





# Climate change threatens the conservation of one of the world's most endangered transboundary tree species: *Magnolia grandis*

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## Abstract

The Sino-Vietnamese border region is known for having unique and high levels of biodiversity. Global climate change is expected to alter the region's climate and related changes in habitats and ecosystems will result in shifts in species' distributions and increase the likelihood of local and global extinctions. Ecological Niche Models (ENMs) are widely used to predict the magnitude of potential species distribution shifts in response to climate change and inform conservation planning. Here, we present climate-based ENM projections of future climatically suitable habitat for the Daguo Mulian tree (*Magnolia grandis*), a critically endangered species of high ecological and cultural value in the Sino-Vietnamese border region. Projections of modeled climatically suitable habitat for *M. grandis*, both for the 2050s and 2070s, suggest significant habitat loss within conservation areas, and a defining shift in the location of suitable habitat. Future projections are conservative and do not account for dispersal limitations or species interactions or other factors, and thus may overestimate potential shifts and underestimate losses. Our results suggest that current conservation management efforts for *M. grandis*, which include community forest conservation monitoring combined with nursery cultivation efforts, can continue to have success if implemented in an adaptive management framework with long-term research and monitoring to inform forward-thinking decisions with future climatic suitability in mind. The results also underline how endangered species' distributions may shift across borders as they track suitable climates, emphasizing that nations will need to cooperate to effectively manage threatened species and habitats and prevent extinctions.

## Highlights

- Changes to habitats and ecosystems from climate change will result in shifts in species' distributions and increase the likelihood of local and global extinctions, especially for species with populations that are already decreasing.
- We built Ecological Niche Model (ENM) projections of future climatically suitable habitat for the Daguo Mulian tree (*Magnolia grandis*), a critically endangered species of high ecological and cultural value, to predict the magnitude of potential distribution shifts in response to climate change.
- Our projections point to significant habitat loss within conservation areas, as well as a potentially considerable shift in the location of suitable habitat, but also that current conservation management efforts for *M. grandis*, which include community forest conservation monitoring and nursery cultivation efforts, can have success if implemented in an adaptive management framework with future climatic suitability in mind.
- A key component to the successful conservation management of *M. grandis* and other transboundary endangered species under climate change will be effective cross-border conservation partnerships.

**Keywords:** bioclimate envelope, climate change, conservation planning, ecological niche modeling, Daguo Mulian, species distribution modeling, cross-border conservation

## Introduction

The Sino-Vietnamese border region has high levels of unique biodiversity as well as a diversity of human cultural groups (Sterling et al. 2006). Mainland Southeast Asia, which includes the Sino-Vietnamese border region, covers only 4% of the earth's land area, but harbors 20-25% of earth's plant and animal species and is considered a global biodiversity hotspot (Myers et al. 2000). The hotspot hosts roughly 7,000 known endemic plant species (which represent 52% of the region's flora; Brooks et al. 2002). Hundreds of new species of vertebrates and plants have been described in Vietnam alone since 1992 (Sterling et al. 2006, Bain and Hurley 2011, Graves 2017).

Global climate change is expected to alter Southeast Asia's climate considerably with a 3°C rise in mean annual temperature, a 7% increase in wet season rainfall, and a drier dry season by the mid to late 21<sup>st</sup> century (Christensen and Hewitson 2007, Corlett 2009, Bickford et al. 2010, IPCC 2013). These changes are likely to cause major shifts in biological communities and resources as novel climates appear and major biomes are redistributed (Parmesan and Yohe 2003, Corlett 2012). Studies in other regions have documented observed impacts on species' distributions, abundance, phenology, and body size (e.g. Rosenzweig et al. 2008) or have predicted future impacts including extinction risk (e.g. Thomas et al. 2004) or vulnerability (e.g. Li et al. 2013). Indeed, anticipated changes in habitats and ecosystems due to climate change will result in shifts in species' distributions that increase the likelihood of local and global extinctions, especially for species with populations that are already decreasing or are otherwise less likely to be able to shift their ranges in response to climate (e.g. specialists, less vagile, or less fecund species; Estrada et al. 2017, MacLean and Beissinger 2017). Although some range shifts poleward and upward have already been observed (e.g. Chen et al. 2011), the velocity of climate change is likely to outpace potential niche-tracking shifts in most geographies (e.g. Corlett and Westcott 2013).

There is a need for robust simulations and evidence to inform decisions and planning (e.g. Blair et al. 2012) especially in border contexts, where diverse and complex needs must be coordinated alongside anticipated climatic shifts. For example, border security measures can be a threat to migrating wildlife, increasing mortality and reducing genetic diversity and effective population sizes (e.g. Linnell et al. 2016), which might be exacerbated under climate change. Also, the Sino-Vietnamese border region is known for its complex social-political history, including most recently the Sino-Vietnamese Border War of 1979 (Zhang 2005). Climate change may put additional pressure on already marginalized border communities (Wilder et al. 2013), and cross-border collaborations will be critical for forward-thinking climate change adaptation and mitigation strategies.

In recognition of the high levels of biodiversity in the Sino-Vietnamese border region, cross-border agreements are already in place between Vietnam, Lao

PDR, and China to demarcate cross-border biodiversity protection zones (Ma et al. 2020). Although promising, progress on coordination is slow, and further, there has been limited work in the region to model climate-driven habitat changes for species under anticipated future climate change to assess their vulnerability and potential gaps in the existing cross-border protected area systems given this threat. Indeed, projecting the impacts of climate change on species and their habitats is one of the main stated needs at the national level in ongoing protected area visioning and planning towards 2030 for both Vietnam and China (MARD 2017).

The Daguo Mulian tree *Magnolia grandis* Hu and W.C. Cheng, V.S. Kumar 2006 is one of the most critically endangered plants in the world (CR, decreasing trend; GTSG 2014). It has characteristic dark red flowers, large oblong-oval fruits, and very large leaves with pale undersides that can grow to over 30 cm in length (Fig. 1). *M. grandis* is endemic to the Sino-Vietnamese border region in evergreen broad-leaved forests between 800-1500 m. elevation (GTSG 2014). Until recently, it was observed only in China (southeastern Yunnan and southwestern Guangxi) in limited numbers, but surveys in 2014-15 revealed previously unknown populations in three protected areas in northern Vietnam (Hà Giang Province (Quản Bạ, Bắc Mê), and Tuyên Quang Province (Na Hang Nature Reserve; Nguyen et al. 2014, 2015, Tu et al. 2015).

While populations are decreasing due to habitat loss for agricultural expansion and logging (Rivers et al. 2016), community conservation combined with nursery cultivation efforts have seen limited success in both Vietnam and China (Gill 2017). However, there is both genetic diversity (Xu 2020) and population ecology evidence (Chen et al. 2012) for restricted gene flow between populations in China that could further endanger population survival, likely due to habitat fragmentation and very small population size. The potential effects of climate change on the habitat of *M. grandis* are unknown.



**Figure 1.** Photograph of *Magnolia grandis* in northern Vietnam showing the characteristic dark red flower and large leaves (photo provided courtesy of Chu Xuan Canh, Fauna and Flora International – Vietnam).

Ecological Niche Models (ENMs, or ‘species distribution models’; Franklin 2009, Peterson et al. 2011, Phillips et al. 2017) are widely used to predict the magnitude of potential species distribution shifts in response to climate change and inform conservation planning (e.g. Blair et al. 2012). Correlative ENMs, such as Maxent (Phillips et al. 2017), use associations between species’ occurrence records and environmental variables to characterize the environments that are climatically suitable for the species. The advantages and disadvantages of these models have been discussed at length elsewhere (e.g. Pearson and Dawson 2003, Kearney and Porter 2009, Dawson et al. 2011). ENMs can be used to infer the areas of a species’ range that are likely to experience large changes in temperature and precipitation, and can therefore be informative about a species’ exposure to climate change (Dawson et al. 2011).

Here, we use the presence-background algorithm Maxent to model the ecological niche of *M. grandis*. Maxent has been shown to have high performance relative to other ENM algorithms (Elith et al. 2006). We present, to our knowledge, the first effort to characterize climatic niche space for *M. grandis* in the current climate and to estimate the potential impacts of global climate change on future climatically suitable habitat for this species. We summarize our results to provide recommendations for policy-based planning and management actions to support coordinated, evidence-based transboundary conservation management in the face of imminent change. A secondary goal of the study is to target new areas to survey to find additional undiscovered populations of this incredibly rare species.

## Materials and Methods

Occurrence locality records for *M. grandis* were downloaded from the Global Biodiversity Information Facility (DOI: 10.15468/dl.sadmk7; Catapano et al. 2011, iBOL 2016, Jennings 2019, Yang and Xu 2019, Zhang and Xu 2019, Bijmoer et al. 2020, Orrell 2020) and from surveys conducted by the Center for Plant Conservation-Vietnam by co-authors NQH and TBN (see Data Accessibility Statement, Nguyen et al. 2015, Tu et al. 2015). Occurrence records were thinned to control for the effects of sampling bias and spatial autocorrelation using the R package *sphin* (Aiello-Lammens et al. 2015) with a thinning distance of 10km (based on consultation with species expert and coauthor NQH), resulting in 11 occurrences to use for the model.

We generated Maxent (v. 3.4; Phillips et al. 2017) models to project areas of suitable habitat, or areas with suitable environmental conditions, for *M. grandis*. Because Maxent is a presence-background modeling approach, to fully capture the climate combinations that *M. grandis* may experience and to which they might possibly disperse, we selected a region incorporating a 500km buffer around minimum convex polygon around occurrence localities. This background region was created after careful consultation with species expert, co-author NQH. We employed 30

arc-second bioclimatic variables available from worldclim.org (Fick and Hijmans 2017) and masked these layers by the selected background region. From this background region, we randomly sampled 10000 background localities. We sampled background from all 19 bioclimatic variables despite many of them being highly correlated; Maxent, a machine-learning algorithm, determines predictor variable importance in the context of other variables using internal variable selection called L1 regularization (Elith et al. 2011). The regularization algorithm can discard redundant information and gain novel information even when that novel information is relatively small. Removing highly correlated variables from the analysis could therefore remove a small amount of data that might potentially be important. Further, collinearity is expected to have a very limited effect on the predictive ability of optimally tuned models (Elith et al. 2011, Radosavljevic and Anderson 2014).

We generated Maxent models using a range of complexities to find the optimally tuned model settings. We controlled Maxent complexity in two ways, which in combination allow for a wide variety of complexities. The first, regularization multiplier, enforces penalties for complexity, with higher numbers giving higher penalties (Radosavljevic and Anderson 2014). The second, feature classes, control the shape of the modelled response to the data (see Merow et al. 2013). Specifically, we allowed Maxent to search a range of regularization multipliers from one to five by intervals of 1. For each of these regularization multiplier values, we used linear, linear and quadratic, and hinge features. This resulted in a total of 15 total models from which to select the optimal settings. Model tuning was performed using the R package ENMeval (Muscarella et al. 2014). Because of the very small sample size of *M. grandis*, we employed an  $n-1$  jackknife approach for withholding testing data (Shcheglovitova and Anderson 2013). The optimal model was selected using the lowest delta Akaike Information Criterion (AICc – small sample size corrected) score. We report the performance of the optimal model using omission error and the area under the receiver operating characteristic curve (AUC). For visualization, models were projected in the complementary log-log transformation.

The optimal model was then projected under six future climate model and socioeconomic pathway projections including two global climate models BCC-CSM2-MR and MIROC6 for each of three Shared Socio-economic Pathways or SSPs from the 2021 IPCC 6th assessment report CMPI6: SSP2-4.5, SSP3-7.0 and SSP5-8.5 (Fick and Hijmans 2017).

We also generated binary model projections for the current and all six future projections to calculate the mean and projected range of change in suitable habitat as well as the proportion of change in suitable habitat within conservation areas, following an ensemble approach (Araújo and New 2007). Here, suitable habitat refers to areas that are predicted as suitable by the optimal ENM with suitability values above a threshold; models were thresholded using the minimum training

presence threshold of the cloglog projection and the total areas of overlap were calculated. Conservation areas were calculated using the IUCN WCPA database (UNEP-WCMC and IUCN 2020) and include all types of protected areas including UNESCO Biosphere reserves, and thus likely represent overestimates. We also calculated the projected amount of shift in suitable habitat as the distance of the shift in the centroid of the thresholded climatically suitable habitat.

## Results

The optimally tuned niche model was made using a regularization multiplier of 3 and the linear and quadratic feature classes. Models made with presence and background data can be evaluated several ways. One popular way is to test the model's ability to predict withheld, or testing, data. Another way to test a model's predictive ability is using the model's evaluation-AUC, a measurement of the model's ability to correctly discriminate between a true presence and a background locality. The optimal model showed an average test omission rate at the minimum training presence threshold of 0.091, and an average evaluation-AUC of 0.977. Maxent also provides users with an assessment of the variables used in the model via the Maxent lambda file. These variables are not necessarily the most important for driving the species' niche, but rather were identified as important for modeling the species. The variables with non-zero lambda values were bio2 (Mean Diurnal Range), bio7 (Temperature Annual Range), bio9 (Mean Temperature of the Driest Quarter), bio15 (Precipitation Seasonality), and bio19 (Precipitation of the Coldest Quarter).

The final resulting model successfully predicts the known range of *M. grandis* including the newly discovered populations in northern Vietnam but also overpredicts outside the current known range (Fig. 2). Some overprediction is expected for a climate-only

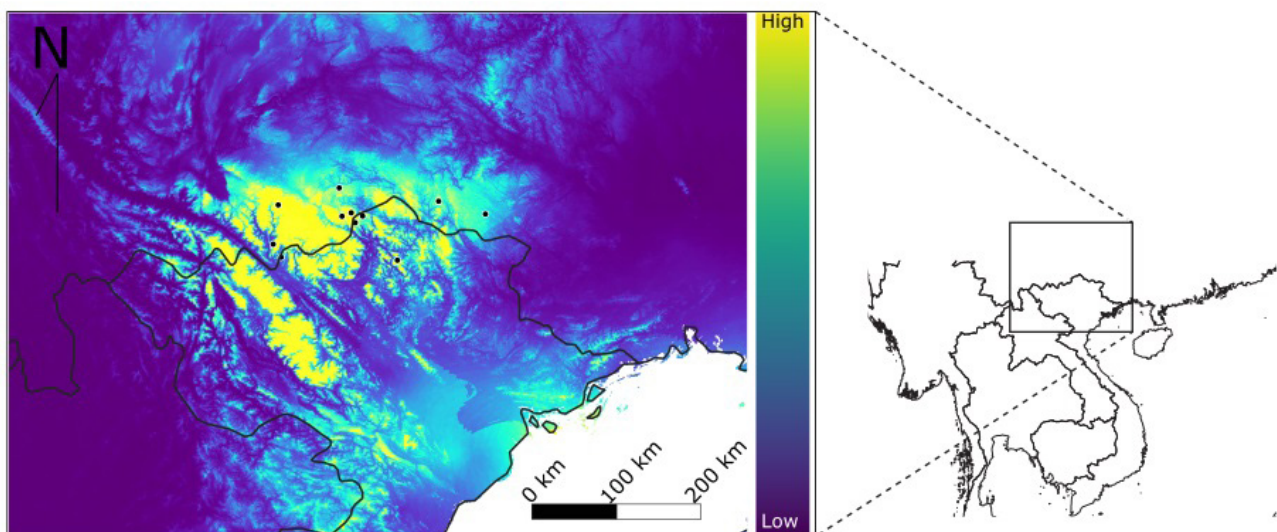
based model that does not take into account dispersal limitations or species interactions and this should be noted when interpreting model results and projections.

Fig. 3 shows the overlap across six future climate model and socioeconomic pathway model projections. Models predict an overall loss in total area of suitable habitat by the 2070s as well as a loss in the amount of suitable habitat in existing conservation areas (Table 1). Models also predict a geographic shift in the location of its most suitable habitat to novel areas that could include countries not a part of current distribution—Lao PDR and Myanmar (Fig. 3, Table 1). Examination of the centroid shifts in suitable habitat show predicted shifts are mostly to the south to Thanh Hoa Province, Vietnam, to similar elevations as the current distribution, while one model projection predicts a centroid shift westwards into Northern Lao PDR (Fig. 4).

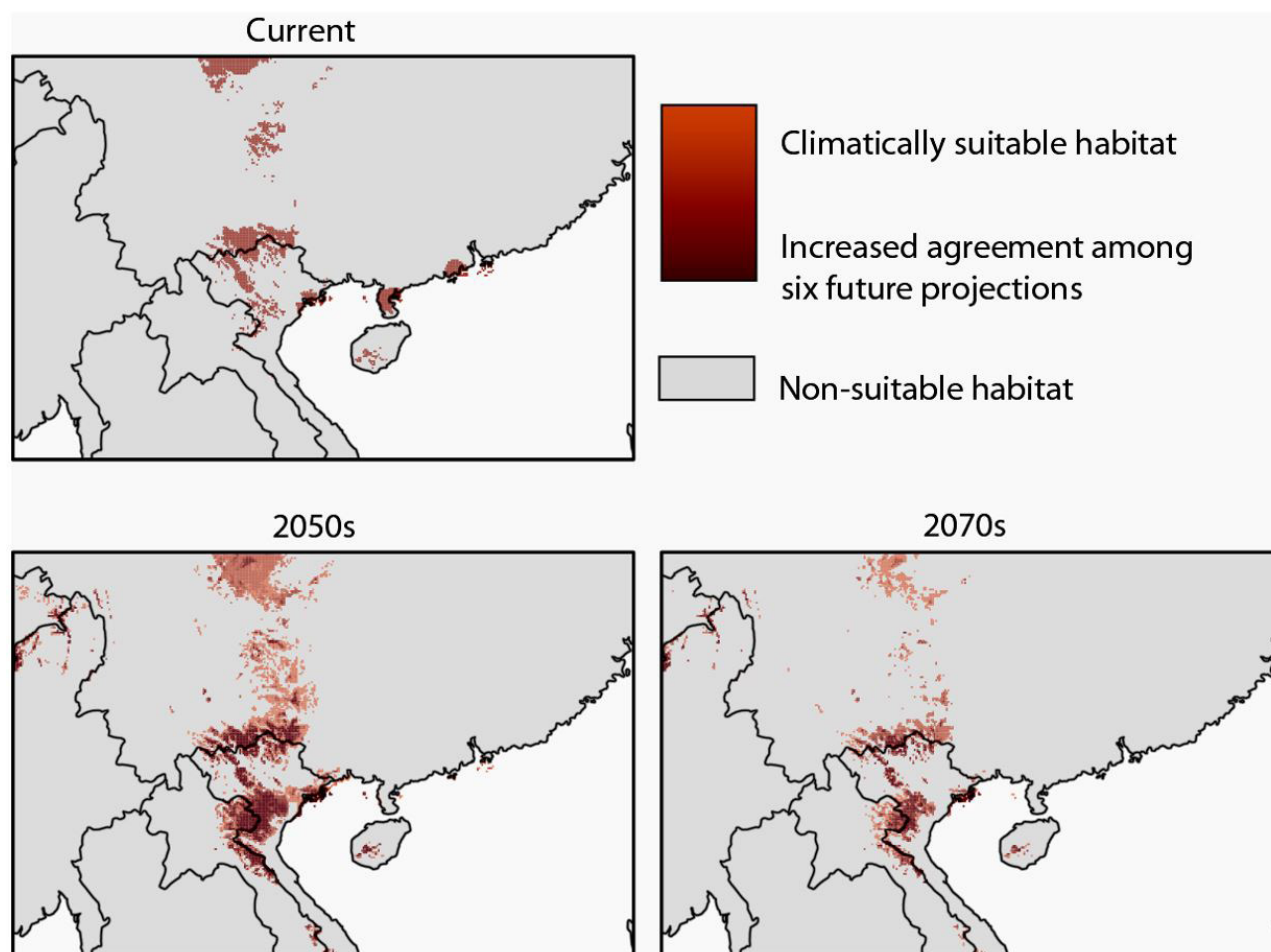
## Discussion

The climate-based ENMs for *M. grandis* performed well against validation criteria and successfully predicted the known range, including recently discovered populations in northern Vietnam, but also with some expected areas of overprediction that are likely far outside the dispersal capacity of the species. The variables that contributed to the optimal ENM were largely related to seasonality and the interactions of temperature and precipitation at extremes. Some of the predicted areas that are closer to the current known range may be worth targeting for future surveys to potentially find additional populations of this rare and endangered species, especially at appropriate elevations along the border with Lao PDR (Fig. 2).

Climate-based ENMs projected across a range of future scenarios estimated an overall loss in total area of climatically suitable habitat for *M. grandis* by the 2070s and a loss in the amount of climatically suitable habitat in existing conservation areas. ENMs



**Figure 2.** Modeled climatically suitable habitat for the current climate for *Magnolia grandis*. Black circles represent occurrence data used to train the model and green and yellow colors on the map indicate higher modeled suitability.



**Figure 3.** Climate-based ENM projections for *Magnolia grandis* for the current climate and future projections to the 2050s and 2070s with darker red shades indicating increased agreement (overlap) across six future climate model and socioeconomic pathway projections (two global climate models BCC-CSM2-MR and MIROC6 for each of three SSPs: SSP2-4.5, SSP3-7.0 and SSP5-8.5).

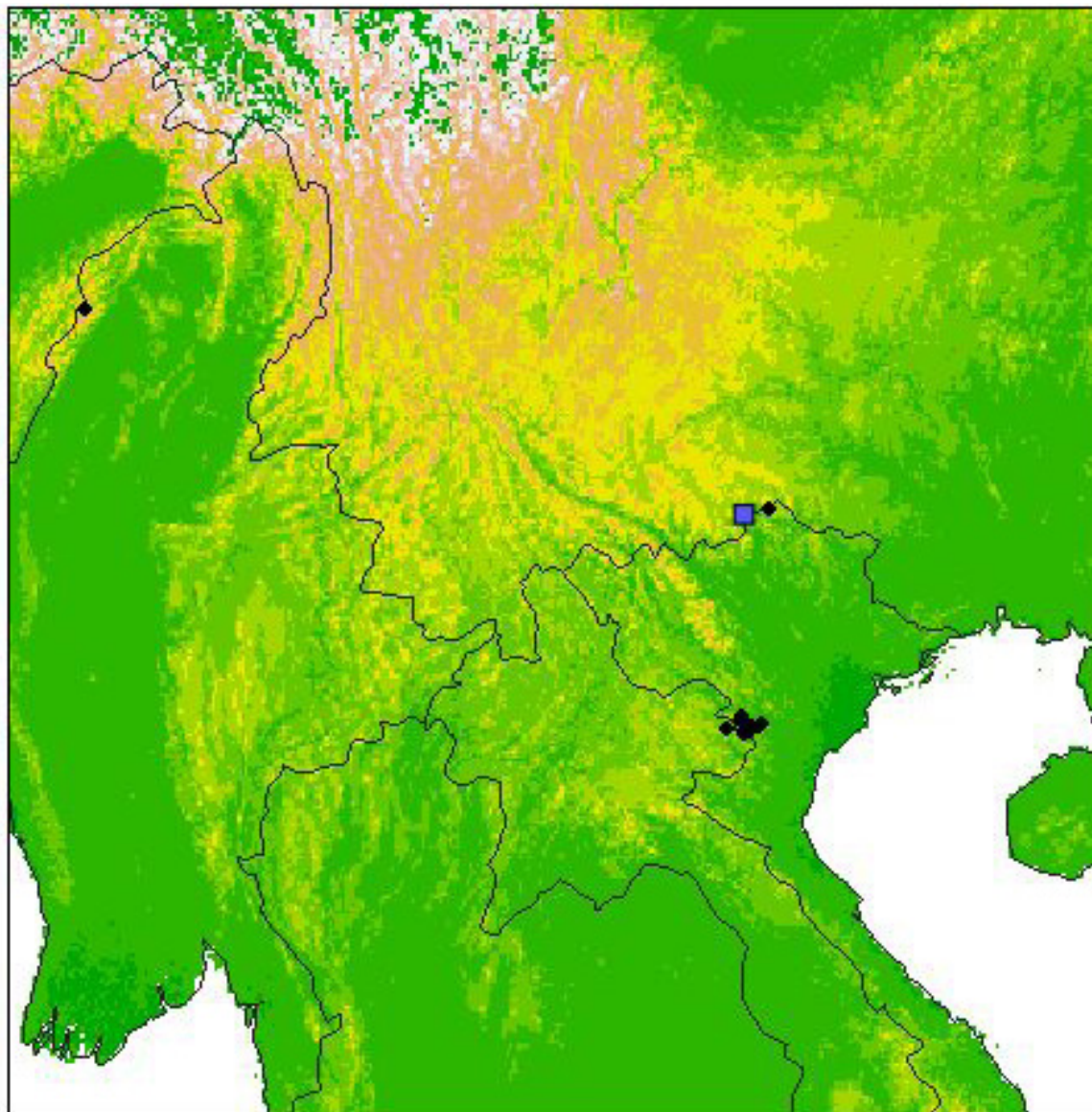
**Table 1.** Summary including mean (and range) of future projected changes in climatically suitable habitat for *Magnolia grandis* across six different climate model and socioeconomic pathway projections.

Time-frame	Change in suitable habitat in conservation areas	Total projected suitable habitat change (km <sup>2</sup> )	Projected amount of shift in the centroid of suitable habitat (km)
2050s	-10.1% (-13.9 to -3.2)	+29,000 (-23,000 to +111,000)	269 (36.1 to 325.0)
2070s	-15.3% (-24.0 to -9.5)	-38,000 (-75,000 to -2,800)	436.8 (313.0 to 1,025.6)

also predict a large geographic shift in the location of climatically suitable habitat to novel areas, with most models projecting a southern shift (Fig. 4).

Given very small population sizes and high levels of fragmentation among existing populations (Chen et al. 2012, Xu 2020) and the threat of ongoing habitat loss for agricultural expansion and logging (Rivers et al. 2016), current conservation management recommendations for *M. grandis* focus on increasing protection of current habitat and *ex situ* cultivation efforts to enable potential population growth through plantings (GTSG 2014). Indeed, community forest conservation monitoring combined with nursery

cultivation efforts have been successful in Vietnam. Community conservation teams conduct regular patrols across critical habitat areas and *M. grandis* seeds are collected and sown in local nurseries until ready to be planted in community forests and in cardamom plantations, where fast-growing *M. grandis* trees provide the service of shade (H.Q. Nguyen, Pers. Comm.). Fauna and Flora International – Vietnam (FFI) reports the successful germination of *M. grandis* seeds in nursery cultivation, with more than 12,000 seedlings in the Tung Vai nursery ready for planting in early 2021 (C.S. Le, Pers. Comm.). Also, surveys by FFI in 2020 confirm the successful regeneration



**Figure 4.** Centroids of modeled climatically suitable habitat for *Magnolia grandis*, with a blue square representing the centroid for the current predicted distribution and black diamonds representing the centroids of six future projections. Background colors depict elevation based upon a SRTM-based elevation data layer (Hijmans et al. 2005) with green representing low elevation, yellow mid-elevation, and lighter orange, pink, and white as high elevation, up to 7000m.

of previously planted trees, with at least 500 small trees regenerating in Quan Ba around past plantings (C.S. Le, Pers. Comm.). The results we present here suggest that the success of the current community-based approach, which combines nursery cultivation, planting, and monitoring, can continue to have success under future climate change, if implemented in an adaptive management framework that takes into consideration future climatic suitability. For example, the inclusion of a climate-monitoring plan may enable adaptive shifts in plans for planting, and potentially expansion to new areas via assisted migration.

Such a plan should be facilitated through the establishment of long-term ecological research studies focused on *M. grandis* microclimate preferences

and ecology (García-Hernández and Toledo-Aceves 2020). While the climate-based ENMs we present here successfully predict broad-scale distribution trends consistent with the boundaries of wet-warm subtropical climate, *M. grandis* is often known specifically to inhabit the sunny south-east or south-west facing valleys of mountains within this climate (GTSG 2014). Indeed, one of the key variables in our optimal ENM was mean diurnal range, which also points to the potential importance of microclimate for fine-scale habitat preference for *M. grandis*. Further, our ENM projections did not display the typical ‘warming footprint’ (a northern and upslope range shift) that many species are predicted to experience under climate change. In such cases, local-scale effects

or aspects of climate change other than temperature, like shifts in the seasonal balance of energy and water availability, may be more important than temperature shifts in determining suitable habitat for the species (Rapacciuolo et al. 2014). A long-term ecological study incorporating microclimate data could provide the input needed to explain the physiological reasons why *M. grandis* diverges from more typical ‘warming footprint’ patterns, and to enable finer-scale projections to facilitate more specific adaptive management plans around new plantings (e.g. García-Hernández and Toledo-Aceves 2020).

Adding forward-thinking (adaptive) climate-based management flexibility to community-based efforts will also serve to strengthen resilience of local livelihoods including cardamom cultivation in the face of anticipated climatic changes. Magnolia conservation has other livelihood and conservation benefits as well; *M. grandis* is highly valued for its use in traditional medicines (Xu 2020), and the world’s largest population of *M. grandis* shares its habitat with the Tonkin snub-nosed monkey (*Rhinopithecus avunculus*), a critically endangered primate (FFI 2020).

The majority of our model projections predicted a large shift in the centroid of *M. grandis* climatically suitable habitat farther south into Vietnam (Fig. 4). Thus, a key component to successful management of *M. grandis* and other transboundary endangered species under climate change will be effective cross-border conservation partnerships. Opportunities should be prioritized to strengthen the capacity of national and regional conservation and land-use planning agency staff in spatial conservation planning and transboundary management for climate change impacts on biodiversity. This could include for example training for scientists, practitioners, and managers in ENM and other climate change research methods and results interpretation, stakeholder engagement, and cross-border cooperation for conservation. Organizations such as FFI and the Center for Plant Conservation – Vietnam are already engaging in such activities. Also, although the guidelines introduced by the IUCN SSC (2016) to assess species’ vulnerability to climate change include ENMs (Foden and Young 2016), these guidelines do not mention potential model interpretation and uncertainty issues when translating these assessments into collaborative management plans and actions in transboundary contexts. Stakeholder engagement is crucial both to generate the most accurate and least biased ENM inputs and outputs, and also to best fit the goals and preferred outcomes of diverse stakeholder communities in complex border contexts (Villero et al. 2016, Sterling et al. 2017).

Importantly, the future projections we report here consider potentially suitable climatic habitat only, and do not account for dispersal limitations, interactions among species, or other factors such as changes in human land use, and thus may overestimate potential shifts, but also are likely to underestimate losses (Segan et al. 2015). It is critical not to take ENM projections as specific predictions for a given species

or suite of species because ENMs can yield unreliable or misleading assessments of relative vulnerability to climate change even despite excellent overall discrimination ability, transferability, or validation (Sofaer et al. 2018). In our case, we focused on generalized estimates of risk and vulnerability that in consultation with stakeholders would be most useful for decision-making. However, additional studies could be helpful to account for the effects of dispersal limitations, species interactions, and human land use changes on our predictions. Further, the long-term ecological study suggested above could investigate the potential for the species’ ability to adapt to climate change.

Also helpful to better inform conservation management would be a more detailed understanding of *M. grandis*’ relationship to geological features such as limestone karst, since *M. grandis* is found in limestone forest valleys in addition to montane evergreen broadleaf forest (GTSG 2014). As discussed in other papers in this issue (Blair et al. 2021), limestone karst geology is an important limiting ecological factor for other species in the region with significant implications for estimations of future climatically suitable habitat.

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## Author Contributions

MEB led study design and led writing of the manuscript, PJG co-led study design, led model training, tuning, and projections, and contributed to writing the manuscript, NQH co-led study design, led the collection of and provided input data, contributed

to model tuning decisions and contributed to writing the manuscript, TBN contributed to the collection of input data and to writing the manuscript, and LSC contributed to writing the manuscript.

## Data Accessibility Statement

Complete R markdown files with model tuning procedures and final results are included as online supplementary materials, Appendices S1, S2 and S3, to this manuscript. Environmental input data used in this study are available for free, online at [worldclim.org](http://worldclim.org). For the *M. grandis* locality data used in this study, the GBIF data can be found using the DOI information provided, and other data are available upon request, due to the sensitive nature of locality information for a highly endangered species.

## Supplementary Material

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

**Appendix S1.** [magnolia\\_modeling.html](#): Rmarkdown file showing the data processing and model tuning for *Magnolia grandis*.

**Appendix S2.** [conservationFunctions.html](#): Rmarkdown file showing the functions that were sourced to calculate several of the metrics presented in this paper.

**Appendix S3.** [magnoliaGrandis.html](#): Rmarkdown file showing the outputs of the conservation functions that were calculated.

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