RESEARCH ARTICLE

Frontiers of Biogeography
the scientific journal of
the International Biogeography Society

Defining the extent of suitable habitat for the endangered Maple-Leaf oak (*Quercus acerifolia*)

Suresh Chandra Subedi[1]*, Boone Ruston[1], J. Aaron Hogan[2], and Mark V. Coggeshall[3,4]

[1]Department of Biological Sciences, Arkansas Tech University, Russellville, AR, 72801, USA;

[2]Department of Biology, University of Florida, Gainesville, FL, USA;

[3]USDA Forest Service, Northern Research Station, Hardwood Tree Improvement Regeneration Center, Purdue University, 715 West State St. West Lafayette, IN 47907, USA;

[4]School of Natural Resources, 203 ABNR Building, University of Missouri, Columbia, MO, 65211, USA.

*Correspondence: Suresh Chandra Subedi, ssubedi2@atu.edu

Abstract

The Maple-leaf oak, *Quercus acerifolia* (E.J.Palmer) Stoynoff & Hess, is listed as Critically Imperiled by the State of Arkansas and considered endangered in the IUCN Red List of Threatened Oak Species. It is endemic to the interior highlands of the Ouachita Mountains in west-central Arkansas, where it is reported to occur in only four isolated locations. No specific research exists regarding predicted climate change impacts on the *Q. acerifolia*, but given its small range and habitat specificity, such climate change-driven impacts will likely pose significant risks to remaining populations. We used an ensemble species distribution modeling (SDM) approach to predict climatically suitable habitat for *Q. acerifolia* within its native range. We investigate how future changes in climate may impact habitat suitability. Currently, the estimated area of climatically suitable habitat area for *Q. acerifolia* is 2,523 km^2. By 2050, the predicted climatically suitable habitat area is 749 km^2, a 70% reduction in habitat extent. By 2100, the model ensemble predicts a suitable habitat of only 285 km^2 or an 89% loss of present suitable habitat. The model ensemble also predicted climatically suitable habitat area in 20 counties (14 in Arkansas and six in Oklahoma), including the currently known four locations in Arkansas. Although *Q. acerifolia* is rare and is at risk of extinction due to potential climate-change driven habitat reduction, the SDM ensemble identified several new habitat areas for the species. New habitat information can be used to search for existing *Q. acerifolia* populations or guide reintroduction efforts, leading to enhanced focus on long-term management, conservation, and restoration of this critically-imperiled species.

Highlights

- Climate change-driven impacts will likely pose significant risks to endangered species.
- We show how ecological niche modeling under climate change can inform the conservation of *Q. acerifolia.*
- We predict suitable habitat for *Q. acerifolia* in 20 counties (Arkansas and Oklahoma) including four currently known locations in Arkansas.
- Bioclimatic and topographic variables were identified as influential factors that affect the distribution of *Q. acerifolia*.
- This study provides important information on the requirements and suitable habitats that will facilitate future restoration efforts, with the goal of increasing population sizes of *Q. acerifolia* across its range.

Keywords: Biomod2, conservation, endangered species, native species, oak, species distribution modelling, suitable habitat

e-ISSN: 1948-6596 https://escholarship.org/uc/fb doi:10.21425/F5FBG58763

Introduction

Oaks (*Quercus* spp.) are keystone species found across a wide range of ecosystems worldwide, including oak-pine forests in North America. They are ecologically valuable because they support critical ecosystem functions, such as hosting unique soil fungal communities which contribute to forest carbon cycling dynamics (Phillips et al. 2013), as well as provide food and habitat for many species of animals (Jerome et al. 2017). Due to the broad range of habitat types and climates found across the continental Unites States, oak species significantly contribute to North American forest species diversity. Out of 91 native U.S. oaks, 28 species are of conservation concern, including some that are critically imperiled (Beckman et al. 2019). One such species is Maple-leaf oak, *Quercus acerifolia* (E.J.Palmer) Stoynoff & Hess, which is endemic to the interior highlands of the Ouachita and Boston Mountains region in west-central Arkansas. *Q. acerifolia* is distributed in only four populations across this area (Fig. 1, Ogle et al. 2020). The species is at risk of extinction, as the total known population size is believed to be fewer than 600 individuals, with just a few individuals per site. It is listed as both Critically Imperiled by the State of Arkansas and as Endangered, per the IUCN Red List of Threatened Species (Beckman et al. 2019).

Despite existing conservation efforts (e.g., *ex-situ* conservation at the Cincinnati Zoo, U.S. National Arboretum, Morton Arboretum and Missouri Botanical Garden, an enhanced focus on establishing new protected areas, and sponsoring education and awareness programs for this species is ongoing), *Q. acerifolia* is facing conservation challenges due to small population sizes, unknown habitat preferences, diseases, insect pests and climate change (Larson 2017, Beckman et al. 2019). The inadequacy of currently available habitat is a challenge for any species of conservation concern, and a better understanding of habitat preferences for imperiled species is an important first step in developing active management strategies for existing populations and highlighting possible new interactions of the species within natural forests (Scott et al. 1993). Although a few studies have recently focused on the *ex-situ* conservation of *Q. acerifolia* in botanic gardens and arboretums (Larson 2017, Beckman et al. 2019), defining its current habitat range, extent of suitable habitat, and possible consequences of climate change in these areas are key to advancing future restoration efforts in natural forests.

The potential risk factors for *Q. acerifolia* population decline (e.g., drought, disturbance, insect and disease pressures) will likely intensify in the future, due to the impacts of climate change (McDowell et.al. 2020). No specific research exists regarding predicted climate change impacts on *Q. acerifolia*, but its limited range and habitat specificity could pose significant challenges to recruitment and population stability within a changing climate (Beckman et al. 2019). According to Conservation Gap Analysis of North American Oaks, research related to ecological niche modeling under climate change should prioritize the conservation of *Q. acerifolia*. To shed light on this, we used species distribution models to predict suitable habitats for *Q. acerifolia* within its native range and investigated the impacts of different climate scenarios on future habitat suitability.

Species distribution models (SDMs) have become a well-accepted tool for understanding the environment of organisms, evaluating habitat quality, and directing management and conservation strategies (Guisan et al. 2017, Adhikari et al. 2022). SDMs define a species-environment relationship to explain and predict the habitat extent of a species' potential distribution (Guisan et al. 2013). A set of scenarios (low, intermediate, high, and extreme) were developed, known as shared socioeconomic pathways (SSPs).

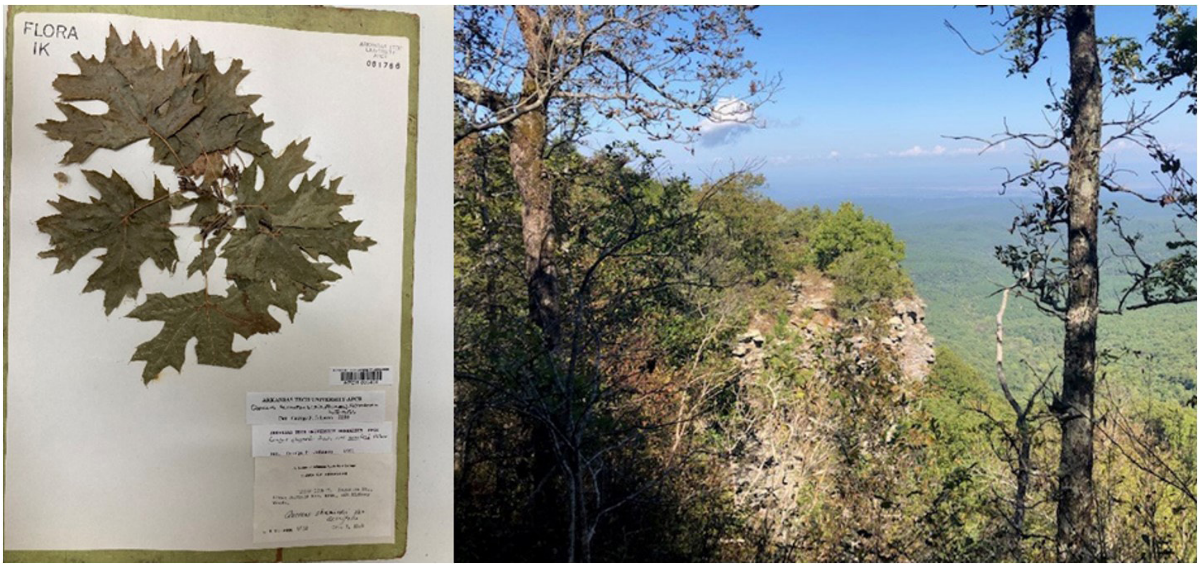

Figure 1. Maple-leaf oak (*Quercus acerifolia*) herbarium specimen and its habitat in a Mount Magazine State Park (Arkansas). Photograph taken by Ryan Russell.

These scenarios are projections of anticipated worldwide socioeconomic trends through the year 2100 and are usually applied to create scenarios for greenhouse gas emissions (GHG) under various climate policies (Rogelj et al. 2018). By incorporating different climate change scenarios, SDMs are effective to predict current and future suitable habitats for species (Coetzee et al. 2009, Bladon et al. 2021, Sierra-Morales et al. 2021). Many recent SDM studies have used the "ensemble" SDM methodology, which incorporates predictions from multiple modeling techniques to make better and more accurate predictions (Meller et al. 2014, Hao et al. 2019, Ahmad et al. 2020). Furthermore, SDMs have the potential to contribute to conservation planning goals by augmenting knowledge of species distributions (Raymond et al. 2020) and predicting the impacts of climate change on species (Schwartz 2012, Foden and Young 2016). SDMs that predict future climate change events can help to prioritize both present and future biodiversity conservation efforts by identifying newly available habitats under changing climate (Bellard et al. 2012, Schwartz 2012).

Utilizing a reliable method of ensemble SDM, by incorporating the effects of topographic and climatic variables, could effectively address the gap in knowledge regarding the extent of distribution and conservation practices of endangered species. This study has two objectives: 1) to evaluate the current extent of *Q. acerifolia* distribution and the variables influencing it; and 2) ascertain how this endangered species' range might shift under future climate change scenarios. We hypothesized that the distribution of *Q. acerifolia* is largely concentrated in its native area in Arkansas, and its distributional range should decline with climatic change.

Materials and Methods

Records of *Q. acerifolia* presence were acquired from both current populations and historical collections (herbarium specimens), from multiple herbaria via the Southeast Regional Network of Collections (Data Portal 2022), encompassing 130 herbarium records from 22 herbaria, and the Global Biodiversity Information Facility (GBIF.org 2022), representing 157 records. Any duplicate, cultivated, and questionable records (hybrids, or outside of their natural habitats) were removed. Overall, we compiled a database of 197 *Q. acerifolia* presence locations based on historical and current records between 1970-2000 to match bioclimatic data for the current climate (1970–2000) and geolocated them.

We used the R package 'SpThin' (Aiello-Lammens et al. 2015) to spatially rarefy the occurrence dataset to ensure that no two points were within a 1km × 1km grid. Therefore, we had no more than one presence at each grid cell (1 km^2) to reduce spatial autocorrelation and avoid inflated measures of accuracy. One-kilometer buffers were placed around each occurrence point. This method also reduces sample bias and improves the predictive performance of the models (Boria et al. 2014).

In this study, suitable habitat for *Q. acerifolia* is defined as the combination of abiotic environmental variables at a site (topographic and bioclimatic variables) – often referred to as environmental suitability, i.e. environmental conditions needed for a species to grow and maintain its viable populations. Bioclimatic and topographic variables were used to predict the current and future suitable habitat extent for *Q. acerifolia* in Arkansas, and adjacent states (Kansas, Oklahoma, Tennessee, Missouri, Texas, Mississippi, and Louisiana), as well as other southeastern states (Alabama, Georgia, South Carolina, and North Carolina) because there are some unconfirmed reports of this species might present in Alabama, Georgia, Missouri, Oklahoma, and Tennessee (Ogle et al. 2020). Altogether, 22 environmental (i.e., 19 bioclimatic and three topographic) variables were considered (Table S1; https://www.worldclim.org/data/bioclim.html).

Environmental variables were checked for multi-collinearity, where we excluded those with correlation coefficients >0.7 and variance inflation factors (VIF) >5 (Dormann et al. 2013, Table S2, Fig. S1). Eleven variables were retained for further analysis (elevation, slope, aspect, mean diurnal temperature range, isothermality, mean temperature of wettest quarter, mean temperature of driest quarter, mean temperature of warmest quarter, precipitation of wettest month, precipitation seasonality, precipitation of warmest quarter). All variables were projected to WGS84 at a spatial resolution of 1 km^2. Nineteen bioclimatic variables for the current climate (1970–2000) and future (2050 and 2100) from WorldClim— Global Climate Data (https://www.worldclim.org/) were downloaded. It was evident that the topographic variables, elevation, aspect, and slope had a predictive influence on the habitat suitability of *Q. acerifolia* (Stoynoff and Hess 1990). While elevation may only indirectly influence plant physiology and may not be relevant to use in SDMs making climate change projections, SDMs for high-elevation plant species have showed that elevation is an essential predictor in future SDMs for mountain species (Oke and Thomson, 2015). The distribution of *Q. acerifolia* only occurs on between bluff outcroppings (Rouw and Johnson, 1994), above 400m and mountain summits around 800-900 m elevation (Beckman et al. 2019). So, we have included elevation as a predictor in SDMs which make climate change projections for *Q. acerifolia.* Thus, model will predict a higher occurrence probability above the 400m elevation. The use of elevation with bioclimatic variables likely leads to more accurate SDMs for *Q. acerifolia*. We derived elevation data from the United States Geological Survey Digital Elevation Model (DEM) database, ~3m resolution, (https://earthexplorer.usgs.gov/). Slope and aspect data were calculated from the DEM with the help of ArcGIS software (esri.com).

As recent SDM studies have successfully achieved improved predictive accuracy by combining models generated from several algorithms (Hao et al. 2020, Adhikari et al. 2023), rather than a single algorithm in SDM (e.g., MAXENT), we used an ensemble modeling approach to develop the habitat suitability models.

We generated ensemble models based on nine algorithms: artificial neural network (ANN), classification tree analysis (CTA), flexible discriminant analysis (FDA), generalized additive model (GAM), generalized boosting model (GBM), generalized linear model (GLM), maximum entropy (MAXENT), random forest (RF), and surface range envelope (SRE) using the BIOMOD2 package (Thuiller et al. 2020) in R v4.0.0 (R Development Core Team 2020). *Q. acerifolia* presence and pseudo-absence data were split into training (80%) and testing data sets (20%).

With the training dataset, we randomly generated 10,000 pseudo-absence points (within the current native range in state of Arkansas, outside of the one-kilometer buffer area placed around each occurrence point) as suggested by Barbet-Massin et al. (2012), where we assigned equal weight to the presence and pseudo-absence datasets and repeated the pseudo-absence generation three times to avoid random bias. This modeling approach, comprising nine algorithms, three pseudo-absence selection, and three evaluation runs resulted in a total of 81 model runs. Moreover, using pseudo-absence data for species distribution modelling for rare species such as *Q. acerifilia*, considering no absent data, is acceptable given the high probability that most selected pseudo-absences locations are likely to be true (Williams et al. 2009). The models were calibrated to generate habitat suitability maps. The area under curve (AUC) and True Skill Statistics (TSS) methods are widely used to evaluate predictive performance (Guisan et al. 2017). We used TSS (ranges from -1 to +1) as a model evaluation criterion. We selected all models having a TSS value >0.8 to build an ensemble model through a weighted mean approach (Marmion et al. 2009). We then generated model ensembles using the 'ensemble modeling' function in BIOMOD2.

After running the models using all the variables described above, the continuous habitat suitability map was converted to a suitable/unsuitable binary map. Pixels (1 × 1 km^2) with probability values below the threshold were categorized as absences and pixels with probability values above the threshold were categorized as presences. We used a probability threshold of 0.8 and transferred into binary distributions. As a result, we calculated the total suitable area for *Q. acerifolia* as a sum of the area of the grid cells above the threshold from the projected current and future suitable habitat maps under different scenarios. Finally, we employed the 'range size' function within the BIOMOD2 package when calculating the range shifts for *Q. acerifolia* under different climate change scenarios. The resulting change in the species range map indicates the following, for each grid cell across multiple climate scenarios: no change—if the species is present in both current and future change predictions; decrease in range—if the species present in the current prediction but absent in future climate change predictions; and increase in species range—if the species is absent in current prediction but present in future prediction. For example, when a pixel with a presence of *Q. acerifolia* in the current binary map became an absence in the future binary map in which only climatic environmental factors changed, it was interpreted as indicating that habitat loss occurred for that pixel.

Results

Model accuracy and important predictor variables

The predictive performance of the model ensemble was excellent, yielding a TSS value of 0.99. Likewise, all algorithms had an average TSS value of >0.95 (Fig. S2). Similarly, the AUC value of the ensemble model was 0.99. Environmental variables contributed differently to the SDMs, but the variables that contributed the most to the model were precipitation of the wettest month (bio13, 37.79%), elevation (22.60%), slope (10.11%), and mean temperature of the driest quarter (bio9, 8.63%) (Fig. 2). Topographic factors (elevation and slope) contributed ~33% in the model, while the aspect contribution was almost negligible (Figs. 2A, 2B, 2C). Temperature-related variables-- mean temperature of warmest quarter (Fig. 2D) and mean temperature of the driest quarter (Fig. 2K) contributed ~15% to the model (Fig. 2). The mean temperature of the driest quarter (bio9) contributed ~9% to our model, with habitat suitability inversely being related to increasing mean temperature of the driest quarter (Fig. 2K). Precipitation-related variables (precipitation of wettest month and precipitation seasonality) contributed ~45% to the model. Response curves showed that areas with ~150 mm of precipitation during the wettest month were suitable for *Q. acerifolia* (Fig. 2E).

Suitable habitat

A summary of suitable habitat areas for *Q. acerifolia* under current and future climate scenarios estimated by the model ensemble are presented in Table 1 and Figure 3. The estimated current suitable habitat for *Q. acerifolia* is 2523 km^2 (Fig. 3A). Among the 12 states, our model predicted that only two states (Arkansas and Oklahoma) have suitable habitat for *Q. acerifolia*; 14 counties (Polk [771km^2], Scott [183km^2], Washington [141 km^2], Montgomery [116 km^2], Crawford [65 km^2], Sebastian [59km^2], Logan [56 km^2], Yell [26 km^2], Johnson [11 km^2], Boone [5 km^2], Franklin [3 km^2], Garland [2 km^2] Pike [1 km^2], and Howard [1 km^2]) have suitable habitat in Arkansas (total area of 1434 km^2), and six counties- (Leflore [695km^2], Pushmataha [231km^2], McCurtain [105 km^2], Latimer [53km^2], Adair [3km^2]) and Haskell [2 km^2] have suitable habitat in Oklahoma (a total area of 1089 km^2) (Fig. S3).

By 2050, the model predicts a suitable habitat of 749 km^2, a loss of 70.31% in current habitat under the SSP 2.45 climate scenario based on the predicted loss of 77.28% (1950 km^2) of current suitable habitats and a gain of 6.97% (176 km^2) new habitat (Table 1; Fig. S4). By 2100, we predicted a suitable habitat of 285 km^2 (88.70% loss of current suitable habitat) under the SSP 2.45 climate scenario based on the predicted loss of 90.60% (2286 km^2) of current habitat and a gain of 1.90% (48 km^2) new habitat (Table 1; Fig. S4).

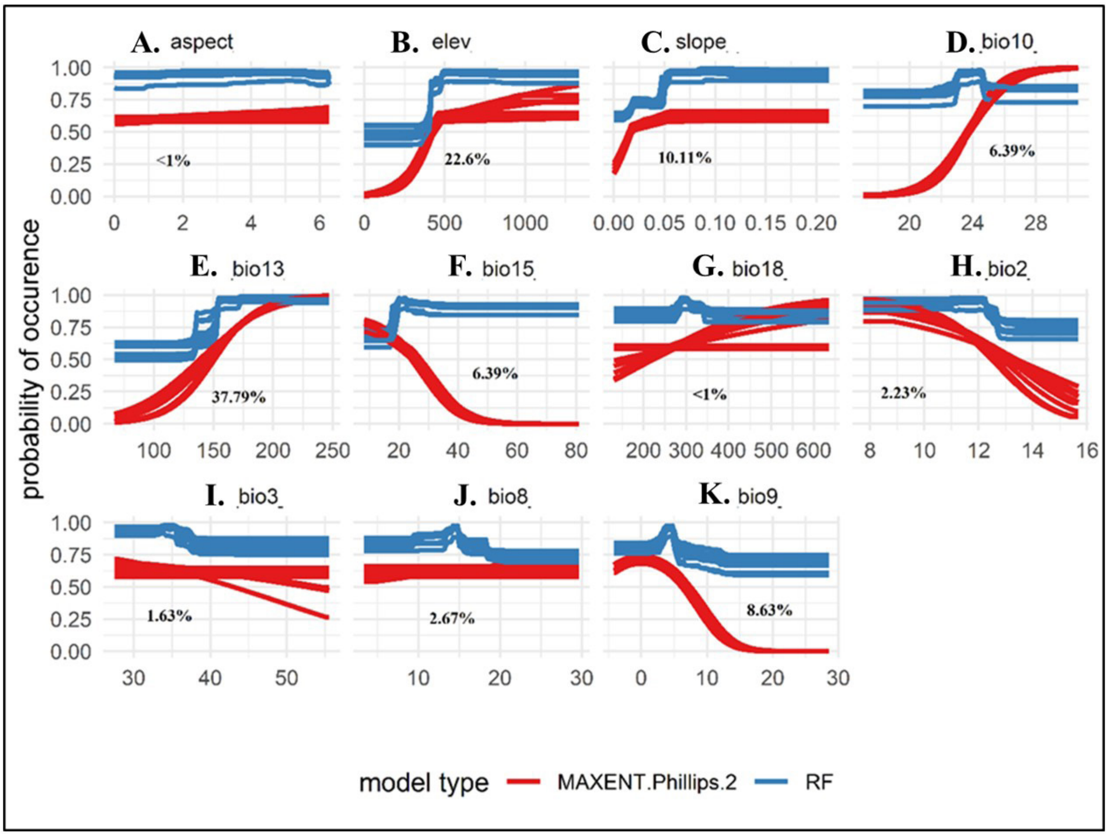

Figure 2. Response curves for environmental variables for two represented models whereas the percentage of contribution provided for each environmental variables is the average contribution of all the models in habitat suitability prediction for *Q. acerifolia,* (A) aspect, (B) elevation (m), (C) slope (degree), (D) Mean Temperature of Warmest Quarter (bio10, °C), (E) Precipitation of Wettest Month (bio13, mm), (F) Precipitation Seasonality (Coefficient of Variation) (bio15, mm), (G) Precipitation of Warmest Quarter (bio18, mm), (H) Mean Diurnal Range (Mean of monthly (max temp - min temp)) (bio2, °C), (I) Isothermality (bio2/bio7) (×100) (bio3, °C), (J) Mean Temperature of Wettest Quarter (bio8, °C), and (K) Mean Temperature of the Driest Quarter (bio9, °C). Note: x-axes are respective units for variables as given in parenthesis.

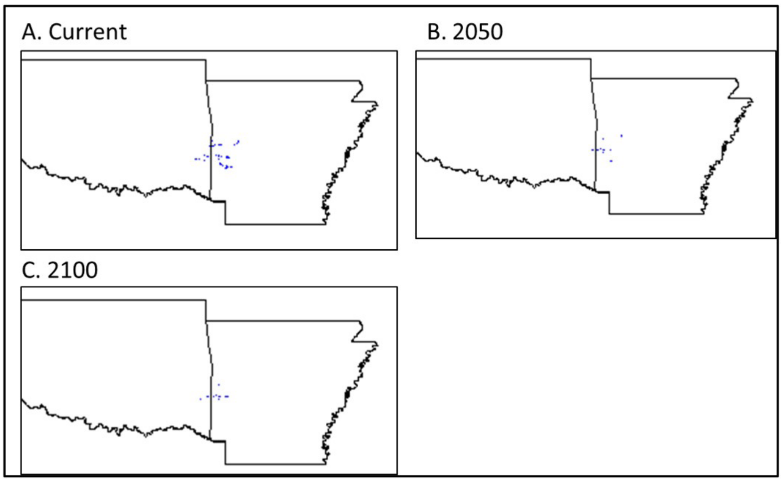

Figure 3. Projected habitat changes for *Q. acerifolia* under climate change scenario by 2050 and 2100. Blue color represents suitable habitats predicted by a model of binary presence/absence of *Q. acerifolia* in Arkansas and Oklahoma based on the combined ensemble model of SDMs for a) current suitable habitat, b) by 2050, and c) by 2100. All pixels with suitability values lower than the threshold probability (0.8) were defined as absences and all pixels with suitability values higher than the optimal threshold were defined as presences. According to this binary presence/absence, approximately 2,523 sq. km of current suitable habitat, 749 sq. km by 2050 and 285 sq. km by 2100 were predicted. All the future climate change scenarios were predicted using SSP2-4.5 scenarios.

Table 1. Projected habitat changes for *Q. acerifolia* under climate change scenario by 2050 and 2100 under the SSP 2.45 climate scenario

Habitat size	Predicted for 2050	Predicted for 2100
Loss (km)	1950	2286
Gain (km)	176	48
Loss (%)	77.29%	90.60%
Gain (%)	6.98%	1.90%
Species Range Change (%)	-70.31%	-88.70%
Current Range Size (km)	2523	2523
No change current area (km)	573	237
Full habitat (km)	749	285

Note: Pixels (1 × 1 km^2) with probability values below the threshold (TSS=0.8) were categorized as absences and pixels with probability values above the threshold were categorized as presences and transferred into binary distributions. Total suitable area as a sum of the area of the grid cells above the threshold from the projected current and future suitable habitat maps under different scenarios.

Discussion

Model accuracy and important predictor variables

Our results across all algorithms showed good SDM fit (TSS>0.95) – an SDM is considered good if it has a TSS value ≥ 0.9. (Allouche et al. 2006, Thuiller et al. 2009). However, in certain situations, it is reported that TSS values can be misleading where the number of true negatives is high by not penalizing overprediction and assigning higher values to species with smaller prevalence for identical discrimination accuracy (Leroy et al. 2018). We used presence-pseudoabsence data in species distribution modelling algorithms in this study. Although we tried to minimized sampling bias and autocorrelation by filtering (Aiello-Lammens et al. 2015, Boria et al. 2014, Kramer-schadt et al. 2013), taking pseudo-absences may still lead to overfit models due to the major underlying assumption of spatial representation (Dormann et al. 2007, Yackulic et al. 2013). Therefore, even selecting high performing models (TSS > 0.9), SDMs still can cause slight uncertainty (Thuller et al. 2019).

Among the bioclimatic and topographic factors used in the model, distribution of *Q. acerifolia* is controlled mainly by precipitation of the wettest month, elevation, and slope, which contributed about 70% to the ensemble model habitat prediction, suggesting that these three variables in combination, effectively describe the most favorable growth environment for this species. Precipitation of the wettest month (typically April or May) was the most influential variable in describing the distribution of *Q. acerifolia*, which may limit its survival and long-term population persistence. It is implicit that long term population sustainability will be reliant on the recruitment of new seed-origin trees, which is the solitary means of regeneration for all the *Quercus* species.

Furthermore, during early spring, a certain amount of precipitation and warm temperature accumulation is also required to satisfy multiple regeneration-centric phases including completion of winter seed dormancy requirements, initiation of both vegetative bud development, and flower bud differentiation. In Missouri, successful flowering, pollination, fertilization, and subsequent acorn production in *Quercus* species was strongly influenced by warm spring temperatures and a lack of summer drought in the fruiting year (Sork et al. 1993). Similarly, rainfall in late winter and early spring is also important for seed germination, as acorns require cool, moist conditions, followed by warming temperatures to germinate.

Elevation is also an influencing factor in the model as the distribution of *Q. acerifolia* only occurs on mountain summits and along bluff lines (Rouw and Johnson 1994) above 400 masl. Topographic aspect did not contribute greatly to the projection of suitable habitat although, it has been reported that *Q. acerifolia* grows best on the north-facing bluffs of Magazine Mountain in Arkansas (Stoynoff and Hess 1990). Additionally, other studies have reported *Q. acerifoli*a tends to establish and grow best on strong slopes along rocky rims (Stoynoff and Hess 1990). However, for species of the red oak subgenus, including *Q. acerifolia*, such harsh sites are also prone to the negative impacts of episodic drought and freeze events, as well as oak decline, that has been reported to cause significant mortality in the Ouachita mountains at least once every decade since the 1960's (Haarvik et al. 2012). The effect of mean temperature during the driest quarter on the distribution of *Q. acerifolia* is mainly reflected by the balance of temperature and water (Schroth et al. 2016). In the driest quarter of the year (typically January, February, and March), when precipitation is low, temperature becomes an important factor reducing the growth of *Q. acerifolia*. This might be because *Q. acerifolia* occurs most often on xeric sites with thin and rocky soils that are likely to be associated with some degree to water stress. It prefers early successional woodland habitats, especially those with open canopies, dry, rocky ledges, steep slopes, and bluff lines (Beckman et al. 2019). Our model projected that a mean temperature of greater than 5°C during the driest quarter might not be suitable for *Q. acerifolia* distribution.

The mean diurnal range in temperature showed a negative relationship with *Q. acerifolia* distribution after diurnal temperatures exceed 12°C. High daily temperatures usually favor photosynthesis, while low night temperatures inhibit respiration, and thus greater diurnal temperature ranges favor tree growth (Liu et al. 2021). However, in the case of *Q. acerifolia*, if this range is too large or highly variable over time, it may limit *Q. acerifolia* distribution via physiological acclimation to temperature shifts. Higher precipitation seasonality had a positive effect on the habitat suitability of *Q. acerifolia*, likely because the species is unable to tolerate lower precipitation seasonality. This may be related to seasonal thermoperiodicity, which is the most important factor controlling growth, development, and flowering in drought-tolerant species (Khodorova and Boitel-Conti 2013). Therefore, high precipitation seasonality, i.e., heavy precipitation concentrated over a few months likely favors *Q. acerifolia* distribution.

Current Suitable habitat

The SDM approach applied here provides a realistic picture of the potential distribution of *Q. acerifolia* within its native range in Arkansas and neighboring states that can be used to guide future conservation strategies for this endemic and threatened species, which is known to occur in only four sites in west central Arkansas. Our results highlight that this species might exist in additional locations within Arkansas and neighboring state in Oklahoma. Speculating that this species might be present in other neighboring states, especially in eastern states, we expanded our projection to 12 states, but our results showed that current suitable habitat only exists in two states Arkansas and Oklahoma but not in other states with high certainty (a probability value >0.8). The suitability map generated from our model effectively captured the current habitat of *Q. acerifolia* that was mainly concentrated in the western and northern highland areas of Arkansas and adjoining areas in Oklahoma. The known distribution of *Q. acerifolia* in Arkansas extends between 400 and 800 m elevation (Beckman et al. 2019), which is consistent with our findings.

While the species has been reported from only four counties in Arkansas, our model predicted that it could potentially occur in a total of 14 counties in Arkansas, plus six counties in Oklahoma. Seven of those 20 counties have more than 100 km^2 of suitable habitat (Polk County in Arkansas has the highest, 771 km^2), four counties have between 50-100 km^2 of suitable habitat, and nine counties have 1-22 km^2 including currently known locations at four counties: Magazine Mountain (Logan County, AR), Porter Mountain (Polk County, AR), Pryor Mountain (Montgomery County, AR), and Sugarloaf Mountain (Sebastian County, AR). More importantly, the model predicted suitable habitats in the neighboring state of Oklahoma in six counties. As efforts have been carried out to locate additional populations of this species within both Arkansas and neighboring states, findings from this study may be helpful to locating other populations in the area, which are not easily explored, since all such areas are in rugged, mountainous terrain.

Impact of climate change on the distribution

Due to climate change, locally and regionally endemic species are likely to be lost (Deb et al. 2017, Ayebare et al. 2018, Subedi et al. 2022). The models used in this study demonstrate that the spatial extent of suitable climate available for *Q. acerifolia* is expected to shift northward and westward geographically over time, because of changes in precipitation and temperature. Such climatic changes may also indirectly affect animal (e.g., squirrel) and microbial (e.g., fungal) species associated with *Q. acerifolia.* Moreover, these changes may also have adverse effects on terrestrial insects, mammals, and birds that are indirectly or directly dependent on the seeds, fruits, and flowers from *Q. acerifolia*.

Suitable habitat ranges of many terrestrial species have shifted toward higher elevations in response to changing climate (Chen et al. 2011, Feeley et al. 2013, Kunwar et al. 2023). However, current *Q. acerifolia* habitat suitability is restricted to elevations above 400 masl. Elevation and slope contributed substantially to the model, as this species is mainly present around mountain summits and exposed bluffs. The future distribution scenario for 2050 and 2100 for *Q. acerifolia* is concerning (70 - 90% current habitat is predicted to be lost), suggesting a significant loss suitable habitat niche space for this species. Therefore, it is important to formulate the conservation planning for the long-term survival of this endangered species against climate change.

Implications for conservation planning

As detected by our models, the potential, suitable habitat of *Q. acerifolia* significantly decreased and shifted under future climate scenarios. The planting of *Q. acerifolia,* as part of a robust restoration program, into such habitats may serve as a species preservation strategy in the presence of future climate change (Deb et al. 2017). Additionally, our results can be utilized for categorizing known *Q. acerifolia* natural habitats based on climate change risk, hopefully leading to better-informed conservation planning efforts in the future. For example, the *Q. acerifolia* plantings could be targeted preferentially into those climatically appropriate areas; in addition, greater effort should be taken to conserve the natural regeneration among currently occupied high-risk areas, to potentially mitigate the impacts of future climate change. Such stable habitats can then serve as refugia in the presence of future climate change, to provide a vital resource for long-term conservation of *Q. acerifolia* both *ex situ* and *in situ*.

Information acquired from this study, which defines both predicted and current suitable habitats should also guide future exploration efforts to identify presently unknown *Q. acerifolia* populations. If such a *Q. acerifolia* population lies on privately owned land where no protective status or conservation agreement exists, the inclusion of these areas in conservation or management plans will be helpful to conserve such populations. Considering its extensive fragmentation of limited suitable habitat, low dispersal ability, and threats posed by climate change, disease, plus other anthropogenic causes to their remaining populations, *Q. acerifolia* is currently facing a high risk of extinction. To reduce this risk, one option for managers to consider would be to identify suitable habitats and target them for planting to establish new, viable populations of these species.

All four known subpopulations of *Q. acerifolia* are now protected, Sugarloaf Mountains-Midland Peak Natural Area, Mount Magazine State Park, and the Ouachita National Forest. These populations are unlikely to be threatened by habitat loss or other anthropogenic causes. More importantly, observations from natural populations reported a high degree of natural regeneration (Wu 2020). However, other subpopulations or suitable habitats have likely been diminished because of human disturbances. Searching for new populations or new suitable habitats on privately owned lands, if any, and bringing them under the management is very important for the conservation of *Q. acerifolia*. Otherwise, such privately owned land is vulnerable to development by future landowners. Additionally, anthropogenic activity has suppressed the natural fire regime in most of these subpopulations resulting in a decline of the early successional open-canopy woodlands where *Q. acerifolia* thrives. A comparative analysis of potential species distribution under current climate conditions and the realized species distribution could be coupled with data on anthropogenic activities to provide information about previously occupied areas to help guide species restoration efforts.

In conclusion, this study provides important information on the environmental conditions and suitable habitat areas that can guide future conservation and restoration efforts, with the goal of increasing populations of *Q. acerifolia* across its range. New habitat information obtained in this study can be used to support management, conservation, and, if needed, future restoration programs. While presently listed as endangered in the IUCN Red List and its critically imperiled status by the State of Arkansas, if future revisions of this status are warranted, the predicted potential distribution map reported here may help in this effort.

Author Contributions

SCS conceived and designed the study; SCS and BR assemble data and performed statistical analysis; SCS wrote the manuscript with the input of all authors.

Acknowledgments

We thank several undergraduate students at Arkansas Tech University for helping in geolocating herbarium specimens, especially Jonathan Aguirre-Lopez and Hannah Bridges for their hard work. We would like to thank the Undergraduate Research Grant program at Arkansas Tech University and Arkansas Division of Higher Education (SURF) grant for covering the undergraduate student stipends. Two anonymous referees and editor Dr. Janet Franklin made very useful suggestions that significantly improved the quality of the paper.

Supplementary Material

The following materials are available as part of the online article at https://escholarship.org/uc/fb

Table S1. Bioclimatic and topographic variables considered for the habitat attributes of Q. acerifolia.

Table S2. Pearson correlations among selected environmental variables which were used for species distribution modelling.

Figure S1. Variance Inflation Factors (VIFs) for environmental variables.

Figure S2. Comparison of performance of different modeling techniques used for species distribution modeling of Q. acerifolia based on true skill statistics (TSS).

Figure S3. Current habitat for Q. acerifolia predicted by model in two states, Arkansas and Oklahoma by county

Figure S4. Projected habitat changes for Q. acerifolia under climate change scenario by 2050 and 2100.

References

Adhikari, B., Subedi, S.C., Bhandari, S., Baral, K., Lamichhane, S. & Maraseni, T. (2023) Climate-driven decline in the habitat of the endemic spiny babbler (*Turdoides nipalensis*). Ecosphere, 14, e4584. https://doi.org/10.1002/ecs2.4584

Adhikari, B., Bhandari, S., Baral, K., Lamichhane, S., & Subedi, S.C. (2022). Raptors at risk: attributes of mortality within an anthropogenic landscape in the Mid-Hills region of Nepal. Global Ecology and Conservation, 38, e02258. https://doi.org/10.1016/j.gecco.2022.e02258

Ahmad, S., Yang, L., Khan, T.U., Wanghe, K., Li, M. & Luan, X. (2020) Using an ensemblemodelling approach to predict the potential distribution of Himalayan gray goral (*Naemorhedus goral bedfordi*) in Pakistan. Global Ecology and Conservation, 21, e00845. https://doi.org/10.1016/j.gecco.2019.e00845

Allouche, O., Tsoar, A. & Kadmon, R. (2006) Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). Journal of Applied Ecology 43, 1223–32. https://doi.org/10.1111/j.1365-2664.2006.01214.x

Aiello-Lammens M.E., Boria, R.A., Radosavljevic, A., Vilela, B. & Anderson, R.P. (2015) spThin: a R package for spatial thinning of species occurrence records for use in ecological niche models. Ecography, 38, 541-545. https://doi.org/10.1111/ecog.01132

Allouche, O., Tsoar, A. & Kadmon, R. (2006) Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). Journal of Applied Ecology 43, 1223–32. https://doi.org/10.1111/j.1365-2664.2006.01214.x

Ayebare, S., Plumptre, A.J., Kujirakwinja, D. & Segan, D. (2018) Conservation of the endemic species of the Albertine Rift under future climate change. Biological Conservation, 220, 67-75. https://doi.org/10.1016/j.biocon.2018.02.001

Barbet-Massin, M., Jiguet, F., Albert, C.H. & Thuiller, W. (2012) Selecting pseudo-absences for species distribution models: how, where and how many? Methods in Ecology and Evolution, 3, 327-338. https://doi.org/10.1111/j.2041-210X.2011.00172.x

Beckman, E., Baker, B., Lobdell, M., Meyer, A. & Westwood, M. (2019) Quercus acerifolia (E.J.Palmer) Stoynoff & Hess. In: Conservation Gap Analysis of Native U.S. Oaks (ed by Beckman, E., Meyer, A., Man, G., Pivorunas, D., Denvir, A., Gill, D., Shaw, K., and Westwood, M.), pp. 50-55). The Morton Arboretum, Lisle, IL.

Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W. & Courchamp, F. (2012) Impacts of climate change on the future of biodiversity. Ecology Letters, 15, 365- 377. https://doi.org/10.1111/j.1461-0248.2011.01736.x

BGCI. (2021). State of the world's trees. BGCI, Richmond, UK.

Boria, R.A., Olson, L.E., Goodman, S.M. & Anderson, R.P. (2014) Spatial filtering to reduce sampling bias can improve the performance of ecological niche models. Ecological Modelling, 275, 73-77. https://doi.org/10.1016/j.ecolmodel.2013.12.012

Cauwer, V. D., Muys, B., Revermann, R. & Trabucco, A. (2014) Potential, realised, future distribution and environmental suitability for Pterocarpus angolensis DC in southern Africa. Forest Ecology and Management, 315, 211–226. https://doi.org/10.1016/j.foreco.2013.12.032

Chen, I.C., Hill, J.K., Ohlemüller, R., Roy, D.B. & Thomas, C.D. (2011) Rapid range shifts of species associated with high levels of climate warming. Science, 333, 1024-1026. https://doi.org/10.1126/science.1206432

Deb, J.C., Phinn, S., Butt, N. & McAlpine, C.A. (2017) The impact of climate change on the distribution of two threatened Dipterocarp trees. Ecology and Evolution, 7, 2238-2248. https://doi.org/10.1002/ece3.2846

Dormann, C.F. (2007) Effects of incorporating spatial autocorrelation into the analysis of species distribution data. Global Ecology and Biogeography, 16, 129-138. https://doi.org/10.1111/j.1466-8238.2006.00279.x

Elith, J. & Leathwick, J.R. (2009) Species distribution models: ecological explanation and prediction across space and time. Annual Review of Ecology, Evolution and Systematics, 40, 677-697. https://doi.org/10.1146/annurev.ecolsys.110308.120159

Feeley, K.J., Hurtado, J., Saatchi, S., Silman, M.R. & Clark, D.B. (2013) Compositional shifts in Costa Rican forests due to climate-driven species migrations. Global Change Biology, 19, 3472-3480. https://doi.org/10.1111/gcb.12300

Foden, W. B. & Young, B.E. (2016) IUCN SSC guidelines for assessing species' vulnerability to climate change. International Union for Conservation of Nature and Natural Resources (IUCN) Species Survival Commission.GBIF.org GBIF Occurrence. Downloaded at https://doi.org/10.15468/dl.k6vjrm on 10 July 2022.

Guisan, A., Tingley, R., Baumgartner, J.B., Naujokaitis-Lewis, I., Sutcliffe, P.R., Tulloch, A.I., et al. (2013) Predicting species distributions for conservation decisions. Ecology Letters, 16, 1424-1435. https://doi.org/10.1111/ele.12189

Guisan, A., Thuiller, W. & Zimmermann, N.E. (2017) Habitat suitability and distribution models: with applications in R. Cambridge University Press, Cambridge.

Haavik, L. J., Jones, J.S., Galligan, L.D., Guldin, J.M. & Stephen, F.M. (2012) Oak decline and red oak borer outbreak: impact in upland oak-hickory forests of Arkansas, USA. Forestry, 85, 341–352. https://doi.org/10.1093/forestry/cps032

Hao, T., Elith, J., Lahoz-Monfort, J.J. & Guillera-Arroita, G. (2020) Testing whether ensemble modelling is advantageous for maximizing predictive performance of species distribution models. Ecography, 43, 549-558. https://doi.org/10.1111/ecog.04890

Jerome, D., Beckman, E., Kenny, L., Wenzell, K., Kua, C. & Westwood, M. (2017) The red list of US oaks. Moreton Arboretum, Lisle, IL, USA.

Khodorova, N.V. & Boitel-Conti, M. (2013) The role of temperature in the growth and flowering of geophytes. Plants, 2, 699-711. https://doi.org/10.3390/plants2040699

Kramer-Schadt, S., Niedballa, J., Pilgrim, J.D., et al. (2013) The importance of correcting for sampling bias in MaxEnt species distribution models. Diversity and Distributions, 19, 1366–79. https://doi.org/10.1111/ddi.12096

Kunwar, R.M., Thapa-Magar, K.B., Subedi, S.C., et al. (2023) Distribution of important medicinal plant species in Nepal under past, present, and future climatic conditions. Ecological Indicators, 146, 109879. https://doi.org/10.1016/j.ecolind.2023.109879

Larson, R.A. (2017) A summary report detailing the results of the 2017 Arkansas collection trip for procurement of seed of *Quercus acerifolia* (maple-leaf oak). The Dawes Arboretum, Newark, OH.

Liu, H., Jia, J., Lin, Z., Wang, Z. & Gong H. (2021) Relationship between net primary production and climate change in different vegetation zones based on EEMD detrending–a case study of Northwest China. Ecological Indicators, 122, 107276. https://doi.org/10.1016/j.ecolind.2020.107276

Leroy, B., Delsol, R., Hugueny, B., Meynard, C.N., Barhoumi, C., Barbet-Massin, M. & Bellard, C. (2018) Without quality presence–absence data, discrimination metrics such as TSS can be misleading measures of model performance. Journal of Biogeography, 45, 1994-2002. https://doi.org/10.1111/jbi.13402

Marmion, M., Parviainen, M., Luoto, M., Heikkinen, R.K. & Thuiller, W. (2009) Evaluation of consensus methods in predictive species distribution modelling. Diversity and Distributions, 15, 59-69. https://doi.org/10.1111/j.1472-4642.2008.00491.x

McDowell, N.G., Allen, C.D., Anderson-Teixeira, K., et al. (2020) Pervasive shifts in forest dynamics in a changing world. Science, 368, eaaz9463. https://doi.org/10.1126/science.aaz9463

Meller, L., Cabeza, M., Pironon, S., Barbet-Massin, M., Maiorano, L., Georges, D., & Thuiller, W. (2014) Ensemble distribution models in conservation prioritization: from consensus predictions to consensus reserve networks. Diversity and Distributions, 20, 309-321. https://doi.org/10.1111/ddi.12162

Ogle, J., Witsell, T. & Gentry, J. (2020) Trees, shrubs, and woody vines of Arkansas. Ozark Society Foundation, Little Rock, Arkansas, USA.

Oke, O.A., & Thompson, K.A. (2015) Distribution models for mountain plant species: the value of elevation. Ecological Modelling, 301, 72-77. https://doi.org/10.1016/j.ecolmodel.2015.01.019

Phillips, R.P., Brzostek, E. & Midgley, M.G. (2013) The mycorrhizal-associated nutrient economy: a new framework for predicting carbon–nutrient couplings in temperate forests. New Phytologist, 199, 41-51. https://doi.org/10.1111/nph.12221

R Core Team (2020) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available at https://www.R-project.org/

Rauschendorfer, J., Rooney, R. & Külheim, C. (2022) Strategies to mitigate shifts in red oak (Quercus sect. Lobatae) distribution under a changing climate. Tree Physiology, 42, 2383-2400. https://doi.org/10.1093/treephys/tpac090

Raymond, C.V., McCune, J.L., Rosner-Katz, H., Chadès, I., Schuster, R., Gilbert, B. & Bennett, J.R. (2020) Combining species distribution models and value of information analysis for spatial allocation of conservation resources. Journal of Applied Ecology, 57, 819-830. https://doi.org/10.1111/1365-2664.13580

Rouw, D.W. & Johnson, G.P. (1994) The vegetation of maple-leaved oak sites on Sugarloaf and Magazine Mountains, Arkansas. Proceedings Arkansas Academy of Science, 48, 154-157. Available at https://scholarworks.uark.edu/jaas/vol48/iss1/32/

Schwartz, M.W. (2012) Using niche models with climate projections to inform conservation management decisions. Biological Conservation, 155, 149-156. https://doi.org/10.1016/j.biocon.2012.06.011

Scott, J.M., Davis, F., Csuti, B., et al. (1993) Gap analysis: a geographic approach to protection of biological diversity. Wildlife Monographs, 3-41. https://www.jstor.org/stable/3830788

Sork, V.L., Bramble, J. & Sexton, O. (1993) Ecology of mast-fruiting in three species of North American deciduous oaks. Ecology, 74, 528-541. https://doi.org/10.2307/1939313

Stoynoff, N. & Hess, W.J. (1990) A new status for *Quercus shumardii* var. *acerifolia* (Fagacaeae). Sida, 14, 267-271. Available at https://www.jstor.org/stable/41966881

Subedi, S.C., Walls, S.C., Barichivich, W. J., Boyles, R., Ross, M.S., Hogan, J.A., & Tupy, J.A. (2022)

Future changes in habitat availability for two specialist snake species in the imperiled rocklands of South Florida, USA. Conservation Science and Practice, 4, e12802. https://doi.org/10.1111/csp2.12802

Thuiller, W., Lafourcade, B., Engler, R. & Araújo, M. B. (2009) BIOMOD—a platform for ensemble forecasting of species distributions. Ecography 32, 369–73. https://doi.org/10.1111/j.1600-0587.2008.05742.x

Thuiller, W., Georges, D., Engler, R. & Breiner, F. (2020) Biomod2: ensemble platform for species distribution modeling. R package version 3.4.6. Available at https://cran.r-project.org/web/packages/biomod2/ index.html.

Wiens, J.J., Graham, C.H., Moen, D.S., Smith, S.A & Reeder, T.W. (2006) Evolutionary and ecological causes of the latitudinal diversity gradient in hylid frogs: treefrog trees unearth the roots of high tropical diversity. The American Naturalist, 168, 579-596. https://doi.org/10.1086/507882

Wu, Y. (2022) A tale of two lonely oaks: *Quercus acerifolia* and *Q. humboldtii*. International Oaks, 33, 15-26. Available at: https://www.internationaloaksociety.org/content/tale-two-lonely-oaks-quercus-acerifolia-and-q-humboldtii

Williams, J.N., Seo, C., Thorne, J., Nelson, J.K., Erwin, S., O'Brien, J.M. & Schwartz, M.W. (2009) Using species distribution models to predict new occurrences for rare plants. Diversity and Distributions, 15, 565-576. https://doi.org/10.1111/j.1472-4642.2009.00567.x

Yackulic, C. B., Chandler, R., Zipkin, E. F., Royle, J. A., Nichols, J. D., Campbell Grant, E. H. & Veran, S. (2013) Presence-only modelling using MAXENT: when can we trust the inferences? Methods in Ecology and Evolution, 4, 236–243. https://doi.org/10.1111/2041-210x.12004

Submitted: 5 September 2022
First decision: 29 November 2022
Accepted: 12 July 2023

Editors: Janet Franklin

