Current conservation status and potential distribution under climate change of *Michelia lacei*, a Plant Species with Extremely Small Populations in Yunnan, China

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Abstract *Michelia lacei* W.W. Smith, a magnolia species categorized as Endangered on the IUCN Red List, is subject to severe disturbance. We carried out field surveys and a review of literature records to present a detailed description of the current status of *M. lacei*. We then predicted the potential distribution of *M. lacei* under different climatic scenarios based on 60 occurrence records (53 recorded during our field surveys and 7 earlier records) and 19 bioclimatic variables from the WorldClim database. We selected 18 locations and four bioclimatic variables for model training. Temperature seasonality and annual temperature range were the most influential variables for predicting the potential distribution of the species. We used *MaxEnt* to model distribution under current climate conditions and four Shared Socioeconomic Pathway scenarios in four future time periods to determine the effects of future climate change on the habitat suitable for the species. We predict areas of moderately and highly suitable habitat will gradually decrease over time. We recommend increased in situ and ex situ conservation efforts to mitigate this habitat decline and protect populations of *M. lacei*.

Keywords China, climate change, conservation status, ex situ conservation, *MaxEnt*, maximum entropy model, *Michelia lacei*, Plant Species with Extremely Small Populations

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Introduction

Global climate change is one of the greatest challenges (Bellard et al., 2012; Franchini & Mannucci, 2015; Malhi et al., 2020). The annual growth rate of global greenhouse gas emissions during 2010–2019 was lower than that during 2000–2009, but overall global carbon emissions are still increasing (IPCC, 2022). If current trends continue, we will face significant climatic, environmental and social risks (Fischer et al., 2013). Climate change affects the survival and distribution of species (Jiang, 2013; Mkala et al., 2022). Changes in global climate can cause the displacement or loss of suitable habitats for some threatened species, leading to a decrease in population numbers and the extinction of species (Cai et al., 2022; Iseli et al., 2023).

Potential distribution areas of species under different scenarios can be predicted using species distribution models (Klanderud & Birks, 2003; Qin et al., 2020; Cai et al., 2022). The most common models include the bioclimatic analysis and prediction system model (BIOCLIM; Busby, 1991), the maximum entropy model (*MaxEnt*; Phillips et al., 2006), the generalized linear model (Guisan et al., 2002), the genetic algorithm for rule-set prediction model (GARP; Sanchez-Flores, 2007) and the DOMAIN model (Carpenter et al., 1993). Although such models can produce species distribution maps, they are limited by the quality of data and so should be accompanied by field surveys to increase the accuracy of predictions (Abdelaal et al., 2019; Mkala et al., 2022).

Compared to other species distribution models, *MaxEnt* is considered to have a relatively high predictive accuracy for species with small sample sizes, small geographical ranges and limited environmental tolerance (Phillips & Dudik, 2008), and has been widely used to predict the ranges of rare and threatened species with few distribution data and narrow distributions (Hernandez et al., 2006; Liu et al., 2022). Predicting the potential distributions of threatened species can help scientists and policymakers understand the effects of environmental change on species survival and can inform the planning of appropriate strategies to reduce the risk of extinction (Lawler et al., 2009; Kamilar & Beaudrot, 2013).

Michelia lacei W.W. Smith is an evergreen tree in the Magnoliaceae family, categorized as a Plant Species with Extremely Small Populations because of its narrow distribution, small number of individuals, the continuing impact of anthropogenic disturbance across its habitat and its high risk of extinction (Sun et al., 2019a, 2019b). The species was categorized as Critically Endangered on the China Species Red List in 2004 (Wang & Xie, 2004), but was recategorized as Endangered in 2015 following additional field

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surveys and the discovery of several new populations in China (Rivers & Wheeler, 2015; Rivers et al., 2016; Cai et al., 2017). Although genomic data can contribute to the knowledge and conservation of this threatened species at the genetic level (Cai et al., 2024; Liu et al., 2024), it is also crucial to understand the threats it faces and its conservation status and potential distribution under current and future climate scenarios. Here we summarize the conservation status of *M. lacei* in China, predict its potential distribution under current and future climate scenarios and discuss strategies for its conservation and management, especially with respect to the impacts of climate change.

Study area

Yunnan Province in south-west China covers an area of 394,100 km², 4% of the total area of the country. *Michelia lacei* is mainly distributed in Yunnan Province, but is also found in northern Viet Nam and Myanmar. It is native to subtropical monsoon evergreen broad-leaved forests at altitudes of 1,000–1,800 m (Liu, 2002; Xia et al., 2008). Since 2014, we have extensively surveyed Yunnan Province every 12-months, finding a small number of *M. lacei* populations in south-east Yunnan (Fig. 1). In the field, *Parakmeria yunnanensis* Hu, *Cornus hongkongensis tonkinensis* (W.P. Fang) Q.Y. Xiang, *Magnolia balansae* (A.DC.) Dandy, *Vernicia fordii* (Hemsl.) Airy Shaw and *Alsophila costularis* Baker are the main species associated with *M. lacei*.

Methods

Investigation of conservation status and species distribution data

To gain a comprehensive understanding of the current conservation status of *M. lacei* in China, in September 2022 we asked local forestry bureaus and residents near its known distribution sites if they had seen any individuals of *M. lacei*, and, if so, how many. We subsequently surveyed all locations in which the plant had been seen or recorded in the wild. For each individual located, we measured its height and diameter at breast height. Where height was < 1.3 m or diameter at breast height was < 2 cm we recorded the plant as a seedling (Tang et al., 2011; Han et al., 2019; Tao et al., 2020). We documented geographical coordinates (using a GPS), fruiting status (yes/no), growth status (i.e. whether or not we observed pests and diseases, as these can destroy plant tissue, impacting development), companion species and whether the plant was in a protected area. We calculated and recorded the extent of occurrence and area of occupancy of *M. lacei* in China using the package *ConR* (Dauby et al., 2017) in *R 4.0.3* (R Core Team, 2020).

In addition to our field surveys, in October 2022 we examined literature and herbarium records (FRPS, 2019; CNKI, 2023; CVH, 2023; POWO, 2023). In total, we obtained 60 records for *M. lacei* in China (53 from our surveys and seven earlier records). We mapped these data using *ArcGIS 10.8* (Esri, USA), retaining only one record per km² to eliminate spatial bias (Rather et al., 2021; Mkala et al., 2022), resulting in 18 locations of *M. lacei* for further analysis. We also investigated the ex situ conservation of *M. lacei* in Chinese botanical gardens by collating information on the institutions where it is cultivated, and data such as the growth, flowering and fruiting status of cultivated plants.

Bioclimatic variables

To predict the potential present and future distribution of *M. lacei*, we used the 19 bioclimatic variables, with a resolution of 2.5 arcminutes, provided by WorldClim 2.1 (Fick & Hijmans, 2017). We used mean climate data

Fig. 1 Locations of *Michelia lacei* individuals recorded during this study.

for 1970–2000 to predict current distribution and for 2021–2040, 2041–2060, 2061–2080 and 2081–2100 to predict future distribution. Shared Socioeconomic Pathways can be used to generate different climate change scenarios to assess the impacts of policies and actions on future climate change (Weng et al., 2020). We modelled each time period using four Pathways (SSP126, SSP245, SSP370, SSP585) under the second-generation Earth system model of the Centre National de Recherches Météorologiques (CNRM-ESM 2-1; Fick & Hijmans, 2017). We chose this model, which was developed for the sixth phase of the Coupled Model Intercomparison Project, because in a number of experiments it has shown a more significant response to the external environment than other models as it includes interactive Earth system components such as the carbon cycle, aerosols and atmospheric chemistry (Seferian et al., 2019). The four Shared Socioeconomic Pathways represent the net radiative forcings at the end of 2100 (2.6, 4.5, 7.0 and 8.5 W/m^2) and simulate global warming trends in the absence of climate policy intervention. As the forcing value increases, so does the radiative capacity, representing higher levels of greenhouse gas emissions that therefore have a stronger impact on environmental changes (Fick & Hijmans, 2017; O'Neill et al., 2017; Riahi et al., 2017).

To reduce analytical interference from strong correlations between the bioclimatic variables, we extracted the 19 bioclimatic variables for each of the 18 locations of *M. lacei*. We ran correlation analyses of these data in *R*, and we analysed the contributions of the 19 bioclimatic variables to the species distribution using *MaxEnt 3.4.3* (Phillips et al., 2006). When screening bioclimatic variables we first retained that with the largest contribution, and then removed variables that had a correlation of $r > 0.8$ with the variable retained, and then retained the remaining variables. We repeated this step until no more variables could be removed. Finally, we used the remaining variables to predict the potential distribution area of *M. lacei* (Dormann et al., 2013; Yi et al., 2016; Wang et al., 2018).

Model description

We divided the species location information into two subsets and used 75% of the location information as training data to build the distribution model. We used the remaining 25% to validate the model, with 10 repetitions and the replicate run type set to bootstrap (Efron, 1979; Khanal et al., 2022; Soilhi et al., 2022). We set the output format to cloglog, which estimates the probability of presence between 0 and 1, as recent studies have suggested that cloglog has greater theoretical support than one of the alternative output formats, logistic (Phillips et al., 2017). We left the remaining parameters as the *MaxEnt 3.4.3* defaults (Phillips & Dudik, 2008). To demonstrate the reliability of the generated model, we calculated the area under the curve (AUC) of the receiver operating characteristic curve (ROC). The AUC value is related to the accuracy of the model, and the closer the AUC value is to 1, the better the test data fit the model (Swets, 1988; Coban et al., 2020).

Suitable habitat classification and distribution changes

We used *SDM_Toolbox 2.5* (Brown et al., 2017) in *ArcGIS* to convert the resulting *MaxEnt* ASCII format files to raster files, and created a map of the potential distribution of *M. lacei*. Cloglog values range from 0 to 1, with 1 being areas most suitable for the species. We then used the Reclassify (Spatial Analyst) tool in *ArcGIS* (Brown et al., 2017) to categorize habitat into four grades based on previous studies of native Chinese species: unsuitable areas (0–0.05), areas of low suitability (0.06–0.33), moderately suitable areas (0.34–0.66) and highly suitable areas (0.67–1.00; He & Zhou, 2011; Gong et al., 2022). Finally, we calculated the area and proportion of each habitat suitability class using *ArcGIS*.

To analyse changes in potential distribution over time, we examined only those areas with suitable habitat (i.e. with a cloglog value > 0.05). We used *SDM_Toolbox* to compare potential distribution in each future period with the current potential area of distribution (Brown et al., 2017), identifying areas that will become more suitable, less suitable or will be unchanged. We viewed this output in *ArcGIS* and graded habitat as: −1 (the future habitat is more suitable than it is at present), 0 (the habitat is suitable neither in the future nor at present), 1 (the habitat is suitable during both periods) or 2 (the habitat is suitable at present but will not be suitable in the future; Mkala et al., 2022).

Results

Population status survey

During our surveys we recorded 10 populations and 53 individuals of *M. lacei*, comprising 50 mature individuals and three seedlings in five counties. Seven individuals were found in Daweishan National Nature Reserve, the remainder were outside protected areas, in villages, along roadsides, on farmland and elsewhere. The extent of occurrence and area of occupancy of *M. lacei* in China are 3,881 km^2 and 52 km^2, respectively.

The height of 90% of the *M. lacei* individuals was 6–30 m (Fig. 2a); 85% had a diameter at breast height of 11–90 cm (Fig. 2b). One tree had a diameter at breast height of 192 cm, which is the largest *M. lacei* individual on record (Plate 1a).

Five institutions run ex situ conservation programmes for *M. lacei* in China: Kunming Botanical Garden, South China Botanical Garden, Wuhan Botanic Garden, Guilin Botanical Garden and Fairy Lake Botanical Garden (Xian

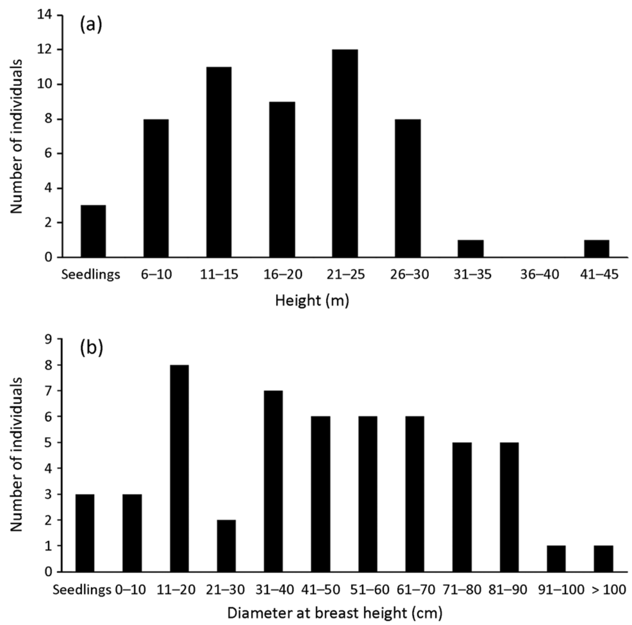

FIG. 2 The (a) height and (b) diameter at breast height of all 53 individuals of *M. lacei* found during our surveys in China.

Hu; Sun et al., 2019a, 2019b; Linsky & Sun, 2022). In 1987, Kunming Botanical Garden planted 12 *M. lacei* individuals, all of which have grown into trees > 10 m tall and are in good condition. Four have flowered, and two have also fruited.

Model performance and the importance of environmental variables

The AUC values of the ROC curve were > 0.9 in all predicted future periods, indicating that the simulation of the area potentially suitable for *M. lacei* is credible (Phillips et al., 2006). Following examination of the correlation coefficients and the contributions of the 19 bioclimatic variables, we selected four to predict the potential distribution of the species (Fig. 3): temperature seasonality (Bio_4), minimum temperature of coldest month (Bio_6), temperature annual range (Bio_7) and precipitation of wettest month (Bio_13). In the *MaxEnt* simulation the two highest-contributing factors were Bio_4 (57.1%) and Bio_7 (19.1%), which together accounted for 76.2% of the total contribution (Table 1).

PLATE 1 (a) The largest *Michelia lacei* individual on record, found during our surveys in Yunnan Province, China, in 2022, and (b) flower bud, (c) flower and (d) fruit.

Potential distribution under current and future climate conditions

In addition to the known current distribution in Yunnan, our model suggests areas of suitable habitat in Xizang, Sichuan, Guizhou, Guangxi, Guangdong, Fujian, Taiwan and Hainan (Fig. 4a). However, during our literature searches, we found no record of *M. lacei* in China beyond Yunnan Province. Within Yunnan, predicted suitable habitat under current conditions is mainly in the west and south-east (Fig. 4b). In western Yunnan, the moderately and highly suitable areas are predominantly in Dehong, and in south-eastern Yunnan these areas are predominantly in Wenshan and Honghe. Of the potentially suitable habitat in Yunnan, 59% (19.38×10^5 km^2) had only low suitability, 33% (10.87×10^5 km^2) was moderately suitable and 8% (2.70×10^5 km^2) was highly suitable. Of the total habitat in Yunnan Province, 16% is unsuitable for *M. lacei* (6.46×10^5 km^2; Table 2).

For each future period we predicted habitat suitability in Yunnan for the four Shared Socioeconomic Pathways (Fig. 5; Table 2). The largest areas of unsuitable and low suitability habitat were both predicted under the worst-case scenario (SSP585), with unsuitable habitat of 8.66×10^5 km^2 predicted during 2061–2080, and low suitability habitat of 28.06×10^5 km^2 predicted during 2081–2100. We predicted areas of moderately and highly suitable habitat to be greatest under the SSP126 scenario during 2041-2060, at 18.05×10^5 and 2.81×10^5 km^2, respectively.

Figure 6 shows the changes in the future potential distribution of *M. lacei* compared to that under current conditions, showing areas of expansion, areas with no change in suitability (the areas are suitable neither in the future nor at present), areas of stability (the areas are suitable during both periods) and areas of contraction. The highest increase in area of suitable habitat is 1.58×10^5 km^2 under SSP585 during 2081–2100. Under the SSP585 scenario during 2061–2080 the area suitable for *M. lacei* decreased by 2.62×10^5 km^2 compared to the present. Based on current and future climate data, we predict that as climate conditions change in the future an increasingly large area will be transformed into habitat with low suitability for *M. lacei*.

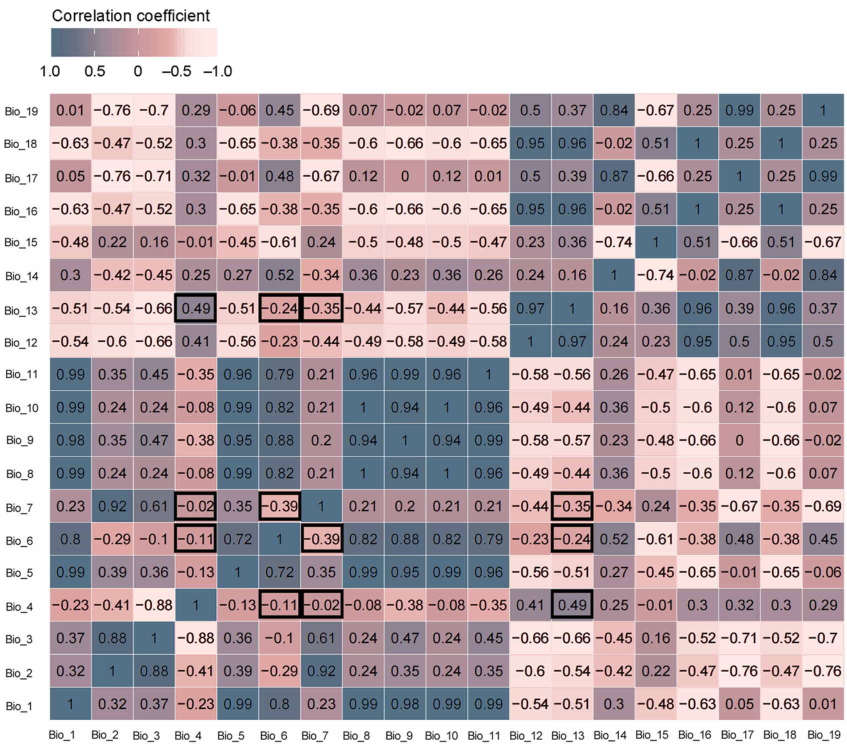

FIG. 3 Pearson's correlation analysis of the 19 bioclimatic variables from WorldClim 2.1 (Fick & Hijmans, 2017). Black outlined boxes indicate the correlation coefficients between the four bioclimatic variables used for modelling (Bio_4, Bio_6, Bio_7 and Bio_13; Table 1), after screening. Correlation coefficients range between −1 and 1. (Readers of the printed journal are referred to the online article for a colour version of this figure.)

TABLE 1 Bioclimatic variables downloaded from WorldClim 2.1 (Fick & Hijmans, 2017) used for modelling and their per cent contributions to the assessment of the distribution of *Michelia lacei* (Fig. 3).

Bioclimatic variable	Code	Contribution (%)
Temperature seasonality	Bio_4	57.1
Minimum temperature of coldest month	Bio_6	12.3
Temperature annual range	Bio_7	19.1
Precipitation of wettest month	Bio_13	11.5

In summary, our modelling predicts that areas of moderately and highly suitable habitat for *M. lacei* will gradually shrink in west and south-east Yunnan. Areas of suitable habitat will also decline in central Yunnan.

Discussion

Modelling performance and the influence of the variables

Reliable distribution data are crucial for accurately predicting species' potential distribution (Phillips & Dudik, 2008; Chen et al., 2012). Modelling location data for 60 individuals of *M. lacei*, the AUC values calculated with *MaxEnt* were all > 0.9, indicating that the simulation prediction is accurate (Swets, 1988). Previous studies have found precipitation and temperature to be important factors influencing the distribution of species (Shi et al., 2020; Rather et al., 2022). In this study, we found that temperature had a greater influence on predicting the potential range of *M. lacei* than precipitation. In addition to the significant influence of climatic and topographic variables on the distribution of species, soil

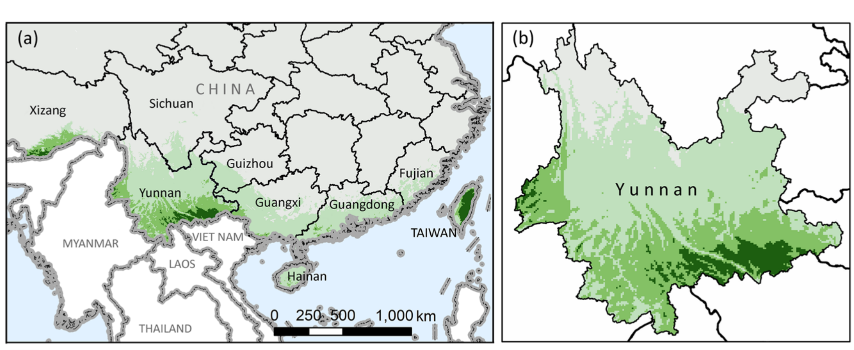

FIG. 4 The current potential distribution of suitable habitat for *M. lacei* (a) in China and (b) in Yunnan Province.

TABLE 2 Predicted areas of *M. lacei* habitat in Yunnan Province, China, for future time periods under four Shared Socioeconomic Pathway global warming scenarios (SSP126, SSP245, SSP370 and SSP585), compared with the current potential distribution of the species.

Climate scenario	Time period	Unsuitable ($\times 10^5$ km^2)	Low suitability ($\times 10^5$ km^2)	Moderately suitable ($\times 10^5$ km^2)	Highly suitable ($\times 10^5$ km^2)
Current	1970–2000	6.46	19.38	10.87	2.70
SSP126	2021–2040	6.87	21.43	8.81	2.30
	2041–2060	5.09	13.46	18.05	2.81
	2061–2080	5.85	20.29	11.55	1.72
	2081–2100	5.23	19.36	13.21	1.62
SSP245	2021–2040	7.18	23.27	7.67	1.29
	2041–2060	5.25	16.23	15.49	2.44
	2061–2080	5.49	26.39	6.82	0.71
	2081–2100	6.54	27.15	5.09	0.63
SSP370	2021–2040	5.20	17.45	14.61	2.16
	2041–2060	5.77	21.83	10.32	1.48
	2061–2080	5.66	22.97	9.84	0.95
	2081–2100	7.09	27.44	4.52	0.36
SSP585	2021–2040	6.63	24.15	7.39	1.23
	2041–2060	6.85	25.87	5.91	0.78
	2061–2080	8.66	27.03	3.45	0.27
	2081–2100	6.60	28.06	4.40	0.34

and hydrogeological variables also play important roles, and we plan to investigate the roles of these variables on the distribution of *M. lacei* in future studies. The current distribution of the species is relatively small compared with the potential area of suitable habitat, and these findings should be taken into account in future field surveys and potential reintroductions of this species.

Predicted habitat suitability for *M. lacei* under current climate conditions

Current predicted suitable habitat for *M. lacei* in China is primarily in the southern provinces. We only surveyed in Yunnan, but we did not find any literature records of the species in China beyond this province. Suitable area

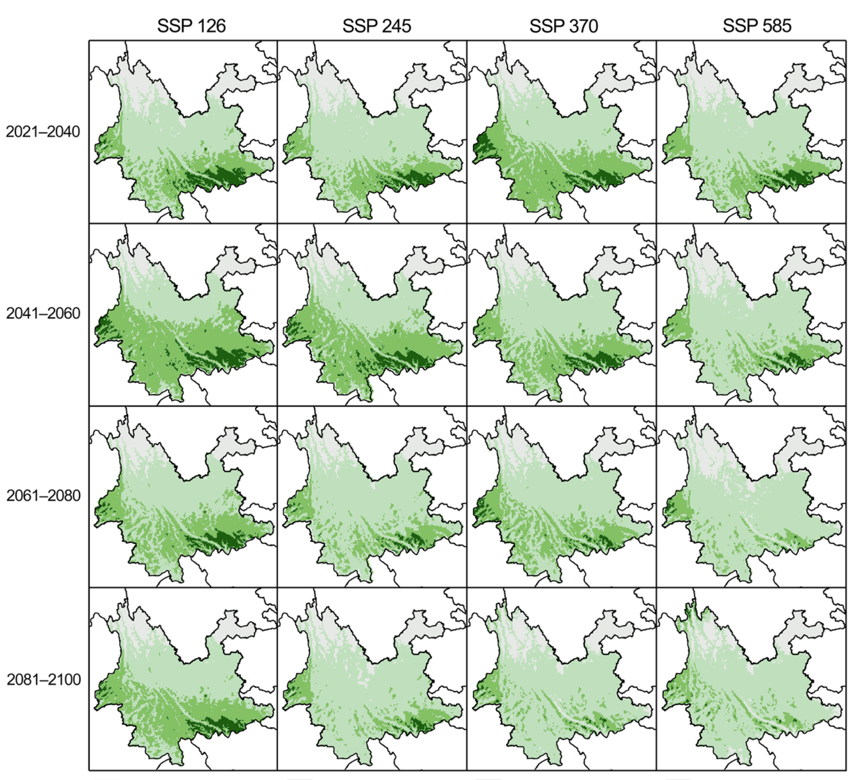

FIG. 5 Predicted future areas of *M. lacei* habitat in Yunnan Province, China, with different levels of suitability under different Shared Socioeconomic Pathways (SSP) climate scenarios.

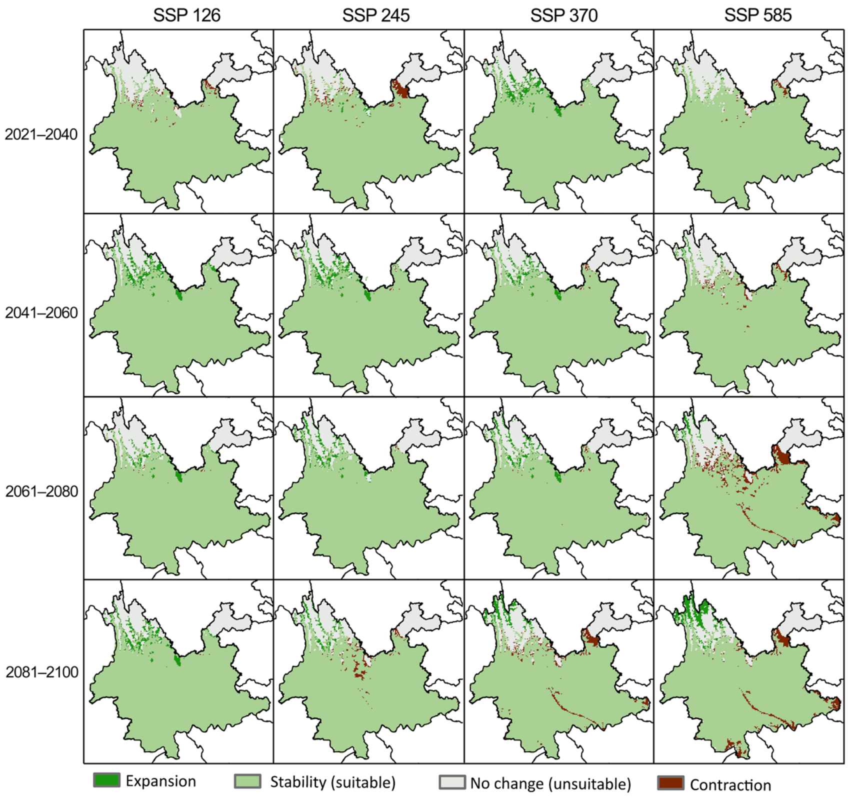

FIG. 6 Changes in future habitat suitability for *Michelia lacei* relative to current habitat suitability in Yunnan Province, China, under different Shared Socioeconomic Pathways. Expansion indicates that the future habitat is more suitable than it is at present, no change (unsuitable) indicates that the habitat is suitable neither in the future nor at present, stability (suitable) indicates that the habitat is suitable both now and in the future, and contraction indicates that the habitat is suitable at present but will not be suitable in the future. (Readers of the printed journal are referred to the online article for a colour version of this figure.)

predicted using species distribution models is often wider than the actual distribution range of a species (Cai et al., 2022; Yan & Zhang, 2022). When determining the distribution of threatened plant species, additional factors such as pollinator numbers, self-breeding, seed dispersal, community competition, habitat destruction, reduced population and habitat fragmentation need to be taken into account. These, amongst other factors, all have a greater impact on the distribution of highly threatened species than on those less threatened (Chen, 2017).

Changes in habitat suitability under future climate change scenarios

Based on our modelling, we predict the distribution of *M. lacei* will gradually decrease in the future, with the highly suitable habitat shrinking in size as the climate warms. This is consistent with previous research on the distribution patterns of threatened species in south-eastern Yunnan (Cai, 2020). In the four future periods we modelled, highly and moderately suitable areas were predicted to become areas of low suitability as temperatures change. In particular, the moderately suitable areas in Xishuangbanna were predicted to decline to almost zero. Under the worst-case scenario (pathway SSP585 during 2061–2080), the moderately and highly suitable habitats were predicted to be restricted to Dehong in western Yunnan, with a few small patches in Honghe and Wenshan in south-eastern Yunnan. In general, rising temperatures will promote the migration of plant populations into boreal forests (Boisvert-Marsh & de Blois, 2021; Behera et al., 2023). Such increases in temperature are likely to be accompanied by the movement of mountain plants to higher elevations. As a Plant Species with Extremely Small Populations, the migratory ability of *M. lacei* is limited compared to other, more widespread species, and its suitable habitat is gradually being reduced.

Protection and management of *M. lacei*

Some of the *M. lacei* individuals we recorded are growing in fengshui forests, preserved by local communities from nearby villages who believe the forests can bring prosperity and good fortune (Coggins & Minor, 2018). Two large individuals growing near a village have been listed as ancient trees by the local forestry bureau, and some individuals are located in a nature reserve, providing some level of protection. However, we found most individuals growing near roadsides, fields or riverbanks, with no protective measures. These individuals are at high risk of being cut down or otherwise destroyed. We found only three seedlings during our field studies, and can infer from this that wild populations are struggling to reproduce naturally. We found these seedlings in a vegetable field, by a roadside and in farmland where black cardomom *Amomum tsaoko* was being cultivated. During our 2022 surveys of wild *M. lacei* populations we found only four adult plants that had fruited.

Conclusion

We predicted suitable habitat for *M. lacei* under current and future climate conditions and found that areas suitable for this species will decline. Furthermore, *M. lacei* populations face significant threats from anthropogenic interference, among other factors. In addition to existing local protection, further appropriate conservation measures are needed for *M. lacei*. In situ conservation should focus on areas where the habitat of this species is predicted to remain stable in the future, by establishing conservation sites. We have achieved germ-free germination and seed propagation of *M. lacei* by collecting fruits from wild habitats and botanic gardens, but these methods are currently still being developed. Collection of fruits from the various *M. lacei* populations should continue and their seedlings should be grown for ex situ or near situ (i.e. establishment of populations at sites near wild populations; Sun et al., 2021; 2024) conservation.

Author contributions Field surveys: all authors; data analysis: YL, LC; writing, revision: all authors.

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Conflicts of interest None.

Ethical standards This research abided by the *Oryx* guidelines on ethical standards.

Data availability All species distribution data and bioclimatic variables have been described in the Supplementary Material.

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