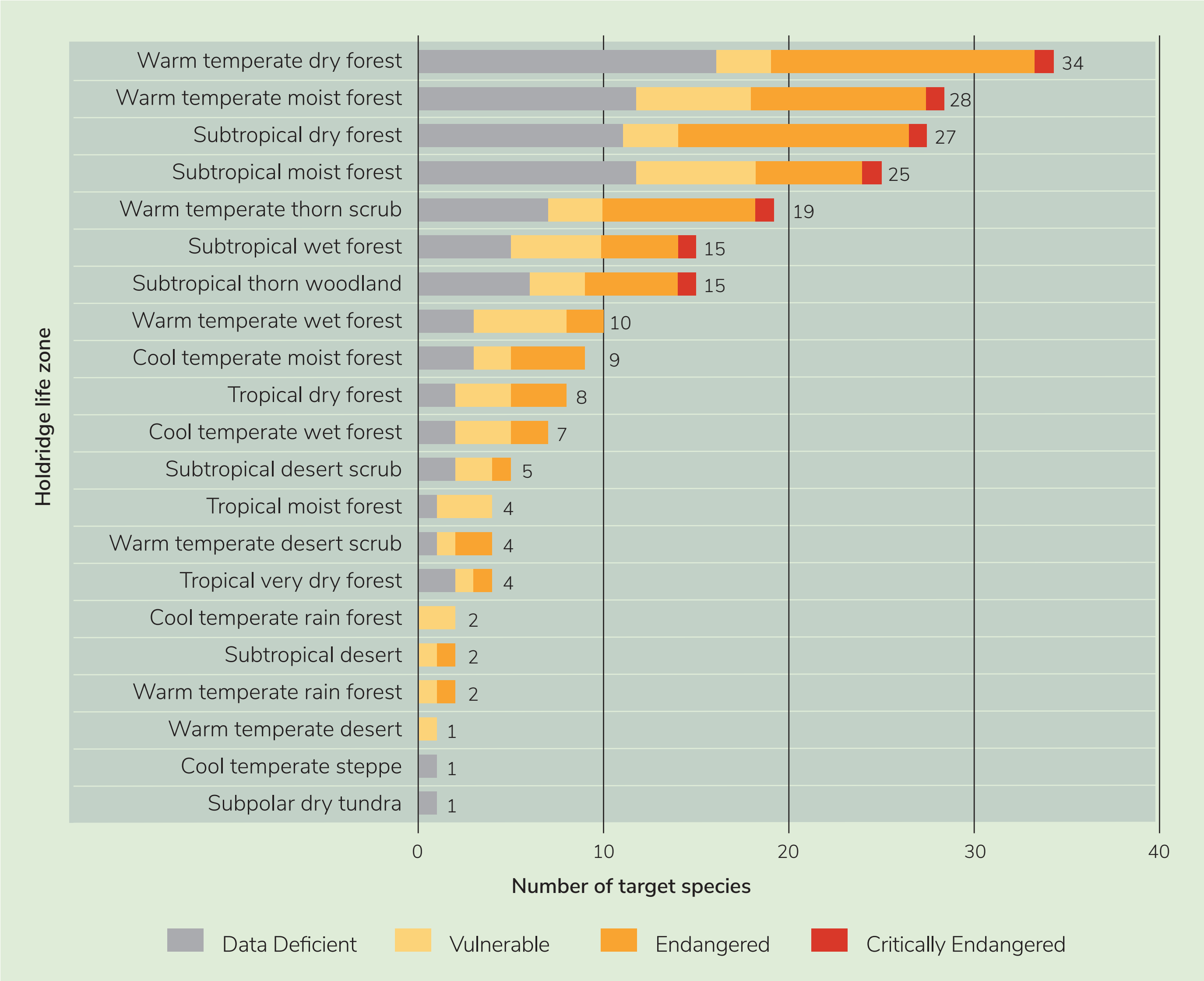


Figure 13. The number of target oak species within each Holdridge life zone in Mesoamerica, grouped by IUCN Red List category.

Quercus acutifolia (Francisco Garin)

Holdridge life zones can also be used to identify *ex situ* institutions that have the appropriate environmental conditions to cultivate oaks within Mexico and Central America. According to BGCI GardenSearch, there are 91 botanic gardens and arboreta in Mesoamerica, a majority of which are in Mexico (58), followed by Costa Rica (13), Panama (7), Honduras (5), Belize (3), Nicaragua (3), El Salvador (1), and Guatemala (1) (Figure 14; BGCI, 2023). These institutions occur within 12 Holdridge life zones, the most common being subtropical moist forest (19 institutions), and warm temperate dry forest (17 institutions; Appendix F). Both of these life zones are within the top four most common ecoregions in which our target oak species occur (Figure 13). All 59 target species inhabit a life zone in which there is also at least one botanic garden and/or arboretum, making these institutions well positioned geographically to support oaks. In general, oaks are very adaptable in cultivation and there are examples of species of oak growing in botanic gardens that come from very different life zones in the wild (Allen Coombes, personal communication, 2024). It should also be noted that the 91 botanic gardens, arboreta, and similar organizations as listed in BGCI GardenSearch are extremely diverse, and not all sites have the ability or space to add oaks to their collections. Nevertheless, we must continue to build capacity with Mesoamerican gardens that do wish to cultivate oaks in order to ensure they have the information and resources necessary to do so. Finally, GardenSearch data is primarily submitted and maintained by individual institutions. In order to be included in GardenSearch, organizations should be open to the public and have a permanent living botanical collection. Regional groups, such as La Asociación Mexicana de Jardines Botánicos (AMJB), may take a different approach to defining and identifying botanic gardens. According to AMJB, the number of official botanic gardens in Mexico is 24, with 24 additional consultant gardens (i.e., gardens in progress). Ethnobiological gardens are increasingly being developed in the region. Some of these gardens are just beginning to establish their collections and policies and their ability to be partners in oak conservation should be explored. See Appendix F for botanic gardens and arboreta used in this analysis, and their associated Holdridge life zones.

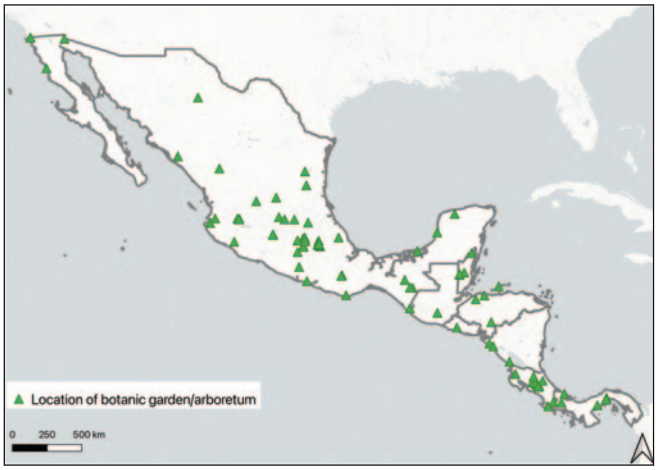


Figure 14. Location of botanic gardens and arboreta in Mesoamerica, as reported to BGCI GardenSearch as of November 2023 (BGCI, 2023).

Oak habitat in Costa Rica (The Morton Arboretum)

CASE STUDY 1:
Quercus insignis - *In situ* conservation from assessment to action

(authors: Silvia Alvarez-Clare, The Morton Arboretum; Karina Orozco, The Morton Arboretum)

Quercus insignis acorns planted in a seed bed by Osa Conservation nursery staff at Asociación Ambiental Finca Cántaros in San Vito, Costa Rica. (The Morton Arboretum)

In 2017, during the initial meeting of the Oaks of the Americas Conservation Network, which became the foundation for the current Global Conservation Consortium for Oak (GCCO; see Case Study 2), participants highlighted *Quercus insignis* as a species in decline and in need of research and conservation. Following this mandate, a team led by The Morton Arboretum set out to use the ASSESS-PLAN-ACT methodology developed by the IUCN Species Survival Commission (SSC) to create an integrated conservation plan for the species.

ASSESS: *Quercus insignis* was first assessed as Near Threatened in 2007 by the Global Tree Specialist Group (Oldfield and Eastwood, 2007). In 2018, The Red Listing team at Morton Arboretum re-assessed the species as Endangered, bringing it to the top of the list of species in need for conservation action (Jerome et al., 2018b). At the same time, a team of Mexican researchers led by H. Rodriguez-Correa (Universidad Nacional Autónoma de México, Morelia) and T. Toledo-Aceves (Instituto Nacional de Ecología, Veracruz) began research on population genetics and ecology of the species. These studies revealed that the populations of *Q. insignis* are extremely fragmented and genetic flow among populations is low (Rodríguez-Correa et al., 2017). They also revealed that the species has high restoration potential and establishes easily when transplanted *in situ* (García-Hernández et al., 2019; Toledo-Aceves et al., 2022). A Master's thesis by L.M. Naranjo Bravo (2021) highlighted Costa Rica as a priority area with high connectivity for the species.

PLAN: Armed with the assessment and biological knowledge of the species, a team led by S. Alvarez-Clare (Morton Arboretum), H. Acevedo (Agathos Natura), and R. De Sousa (Osa Conservation) outlined an integrated approach to develop a conservation management plan for *Q. insignis* for Costa Rica. This included preparing a Conservation Action Plan following participatory decision-making practices. Workshops were held to gather input from multiple stakeholders from academia, government, communities, students, and NGO's (Acevedo-Mairena et al., 2024). The Action Plan serves as a road map for species recovery.

ACT: The team launched a restoration campaign to plant more than 5,000 seedlings of *Q. insignis* first in southern Costa Rica (as part of the Ridge to Reef project led by Osa Conservation), and then in several other locations across its national range. The team created a propagation manual for the species (Orozco et al., 2023), and hosted capacity-building workshops so that local para taxonomists could learn to identify this and other rare tree species. In collaboration with Asociación Ambientalista Finca Cántaros, a local NGO focused on environmental education (among other priorities), the team also worked with a group of local women who have started their own tree nursery called "Bellota" (acorn in Spanish). Educational activities that included tree plantings with children have also been led by Cántaros.

Since 2015, the total number of *ex situ* accessions for *Q. insignis* has increased by 20%. Twenty-four gardens now hold at least one *Q. insignis* tree, including Finca Cántaros, which is an accredited Arboretum through ArbNet (arbnet.org), and holds dozens of *Q. insignis* trees. Since 2017, we have secured more than $250,000 US in grants for research and conservation work that includes *Q. insignis*. In sum, *Q. insignis* could be used as a flagship species to promote the conservation of tropical montane cloud forest, an extremely threatened ecosystem, and activate key audiences toward conserving threatened oaks.

CASE STUDY 2:
The GCCO Mexico and Central America - an innovative network to promote oak conservation in the region

(author: Maricela Rodríguez-Acosta, GCCO Coordinator Mexico and Central America)

Oak propagation nursery in Hueytamalco, Puebla, Mexico. Dr. Maricela Rodriguez and team are working with the Ejidatarios growing *Quercus paxtalensis* and *Quercus cortesii*, as well as other oaks, as part of the Franklinia project. (Cesar Flores)

The Global Conservation Consortium for Oak (GCCO) is a network dedicated to the preservation and protection of oaks worldwide, currently led by The Morton Arboretum, in partnership with Botanic Gardens Conservation International (BGCI). This Consortium is made up of scientists, conservation experts and nature enthusiasts. The GCCO works closely with governments, non-governmental organizations, and local communities to promote research, living collections curation, habitat conservation, and education about oaks. Its main objective is to address the challenges that threaten these valuable tree species, such as deforestation, climate change, pests and pathogens, and soil degradation, by implementing innovative and sustainable strategies.

The GCCO is a collaborative initiative that seeks to protect and preserve oak species and forests, recognized as key ecosystems for biodiversity and environmental health, a necessary program due to the accelerated loss of oaks in recent years. The GCCO is currently working in the oak biodiversity hotspots around the world: Mexico and Central America, China, Southeast Asia, United States of America, and Europe.

The most oak biodiverse region is Mexico and Central America with more than 160 species distributed in multiple habitats and including around 32 threatened and 27 Data Deficient species in the wild. The GCCO Coordinator in Mexico and Central America is focusing efforts on priority, threatened and data-deficient species in this region, described in The Red List of Oaks 2020 report.

The GCCO in Mexico and Central America has focused on several objectives, such as: 1) the recruitment of Consortium members throughout Mexico and Central America, with different levels of participation, 2) the training and formation of a group of qualified stewards or guardians, with the purpose of taking responsibility for the care and protection of the priority oak species, and 3) an increase in the propagation of different species of oak, for the formation of a metacollection so as to enrich the living conservation collections of Mexican botanical gardens. The work carried out so far by the GCCO has formed a strong, committed, and organized network, leading and growing oak conservation and research efforts to preserve the world's threatened oaks now and into the future.

CLIMATE CHANGE VULNERABILITY

Climate change has the potential to drastically alter both the overall area and the distribution of Holdridge life zones within Mesoamerica. Because Holdridge life zones are dependent on precipitation and temperature, any change in these two parameters will result in a new climate classification. Predictions under diverse emission scenarios suggest that Mexico will face more recurrent and intense droughts, with an overall decrease in precipitation (CMCC, 2021). This will lead to a more arid environment and a reduction in suitable habitat for the pine-oak biomes of Mexico (Rehfeldt et al., 2012; Sáenz-Romero et al., 2020). Central America as a whole is expected to become hotter and drier with more frequent extreme weather events, and globally it is considered to be the tropical region with the strongest predicted changes in climate (Giorgi, 2006; Imbach et al., 2018). Many native Mesoamerican oaks have very specific habitat requirements, and tend to occur in a small number of life zones. As such, even a subtle change in precipitation and/or temperature can have drastic impacts on a species' available habitat. In addition, the rapid rate of climate change is outpacing many species' ability to adapt or migrate to more suitable habitats. Here, we assessed a species' vulnerability to climate change by measuring the change in total area of their preferred Holdridge life zone in an overall warmer and drier climate relative to current conditions. We determined the preferred life zone for each species by identifying the life zone in which the greatest number of wild occurrence points were found (Table 5). For an example of this analysis, see results generated for *Q. dumosa* in Figure 15.

Table 5. The preferred Holdridge life zone for each target species. Preferred life zones are defined as the life zone in which the greatest number of wild occurrence points are found. Note: this does not indicate that this is the only life zone in which a species occurs. In fact, most species naturally occur in several life zones.

Life zone	Species
Subtropical dry forest	*Q. cupreata, Q. opaca, Q. perpallida, Q. porphyrogenita, Q. runcinatifolia*
Cool temperate wet forest	*Q. macdougallii*
Subtropical moist forest	*Q. acutifolia, Q. breedloveana, Q. gracilior, Q. hintonii, Q. insignis, Q. mulleri, Q. nixoniana, Q. paxtalensis, Q. rekonis, Q. tuitensis, Q. vicentensis*
Warm temperate moist forest	*Q. centenaria, Q. cualensis, Q. delgadoana, Q. ghiesbreghtii, Q. gulielmi-treleasei, Q. hirtifolia, Q. meavei, Q. melissae, Q. mexiae, Q. rubramenta, Q. toxicodendrifolia, Q. trinitatis*
Cool temperate moist forest	*Q. hintoniorum*
Subtropical thorn woodland	*Q. ajoensis, Q. brandegeei, Q. ignaciensis*
Subtropical wet forest	*Q. sarahmariae*
Warm temperate thorn scrub	*Q. carmenensis, Q. cedrosensis, Q. coahuilensis, Q. deliquescens, Q. dumosa, Q. engelmannii, Q. galeanensis, Q. graciliformis, Q. tinkhamii, Q. tomentella, Q. verde*
Warm temperate dry forest	*Q. acherodophylla, Q. aerea, Q. barrancana, Q. coffeicolor, Q. devia, Q. diversifolia, Q. flocculenta, Q. grahamii, Q. miquihuanensis, Q. radiata, Q. supranitida, Q. toumeyi, Q. undata*
Cool temperate rain forest	*Q. costaricensis*

For a majority of species (50 of 59, 85%), the area of their preferred life zone is predicted to decrease across the ensemble climate models (Figure 16). There are 26 species that showed a 50% or greater average decrease in preferred life zone area, and two species that showed a 100% average decrease: *Q. macdougallii* and *Q. hintoniorum*. For both *Q. macdougallii* and *Q. hintoniorum*, there was strong agreement between the climate models, with the percent decrease in preferred habitat area for *Q. macdougallii* ranging from -99.4% to -100% and *Q. hintoniorum* ranging from -98% to -100% across all ten models. These species may especially benefit from conservation activities that address the impact of climate change, such as assisted migration.

There were several species, notably *Q. ajoensis*, for which there was large variability across the different climate models, with some suggesting an increase in area and others a decrease (Figure 16). Under reference conditions, these species tend to exist on the edge of their preferred life zone. As a result, a small change in life zone location can cause it to shift entirely into or out of the species' inferred range. This results in either a large increase or decrease in area relative to reference conditions, depending on the model.

Our results show that oak species that prefer warm temperate ecosystems are particularly vulnerable to climate change. Out of the 26 species that showed an overall average decrease in

Quercus brandegeei (The Morton Arboretum)

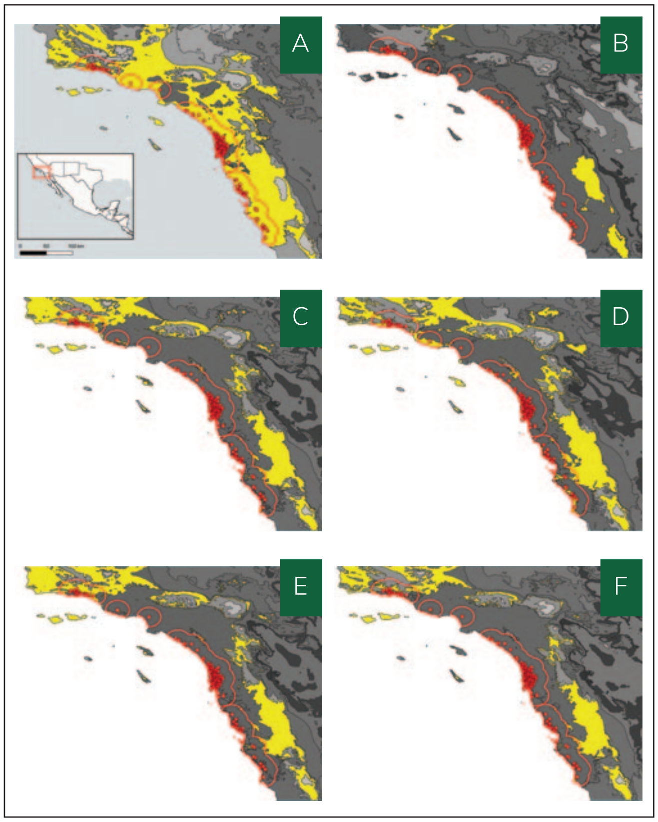


Figure 15. The distribution of *Quercus dumosa* with its preferred Holdridge life zone (warm temperate thorn scrub) highlighted in yellow under reference conditions (A) compared to conditions generated from five different climate change models: UKESM (B), MRI-ESM2 (C), MRI-ESM1 (D), MIROC-6 (E), and IPSL-CM6A-LR (F). A 20 km buffer is placed around each wild occurrence point in red to indicate the species' inferred native range.

50% or more of their preferred life zone area, the most common preferred life zones were the warm temperate thorn scrub (10 species, 38%) and warm temperate moist forest (10 species, 38%). This is in agreement with a study by Villers-Ruiz and Trejo-Vázquez (1997), who showed that the life zones most affected by climate change in Mexico are the cool and warm temperate forests, which would be significantly reduced in area or even disappear entirely. Historically, the Neotropical region of Mexico, where warm temperate moist forest is concentrated, has experienced a pronounced decline in overall precipitation (Cuervo-Robayo et al., 2020). Warm temperate moist forest and subtropical moist forest are typically associated with montane cloud forest. This habitat is preferred by many Mesoamerican oak species and is especially vulnerable to climate change. It is estimated that by 2080, 68% of cloud forest habitat in Mexico may vanish (Ponce-Reyes et al., 2012).

Figure 16. The mean percentage change in total area of the preferred Holdridge life zone for each target species under the ten climate change models, relative to reference conditions. Green bars represent an increase in overall area, and orange bars represent a decrease. Error bars are +/- 2 SE. Note change in scale of Y-axis.

CASE STUDY 3:
Quercus agrifolia: a culturally significant oak in Baja California

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Quercus agrifolia riparian corridor (Jesús Serrano)

Quercus agrifolia, commonly known as Coast Oak, California Oak or Perennial Coastal Oak is a characteristic evergreen mesophyllous tree native to California of mesic habitats. Its regional distribution occurs in an elongated strip adjacent to the Pacific coast, stretching from the western Sierra Nevada in Mendocino County, California, to the north of Baja California. In Baja California, it is found primarily in coastal regions, riparian zones, and mountain slopes mainly at elevations of 30 to 700 meters above sea level, although at the regional level there are reports of occasional occurrence up to 1,500 meters above sea level.

Quercus agrifolia prefers Mediterranean climates with dry summers, humid winters and well-developed, drained soils. Its distribution is influenced by soil moisture and the availability of water. As a result, it can be found associated with chaparral in its tree form, or in shrub form in its coastal habitat. In oak forests it is co-dominant with other oak species, with which it can form hybrids (*Q. engelmannii, Q, lobata, Q. dumosa, Q. parvula* var *shrevei*), and shrubs. In riparian zones it is common occurrence in co-dominance with other tree species such as sycamores (*Platanus racemosa*), alders (*Alnus rhombifolia* and *A. rubra*) and alamillo (*Populus fremontii*), as well as with other *Quercus* species.

Quercus agrifolia forests, riparian or hillside, form cool microclimates that favor the development of other plant species with greater humidity requirements. They retain water in the subsoil and promote a balanced ecological system, which in various places contrasts with the lower and drier vegetation of the surroundings. Consequently, its forest aggregates provide shelter and food for a variety of animals, including insects (ants, various pollinators), birds (woodpeckers acorns, charas, birds of prey, etc.), mammals (squirrels, foxes, wild cats, etc.) and reptiles (lizards, snakes).

In addition to its ecological value, it has great cultural-ancestral value for various groups native to the region of California and northern Baja California, and it has been appreciated historically for its various traditional uses: a) the acorn was the basis of food of various native groups, an example is the current use of the Kumiai communities of Ensenada that preserve the tradition of making a paste known as Atole de Bellota, the same one they use as a seasoning for their food; b) various parts of the oak (leaves, bark, root) have been used for medicinal uses. Currently the Kumiai communities from Ensenada use the bark as an oral antiseptic and the leaves as teas against intestinal or respiratory discomfort; and c) it has been used ancestrally as material for construction, as well as to make crafts and utensils. There are records that the Ancestral Kumiai indigenous people set up camps in the oak forests, due to the great variety of resources that it offered them for their survival. *Quercus agrifolia* had a spiritual and symbolic meaning, which is why they were used in ceremonies, rituals, and festivals. Currently, the distribution of *Q. agrifolia* forests puts the species at risk from several threats because the main cities of Baja California are located in the northern part of its range. Urban expansion and agriculture have negatively affected their habitat and occurrence. Among the challenges are the felling of oaks to be used as firewood, the extraction of the so-called oak land for gardening, deforestation for the construction of housing areas, forest fires caused by irregular urban settlements and burning of garbage, the dumping of wastewater into the main streams of urban centers, the development of streets and highways, among others.

This species is vital for the biodiversity and health of ecosystems in the region. It represents a cultural heritage and spiritual symbolism for the native communities. In urban centers it offers ecosystem services of cool microclimates in the face of climate change (up to 15°C cooler in the oak forest than in the adjacent urban area), promotes the conservation of aquifers, provides places of recreation, and reduces urban stress. They are also ideal places for environmental education. Its preservation is vital to maintain its rich history and its contribution to culture and regional biodiversity. The collaboration between scientists, local communities and conservation organizations is essential to ensure the long-term survival of this emblematic species.

Quercus agrifolia at Cañón Doña Petra (Isabel Raymundo)

THREATS

Through literature review and interviews with species experts, we identified the current threats facing all 32 species assessed on the IUCN Red List as Critically Endangered, Endangered, or Vulnerable (Table 6). We did not assess the degree of threat for each species, but rather identified if a threat was present, not present, or unknown. The IUCN recommends that for each threat, the timing, scope, and severity should be analyzed (IUCN Threats Classification Scheme, Version 3.3). For example, the scope of a threat can be categorized into one of four groups: 1) affects the whole population (>90%), 2) affects the majority of the population (50–90%), 3) affects the minority of the population (<50%), or 4) unknown. For a majority of our target oak species in Mesoamerica, the scope, timing, and severity are oftentimes unknown. More work is needed to fully assess the degree of threat for each species.

The most common threat identified was climate change, which was reported to impact all 32 threatened species at some level. These results are similar to those found in the gap analysis of native U.S. oaks, where climate change was identified as a threat for all oaks of concern in the United States (Beckman et al., 2019). We found that the preferred life zone area for a vast majority of threatened Mesoamerican oaks is expected to decrease as a result of climate change (Figure 16). Climate change is expected to widely impact oaks in Mexico, in some cases decreasing suitable habitat by up to 48% by the year 2050 (Gómez-Mendoza and Arriaga, 2007).

The second most common threat was human use of landscape (agriculture, silviculture, ranching and/or grazing), which was identified as threatening 72% (23 of 32) of species. According to the Red List of Oaks, agriculture is the most common threat to oaks both globally as well as in Mexico and Central America (Carrero et al., 2020). Between 2001 and 2018, Mexico lost nearly 42,785 hectares of primary forest per year to agriculture, and 157,528 hectares per year for cattle grazing (CONAFOR, 2020). This threat is only expected to increase in the future; in Mexico, agricultural production is estimated to grow by 28% by the year 2030 (Santini et al., 2023). More recently, avocado production has emerged as a pressing threat, especially in the Mexican state of Michoacán, which has experienced large-scale deforestation in the oak-pine forests. Deforestation is concentrated along the Pacific coast in the Sierra Costa region as well as the central part of the state, two areas of high biodiversity. In fact, a recent study found that one fourth of all avocado plantations in Michoacán are within KBAs (Cho et al., 2021; Denvir et al., 2022). Similar trends in land conversion can be found in Central America, which has converted a greater percentage of its forests for agriculture than any other major region within the last few decades (Carr et al., 2006).

Human use of landscape (residential/commercial development, mining, roads; 22 of 32 species) and extremely small/restricted populations (21 of 32 species) were also commonly identified as threats. Many Mesoamerican oaks have small populations with restricted or fragmented distributions. We found that 73% of our target species have an Extent of Occurrence (EOO) less than 20,000 km^2, which is the threshold set by the IUCN to consider a species vulnerable to extinction. For several species, these small populations are located near major cities (e.g., *Q. flocculenta* near Monterrey) or are in prime residential areas undergoing rapid development (e.g., *Q. dumosa* in coastal Baja California).

The threat with the greatest level of uncertainty is pests and pathogens: for 22 species this threat was listed as "unknown". There is a lack of data and research focused on the impact of pests and pathogens on Mesoamerican oaks. This is similar to the results of the gap analysis of U.S. oaks, which found that pests and/or pathogens were listed as a threat for very few species (Beckman et al., 2019). This was attributed to a lack of data on current and future impacts caused by disease and pests. Within the past several decades, increased mortality of oaks within Mexican montane forests has been observed, with symptoms including bleeding trunk cankers, crown dieback, and decline (Davidson et al., 2003). In 1987 there was a severe outbreak of oak mortality in the state of Colima, Mexico, which spread to impact an area over 300 ha by 1997. The root pathogen *Phytophthora cinnamomi* was identified as the main cause of mortality here (Tainter et al., 2000). In the early 2000s, oak decline and death in five Mexican states (Aguascalientes, Colima, Guanajuato, Jalisco, and Nayarit) was determined to be primarily caused by infestation of *P. cinnamomi* and *Hypoxylon atropunctatum* (Alvarado-Rosales et al., 2007). This threat is expected to become more common in the future, since climate change favors the appearance of disease outbreaks caused by pests and pathogens. An increase in temperature and changing precipitation patterns have already been shown to cause forest decline and an increase in proliferation of *Phytophthora* sp. in forest ecosystems (Contreras-Cornejo et al., 2023).

Table 6. Threats identified for each target species assessed as Critically Endangered, Endangered, or Vulnerable.

	Wild harvesting	Agriculture, silviculture, ranching, grazing	Residential/commercial development, mining, roads	Tourism/recreation	Fire regime modification, pollution, eradication	Invasive species competition/disturbance	Climate change	Genetic material loss	Pests/pathogens	Extremely small/restricted population
Q. acutifolia	Known threat	Known threat	Known threat	Known threat	Known threat	Unknown threat	Known threat	Known threat	Unknown threat	Not currently a threat
Q. ajoensis	Unknown threat	Known threat	Not currently a threat	Known threat	Known threat	Unknown threat	Known threat	Known threat	Unknown threat	Known threat
Q. brandegeei	Known threat	Known threat	Known threat	Known threat	Known threat	Known threat	Known threat	Known threat	Not currently a threat	Known threat
Q. carmenensis	Not currently a threat	Unknown threat	Not currently a threat	Not currently a threat	Not currently a threat	Not currently a threat	Known threat	Known threat	Not currently a threat	Known threat
Q. cedrosensis	Not currently a threat	Not currently a threat	Known threat	Known threat	Known threat	Known threat	Known threat	Unknown threat	Known threat	Unknown threat
Q. costaricensis	Not currently a threat	Not currently a threat	Not currently a threat	Not currently a threat	Known threat	Known threat	Known threat	Unknown threat	Known threat	Not currently a threat
Q. cualensis	Unknown threat	Known threat	Known threat	Known threat	Known threat	Unknown threat	Known threat	Unknown threat	Unknown threat	Known threat
Q. cupreata	Not currently a threat	Known threat	Known threat	Known threat	Known threat	Known threat	Known threat	Unknown threat	Unknown threat	Known threat
Q. delgadoana	Unknown threat	Known threat	Known threat	Unknown threat	Unknown threat	Not currently a threat	Known threat	Unknown threat	Unknown threat	Known threat
Q. devia	Not currently a threat	Known threat	Known threat	Known threat	Known threat	Unknown threat	Known threat	Unknown threat	Unknown threat	Known threat
Q. diversifolia	Known threat	Unknown threat	Known threat	Unknown threat	Unknown threat	Unknown threat	Known threat	Unknown threat	Unknown threat	Unknown threat
Q. dumosa	Known threat	Not currently a threat	Known threat	Not currently a threat	Known threat	Not currently a threat	Known threat	Not currently a threat	Unknown threat	Known threat
Q. engelmannii	Unknown threat	Known threat	Known threat	Unknown threat	Known threat	Known threat	Known threat	Not currently a threat	Known threat	Unknown threat
Q. flocculenta	Unknown threat	Known threat	Known threat	Not currently a threat	Known threat	Unknown threat	Known threat	Unknown threat	Unknown threat	Known threat
Q. galeanensis	Not currently a threat	Known threat	Known threat	Not currently a threat	Known threat	Known threat	Known threat	Not currently a threat	Unknown threat	Known threat
Q. graciliformis	Unknown threat	Not currently a threat	Not currently a threat	Known threat	Not currently a threat	Not currently a threat	Known threat	Not currently a threat	Unknown threat	Known threat
Q. gulielmi-treleasei	Known threat	Known threat	Not currently a threat	Known threat	Unknown threat	Not currently a threat	Known threat	Unknown threat	Unknown threat	Unknown threat
Q. hintonii	Known threat	Known threat	Known threat	Unknown threat	Not currently a threat	Unknown threat	Known threat	Unknown threat	Known threat	Not currently a threat
Q. hintoniorum	Not currently a threat	Not currently a threat	Not currently a threat	Not currently a threat	Known threat	Not currently a threat	Known threat	Not currently a threat	Not currently a threat	Unknown threat
Q. hirtifolia	Known threat	Known threat	Known threat	Known threat	Unknown threat	Known threat	Known threat	Known threat	Unknown threat	Known threat
Q. insignis	Known threat	Known threat	Known threat	Known threat	Known threat	Known threat	Known threat	Not currently a threat	Unknown threat	Known threat
Q. macdougallii	Unknown threat	Known threat	Known threat	Known threat	Known threat	Unknown threat	Known threat	Known threat	Known threat	Known threat
Q. meavei	Known threat	Known threat	Known threat	Not currently a threat	Unknown threat	Unknown threat	Known threat	Not currently a threat	Unknown threat	Known threat
Q. miquihuanensis	Unknown threat	Known threat	Known threat	Known threat	Not currently a threat	Unknown threat	Known threat	Unknown threat	Unknown threat	Known threat
Q. mulleri	Known threat	Known threat	Unknown threat	Unknown threat	Unknown threat	Known threat	Known threat	Known threat	Unknown threat	Known threat
Q. nixoniana	Known threat	Known threat	Known threat	Unknown threat	Known threat	Unknown threat	Known threat	Known threat	Unknown threat	Known threat
Q. radiata	Known threat	Not currently a threat	Known threat	Not currently a threat	Not currently a threat	Not currently a threat	Known threat	Not currently a threat	Not currently a threat	Not currently a threat
Q. rubramenta	Known threat	Known threat	Unknown threat	Not currently a threat	Known threat	Known threat	Known threat	Known threat	Unknown threat	Unknown threat
Q. runcinatifolia	Unknown threat	Known threat	Known threat	Known threat	Not currently a threat	Known threat	Known threat	Known threat	Known threat	Known threat
Q. tomentella	Not currently a threat	Not currently a threat	Not currently a threat	Not currently a threat	Known threat	Not currently a threat	Known threat	Known threat	Unknown threat	Known threat
Q. tuitensis	Unknown threat	Known threat	Known threat	Known threat	Known threat	Unknown threat	Known threat	Unknown threat	Unknown threat	Known threat
Q. vicentensis	Unknown threat	Known threat	Not currently a threat	Known threat	Not currently a threat	Unknown threat	Known threat	Unknown threat	Unknown threat	Not currently a threat

Known threat | Not currently a threat | Unknown threat

CONSERVATION ACTIVITIES

For each threatened species, we performed a literature review and interviewed species' experts to identify current conservation activities (Table 7). Data Deficient species were excluded because in general no conservation work is being done for this group. The most common activity was wild collection and/or *ex situ* curation, with 84% (27 of 32) of threatened species reporting this activity. Land protection was reported for 38% of species. Protecting a species in its native habitat is typically considered the ideal method for which to prevent species extinction and maintain the genetic diversity of a population, and is ultimately the long-term goal (Potter et al., 2017). *In situ* conservation activities include the establishment and maintenance of protected areas, sustainable land management, reforestation, and restoration. Conservation in Mexico relies heavily on the development of protected areas. Despite their conservation value, these areas often face several challenges, including deforestation, fragmentation, wildfires, and agriculture. A study investigating the effectiveness of protected areas in Mexico found just over 54% of natural protected areas are effective in preventing land use change, whereas 23% were weakly effective and 25% non-effective (Figueroa and Sánchez-Cordero, 2008). In light of these challenges, the value of high quality living collections as a complement to *in situ* conservation is widely recognized (Cavender et al., 2015). Through tools such as BGCI's PlantSearch, information on the number of living collections per species is readily available. It is possible that conservation activities other than *ex situ* collections such as population monitoring and occurrence surveys do not occur less frequently, but are simply less likely to be reported.

The second most common conservation activity was research, which was reported for 66% of threatened species. Rather than arbitrarily establish a requirement for the topic and number of studies necessary for research to be considered a conservation activity, we decided to take a broad approach and count research as an activity if there is even one published paper in which the species is a subject. Therefore, this conservation activity is likely an overestimate. Research on topics such as genetics, ecology, threats, and population trends are oftentimes lacking.

The least common conservation activity reported was species protection policies, which are currently in place for only two species: *Q. vicentensis* and *Q. macdougallii*. In El Salvador, *Q. vicentensis* is on the Ministry of Environment and Natural Resources (MARN) Official List of Wildlife Species that are endangered or at risk of extinction under the threatened category. *Quercus macdougallii* is the only endemic Mexican oak that is listed as threatened in the Mexican Federal List of Endangered Species (NOM-59). Work is also underway to develop the State Standard Proposal for the Protection of Native Plants in Baja California, which would offer protection of oaks at the state level. This proposal is a collaboration between the Secretaría de Medio Ambiente y Desarrollo Sustentable de Baja California, the San Diego Museum of Natural History, Terra Peninsular, the San Diego Zoo Wildlife Alliance, and Baja Rare Plants Project (Mariana Delgado Fernandez, personal communication, 2024). If successful, this plan has the potential to be replicated throughout Mexico to offer even more species of oak legal protection.

Reintroduction, reinforcement, and/or translocation as well as education, training, and/or outreach were also less frequently reported. This is likely due to the fact that in order for these activities to occur, several different conservation actions need to take place first. For example, for a successful reintroduction program, occurrence surveys must be conducted, permits obtained, propagation protocols developed, and land secured. As expected, a vast majority of species that listed reintroduction, reinforcement, and/or translocation as a conservation activity also reported population monitoring/occurrence surveys as well as propagation and/or breeding programs as being performed for the species.

The two species with the most comprehensive conservation are *Q. tomentella* and *Q. insignis*. These are the only threatened species for which eight out of nine conservation activities were recorded. There is a very active conservation group, Conservación de Islas, that works with *Q. tomentella* on Guadalupe Island. Each of the 50 known adults on the island are closely monitored, there are active reintroduction and education campaigns, and it is propagated in a local nursery. *Quercus insignis* is a wide ranging species that occurs in southern Mexico, Guatemala, Belize, Honduras, Nicaragua, Costa Rica, and western Panama. This species is the focus of a variety of conservation activities, especially in Costa Rica, where it is used as a flagship species to promote the conservation of the extremely biodiverse but also highly threatened montane cloud forest habitat. A multidisciplinary group of stakeholders, including conservation organizations, local scientists, researchers, as well as botanic gardens and arboreta are actively involved in the conservation of *Q. insignis*. It is currently held in 24 *ex situ* collections, making it one of the more common Mesoamerican species held in collections worldwide. This species also highlights the importance of field surveys. Since 2015 there has been an effort to validate old occurrence points and survey for new populations. Of the 251 occurrence points that have a collection or observation date, 20% have been added since 2015.

For this species, a comprehensive action plan is also being published for Costa Rica (Acevedo-Mairena et al., in prep). See Case Study 1 (page 31) for more information on the conservation activities focused on this species. *Quercus engelmannii* and *Q. brandegeei* are also among the top species with the greatest variety of conservation activities. Each of these species are in *ex situ* collections, have been reintroduced to the wild, are the focus of successful education campaigns, and there are ongoing research projects involving a variety of stakeholders for each.

There are seven species where two or fewer conservation activities were reported: *Q. cupreata*, *Q. diversifolia*, *Q. flocculenta*, *Q. gulielmi-treleasei*, *Q. mulleri*, *Q. nixoniana*, and *Q. runcinatifolia*. For *Q. nixoniana* and *Q. mulleri*, the only conservation activities are sustainable management of land and research. For both of these species, the research that does exist is not extensive, and consists of a small number of published papers (see Species Profiles for research details, Appendix G). In addition, the sustainable management of land only applies to a small portion of their range, and it is unclear if it has any effect on oak habitat. It could therefore be argued that due to the limited scope of research and land management, it is more appropriate to consider there to be no conservation for these species. In the absence of targeted recovery actions, their current outlook is dire.

We also asked each species' expert what they consider to be the highest priorities for future conservation action. In several cases, priority conservation activities were identified that are already occurring for a species. This indicates that additional effort in this category is needed in order to ensure the health of the species. For some species a single conservation activity was selected, and for others multiple activities were determined to be a priority. In each instance, the number of priorities was left up to the discretion of the species' expert. Ideally, many different conservation activities, both *in situ* and *ex situ*, would be undertaken simultaneously for each threatened species. However, in the face of limited time and resources, it is useful to prioritize the activities that have the highest potential for impact.

There were three conservation activities that were most commonly considered a priority for the future: 1) research, 2) propagation and/or breeding programs, and 3) education, outreach, or training. Research topics that were commonly mentioned include reproductive biology, demographic studies, population genetics, and taxonomy/phylogenetics. There is still a considerable amount of taxonomic uncertainty between closely related species of oak. This is especially true for Mexican shrub oaks, which often receive less attention than other growth forms and basic taxonomic questions are unresolved (De Luna-Bonilla et al., 2024). Widespread species that are found within several different habitat types also warrant further investigation, as recent studies suggest these species may need to be broken up and may potentially include endemics that are not currently known (McCauley et al., 2019; Morales-Saldaña et al., 2021). For some species, such as *Q. ajoensis*, research to verify the taxonomic identity of the species in Mexico should be undertaken before further conservation efforts take place.

Propagation and/or breeding programs were typically mentioned in tandem with reintroduction or reinforcement. This is expected, since a successful propagation program is necessary to support reintroduction efforts, especially when seed is not readily available in the species' native habitat. Reintroduction and reinforcement are typically prioritized in cases were wild populations are small or fragmented (e.g., *Q. mulleri*), regeneration in the wild is unsuccessful (e.g., *Q. brandegeei*), or populations have been diminished from threats such as agriculture or grazing (e.g., *Q. delgadoana*; Beckman et al., 2019). The need to consider assisted migration as a priority was also mentioned for species such as *Q. macdougallii*, *Q. rubramenta*, and *Q. delgadoana*. Assisted migration is the human induced movement of species to sites where their preferred habitat is projected to exist in the future (typically at higher altitude and toward the poles of each hemisphere) as a result of climate change (Sáenz-Romero et al., 2020). This would require collection of acorns in the wild, propagation of seedlings, climate modeling to determine the timing and location of movement, and finally translocation of the seedlings. Assisted migration field tests have been recently performed in Mexico for *Q. insignis* (Toledo-Aceves et al., 2023), *Q. germana*, and *Q. sartorii* (Toledo-Aceves and del-Val, 2021). All three species showed high survival rates after four years when transplanted at elevations above their typical range.

Education, outreach, and training were also listed as top conservation priorities. Threatened Mesoamerican oaks are often found on privately owned land and ejidos. It is common practice within Mexico to use oaks as firewood and charcoal. Outreach to landowners and community members on the conservation value of the oaks on their property as well as sustainable land management could play a critical role in the preservation of these species. Several of our target species are also known to occur on indigenous reserves. For example, some populations of *Q. radiata* are on O'dam (Southeastern Tepehuan), Audam (Southwestern Tepehuan) and Wixárika (Huichol) land (M. Socorro González Elizondo, personal communication, 2023). Indigenous people play a crucial role in equitable and effective conservation, and outreach to these communities should be a top priority.

Table 7. Current conservation activities identified for each target species assessed as Critically Endangered, Endangered, or Vulnerable. A ● indicates activties considered a priority. Note: land protection is a conservation activtiy if at least 30% of a species' inferred native range is protected.

	Land protection	Sustainable management of land	Population monitoring and/or occurrence surveys	Wild collecting and/or ex situ curation	Propogation and/or breeding programs	Reintroduction, reinforcement, and/or translocation	Research	Education, outreach, and/or training	Species protection policies
Q. acutifolia	Orange	Green	Orange	Green	Orange ●	Orange	Green	Orange ●	Orange
Q. ajoensis	Green	Green	Green ●	Green	Green ●	Orange	Orange	Orange	Orange
Q. brandegeei	Orange	Green	Green ●	Green	Green	Green ●	Green ●	Green ●	Orange
Q. carmenensis	Green	Green	Orange ●	Green	Orange ●	Orange	Orange	Orange	Orange
Q. cedrosensis	Green	Green	Green	Green	Green	Orange	Green	Orange	Orange
Q. costaricensis	Green	Green	Orange ●	Green	Green ●	Green ●	Green	Gray	Orange
Q. cualensis	Orange ●	Gray	Orange	Green ●	Green	Orange	Green	Green	Orange
Q. cupreata	Orange	Green	Orange ●	Green	Orange ●	Orange	Orange ●	Orange ●	Orange
Q. delgadoana	Orange ●	Orange	Green	Green	Green ●	Green ●	Green	Green	Orange
Q. devia	Green	Green	Orange	Orange	Orange	Orange	Green ●	Orange	Orange ●
Q. diversifolia	Orange	Orange	Orange	Green	Orange	Orange	Orange ●	Orange	Orange
Q. dumosa	Orange	Gray	Green	Green ●	Green	Green	Green	Green ●	Orange
Q. engelmannii	Orange ●	Green	Green ●	Green	Green	Green	Green	Green	Orange
Q. flocculenta	Orange	Orange	Green	Green	Gray	Gray	Orange	Gray ●	Orange ●
Q. galeanensis	Orange	Green	Green ●	Green	Orange	Orange	Orange ●	Orange	Orange
Q. graciliformis	Green	Green	Green ●	Green	Green	Orange	Green	Gray	Orange
Q. gulielmi-treleasei	Orange ●	Green ●	Orange	Green	Orange	Orange	Orange ●	Orange ●	Orange
Q. hintonii	Green	Green	Orange ●	Green	Orange ●	Orange	Green ●	Green ●	Orange
Q. hintoniorum	Green	Orange	Green ●	Green ●	Orange	Orange ●	Orange	Orange	Orange
Q. hirtifolia	Orange ●	Orange	Green	Green ●	Green ●	Green ●	Green	Green	Orange
Q. insignis	Green ●	Green	Green	Green	Green	Green ●	Green	Green ●	Orange
Q. macdougallii	Orange ●	Gray	Green	Green	Gray ●	Green ●	Green	Green ●	Green
Q. meavei	Orange ●	Gray	Green	Green ●	Green	Green ●	Green	Green	Orange
Q. miquihuanensis	Orange	Gray	Gray	Green ●	Green	Gray	Green	Green ●	Orange
Q. mulleri	Orange ●	Green	Gray	Orange	Gray	Gray	Green ●	Orange ●	Orange
Q. nixoniana	Orange ●	Green	Orange	Orange	Orange	Orange	Green ●	Orange ●	Orange
Q. radiata	Green	Green	Green	Orange	Orange	Orange	Orange ●	Orange ●	Orange
Q. rubramenta	Orange ●	Gray	Green	Green	Green ●	Green ●	Green ●	Green ●	Orange
Q. runcinatifolia	Green	Orange	Orange ●	Green	Orange ●	Orange	Orange ●	Orange	Orange
Q. tomentella	Green	Green	Green	Green ●	Green ●	Green	Green	Green	Orange
Q. tuitensis	Orange ●	Orange	Gray	Orange ●	Green	Orange	Green	Green	Orange
Q. vicentensis	Orange	Gray	Green ●	Green	Orange ●	Gray ●	Orange ●	Gray	Green

Green: Past or present conservation activity | Orange: Not a conservation activtiy | Gray: Unknown

CONSERVATION ACTION SCORE

For each target species, we calculated a Conservation Action Score to prioritize species for *ex situ* and *in situ* conservation efforts by modifying the methods outlined in Khoury et al. (2020). Final scores ranged from 0–100, with scores near 100 indicating comprehensive *in situ* and *ex situ* conservation, and scores near 0 indicating poor conservation. Prioritization in the context of this gap analysis should not be interpreted as an overly prescriptive tool, but rather as a guide. We encourage GCCO members, botanic gardens, and academics to prioritize research and conservation action for any rare or threatened oak occurring in your region.

There were 19 species that had a final Conservation Action Score of <25, flagging them as urgent priority (Figure 17). These 19 species are not associated with one particular geographic region, but rather occur in a variety of ecoregions throughout Mexico and into Guatemala. There were three species that received a score of zero: *Q. ignaciensis*, *Q. tuitensis*, and *Q. aerea*. *Quercus tuitensis* is endemic to Jalisco, Mexico with an Extent of Occurrence (EOO) of 62 km^2. This species is assessed as Vulnerable, it is not held in any *ex situ* collections, and 0% of its range falls within protected areas. It should be considered a high priority for both *ex situ* collection and establishment in protected areas. *Quercus aerea* and *Q. ignaciensis* are both assessed as Data Deficient, and like the aforementioned species are not held in *ex situ* collections and their native range is not protected. These species should be prioritized for additional research and survey work to better understand population distribution, size, trends, and threats.

The Conservation Action Score could also be used to prioritize species for conservation among the 22 target species that are currently not held in any *ex situ* collections. The survey work, wild collecting, propagation, and coordination with local gardens required to close this gap will take a significant amount of time, resources, and effort. We suggest that the focus should first be on those 22 species that have little to none of their native range covered by protected areas. There are 16 species with less than 10% of their range protected, and eight of those are currently not held in any *ex situ* collections, or do not have wild provenance individuals in collections: *Q. ignaciensis, Q. tuitensis, Q. aerea, Q. melissae, Q. rubramenta, Q. verde, Q. ghiesbreghtii*, and *Q. macdougallii*. *Quercus macdougallii* should especially be a priority for *ex situ* conservation, as this species is predicted to lose 100% of its preferred habitat by the year 2061–2080 as a result of climate change (Figure 16).

Eleven species received a conservation action score of 50 or higher. *Quercus carmenensis* scored the highest at 76. It should be stressed that a species receiving a relatively high final score does not indicate that it is safe from extinction and does not require conservation action. Although the native range of these species may be relatively well-protected and they may be represented in *ex situ* collections, they are still assessed on the IUCN Red List as threatened. Rather than additional habitat protected or *ex situ* collection efforts, these species may benefit more from conservation activities such as population reinforcement, habitat restoration, or education. For example, *Q. brandegeei* has a conservation action score of 66, making it the 5th highest scoring species. This species is currently held in 10 *ex situ* collections, and many known occurrence points are within the Sierra la Laguna Biosphere Reserve. However, predation of acorns by pigs, trampling and herbivory by domestic animals from ranches within the reserve, and climate change have resulted in lack of regeneration for this species (Cavender-Bares et al., 2015; Denvir and Westwood, 2016; Denvir et al., 2019). In this case, active restoration and enrichment plantings in collaboration with the San Dionisio community have been crucial for reversing the decline of this charismatic oak (Alvarez-Clare et al., in prep.; Morton Arboretum, 2023). To find out more about this project visit mortonarb.org/arroyo.

Quercus macdougallii (Nelly Pacheco)

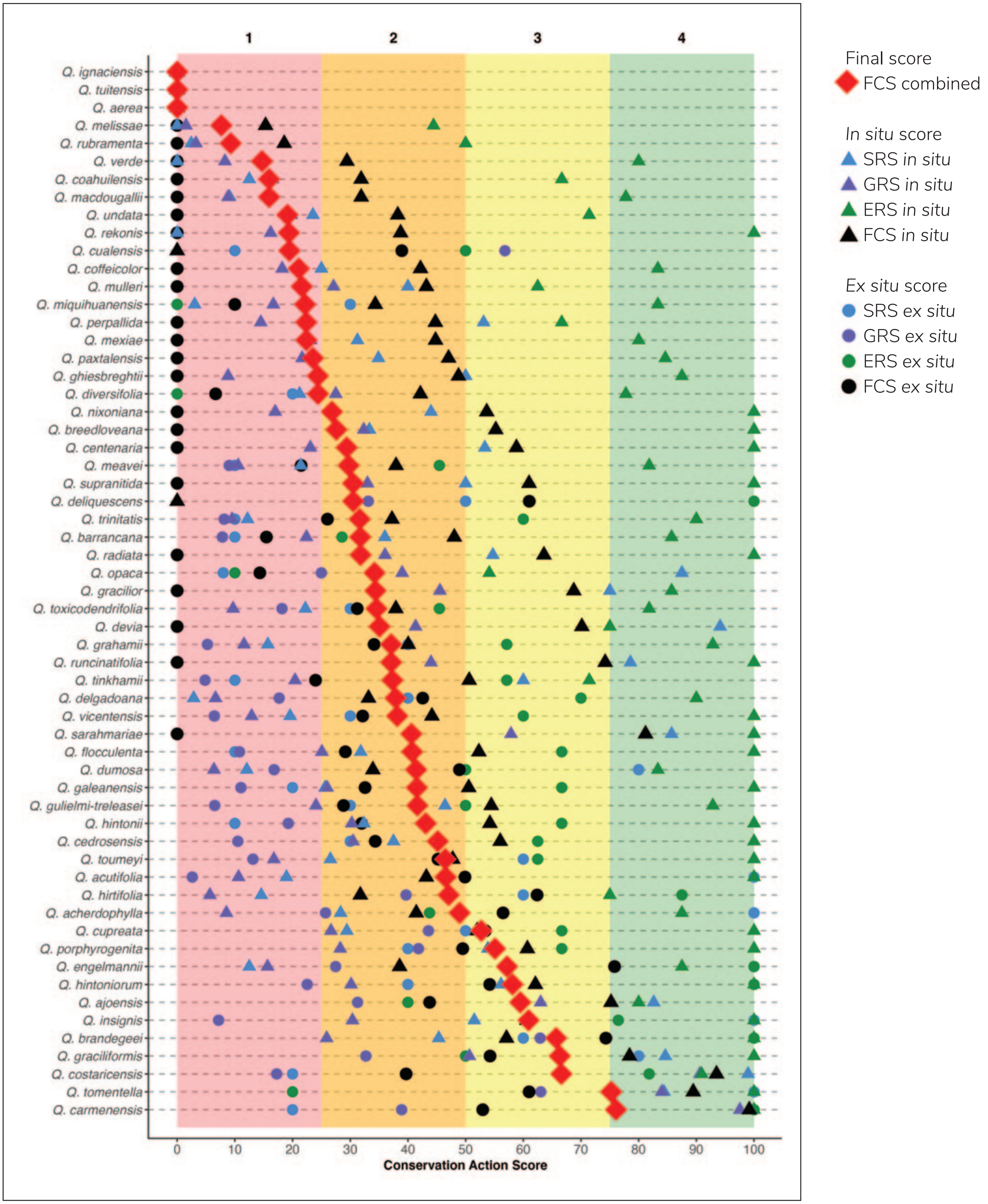

Figure 17. Summary of Conservation Action Scores for 59 target species. Scores range from 0–100, with 100 indicating comprehensive conservation and 0 indicating an extremely poor conservation status.

Case Study 4: *Quercus rubramenta* -a success story for ex *situ* conservation

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Aaron Sandoval and his niece planting *Quercus rubramenta* seedlings *in situ* in Guerrero State, Mexico (Paola Aldaba)

The project sponsored by the International Oak Society (IOS), "*Quercus rubramenta* in Guerrero State, a giant understudied tree", began at the community Estación Toro Muerto in 2022 with the main objective of exploring the distribution, population status, and propagation of this species. Classified as Vulnerable in the IUCN Red List, there are no living collections of this species, in botanical gardens or in known protected natural areas, and knowledge of its propagation and cultivation is considered a priority for its conservation in its natural habitat. In this project we worked in collaboration with the Fauna Special Protection NGO (Profauna) and a local forestry technician in charge of seed collection and plant production in the community.

After collecting the acorns, they were grown in the community, and some were donated to the BUAP Botanical Garden for propagation and planting in different living collections of Mexican gardens. Six months into the project, there are more than 1,900 plants growing in the community nursery, which have reached a size greater than 20 cm. One unique aspect of this project is the involvement of the entire family in this quasi-family nursery.

Through communication with Commissioner Senorino Sandoval Zaragoza, the community knows that:

- *Quercus rubramenta* is an important tree for the conservation and protection of the forests in the area.
- Plant production is required to recover the disturbed areas of the forest and guarantee the permanence of this species.
- The trees that are propagated are at the disposal of the inhabitants of the community.

Due to the remoteness of these forests, they maintain a good state of conservation. Adult trees reach sizes between 50 and 60 m in height with diameters of 1.30 to 1.60 m, and evidence of regeneration is observed, with different sizes and ages of the plants. The main threat detected is excessive logging and looting of wood.

The work that the GCCO Mexico and Central America are carrying out in conjunction with the IOS for this species shows a new way of approaching conservation work for *Quercus* species that are found in areas considered difficult to access, as well as how to include research in conservation activities through collaboration.

CONCLUSIONS

Quercus coahuilensis (J.S. Strijk, Alliance for Conservation Tree Genomics)

For this gap analysis, we performed an extensive literature review, distributed and analyzed the results from global *ex situ* surveys over the course of six years, and interviewed and met with dozens of experts from countries throughout Mesoamerica. Through close collaboration with regional experts, we created a curated dataset of over 4,400 occurrence points and generated over 170 maps. By determining threats, prioritizing species for conservation action, and identifying knowledge gaps, our analysis aims to guide and inspire further conservation efforts for threatened oaks in Mesoamerica.

Accurate identification of a species' native distribution is a crucial first step in any conservation gap analysis. We gathered and cleaned data for 59 threatened and Data Deficient species from a variety of publicly available datasets (e.g., GBIF, Red List, iDigBio), herbarium records, published literature, and conversations with experts. This dataset will be a valuable resource for future studies on Mesoamerican oaks, including the development of species distribution models (Loza et al., in prep). The dataset should continue to be updated and cleaned into the future as taxonomic changes occur, herbarium records are reviewed, and additional survey work and population monitoring are undertaken. It is crucial that conservation practitioners, across all sectors, work collaboratively in the gathering and sharing of data.

This analysis highlights the need to expand *ex situ* collection for threatened and Data Deficient species in Mesoamerica, which has been identified as a priority by the Global Conservation Consortium for Oak (GCCO). As of 2022, there were 22 target taxa not found in any *ex situ* collection. Additionally, even when wild provenance individuals are held in *ex situ* collections, they are typically collected from a very narrow geographic area in a small number of ecoregions relative to the species' native range. Furthermore, 62% of species of wild provenance that are held in *ex situ* collections are represented by ten or fewer individuals. The maps presented in this analysis can be used to identify populations and ecoregions that are especially under-represented *ex situ*, and should be targeted for future collecting efforts. Maximizing the depth and breadth of genetic diversity of *ex situ* collections, relative to wild populations, should be a priority. This is an urgent challenge, as high levels of genetic diversity are required for tree species to adapt to a changing climate (Potter et al., 2017).

Quercus hirtifolia habitat (Maricela Rodríguez-Acosta)

Quercus tomentella planting on Guadalupe Island, Mexico (GECI archive/J.A. Soriano)

Cultivating threatened species *ex situ* is especially important for oaks, since they are considered an exceptional species and cannot be stored with conventional seed banking methods. It is a priority to support institutions that house *ex situ* collections such as arboreta and botanic gardens within the species' native country. Target 8 of the Global Strategy for Plant Conservation specifically recommends that *ex situ* collections are established when possible in the species' country of origin (Convention on Biological Diversity, 2011). This is an important goal since a majority of gardens are located outside of the most biodiverse regions (Westwood et al., 2021). According to BGCI GardenSearch, there are 91 botanic gardens and arboreta in Mesoamerica, yet only nine reported holding collections of a native Mesoamerican oak. We must continue to prioritize building the capacity of local gardens so they can meet the challenge of increasing the representation of native oaks *ex situ*. This work should be done in tandem with supporting the creation of protected areas where priority species can be grown and, when possible, threats minimized.

One objective of a comprehensive gap analysis is to shine a light on what we do not know. Mesoamerica is one of the most biodiverse regions on the planet. Although there has been significant recent progress on studying the unique flora of this region, knowledge on species' distribution, population size, and threats often remains lacking. This is especially true for oaks, which pose their own unique set of challenges. Many threatened Mesoamerican oak species grow in areas that are difficult or unsafe to access, they can be extremely challenging to identify in the field, they hybridize readily, and the taxonomy of certain species is oftentimes contested. In Mesoamerica, there are 27 Data Deficient oak species. Unknown provenance, taxonomic uncertainty, few or old records, uncertain threats, small population size, or limited distribution are the most common justifications for assessing a species as Data Deficient (Bland et al., 2016). Recent studies suggest that Data Deficient species as a whole may be more threatened than data-sufficient species, and yet they are typically excluded from conservation priorities and funding opportunities (Borgelt et al., 2022). These species should be prioritized for research and field work. This will hopefully lead to a greater understanding of their status and ultimately allow them to be identified as either threatened, Near Threatened, or Least Concern on the IUCN Red List.

In the face of such pressing threats, it is essential for conservation practitioners to work collaboratively across sectors to share knowledge and resources. One such group is the GCCO Mexico and Central America, which is bringing together a network of institutions and experts working toward the common goal of preventing extinction. Launched in February 2021, the GCCO Mexico and Central America hosts propagation workshops, supports the development of metacollections of priority oaks throughout the region, and leads the Species Stewards Training Program, which works with local partners to build capacity in identification, propagation, and restoration of threatened species. Networks such as these that bring together multidisciplinary groups are vital in addressing a conservation challenge of this magnitude. It is our hope that this gap analysis further facilitates partnerships, supports the prioritization of conservation action, and ultimately makes progress toward the goal of conserving threatened Mesoamerican oaks.

REFERENCES

Quercus miquihuanensis (Arturo Mora Olivo)

Acevedo-Mairena, H., Orozco, K. and Álvarez-Clare, S. 2024. Plan de conservación para el roble blanco, *Quercus insignis*, en Costa Rica. The Morton Arboretum. Lisle, IL.

Alvarado-Rosales, D., de L. Saavedra-Romero, L., Almaraz-Sánchez, A., Tlapal-Bolaños, B., Trejo-Ramírez, O., Davidson, J. M., Kliejunas, J. T., Oak, S., O'Brien, J. G., Orozco-Torres, F., and Quiroz-Reygadas, D. 2007. Agentes asociados y su papel en la declinación y muerte de encinos (Quercus, Fagaceae) en el centro-oeste de México. *Polibotánica* 23: 1–21.

Ballesteros, D., and Pritchard, H. W. 2020. The cryobiotechnology of oaks: An integration of approaches for the long-term *ex situ* conservation of *Quercus* Species. Forests 11(12): 1281. https://doi.org/10.3390/f11121281

Beckman, E., Meyer, A., Denvir, A., Gill, D., Man, G., Pivorunas, D., Shaw, K., and Westwood, M. 2019. *Conservation Gap Analysis of Native U.S. Oaks*. Lisle, IL: The Morton Arboretum.

Beckman, E., Meyer, A., Pivorunas, D., Hoban, S., and Westwood, M. 2021. *Conservation gap analysis of U.S. trees in nine priority genera*. Lisle, IL: The Morton Arboretum.

Beckman Bruns, E. 2023. *Conservation Gap Analysis Methodology User Guide, Version 1.0.* The Morton Arboretum. https://mortonarb.org/gap-analysis-materials/

Beckman Bruns, E., Khoury, C. K., McCarry, N., Meyer, A., Mims, R., and Warschefsky, E. 2023a. Distributions and conservation status of North American fruit and nut tree crop wild relatives. https://northamericanfruitnuttreecwr.github.io

Beckman Bruns, E., Still, S. M., Good, K., and Hoban, S. 2023b. Conservation-gap-analysis (Version 1.0.0) [Computer software]. https://doi.org/10.5281/zenodo.8246949

Beckman Bruns, E. , Westwood, M., Griffith, M. P., Hipp, A. L., Lobdell, M., Meyer, A., Rollinson, C. R., Still, S., Worcester, L., and Hoban, S. 2023c. Quantifying endangerment value: a promising tool to support curation decisions. Sibbaldia: The *International Journal of Botanic Garden Horticulture* 22: https://doi.org/10.24823/Sibbaldia.2022.1970

Beech, E., Rivers, M., Oldfield, S., and Smith, P. P. 2017. GlobalTreeSearch: The first complete global database of tree species and country distributions. *Journal of Sustainable Forestry* 36(5): 454–489. DOI: 10.1080/10549811.2017.1310049

BGCI. 2014. Building Living Collections to Support Conservation: a guide for public gardens. Available at https://www.bgci.org/files/UnitedStates/MBC_Collections_Guide_2014.pdf. Accessed February 2024.

BGCI. 2022. PlantSearch. Botanic Gardens Conservation International. Richmond, U.K. Available at https://tools.bgci.org/plant_search.php. Accessed January 2022.

BGCI. 2023. GardenSearch. Botanic Gardens Conservation International. Richmond, U.K. Available at http://gardensearch.bgci.org. Accessed November 2023.

BIEN. 2023. Occurrence data downloaded via the R package 'BIEN'. Accessed January 2023.

Bland, L. M., Bielby, J., Kearney, S., Orme, C. D. L., Watson, J. E. M, and Collen, B. 2016. Toward reassessing data-deficient species. *Conservation Biology* 31(3): 531–539. https://doi.org/10.1111/cobi.12850

Borgelt, J., Dorber, M., Høiberg, M. A., and Verones, F. 2022. More than half of data deficient species predicted to be threatened by extinction. Communication Biology 5 (679): https://doi.org/10.1038/s42003-022-03638-9

Boucher, O., Denvil, S., Levavasseur, G., Cozic, A., Caubel, A., Foujols, M-A., Meurdesoif, Y., Cadule, P., Devilliers, M., Ghattas, J., Lebas, N., Lurton, T., Mellul, L., Musat, I., Mignot, J., and Cheruy, F. 2018. IPSL IPSL-CM6A-LR model output prepared for CMIP6 CMIP. Version 2023-09-21. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.1534

California Natural Diversity Database (CNDDB). 2023. [Internet]. California Department of Fish and Wildlife [2023].

Carr, D., Barbieri, A., Pan, W., and Iranavi, H. 2006. Agricultural change and limits to deforestation in Central America. In F. Brouwer and B. A. McCarl (Eds.), *Agriculture and climate beyond 2015.* (pp 91–107) Springer.

Carrero, C., Jerome, D., Beckman, E., Byrne, A., Coombes, A. J., Deng, M., González-Rodríguez, A., Hoang, V. S., Khoo, E., Nguyen, N., Robiansyah, I., Rodríguez-Correa, H., Sang, J., Song, Y-G., Strijk, J. S., Sugau, J., Sun, W. B., Valencia-Ávalos, S., and Westwood, M. 2020. *The Red List of Oaks 2020*. The Morton Arboretum. Lisle, IL.

Cavender, N., Westwood, M., Bechtold, C., Donnelly, G., Oldfield, S., Gardner, M., Rae, D., and McNamara, W. 2015. Strengthening the conservation value of ex *situ* tree collections. *Oryx* 49(3): 416–424. https://doi.org/10.1017/S0030605314000866

Cavender-Bares, J., González-Rodríguez, A., Eaton, D. A. R., Hipp, A. A. L., Beulke, A. and Manos, P. S. 2015. Phylogeny and biogeography of the American live oaks (*Quercus* subsection *Virentes*): a genomic and population genetics approach. *Molecular Ecology* 24: 3668–3687. doi: 10.1111/mec.13269

Chamberlain, S., Barve, V., Mcglinn, D., Oldoni, D., Desmet, P., Geffert, L., and Ram, K. 2024. _rgbif: Interface to the Global Biodiversity Information Facility API_. R package version 3.7.2, <https://CRAN.R-project.org/package=rgbif>

Chamberlain, S., and Boettiger, C. 2017. "R Python, and Ruby clients for GBIF species occurrence data." _PeerJ PrePrints_. <https://doi.org/10.7287/peerj.preprints.3304v1>

Cho, K., Goldstein, B., Gounaridis, D., and Newell, J. P. 2021. Where does your guacamole come from? Detecting deforestation associated with the export of avocados from Mexico to the United States. *Journal of Environmental Management* 278(1): https://doi.org/10.1016/j.jenvman.2020.111482

CMCC Foundation. 2021. *Mexico: G20 Climate Risk Atlas*. Available at https://files.cmcc.it/g20climaterisks/Mexico.pdf. Accessed December 2023.

CONAFOR. 2020. *Estimación de la tasa de deforestación en México para el periodo 2001–2018 mediante el método de muestreo*. Documento Técnico, Jalisco, México. Available at http://www.conafor.gob.mx:8080/documentos/docs/1/7767Resumen%20Ejecutivo%20Deforestaci%C3%B3n%202001-2018%20M%C3%A9xico.pdf. Accessed April 2024.

Conservation Measures Partnership. 2016. Classification of conservation actions and threats (Version 2.0). Available at https://conservationstandards.org/library-item/threats-and-actions-taxonomies/ Accessed January 2024.

Contreras-Cornejo, H. A., Larsen, J., Fernández-Pavía, S. P., and Oyama, K. 2023. Climate change, a booster of disease outbreaks by the plant pathogen *Phytophthora* in oak forests. *Rhizosphere* 27: https://doi.org/10.1016/j.rhisph.2023.100719

Convention on Biological Diversity. 2011. Global Strategy for Plant Conservation. Available at https://www.cbd.int/gspc/targets.shtml. Accessed April 2024.

Convention on Biological Diversity. 2024. Consolidated guidance notes for the targets of the Kunming-Montreal Biodiversity Framework. Available at https://www.cbd.int/gbf/targets/notes.shtml#_Toc157069081. Accessed April 2024.

Crowley, D. 2019. *Prioritization of Acer species and populations for ex situ conservation based on threat level and current representation in living collections* [Unpublished master's thesis]. University of Reading. Reading, Berkshire, England.

Cuervo-Robayo, A. P., Uerta, C., Gómez-Albores, M. A., Meneses-Mosquera, A. K., Téllez-Valdés, O., and Martínez-Meyer, E. 2020. One hundred years of climate change in Mexico. *PLoS One* 15(7): https://doi.org/10.1371/journal.pone.0209808

Davidson, O'Brien, Oak, and Kliejunas. 2003. Report on a Site Visit to Mexico – Muerte del Encino. US Forest Service. Available at https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fsbdev2_026292.pdf. Accessed January 2024.

De Luna-Bonilla, O. Á., Valencia-A, S., Ibarra-Manríquez, G., Morales-Saldaña, S., Tovar-Sánchez, E., and González-Rodríguez, A. 2024. Leaf morphometric analysis and potential distribution modelling contribute to taxonomic differentiation in the *Quercus microphylla* complex. *Journal of Plant Research* 137: 3–19. https://doi.org/10.1007/s10265-023-01495-z

Denvir, A., Cavender-Bares, J. and González-Rodríguez, A. 2019. The role of gardens in integrated conservation practice: the case of conserving *Quercus brandegeei* in Baja California Sur, Mexico. *Sibbaldia: The International Journal of Botanic Garden Horticulture* 17: 177–188: https://doi.org/10.24823/Sibbaldia.2019.273

Denvir, A., Arima, E. Y., González-Rodríguez, A., and Young, K. R. 2022. Ecological and human dimensions of avocado expansion in México: Towards supply-chain sustainability. *Abmio* 51(1): 152–166. doi: 10.1007/s13280-021-01538-6

Denvir, A. and Westwood, M. 2016. *Quercus brandegeei*. The IUCN Red List of Threatened Species 2016: e.T30726A2795363. Available at https://dx.doi.org/10.2305/IUCN.UK.2016-3.RLTS.T30726A2795363.en. Accessed January 2024.

Derguy, M. R., Martinuzzi, S., and Arturi, M. 2022. Bioclimatic changes in ecoregions of southern South America: Trends and projections based on Holdridge life zones. *Austral Ecology* 47:580–589. https://doi.org/10.1111/aec.13142

Di Santo, L. N., and Hamilton, J. A. 2020. Using environmental and geographic data to optimize *ex situ* collections and preserve evolutionary potential. *Conservation Biology* 35(2): 733–744. https://doi.org/10.1111/cobi.13568

Dix, M., Bi, D., Dobrohotoff, P., Fiedler, R., Harman, I., Law, R., Mackallah, C., Marsland, S., O'Farrell, S., Rashid, H., Srbinovsky, J., Sullivan, A., Trenham, C., Vohralik, P., Watterson, I., Williams, G., Woodhouse, M., Bodman, R., Dias, F. B., Domingues, C. M., Hannah, N., Heerdegen, A., Savita, A., Wales, S., Allen, C., Druken, K., Evans, B., Richards, C., Ridzwan, S. M., Roberts, D., Smillie, J., Snow, K., Ward, M., and Yang, R. 2019. CSIRO-ARCCSS ACCESS-CM2 model output prepared for CMIP6 CMIP historical. Version 2023-09-2.Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.4271

EC-Earth Consortium (EC-Earth). 2019. EC-Earth-Consortium EC-Earth3-Veg model output prepared for CMIP6 ScenarioMIP. Version 2023-09-21. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.727

Environmental education program at El Cuale, Mexico (Maribel Arenas Navarro)

FIA DataMart, USDA Forest Service. 2023. Forest Inventory and Analysis database. USDA Forest Service, Northern Research Station. Available at https://doi.org/10.2737/RDS-2001-FIADB. Accessed July 2023.

Fick, S. E. and Hijmans, R. J. 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology 37* (12): 4302–4315. https://doi.org/10.1002/joc.5086

Figueroa, F., and Sánchez-Cordero, V. 2008. Effectiveness of natural protected areas to prevent land use and land cover change in Mexico. *Biodiversity Conservation* 17: 3223–3240.

García-Hernández, M. A., Toledo-Aceves, T., López-Barrera, F., Sosa, V. J., and Paz, H. 2019. Effects of environmental filters on early establishment of cloud forest trees along elevation gradients: Implications for assisted migration. *Forest ecology and management* 432: 427–435.

GBIF.org. 2023. GBIF Occurrence Download https://doi.org/10.15468/dl.hj79d7. Downloaded via the R package 'rgbif'. Accessed January 2023.

Giorgi, F. 2006. Climate change hot-spots. *Geophysical Research Letters* 33(8): https://doi.org/10.1029/2006GL025734.

Gómez-Mendoza, L., and Arriaga, L. 2007. Modeling the effect of climate change on the distribution of oak and pine species of Mexico. *Conservation Biology* 21(6):1545–1555. https://doi.org/10.1111/j.1523-1739.2007.00814.x

González-Espinosa, M., Meave, J. A., Lorea-Hernández, F. G., Ibarra-Manríquez, G. and Newton, A. C. (Eds) 2011. *The Red List of Mexican Cloud Forest Trees*. Fauna and Flora International, Cambridge, UK.

Graul, C. 2016. LeafletR: Interactive Web-Maps Based on the Leaflet JavaScript Library. R package version 0.4-0.

Hausfather, Z. 2019. CMIP6: the next generation of climate models explained. CarbonBrief. Available at https://www.carbonbrief.org/cmip6-the-next-generation-of-climate-models-explained/. Accessed February 2024.

Hipp, A. L., Manos, P. S., González-Rodríguez, A., Hahn, M., Kaproth, M., McVay, J. D., Valencia-A., S., and Cavender-Bares, J. 2018. Sympatric parallel diversification of major oak clades in the Americas and the origins of Mexican species diversity. *New Phytologist* 217(1): 439–452. https://doi.org/10.1111/nph.14773

Hoban, S. 2019. New guidance for *ex situ* gene conservation: Sampling realistic population systems and accounting for collection attrition. *Biological Conservation* 235: 199–208. https://doi.org/10.1016/j.biocon.2019.04.013

Hoban, S., Kallow, S., and Trivedi, C. 2018. Implementing a new approach to effective conservation of genetic diversity, with ash (*Fraxinus excelsior*) in the UK as a case study. *Biological Conservation* 225:10–21. https://doi.org/10.1016/j.biocon.2018.06.017

Hoban, S., Archer, F. I., Bertola, L. D., Bragg, J. G., Breed, M. F., Bruford, M. W., Coleman, M. A., Ekblom, R., Funk, W. C., Grueber, C. E., Hand, B. K., Jaffé, R., Jensen, E., Johnson, J. S., Kershaw, F., Liggins, L., MacDonald, A. J., Mergeay, J., Miller, J. M., Muller-Karger, F., O'Brien, D., Paz-Vinas, I., Potter, K. M., Razgour, O., Vernesi, C., and Hunter, M. E. 2022. Global genetic diversity status and trends: towards a suite of Essential Biodiversity Variables (EBVs) for genetic composition. *Biological Reviews* 97(4): 1511–1538. https://doi.org/10.1111/brv.12852

Hoban, S., Beckman Bruns, E., Griffith, M. P., Hahn, M., Hipp, A., Lobdell, M., Meyer, A., Rollinson, C., Worcester, L., and Westwood, M. 2023. *Integrated Collections Development: Quantifying value of garden collections for decision making and prioritization*. Botanic Gardens Conservation International-U.S. Available at https://www.bgci.org/news-events/new-integrated-collections-development-report-led-by-the-morton-arboretum/. Accessed April 2024.

Holdridge, L. R. 1967. *Life zone ecology*. Tropical Science Center: San José, Costa Rica.

Hu, X., Huang, B., Verones, F., Cavalett, O., and Cherubini, F. 2020. Overview of recent land-cover changes in biodiversity hotspots. *Frontiers in Ecology and the Environment* 19(2): 91–97. https://doi.org/10.1002/fee.2276

iDigbio. 2022. Occurrence download. Downloaded via the R package 'ridigbio'. Accessed January 2023.

Imbach, P., Chan Chou, S., Lyra, A., Rodrigues, D., Rodriguez, D., Latinovic, D., Siqueira, G., Silva, A., Garofolo, L., and Georgiou, S. 2018. Future climate change scenarios in Central America at high spatial resolution. *PLoS ONE* 13(4): e0193570. https://doi.org/10.1371/journal.pone.0193570

IUCN. 2016. A Global Standard for the Identification of Key Biodiversity Areas, Version 1.0. Gland, Switzerland: IUCN. Available at https://portals.iucn.org/library/sites/library/files/documents/2016-048.pdf. Accessed January 2023.

IUCN. 2023. The IUCN Red List of Threatened Species. Version 2023-1. Available at https://www.iucnredlist.org. Accessed January 2023.

Jerome, D. 2018a. *Quercus acherdophylla*. The IUCN Red List of Threatened Species 2018: e.T89174970A89174976. Available at https://dx.doi.org/10.2305/IUCN.UK.2018-2.RLTS.T89174970A89174976.en. Accessed March 2024.

Jerome, D. 2018b. *Quercus insignis*. The IUCN Red List of Threatened Species 2018: e.T194177A2302931. https://dx.doi.org/10.2305/IUCN.UK.2018-1.RLTS.T194177A2302931.en.

KBA. 2023. KBA Data. Available at https://www.keybiodiversityareas.org/kba-data. Accessed March 2024.

Khatun, K., Imbach, P., and Zamora, J. 2013. An assessment of climate change impacts on the tropical forests of Central America using the Holdridge Life Zone (HLZ) land classification system. iForest - *Biogeosciences and Forestry* 6(4): 183–189. https://doi.org/10.3832/ifor0743-006

Khoury, C. K., Amariles, D., Soto, J. S., Diaz, M. V., Sotelo, S., Sosa, C. C., Ramírez-Villegas, J., Achicanoy, H. A., Velásquez-Tibatá, J., Guarino, L., León, B., Navarro-Racines, C., Castañeda-Álvarez, N. P., Dempewolf, H., Wiersema, J. H., and Jarvis, A. 2019. Comprehensiveness of conservation of useful wild plants: an operational indicator for biodiversity and sustainable development targets. *Ecological Indicators* 98: 420–429. https://doi.org/10.1016/j.ecolind.2018.11.016

Khoury, C. K., Carver, D., Greene, S. L., and Frances, A. 2020. Crop wild relatives of the United States require urgent conservation action. *PNAS* 117(52): 33351–33357. https://doi.org/10.1073/pnas.2007029117

Le Berre, M., Noble, V., Pires, M., Médail, F., and Diadema, K. 2019. How to hierarchise species to determine priorities for conservation action? A critical analysis. *Biodiversity and Conservation* 28: 3051–3071. https://doi.org/10.1007/s10531-019-01820-w

Linsky, J., Crowley, D., Beckman Bruns, E. and Coffey, E. E. D. 2022a. *Global Conservation Gap Analysis of Magnolia*. Atlanta, GA: Atlanta Botanical Garden.

Linsky, J., Bellemare, J., Berryhill, J., Conrad, K., Lobdell, M., Moon, B., de la Mota Daniel, F.J., Rahaim, K., Rounsaville, T., Sanders, A., West, T., Zale, P.J., Meyer, A., Beckman Bruns, E., and Coffey, E. E. D. 2022b. *Conservation Gap Analysis of Native Magnolias of the U.S. and Canada*. Atlanta, GA: Atlanta Botanical Garden

Mace, G. M., Possingham, H. P., and Leader-Williams, N. 2006. Prioritizing Choices in Conservation. In D. MacDonald and K. Service (Eds.) *Key Topics in Conservation Biology* (pp 17-34). Blackwell Publishing Ltd.

Maitner, B. 2022. _BIEN: Tools for Accessing the Botanical Information and Ecology Network Database_. R package version 1.2.5, https://CRAN.R-project.org/package=BIEN.

Massicotte, P. and South, A. 2023. rnaturalearth: World Map Data from Natural Earth. R package version 0.3.3, https://CRAN.R-project.org/package=rnaturalearth.

McCauley, R. A., Cortés-Palomec, A. C. and Oyama, K. 2019. Species diversification in a lineage of Mexican red oak (*Quercus* section *Lobatae* subsection Racemiflorae)—the interplay between distance, habitat, and hybridization. *Tree Genetics & Genomes* 15(27). https://doi.org/10.1007/s11295-019-1333-x

Meyad, C., Henkrar, F., Bouhaddou, N., and Khabar, L. 2023. Micropropagation of Quercus spp., complications and solutions—an overview. *In Vitro Cellular & Developmental Biology-Plant* 59(4): 446–460. https://doi.org/10.1007/s11627-023-10354-4

Michonneau, F., and Collins, M. 2022. _ridigbio: Interface to the iDigBio Data API_. R package version 0.3.6, https://CRAN.R-project.org/package=ridigbio.

Missanjo, E., Utila, H., Munthali, M., and Mitembe, W. 2019. Modelling of climate conditions in forest vegetation zones in Malawi. *World Journal of Advanced Research and Reviews* 1(03): 036–044. https://doi.org/10.30574/wjarr.2019.1.3.0023

Morales-Saldaña, S., Valencia-Ávalos, S., Oyama, K., Tovar-Sánchez, E., Hipp, A. L., & González-Rodríguez, A. 2022. Even more oak species in Mexico? Genetic structure and morphological differentiation support the presence of at least two specific entities within *Quercus* laeta. *Journal of Systematics and Evolution* 60(5): 1124–1139.

Morrone, J. J., Escalante, T., and Rodríguez-Tapia, G. 2017. Mexican biogeographic provinces: Map and Shapefiles. *Zootaxa* 4277(2): 277–279. https://doi.org/10.11646/zootaxa.4277.2.8

Morton Arboretum. 2023. Plan de Acción, Conservación y Manejo para el Encino Arroyero (*Quercus brandegeei*) en la Región del Cabo, Baja California Sur, México. La Paz, Baja California Sur, México.

Naranjo Bravo, L. M. 2021. Genética de la conservación y nicho ecológico del encino *Quercus insignis* (Fagaceae) en México [Tesis de maestría, Universidad Nacional Autónoma de México. Repositorio Institucional de la UNAM. https://repositorio.unam.mx/contenidos/3562174.

NASA Goddard Institute for Space Studies (NASA/GISS). 2018. NASA-GISS GISS-E2.1G model output prepared for CMIP6 CMIP. Version 2023-09-21. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.1400

Oldfield, S. and Eastwood, A. 2007. *The Red List of Oaks*. Flora and Fauna International. Cambridge, UK.

Peano, D., Lovato, T., and Materia, S. 2020. CMCC CMCC-ESM2 model output prepared for CMIP6 LS3MIP. Version 2023-09-21. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.13165

Ponce-Reyes, R., Reynoso-Rosales, V.-H., Watson, J. E. M., VanDerWal, J., Fuller, R. A., Pressey, R. L., and Possingham, H. P. 2012. Vulnerability of cloud forest reserves in Mexico to climate change. *Nature Climate Change* 2: 448–452. https://doi.org/10.1038/nclimate1453

Potter, K. M., Jetton, R. M., Bower, A., Jacobs, D. F., Man, G., Hipkins, V. D., and Westwood, M. 2017. Banking on the future: progress, challenges and opportunities for the genetic conservation of forest trees. *New Forests* 48: 153–180. https://doi.org/10.1007/s11056-017-9582-8

R Core Team. 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available at https://www.R-project.org/. Accessed September 2022.

Rehfeldt, G. E., Crookston, N. L., Sáenz-Romero, C., and Campbell, E. M. 2012. North American vegetation model for land-use planning in a changing climate: a solution to large classification problems. *Ecological Applications* 22(1): 119–141. https://doi.org/10.1890/11-0495.1

Rodrigues, A. S. L., Akçakaya, H. R., Andelman, S. J., Bakarr, M. I., Boitani, L., Brooks, T. M., Chanson, J. S., Fishpool, L. D. C., Da Fonseca, G. A. B., Gaston, K. J., Hoffmann, M., Marquet, P. A., Pilgrim, J. D., Pressey, R. L., Schipper, J., Sechrest, W., Stuart, S. N., Underhill, L. G., Waller, R. W., Watts, M. E. J., and Yan, X. 2004. Global Gap Analysis: Priority Regions for Expanding the Global Protected-Area Network. BioScience 54(12): 1092–1100. https://doi.org/10.1641/0006-3568(2004)054[1092:GGAPRF]2.0.CO;2

Rodríguez-Correa, H., Oyama, K., Quesada, M., Fuchs, E.J., Quezada, M., Ferrufino, L., Valencia-Ávalos, S., Cascante-Marín, A. and González-Rodríguez, A. 2017. Complex phylogeographic patterns indicate Central American origin of two widespread Mesoamerican *Quercus* (Fagaceae) species. *Tree Genetics & Genomes* 13: 62 https://doi.org/10.1007/s11295-017-1147-7

Sáenz-Romero, C., Mendoza-Maya, E., Gómez-Pineda, E., Blanco-García, A., Endara-Agramont, A. R., Lindig-Cisneros, R., López-Upton, J., Trejo-Ramírez, O., Wehenkel, C., Cibrián-Tovar, D., Flores-López, C., Plascencia-González, A., and Vargas-Hernández, J. J. 2020. Recent evidence of Mexican temperate forest decline and the need for *ex situ* conservation, assisted migration, and translocation of species ensembles as adaptive management to face projected climatic change impacts in a megadiverse country. *Canadian Journal of Forest Research* 50(9): 843–854. https://doi.org/10.1139/cjfr-2019-0329

Salinas-Rodríguez, M. M., Sajama, M. J., Gutiérrez-Ortega, J. S., Ortega-Baes, P., and Estrada-Castillón, A. E. 2018. Identification of endemic vascular plant species hotspots and the effectiveness of the protected areas for their conservation in Sierra Madre Oriental, Mexico. *Journal for Nature Conservation* 46: 6–27. https://doi.org/10.1016/j.jnc.2018.08.012

Santini, N. S., Cuervo-Robayo, A. P., and Fernanda Adame, M. 2023. Agricultural soil degradation in Mexico. In P. Pereira, M. Muñoz-Rojas, I. Bogunovic, and W. Zhao (Eds.) *Impact of Agriculture on Soil Degradation I: Perspectives from Africa, Asia, America and Oceania* (pp 301 - 323). Springer Nature, Switzerland.

Shiogama, H., Abe, M., and Tatebe, H. 2019. MIROC MIROC6 model output prepared for CMIP6 ScenarioMIP. Version 2023-09-21 .Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.898

South, A. 2017. rnaturalearthdata: World Vector Map Data from Natural Earth Used in 'rnaturalearth'. R package version 0.1.0, https://CRAN.R-project.org/package=rnaturalearthdata.

South, A., Michael, S., and Massicotte, P. 2023. rnaturalearthhires: High Resolution World Vector Map Data from Natural Earth used in rnaturalearth https://docs.ropensci.org/rnaturalearthhires, https://github.com/ropensci/rnaturalearthhires.

Suzart de Albuquerque, F., Benito, B., Beier, P., Assunção-Albuquerque, M. J., and Cayuela, L. 2015. Supporting underrepresented forests in Mesoamerica. *Natureza & Conservação* 13(2): 152–158. https://doi.org/10.1016/j.ncon.2015.02.001

Tainter, F. H., O'Brien, J. G., Hernández, A., Orozco, F., and Rebolledo, O. 2000. *Phytophthora cinnamomi* as a Cause of Oak Mortality in the State of Colima, Mexico. Plant Disease 84(4): 394–398. https://doi.org/10.1094/PDIS.2000.84.4.394

Tang, Y., Rumbold, S., Ellis, R., Kelley, D., Mulcahy, J., Sellar, A., Walton, J., and Jones, C. 2019. MOHC UKESM1.0-LL model output prepared for CMIP6 CMIP. Version 2023-09-21. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.1569

Tellez, O., Mattana, E., Diazgranados, M., Kühn, N., Castillo-Lorenzo, E., Lira, R., Montes-Leyva, L., Rodriguez, I., Flores Ortiz, C. M., Way, M., Dávila, P., and Ulian, T. 2020. Native trees of Mexico: diversity, distribution, uses and conservation. PeerJ: e9898. https://doi.org/10.7717/peerj.9898

The Convention on Wetlands. 2023. Countries. Available at https://www.ramsar.org/countries. Accessed December 2023.

Toledo-Aceves, T., López-Barrera, F., Vásquez-Reyes, V., and Günter, S. 2022. Restoration of tropical montane cloud forest in bracken dominated pastures: The role of nurse shrubs. *Forest Ecology and Management* 508: 120055.

Toledo-Aceves, T., Sáenz-Romero, C., Cruzado-Vargas, A. L., and Vásquez-Reyes, V. 2023. *Quercus insignis* seedling response to climatic transfer distance in the face of climate change. *Forest Ecology and Management* 533: 120855. https://doi.org/10.1016/j.foreco.2023.120855

Toledo-Aceves, T. and del-Val, E. 2021. Do plant-herbivore interactions persist in assisted migration plantings? *Restoration Ecology* 29(3): e13318. https://doi.org/10.1111/rec.13318

Trejo, I. and Cuervo, A. 2016. Cartographic model for the life zone system according to Holdridge (1971). GitHub Repository. Available at https://github.com/AngelaCrow/Zonas-de-vida-Futuro/blob/master/zonasdevida.R. Accessed September 2023.

UNEP-WCMC and IUCN. 2023. Protected Planet: The World Database on Protected Areas (WDPA) [Online], October 2023, Cambridge, UK: UNEP-WCMC and IUCN. Available at www.protectedplanet.net.

USFWS. 2023. Five species on San Clemente Island declared fully recovered. Available at https://www.navy.mil/Press-Office/News-Stories/Article/3275895/five-species-on-san-clemente-island-declared-fully-recovered/. Accessed January 2024.

Valencia-A., S. 2010. Notes on the Genus *Quercus* in Mexico. International Oaks 21: 100–120.

Quercus insignis inhabits the “coffee belt”, a habitat that has been mostly converted to agriculture and farming (The Morton Arboretum)

Villaseñor, J. L. 2016. Checklist of the native vascular plants of México. *Revista Mexicana de Biodiversidad* 87(3): 559-902. https://doi.org/10.1016/j.rmb.2016.06.017

Villers-Ruiz, L., and Trejo-Vázquez, I. 1997. Assessment of the vulnerability of forest ecosystems to climate change in Mexico. *Climate Research* 9: 87–93. https://doi.org/10.3354/cr009087

Visconti, P., Butchart, S. H., Brooks, T. M., Langhammer, P. F., Marnewick, D., Vergara, S., Yanosky, A., and Watson, J. E. 2019. Protected area targets post-2020. Science 364(6437): 239–241. DOI: 10.1126/science.aav6886

Volodin, E., Mortikov, E., Gritsun, A., Lykossov, V., Galin, V., Diansky, N., Gusev, A., Kostrykin, S., Iakovlev, N., Shestakova, A., and Emelina, S. 2019. INM INM-CM5-0 model output prepared for CMIP6 CMIP piControl. Version 2023-09-21. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.5081

von Storch, J-S, Putrasahan, D., Lohmann, K., Gutjahr, O., Jungclaus, J., Bittner, M., Haak, H., Wieners, K-H, Giorgetta, M., Reick, C. Esch, M., Gayler, V., de Vrese, P., Raddatz, T., Mauritsen, T., Behrens, J., Brovkin, V., Claussen, M., Crueger, T., Fast, I., Fiedler, S., Hagemann, S., Hohenegger, C., Jahns, T., Kloster, S., Kinne, S., Lasslop, G., Kornblueh, L., Marotzke, J., Matei, D., Meraner, K., Mikolajewicz, U., Modali, K., Müller, W., Nabel, J., Notz, D., Peters-von Gehlen, K., Pincus, R., Pohlmann, H., Pongratz, J., Rast, S., Schmidt, H., Schnur, R., Schulzweida, U., Six, K., Stevens, B., Voigt, A., and Roeckner, E. 2017. MPI-M MPIESM1.2-HR model output prepared for CMIP6 HighResMIP. Version 2023-09-21. Earth System Grid Federation.

Wenzell, K., Kenny, L., Beckman, E. and Jerome, D. 2020. *Quercus cualensis*. The IUCN Red List of Threatened Species 2020: e.T194105A2299318. Available at https://dx.doi.org/10.2305/IUCN.UK.2020-2.RLTS.T194105A2299318.en. Accessed January 2024.

Westwood, M., Cavender, N., Meyer, A., and Smith, P. 2021. Botanic garden solutions to the plant extinction crisis. *Plants People Planet* 3(1): 22–32. https://doi.org/10.1002/ppp3.10134

Wood, J., Ballou, J. D., Callicrate, T., Fant, J. B., Griffith, M. P., Kramer, A. T., Lacy, R. C., Meyer, A., Sullivan, S., Traylor-Holzer, K., Walsh, S. K., and Havens, K. 2020. Applying the zoo model to conservation of threatened exceptional plant species. *Conservation Biology* 34(6): 1416–1425. https://doi.org/10.1111/cobi.13503

WorldClim. 2022. Future climate, 30 seconds spatial resolution. Available at https://www.worldclim.org/data/cmip6/cmip6_clim30s.html. Accessed February 2024.

Yukimoto, S., Koshiro, T., Kawai, H., Oshima, N., Yoshida, K., Urakawa, S., Tsujino, H., Deushi, M., Tanaka, T., Hosaka, M., Yoshimura, H., Shindo, E., Mizuta, R., Ishii, M., Obata, A., and Adachi, Y. 2019. MRI MRI-ESM2.0 model output prepared for CMIP6 CMIP. Version 2023-09-21. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.621

Zeng, Y., Senior, R. A., Crawford, C. L., and Wilcove, D. S. 2023. Gaps and weaknesses in the global protected area network for safeguarding at-risk species. *Science Advances* 9(22): DOI: 10.1126/sciadv.adg0288

Zizka, A., Silvestro, D., Andermann, T., Azevedo, J., Duarte Ritter, C., Edler, D., Farooq, H., Herdean, A., Ariza, M., Scharn, R., Svanteson, S., Wengstrom, N., Zizka, V., and Antonelli, A. 2019. “CoordinateCleaner: standardized cleaning of occurrence records from biological collection databases.” Methods in Ecology and Evolution, -7. doi:10.1111/2041-210X.13152, R package version 3.0.1, https://github.com/ropensci/CoordinateCleaner

APPENDICES

Quercus hintoniorum habitat (Maricela Rodríguez-Acosta)

APPENDIX A

Institutional contributors of *Quercus* data during annual requests for ex *situ* accessions data between 2017 and 2022.

Adelaide Botanic Gardens | Adkins Arboretum | Aiken City Arboretum | Ambler Arboretum of Temple University | Arboreto de la Mota, Miraflores de la Sierra, Madrid, Spain | Arboretum at Penn State, The | Arboretum Chocha | Arboretum de la Bergerette | Arboretum des Pouyouleix | Arboretum du Passadou | Arboretum Leśnego Banku Genów Kostrzyca | Arboretum Mustila | Arboretum Robert Lenoir | Arboretum Wespelaar | Arboretum Zampach | Arboretum-Pinetum Lucus Augusti | Arizona-Sonora Desert Museum | Arnold Arboretum of Harvard University, The | Atlanta Botanical Garden | Auckland Botanic Gardens | Australian Botanic Garden, Mount Annan, The | Baker Arboretum | Bamboo Brook Outdoor Education Center | Bangladesh Agricultural University Botanic Garden | Barnea Oak Nursery | Bartlett Arboretum | Bartlett Tree Research Laboratories Arboretum | Barton Arboretum and Nature Reserve of Medford Leas | Batumi Botanical Garden | Bayard Cutting Arboretum | Bedgebury National Pinetum and Forest | Bellefontaine Cemetery and Arboretum | Bendigo Botanic Gardens | Bergen Botanical Garden | Bergius Botanic Garden | Bernheim Arboretum and Research Forest | Birmingham Botanical Gardens and Glasshouses | Blue Mountains Botanic Garden, Mount Tomah | Bok Tower Gardens | Bonn University Botanic Gardens | Boone County Arboretum | Borde Hill Garden | Botanic Garden Meise | Botanic Garden of Smith College, The | Botanic Garden, Delft University of Technology | Botanic Gardens of South Australia | Botanical Garden of Moscow Palace of Pioneers | Botanical Garden of the University of Bern | Botanischer Garten der Philipps-Universität Marburg | Botanischer Garten der Universität Osnabrück | Botanischer Garten der Universitaet Zürich | Botanischer Garten Frankfurt am Main | Botanischer Garten Oldenburg | Bowman's Hill Wildflower Preserve | Boyce Thompson Arboretum | Brenton Arboretum, The | Brookgreen Gardens | Brooklyn Botanic Garden | Buckingham Palace | Butte County (Butte Environmental Council) | California Botanic Garden | Cambridge University Botanic Garden | Carl von Ossietzky Universität | Cephalonia Botanica | Chateau Perouse | Chelsea Physic Garden | Chicago Botanic Garden | Chollipo Arboretum Foundation | Cincinnati Zoo & Botanical Garden | Cindy Newlander, PCN Quercus Multisite | Connecticut College Arboretum | Cornell Botanic Gardens | Cultivated Oaks of the World | Darts Hill Garden Park | Dawes Arboretum, The | Dayton VA Medical Center Gardens & Grotto | Delft University of Technology Botanic Garden (Botanische Tuinen) | Dendrologická Zahrada | Denver Botanic Gardens | Denver Zoological Gardens | Descanso Gardens | Desert Botanical Garden | Donald E. Davis Arboretum | Dr. Cecilia Koo Botanic Conservation Center | Dunedin Botanical Garden | Eastwoodhill Arboretum | EcoJardín IIES-UNAM | Ed Shinn | Eden Project, The | Eddy Arboretum | El Colegio de la Frontera Sur - San Cristóbal de las Casas | Elmhurst College Arboretum | Estancia San Miguel | Evergreen Burial Park and Arboretum | Exbury Gardens | Fairchild Tropical Botanic Garden | Ferme d'Azy at Chassepierre Belgium | Fernwood Botanical Garden and Nature Preserve | Finnish Museum of Natural History / Helsinki University Botanic Garden / Kaisaniemi Botanic Garden, Kumpula Botanic Garden | Florida field genebank | For-Mar Nature Preserve & Arboretum | Forstbotanischer Garten Tharandt | Franklin Park Conservatory and Botanical Gardens | Frelinghuysen Arboretum, The | Gabis Arboretum at Purdue Northwest (Taltree Arboretum) | Ganna Walska Lotusland | Gardens of the Big Bend: Magnolia Garden | George G. Willis Jr. Arboretum at Furman University | Georgia Tech Arboretum | Giardino Botánico "Nuova Gussonea" Monte Etna |

Quercus hintoniorum (Maricela Rodríguez-Acosta)

Quercus ajoensis (John Wiens)

Gothenburg Botanical Garden | Gradina Agrobotanica din Cluj-Napoca | Green Bay Botanical Garden | Green Spring Gardens | Greenwood Cemetery | Grigadale Arboretum | GRIN National Plant Germplasm System | Grounds and Gardens University of Exeter, The | Hackfalls Arboretum | Harmas de Fabre | Hergest Croft Gardens | Hof ter Saksen Arboretum | Holden Arboretum, The | Holden Forest and Garden | Hollard Garden | Horsholm Arboretum | Hortus Botanicus Amsterdam | Houston Botanic Garden | Hoyt Arboretum | Huntington Botanical Gardens | Huntsville Botanical Garden | Jardín Botànic de Sóller | Jardín Botánico “Carlos Thays” | Jardín Botánico de Acapulco | Jardín Botánico Universitario de la Benemérita Universidad Autónoma de Puebla (JBU-BUAP) | Jardín Botánico del Instituto de Biología (UNAM) | Jardín Botánico Francisco Javier | Jardín Botánico Francisco Javier Clavijero | Jardín Botánico Iturraran | Jardín Botánico Louise Wardle de Camacho | Jardin Botanique Alpin de la Jaÿsinia | Jardin Botanique de l’Université de Strasbourg | Jardin Botanique de le Villa Thuret | Jardin botanique de Lyon | Jardin botanique de Paris | Jardin Botanique Exotique | JC Raulston Arboretum | Jean Louis Helardot | Jerusalem Botanical Gardens | Keith Arboretum, The Charles R. | Kruckeberg Botanic Garden | Lady Bird Johnson Wildflower Center | Landis Arboretum | Le Havre | Le Jardín Le Vasterival | Les chênes plantés à l’Arboretum de La Bergerette | Les Souffrettes | Lewis Ginter Botanical Garden | Lincoln Park Zoo | Linnaean Gardens of Uppsala (Uppsala University), The | Living Desert Zoo & Gardens State Park | Longwood Gardens | Los Angeles County Arboretum and Botanic Garden | Madison Park, Chicago | Madronia Cemetery and Arboretum | Main Botanical Garden of Russian Academy of Sciences, Arboretum (Department of Dendrology) | Marie Selby Botanical Gardens | Masaryk University Faculty of Medicine Medicinal Herbs Centre | Maymont Foundation | Memorial University of Newfoundland Botanical Garden | Mercer Botanic Gardens | Michigan State University | Missouri Botanical Garden | MNHN: Arboretum de Chèvreloup | MNHN: Harmas de Fabre | MNHN: Jardin botanique alpin la Jaysinia | MNHN: Jardin botanique du Val Rahmeh | MNHN: Jardín des Plantes de Paris | Montgomery Botanical Center | Montreal Botanic Garden (Jardin botanique de Montreal) | Moore Farms Botanical Garden | Morris Arboretum of the University of Pennsylvania | Morris Arboretum, The | Morris County Park Commission | Morton Arboretum, The | Moscow State University Botanical Garden | Mount Auburn Cemetery | Mount Lofty Botanic Garden | Mt. Airy Arboretum | Mt. Cuba Center | Muséum National d'Histoire Naturelle | Nanjing Botanical Garden Memorial Sun Yat-Sen | Naples Botanical Garden | National Arboretum Canberra | National Botanic Garden of Georgia | National Museum “d’Histoire Naturelle”-Seed Bank | National Tropical Botanical Garden | New Plymouth Reserves/ Parklands | New York Botanical Garden | Niagara Parks Botanical Gardens | Nicholas Reis | Norfolk Botanical Garden | North Carolina Arboretum Society, The | North Carolina Botanic Garden | Ohio DNR Park | Orto Botánico dell'Università degli studi di Siena | Orto Botánico dell'Universita di Pavia | Paignton Zoo Environmental Park | Palomar College | Parque Ecológico y Estación Experimental la Soledad | Patterson Garden Arboretum | PCN Quercus Multisite (APGA) | Peckerwood Garden | Penrice Castle | Polly Hill Arboretum, The | Pukekura Park | Quarryhill Botanical Garden | Quercus Collection of Terry Hanlon | Rancho Santa Ana Botanic Garden | Real Jardín Botánico Juan Carlos I | Red Butte Garden and Arboretum | Regis University Arboretum | Riverwoods Arboretum | Rogów Arboretum of Warsaw University of Life Sciences | Royal Botanic Garden Edinburgh | Royal Botanic Garden Kew | Royal Botanic Gardens Sydney | Royal Botanic Gardens Victoria | Royal Botanical Gardens, Hamilton | Royal Botanical Gardens, Ontario | Royal Tasmanian Botanical Gardens | San Diego Botanic Garden | San Diego Zoo Safari Park | San Francisco Botanical Garden | San Luis Obispo Botanic Garden | Santa Barbara Botanic Garden | Sarah P. Duke Gardens | Scott Arboretum of Swarthmore College | Shaw Nature Reserve | Sheffield Botanical Gardens | Sir Harold Hillier Gardens, The | Sister Mary Grace Burns Arboretum of Georgian Court University | Smithsonian Gardens - Tree Collection | St. Andrews Botanic Garden | Starhill Forest Arboretum | State Botanical Garden of Georgia, University of Georgia | State Botanical Garden of Kentucky | Stavanger Botanic Garden | Stephen's Lake Park Arboretum | Stichting Belmonte Arboretum | Tallinn Botanic Garden | Taltree Arboretum | Tasmanian Arboretum Inc., The | Thenford House | Timaru Botanic Gardens | Trompenburg Gardens & Arboretum | Tulsa Botanic Garden | Tupare Garden | Tyler Arboretum | U.S. Botanic Garden | UC Davis Arboretum and Public Garden | United States National Arboretum | Universidad Zamorano | University of British Columbia Botanical Garden | University of California Botanic Garden | University of California Botanical Garden at Berkeley | University of California Davis Arboretum | University of Exeter Grounds | University of Guelph Arboretum | University of Oslo Botanical Garden | University of Turku - Botanic Garden | University of Washington Botanic Gardens | Uppsala Linnaean Gardens | US Capitol Grounds and Arboretum | USDA North Central Regional Plant Introduction Station | VanDusen Botanical Garden | Village of Riverside, Illinois | Von Gimborn Arboretum | W. J. Beal Botanical Garden and Campus Arboretum | Wellington Botanic Garden | Wesleyan College Arboretum | West Chester University Arboretum | West Laurel Hill Cemetery | Willowwood Arboretum | Winona State University, The Landscape Arboretum at | Wynkcoombe Arboretum | Xishuangbanna Tropical Botanical Garden | Yorkshire Arboretum, The | Zoo and BG Plzeň

Quercus costaricensis (Francisco Garin)

APPENDIX B

Details regarding *ex situ* surveys performed by The Morton Arboretum and BGCI, which gathered data for *Quercus* species.

Project	Survey year	Data requested	Institutions contacted
Conservation Gap Analysis of Native U.S. Oaks (Beckman et al., 2019)	2017	Genus-level: *Quercus*	Targeted institutions based on those reporting US native oaks to BGCI PlantSearch, plus shared via professional networks (see Beckman et al., 2019 for details)
Conservation Gap Analysis of U.S. Trees in Nine Priority Genera (Beckman et al., 2021)	2018	Genus-level: *Carya, Fagus, Gymnocladus, Juglans, Lindera, Persea, Pinus, Sassafras, Taxus*	Targeted institutions based on those reporting target species to BGCI PlantSearch, plus shared via professional networks (see Beckman et al., 2021 for details)
Quantifying and Sustaining Conservation Value of Four Tree Collections (Beckman Bruns et al., 2023c; Hoban et al., 2023)	2019	Genus-level: *Acer, Magnolia, Malus, Quercus, Tilia, Ulmus*	Targeted institutions based on those reporting target species to BGCI PlantSearch, plus shared via professional networks
Conservation Gap Analysis of Native U.S. Oaks (Beckman et al., 2019)	2020	Genus-level: *Quercus*	Targeted institutions based on those reporting the 29 species of conservation concern (as highlighted in the gap analysis publication) to BGCI PlantSearch, plus shared via professional networks (GCCO mailing list)
Conservation Gap Analysis of Native Mesoamerican Oaks (Good et al., 2024)	2021	Mesoamerican *Quercus*	Targeted institutions based on those reporting Mexico and Central America native oaks to BGCI PlantSearch (who are based in Mexico and Central America), plus shared via contacts from Maricela Rodriguez and Allen Coombes
Conservation Gap Analysis of Native U.S. Oaks (Beckman et al., 2019) **& Conservation Gap Analysis of Native Mesoamerican Oaks** (Good et al., 2024)	2022	Mesoamerican *Quercus*	Targeted institutions based on those reporting the 29 species of conservation concern as highlighted in the gap analysis publication, and the threatened and Data Deficient species native to Mexico and Central America to BGCI PlantSearch, plus shared via professional networks (GCCO mailing list)

APPENDIX C

State-level species richness for target species, by Mesoamerican country.

BELIZE		
State	Number of target species	Species
Belize	0	
Cayo	1	*Q. insignis*
Corozal	0	
Orange Walk	0	
Stann Creek	0	
Toledo	1	*Q. insignis*

Oak forest in San Pablito Pahuatlan, Hidalgo state, Mexico (Maricela Rodríguez-Acosta)

COSTA RICA		
State	Number of target species	Species
Alajuela	2	*Q. costaricensis, Q. insignis*
Cartago	3	*Q. costaricensis, Q. gulielmi-treleasei, Q. insignis*
Guanacaste	1	*Q. insignis*
Heredia	2	*Q. costaricensis, Q. insignis*
Limón	3	*Q. costaricensis, Q. insignis, Q. sarahmariae*
Puntarenas	4	*Q. costaricensis, Q. gulielmi-treleasei, Q. insignis, Q. sarahmariae*
San José	3	*Q. costaricensis, Q. gulielmi-treleasei, Q. insignis*

EL SALVADOR		
State	Number of target species	Species
Ahuachapan	0	
Cabanas	0	
Chalatenango	2	*Q. insignis, Q. vicentensis*
Cuscatlan	0	
La Libertad	0	
La Paz	1	*Q. vicentensis*
La Union	0	
Morazan	0	
San Miguel	1	*Q. vicentensis*
San Salvador	1	*Q. vicentensis*
San Vicente	1	*Q. vicentensis*
Santa Ana	1	*Q. vicentensis*
Sonsonate	0	
Usulutan	0	

Cloud forest converted pasture in San Vito, Costa Rica (The Morton Arboretum)

GUATEMALA		
State	Number of target species	Species
Alta Verapaz	3	*Q. acutifolia, Q. gulielmi-treleasei, Q. insignis*
Baja Verapaz	5	*Q. acutifolia, Q. gulielmi-treleasei, Q. insignis, Q. paxtalensis, Q. vicentensis*
Chimaltenango	4	*Q. acutifolia, Q. gulielmi-treleasei, Q. melissae, Q. paxtalensis*
Chiquimula	3	*Q. gulielmi-treleasei, Q. insignis, Q. vicentensis*
El Progreso	4	*Q. acutifolia, Q. gulielmi-treleasei, Q. insignis, Q. vicentensis*
El Quiché	3	*Q. acutifolia, Q. gulielmi-treleasei, Q. vicentensis*
Escuintla	0	
Guatemala	4	*Q. gulielmi-treleasei, Q. melissae, Q. vicentensis*
Huehuetenango	5	*Q. acutifolia, Q. gulielmi-treleasei, Q. insignis, Q. melissae, Q. vicentensis*
Izabal	0	
Jalapa	4	*Q. acutifolia, Q. gulielmi-treleasei, Q. melissae, Q. vicentensis*
Jutiapa	3	*Q. acutifolia, Q. gulielmi-treleasei, Q. insignis*
Petén	1	*Q. insignis*
Quetzaltenango	1	*Q. acutifolia*
Retalhuleu	0	
Sacatepéquez	3	*Q. acutifolia, Q. paxtalensis, Q. vicentensis*
San Marcos	1	*Q. acutifolia*
Santa Rosa	2	*Q. acutifolia, Q. vicentensis*
Sololá	0	
Suchitepéquez	0	
Totonicapán	2	*Q. acutifolia, Q. vicentensis*
Zacapa	2	*Q. acutifolia, Q. gulielmi-treleasei*

HONDURAS		
State	Number of target species	Species
Atlantida	0	
Choluteca	1	*Q. insignis*
Colon	0	
Comayagua	2	*Q. acutifolia, Q. insignis*
Copan	0	
Cortes	0	
El Paraiso	1	*Q. insignis*
Francisco	4	*Q. acutifolia, Q. gracilior, Q. gulielmi-treleasei, Q. insignis*
Morazan	0	
Gracias a Dios	0	
Intibuca	0	
Islas de la Bahia	2	*Q. gulielmi-treleasei, Q. insignis*
La Paz	0	
Lempira	2	*Q. gulielmi-treleasei, Q. vicentensis*
Ocotepeque	1	*Q. insignis*
Olancho	1	*Q. insignis*
Santa Barbara	0	
Valle	1	*Q. insignis*
Yoro		

MEXICO		
State	Number of target species	Species
Aguascalientes	0	
Baja California	4	*Q. cedrosensis, Q. dumosa, Q. engelmannii, Q. tomentella*
Baja California Sur	3	*Q. ajoensis, Q. brandegeei, Q. devia*
Campeche	0	
Chiapas	8	*Q. acutifolia, Q. breedloveana, Q. ghiesbreghtii, Q. insignis, Q. melissae, Q. mulleri, Q. paxtalensis, Q. vicentensis*
Chihuahua	5	*Q. aerea, Q. barrancana, Q. deliquescens, Q. perpallida, Q. toumeyi*
Coahuila	5	*Q. carmenensis, Q. coahuilensis, Q. cupreata, Q. galeanensis, Q. hintoniorum*
Colima	2	*Q. acutifolia, Q. nixoniana*
Durango	3	*Q. aerea, Q. radiata, Q. undata*
Guanajuato	0	
Guerrero	7	*Q. acutifolia, Q. breedloveana, Q. grahamii, Q. hintonii, Q. insignis, Q. nixoniana, Q. rubramenta*
Hidalgo	10	*Q. acherdophylla, Q. delgadoana, Q. diversifolia, Q. grahamii, Q. hirtifolia, Q. meavei, Q. opaca, Q. tinkhamii, Q. toxicodendrifolia, Q. trinitatis*
Jalisco	10	*Q. acutifolia, Q. centenaria, Q. coffeicolor, Q. cualensis, Q. grahamii, Q. insignis, Q. mexiae, Q. nixoniana, Q. radiata, Q. tuitensis*
México	4	*Q. acutifolia, Q. diversifolia, Q. grahamii, Q. hintonii*
Mexico City	1	*Q. diversifolia*
Michoacán	2	*Q. acutifolia, Q. grahamii*
Morelos	1	*Q. diversifolia*
Nayarit	4	*Q. centenaria, Q. coffeicolor, Q. insignis, Q. radiata*
Nuevo León	12	*Q. cupreata, Q. flocculenta, Q. galeanensis, Q. graciliformis, Q. hintoniorum, Q. miquihuanensis, Q. opaca, Q. porphyrogenita, Q. runcinatifolia, Q. supranitida, Q. tinkhamii, Q. verde*
Oaxaca	10	*Q. acherdophylla, Q. acutifolia, Q. grahamii, Q. insignis, Q. macdougallii, Q. mulleri, Q. nixoniana, Q. paxtalensis, Q. rekonis, Q. rubramenta*
Puebla	12	*Q. acherdophylla, Q. acutifolia, Q. delgadoana, Q. diversifolia, Q. ghiesbreghtii, Q. grahamii, Q. hirtifolia, Q. insignis, Q. meavei, Q. paxtalensis, Q. toxicodendrifolia, Q. trinitatis*
Querétaro	2	*Q. diversifolia, Q. tinkhamii*
Quintana Roo	0	
San Luis Potosí	4	*Q. galeanensis, Q. meavei, Q. opaca, Q. tinkhamii*
Sinaloa	2	*Q. coffeicolor, Q. perpallida*
Sonora	4	*Q. barrancana, Q. ignaciensis, Q. perpallida, Q. toumeyi*
Tabasco	0	
Tamaulipas	10	*Q. cupreata, Q. galeanensis, Q. hintoniorum, Q. miquihuanensis, Q. opaca, Q. paxtalensis, Q. porphyrogenita, Q. runcinatifolia, Q. tinkhamii, Q. verde*
Tlaxcala	1	*Q. grahamii*
Veracruz	10	*Q. acherdophylla, Q. acutifolia, Q. delgadoana, Q. grahamii, Q. hirtifolia, Q. insignis, Q. meavei, Q. paxtalensis, Q. toxicodendrifolia, Q. trinitatis*
Yucatán	0	
Zacatecas	1	*Q. radiata*

NICARAGUA

State	Number of target species	Species
Boaco	1	*Q. insignis*
Carazo	0	
Chinandega	0	
Chontales	0	
Estelí	1	*Q. insignis*
Granada	0	
Jinotega	1	*Q. insignis*
Leon	0	
Madriz	0	
Managua	0	
Masaya	0	
Matagalpa	1	*Q. insignis*
Nueva Segovia	1	*Q. insignis*
Rivas	0	
Río San Juan	0	
North Caribbean Coast Autonomous Region	1	*Q. gracilior*
South Caribbean Coast Autonomous Region	0	

PANAMA

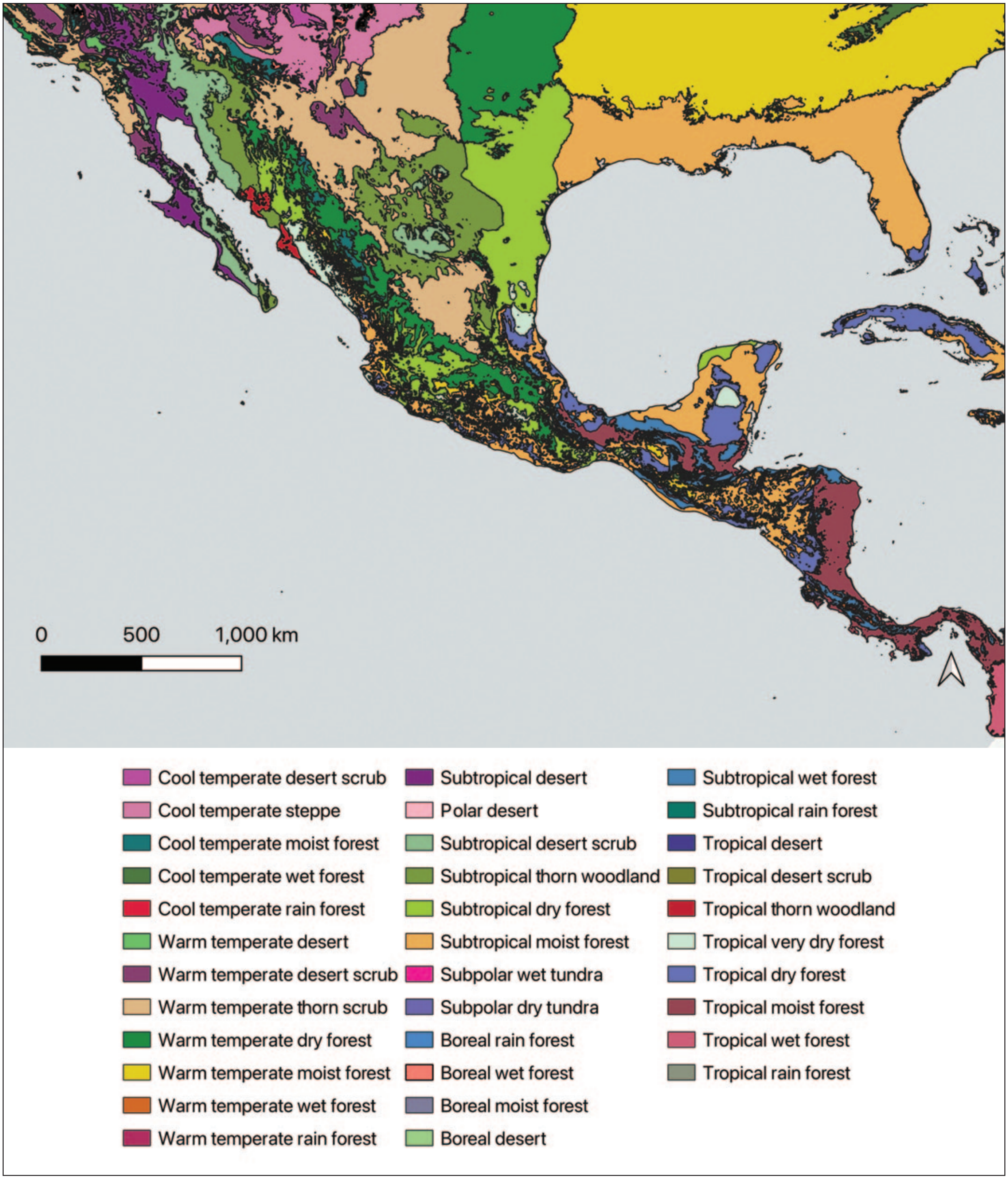
State	Number of target species	Species
Bocas del Toro	1	*Q. costaricensis*
Chiriquí	3	*Q. gulielmi-treleasei, Q. insignis, Q. sarahmariae*
Coclé	1	*Q. gulielmi-treleasei*
Colón	0	
Darién	0	
Herrera	0	
Los Santos	0	
Panamá	1	*Q. gulielmi-treleasei*
Veraguas	0	

Pahuatlan Oak forest (Maricela Rodríguez-Acosta)

Quercus trinitatis (Francisco Garin)

APPENDIX D

Holdridge life zone map of Mesoamerica.



APPENDIX E

Summary results of ex *situ* collections surveys for target Mesoamerican species.

Species Name	Number of ex *situ* collections reporting this species	Number of plants in ex situ collections	Number of plants marked as wild origin	Number of wild plants of known locality
Quercus acherdophylla	19	36	19	16
Quercus acutifolia	34	91	34	17
Quercus aerea	0	0	0	0
Quercus ajoensis	9	87	72	62
Quercus barrancana	1	1	1	1
Quercus brandegeei	10	49	32	13
Quercus breedloveana	0	0	0	0
Quercus carmenensis	4	6	4	2
Quercus cedrosensis	2	6	6	6
Quercus centenaria	0	0	0	0
Quercus coahuilensis	0	0	0	0
Quercus coffeicolor	1	3	0	0
Quercus costaricensis	3	9	8	5
Quercus cualensis	1	4	4	4
Quercus cupreata	6	19	18	18
Quercus delgadoana	11	20	4	4
Quercus deliquescens	6	39	38	38
Quercus devia	0	0	0	0
Quercus diversifolia	4	7	5	0
Quercus dumosa	23	359	299	297
Quercus engelmannii	32	2604	225	160
Quercus flocculenta	3	7	5	5
Quercus galeanensis	9	20	4	3
Quercus ghiesbreghtii	0	0	0	0
Quercus graciliformis	24	189	74	18
Quercus gracilior	0	0	0	0
Quercus grahamii	7	25	7	2
Quercus gulielmi-treleasei	4	4	3	3
Quercus hintonii	3	4	1	1
Quercus hintoniorum	10	21	12	10
Quercus hirtifolia	10	21	14	12
Quercus ignaciensis	0	0	0	0
Quercus insignis	24	65	36	30
Quercus macdougallii	1	1	0	0
Quercus meavei	3	6	2	2
Quercus melissae	0	0	0	0
Quercus mexiae	0	0	0	0
Quercus miquihuanensis	16	26	9	0
Quercus mulleri	0	0	0	0
Quercus nixoniana	0	0	0	0
Quercus opaca	1	3	3	3
Quercus paxtalensis	0	0	0	0

Species Name	Number of ex *situ* collections reporting this species	Number of plants in ex *situ* collections	Number of plants marked as wild origin	Number of wild plants of known locality
Quercus perpallida	0	0	0	0
Quercus porphyrogenita	4	5	5	3
Quercus radiata	0	0	0	0
Quercus rekonis	0	0	0	0
Quercus rubramenta	0	0	0	0
Quercus runcinatifolia	1	1	0	0
Quercus sarahmariae	0	0	0	0
Quercus supranitida	0	0	0	0
Quercus tinkhamii	1	1	1	1
Quercus tomentella	28	99	28	13
Quercus toumeyi	8	22	10	7
Quercus toxicodendrifolia	2	2	2	2
Quercus trinitatis	1	4	4	0
Quercus tuitensis	0	0	0	0
Quercus undata	0	0	0	0
Quercus verde	0	0	0	0
Quercus vicentensis	3	9	9	5

Quercus peduncularis in El Salvador (Roderick Cameron)

APPENDIX F

The Holdridge life zone in which each arboretum and botanic garden in Mesoamerica is found (as reported to BGCI GardenSearch as of November 2023), as well as a list of target oak species that occur within that life zone. Species names that are colored red are those species for which the greatest number of occurrence points occur within the life zone. Note: a complete analysis identifying the botanic gardens and arboreta in GardenSearch that have the facilities necessary to establish oaks in living collections has not been done. However, it is estimated that approximatley 60% of the gardens listed below have the potential to add oaks to their collections and participate in conservation activities (Maricela Rodríguez-Acosta and Allen Coombes, personal communication, 2024).

SUBTROPICAL DESERT

Botanic gardens and arboreta

- Jardín Botánico 'Ing. Gustavo Aguirre Benavides' (Mexico)
- Jardín Botánico ISIMA-UJED (Mexico)
- Jardín Botánico 'Jerzy Rzedowski Rotter' (Mexico)

Species

Q. cedrosensis
Q. tomentella

Quercus brandegeei (The Morton Arboretum)

Quercus agrifolia riparian corridor (Jésus Serrano)

SUBTROPICAL DRY FOREST

Botanic gardens and arboreta

- El Jardín de Piedras (Mexico)
- Jardín AgroBotánico del Centro Regional Universitario Península de Yucatán (Mexico)
- Jardín Botánico de Culiacán (Mexico), Jardín Botánico de la Universidad Autónoma de Guerrero (Mexico)
- Jardín Botánico Didáctico Instituto de Botánica CUCBA (Mexico)
- Jardín Botánico Dra. Luz María Villarreal de Puga (Mexico)
- Jardín Botánico 'Jorge Victor Eller T.' (Mexico)
- Jardín Botánico Regional Cassiano Conzatti (Mexico)
- Jardín Botánico Regional 'Roger Orellana' (Mexico)
- Jardín Botánico Tropical Comala, A.C. (Mexico)
- Jardín Etnobotánico de Oaxaca (Mexico)
- Orquidario de Morelia (Mexico)
- Pabellón de las Orquídeas Ye'Tsil (Mexico)
- Escuela Agrícola Panamericana (Honduras)
- Zamorano Botanical Garden (Honduras)

Species

Q. barrancana
Q. brandegeei
Q. coahuilensis
Q. coffeicolor
Q. cupreata
Q. devia
Q. diversifolia
Q. engelmannii
Q. flocculenta
Q. galeanensis
Q. graciliformis
Q. grahamii
Q. hintoniorum
Q. insignis
Q. miquihuanensis
Q. nixoniana
Q. opaca
Q. paxtalensis
Q. perpallida
Q. porphyrogenita
Q. radiata
Q. rubramenta
Q. runcinatifolia
Q. tinkhamii
Q. toumeyi
Q. trinitatis

SUBTROPICAL MOIST FOREST

Botanic gardens and arboreta

- Arboretum de la Universidad Autónoma de Campeche (Mexico)
- Jardín Botánico de Acalpulco 'Esther Pliego de Salinas' (Mexico)
- Jardín Botánico de Hampolol (Mexico)
- Jardín Botánico de La Facultad de Ciencias Agronòmicas, UNACH (Mexico)
- Jardín Botánico 'Dr. Alfredo Barrera Marín' de ECOSUR (Mexico)
- Jardín Botánico Dr. Faustino Miranda (Mexico)
- Jardín Botánico Estatal 'Toka, Naturaleza y Cultura' (Mexico)
- Jardín Botánico Francisco Javier Clavijero (Mexico)
- Jardín Botánico Haravéri (Mexico)
- Jardín Botánico Hernando Ruiz de Alarcón (Mexico)
- Jardín Botánico Puerto Escondido (Mexico)
- Jardín Botánico Regional Carmen de la Unacar (Mexico)
- Jardín EtnoBotánico y Museo de Medicina Tradicional y Herbolaria (Mexico)
- Vallarta Botanical Gardens, A.C. (Mexico)
- Jardín Botánico CECON-USAC (Guatemala)
- Jardín Botánico La Laguna (El Salvador)
- Fundación el árbol (Nicaragua)
- Jardín Botánico Ambiental (Nicaragua)
- Jardín Botánico Municipal Perez Estrada (Honduras)

Species

Q. acherdophylla
Q. acutifolia
Q. breedloveana
Q. centenaria
Q. cualensis
Q. delgadoana
Q. gracilior
Q. grahamii
Q. gulielmi-treleasei
Q. hintonii
Q. insignis
Q. meavei
Q. melissae
Q. mexiae
Q. mulleri
Q. nixoniana
Q. paxtalensis
Q. perpallida
Q. radiata
Q. rekonis
Q. rubramenta
Q. toxicodendrifolia
Q. trinitatis
Q. tuitensis
Q. vicentensis

SUBTROPICAL THORN WOODLAND

Botanic gardens and arboreta

- EcoParque COLEF (Mexico)
- Jardín Botánico Universidad Autónoma de Baja California (Mexico)
- Proyecto Jardín Botánico del Desierto Chihuahuense (Mexico)

Species

Q. acutifolia
Q. ajoensis
Q. brandegeei
Q. cedrosensis
Q. coahuilensis
Q. deliquescens
Q. devia
Q. dumosa
Q. engelmannii
Q. graciliformis
Q. ignaciensis
Q. miquihuanensis
Q. opaca
Q. tinkhamii
Q. toumeyi

SUBTROPICAL WET FOREST

Botanic gardens and arboreta

- Jardín Etnobiológico de las selvas del Soconusco (Mexico)
- Blue Harbor Tropical Arboretum (Honduras)
- Jardín Botánico Lancetilla (Honduras)
- Else Kientzler Botanical Garden (Costa Rica)
- Hotel Bougainvillea Botanical Garden (Costa Rica)
- Jardín Botánico José Maria Orozco (JBO) (Costa Rica)
- Jardín Botánico Lankester (Costa Rica)
- La Selva's Holdridge Arboretum (Costa Rica)
- The Green Ark Foundation (Costa Rica)
- Robert & Catherine Wilson Botanical Garden (Costa Rica)
- Crater Valley Gardens (Panama)
- Jardín Botánico Arco Luna (Panama)
- Rainforest Foundation (Panama)

Species

Q. acherdophylla
Q. acutifolia
Q. costaricensis
Q. delgadoana
Q. grahamii
Q. gulielmi-treleasei
Q. hirtifolia
Q. insignis
Q. meavei
Q. mulleri
Q. nixoniana
Q. paxtalensis
Q. sarahmariae
Q. trinitatis
Q. vicentensis

TROPICAL DRY FOREST

Botanic gardens and arboreta

- Jardín Botánico y Arboreta de Alta Cima (Mexico)
- Belize Botanic Gardens (Belize)
- Botanic and Zoological Garden (Belize)
- Twin Town Botanic Garden (Belize)
- Arboretum Anita Holmann (Nicaragua)
- Parque Municipal Summit (Panama)

Species

Q. acutifolia
Q. grahamii
Q. hintonii
Q. insignis
Q. nixoniana
Q. paxtalensis
Q. rubramenta
Q. vicentensis

TROPICAL MOIST FOREST

Botanic gardens and arboreta

- Arboretum del Bosque Seco Tropical (Costa Rica)
- Área de Conservación Guanacaste (Costa Rica)
- Flores y Follajes del Caribe S.A. (Costa Rica)
- Jardín EtnoBotánico Dominga (Costa Rica)
- Osa Conservation (Costa Rica)
- Federacion de Clubes de Jardinería de Panama (Panama)
- Finca Los Monos Botanical Garden (Panama)
- Universidad de Panamá, Herbario (PMA) (Panama)

Species

Q. acutifolia
Q. gracilior
Q. gulielmi-treleasei
Q. vicentensis

WARM TEMPERATE DRY FOREST

Botanic gardens and arboreta

- Asociación Mexicana de Orquideologia A.C. (Mexico)
- EcoJardín Instituto Investigaciones en Ecosistemas y Sustentabilidad (Mexico)
- Jardín Botánico de Ciceana (Mexico)
- Jardín Botánico de Fundación Xochitla (Mexico)
- Jardín Botánico de las Plantas Medicinales 'Maximino Martinez' (Mexico)
- Jardín Botánico del Instituto de Biología (UNAM) (Mexico)
- Jardín Botánico El Charco del Ingenio (Mexico)
- Jardín Botánico Facultad de Ciencias Naturales UAQ (Mexico)
- Jardín Botánico Facultad de Estudios Superiores Cuautitlán UNAM (Mexico)
- Jardín Botánico "Louise Wardle de Camacho" (Mexico)
- Jardín Botánico 'Ollintepetl' (Mexico)
- Jardín Botánico San Juan Bautista De La Salle (Mexico)
- Jardín Botánico Tizatlán (Mexico)
- Jardín Botánico Universitario de la Benemérita Universidad Autónoma de Puebla (JBU-BUAP) (Mexico)
- Jardín Botánico Xochiltlalyocan UAM-Xochimilco (Mexico)
- Jardín EtnoBotánico Francisco Peláez R. A.C (Mexico)
- Jardín EtnoBotánico Tzapoteca 'Dra Helia Bravo Hollis' (Mexico)

Species

Q. acherdophylla
Q. acutifolia
Q. aerea
Q. barrancana
Q. brandegeei
Q. carmenensis
Q. coahuilensis
Q. coffeicolor
Q. cupreata
Q. delgadoana
Q. devia
Q. diversifolia
Q. dumosa
Q. engelmannii
Q. flocculenta
Q. galeanensis
Q. graciliformis
Q. grahamii
Q. hintoniorum
Q. hirtifolia
Q. meavei
Q. miquihuanensis
Q. opaca
Q. perpallida
Q. porphyrogenita
Q. radiata
Q. runcinatifolia
Q. supranitida
Q. tinkhamii
Q. toumeyi
Q. toxicodendrifolia
Q. trinitatis
Q. undata
Q. verde

WARM TEMPERATE DESERT SCRUB

Botanic gardens and arboreta

- Jardín Botánico de San Quintín (Mexico)

Species

Q. cedrosensis	*Q. tomentella*
Q. dumosa	*Q. toumeyi*

WARM TEMPERATE MOIST FOREST

Botanic gardens and arboreta

- Museo de la Medicina Maya (Mexico)
- Orquidario Moxquivil (Mexico)

Species

Q. acherdophylla	*Q. macdougallii*
Q. acutifolia	*Q. meavei*
Q. barrancana	*Q. melissae*
Q. centenaria	*Q. mexiae*
Q. cualensis	*Q. mulleri*
Q. delgadoana	*Q. nixoniana*
Q. diversifolia	*Q. paxtalensis*
Q. ghiesbreghtii	*Q. perpallida*
Q. gracilior	*Q. radiata*
Q. grahamii	*Q. rubramenta*
Q. gulielmi-treleasei	*Q. toxicodendrifolia*
Q. hintonii	*Q. trinitatis*
Q. hirtifolia	*Q. tuitensis*
Q. insignis	*Q. vicentensis*

WARM TEMPERATE WET FOREST

Botanic gardens and arboreta

- Green Mountain Cloud Forest Gardens (Costa Rica)

Species

Q. acutifolia	*Q. meavei*
Q. costaricensis	*Q. paxtalensis*
Q. gulielmi-treleasei	*Q. sarahmariae*
Q. insignis	*Q. toxicodendrifolia*
Q. macdougallii	*Q. vicentensis*

WARM TEMPERATE THORN SCRUB

Botanic gardens and arboreta

- Jardín Botánico El Izotal (Mexico)
- Jardín Botánico Regional de Cadereyta 'Ing. Manuel González de Cosío' (Mexico)
- Jardín Botánico 'Rey Nezahualcóyotl' (Mexico)

Species

Q. acutifolia	*Q. graciliformis*
Q. carmenensis	*Q. grahamii*
Q. cedrosensis	*Q. hintoniorum*
Q. coahuilensis	*Q. miquihuanensis*
Q. cupreata	*Q. opaca*
Q. deliquescens	*Q. tinkhamii*
Q. dumosa	*Q. tomentella*
Q. engelmannii	*Q. toumeyi*
Q. flocculenta	*Q. verde*
Q. galeanensis	

Quercus grisea in ejido la Casita, Nuevo Léon, Mexico (The Morton Arboretum)

APPENDIX G

Species Profiles for each of the 32 threatened and 27 Data Deficient species can be accessed at the link provided in the table below. The page numbers within the full electronic report are also given.

Species	URL	Page numbers
Quercus acutifolia	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-acutifolia	69-76
Quercus ajoensis	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-ajoensis	77-84
Quercus brandegeei	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-brandegeei	85-92
Quercus carmenensis	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-carmenensis	93-100
Quercus cedrosensis	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-cedrosensis	101-108
Quercus costaricensis	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-costaricensis	109-116
Quercus cualensis	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-cualensis	117-124
Quercus cupreata	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-cupreata	125-132
Quercus delgadoana	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-delgadoana	133-140
Quercus devia	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-devia	141-148
Quercus diversifolia	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-diversifolia	149-156
Quercus dumosa	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-dumosa	157-164
Quercus engelmannii	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-engelmannii	165-172
Quercus flocculenta	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-flocculenta	173-180
Quercus galeanensis	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-galeanensis	181-188
Quercus graciliformis	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-graciliformis	189-196
Quercus gulielmi-treleasei	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-gulielmi-treleasei	197-204
Quercus hintonii	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-hintonii	205-212
Quercus hintoniorum	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-hintoniorum	213-220
Quercus hirtifolia	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-hirtifolia	221-228
Quercus insignis	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-insignis	229-236
Quercus macdougallii	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-macdougallii	237-244
Quercus meavei	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-meavei	245-252
Quercus miquihuanensis	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-miquihuanensis	253-260
Quercus mulleri	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-mulleri	261-268
Quercus nixoniana	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-nixoniana	269-276
Quercus radiata	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-radiata	277-284
Quercus rubramenta	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-rubramenta	285-292
Quercus runcinatifolia	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-runcinatifolia	293-300
Quercus tomentella	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-tomentella	301-308
Quercus tuitensis	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-tuitensis	309-316
Quercus vicentensis	mortonarb.org/gap-analysis/mesoamerica/species-profile-quercus-vicentensis	317-324
Data Deficient species	mortonarb.org/gap-analysis/mesoamerica/species-profile-data-deficient	325-384

Conservation Gap Analysis of Native

Mesoamerican Oaks

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