Potential Distribution of *Blumea Balsamifera* in China Using MaxEnt and The Ex-Situ Conservation Based on its Effective Components and Fresh Leaf Yield

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Abstract

Blumea balsamifera is a famous Chinese Minority Medicine, which has a long history in Miao, Li, Zhuang and other minority areas. In recent years, due to the influence of natural and human factors, the distribution area of *B. balsamifera* resources has a decreasing trend. Therefore, it is very important to analyze the suitability of *B. balsamifera* in China. Following three climate change scenarios (SSP1-2.6, SSP2-4.5 and SSP5-8.5) under 2050s and 2070s, geographic information technology (GIS) and maximum entropy model (MaxEnt) were used to simulate the ecological suitability of *B. balsamifera*. The contents of L-borneol and total flavonoids of *B. balsamifera* in different populations were determined by gas chromatography (GC) and ultraviolet spectrophotometry (UV). The results showed that the key environmental variables affecting the distribution of *B. balsamifera* were mean temperature of coldest quarter (6.18-26.57 °C), precipitation of driest quarter (22.46-169.7 mm), annual precipitation (518.36-1845.29 mm) and temperature seasonality (291.31-878.87). Under current climate situation, the highly suitable habitat was mainly located western Guangxi, southern Yunnan, most of Hainan, southwestern Guizhou, southwestern Guangdong, southeastern Fujian and western Taiwan, with a total area of $24.1 \times 10^4 \text{ km}^2$. The areas of the moderately and poorly suitable habitats were $27.57 \times 10^4 \text{ km}^2$ and $42.43 \times 10^4 \text{ km}^2$, respectively. Under the future climate change scenarios, the areas of the highly, moderately, and poorly suitable habitats of *B. balsamifera* showed a significant increasing trend, the geometric center of the total suitable habitats of *B. balsamifera* would move to the northeast. In recent years, the planting area of *B. balsamifera* has been reduced on a large scale in Guizhou, and its ex situ protection is imperative. By comparison, the content of L-borneol, total flavonoids and fresh leaf yield had no significant difference between Guizhou and Hainan ($P > 0.05$), which indicated that Hainan one of the best choice for ex-situ protection of *B. balsamifera*.

Introduction

According to the fifth IPCC Assessment Report (IPCC AR5), the global average land surface temperature has increased by 0.85 °C from 1880 to 2012, and the average temperature from 2003 to 2012 has increased by 0.78 °C compared with that from 1850 to 1900, and it is expected that it will continue to increase by 0.3 °C to 0.7 °C in 2035 (Zou et al., 2015). With the rising temperature, the extreme weather increases, the cryosphere begins to degenerate, and the ecological environment continues to deteriorate, which leads to significant changes in species migration patterns, seasonal activities, phenology, and geographical distribution, and has a profound impact on the natural ecosystem and the sustainable development of human society (Fu et al., 2005; Abrahms et al., 2017; Williams et al., 2020). Climate, topography, soil and other environmental factors have a significant impact on the growth and geographical distribution of species. In the future, under the background of rising temperature and changing precipitation pattern, the living environment of species will also change, and some of them will migrate to high latitude areas (Wu et al., 2011; Läderach et al., 2016; Guo et al., 2017; Yang et al., 2020; Zhang et al., 2020). Climate change may accelerate species extinction, reduce species diversity, and make regional ecosystems more vulnerable, while some species will form new physiological characteristics to

adapt to climate change (Bowling et al., 2020; Wang et al., 2020; He et al., 2021). In order to understand the change of species adaptability and geographical distribution under the future climate change, and how to take targeted measures to protect rare species and maintain species diversity, many scholars have carried out the simulation and prediction of species geographical distribution under different climate scenarios (Wróblewska and Mirski, 2018; Donatti et al., 2020; Momblanch et al., 2020; Wu et al., 2021).

Niche is the sum of all the abiotic conditions necessary for the survival of species, which can effectively reflect the physiological and ecological needs of species (Godsoe et al., 2017; Citores et al., 2020). In recent years, niche models have been widely used to study the effects of global climate change on species distribution. Common models include classification and regression tree (CART) (Cao et al., 2005; Zhang et al., 2014), artificial neural network (ANN) (Wang et al., 2012; Su et al., 2018), genetic algorithm for rule set prediction (GARP) (Yu et al., 2009; Padalia et al., 2014), biological prediction system (Bioclim) (Booth et al., 2013; Venette, 2017), ecological niche factor analysis (ENFA) (Farashi and Naderi, 2017; Bashir et al., 2018) and maximum entropy model (MaxEnt) (Phillips et al., 2006; Kumar and Stohlgren, 2019), among which MaxEnt is widely used by researchers due to its advantages such as reasonable construction scheme, simple operation, graphical parameter configuration interface, and high combination of input data and GIS (Elith et al., 2010; Petitpierre et al., 2012). MaxEnt is a niche model based on the known distribution information of species and related environmental variables, which is mainly used to judge the ecological needs of species and predict potential suitable habitats based on the actual distribution of species (Warren and Seifert, 2011; Elith et al., 2015). In recent years, scholars at home and abroad have tried to use MaxEnt to study the habitat suitability of medicinal plants, such as *Fritillaria cirrhosa* D. Don (Zhao et al., 2018), *Phellodendron amurense* Rupr (Wan et al., 2014), *Houttuynia cordata* Thunb (Liu et al., 2021), *Daphne mucronata* Royle (Abolmaali et al., 2018), *Brucea mollis* Wall (Borthakur et al., 2018), etc., and achieved good results.

In recent years, with the rapid development of traditional Chinese medicine industry, the reserve of traditional Chinese medicine resources has decreased sharply, and the protection is imminent. At present, the protection methods of biological resources mainly include in-situ protection and ex-situ protection. In-situ conservation refers to maintaining and restoring the survival of species in their natural environment by protecting local ecosystems and natural habitats. Ex-situ conservation refers to the migration of species to areas outside their natural habitat for protection. Compared with local protection, ex-situ protection can reduce the impact of the external environment through human intervention and reduce the constraints of time and space. Therefore, ex-situ protection plays an irreplaceable role in the first aid of rare and endangered species, resource protection and development, and is an important way to protect the resources of traditional Chinese medicine (Que et al., 2016).

Blumea balsamifera (L.) DC. (Asteraceae: *Blumea*), is a perennial herb that likes warm climates and grows in tropical areas at an altitude of 400-800 m. In the world, *B. balsamifera* is mainly distributed in China, Thailand, Myanmar, Indonesia, Philippines, Indochina Peninsula, India and Pakistan, while in China, it is mainly distributed in Yunnan, Guizhou, Hainan, Guangxi, Guangdong, Fujian and Taiwan provinces (Xie et al., 2017). *Blumea balsamifera* is a pioneer vegetation for soil and water conservation

because of its strong adaptability. It is the only raw material for the extraction of L-borneolum, which has the effects of analgesia, sweating, dispelling wind and dampness, eliminating phlegm and relieving cough (Yuan et al., 2011). *Blumea balsamifera* is a famous Chinese Minority Medicine, which has a long history in Miao, Li, Zhuang and other minority areas (Guan et al., 2012). With the development of national medicine industry, *B. balsamifera* has been used in medicine, cosmetics, daily necessities and other industries, resulting in great economic and social benefits (Wang et al., 2014). According to our field investigation in Guizhou and Hainan, it is difficult to find the population distribution of *B. balsamifera* in some suitable habitat areas recorded in historical literature and specimen information. People's weak awareness of the protection of wild resources and unreasonable adjustment of agricultural industrialization structure are the direct reasons for the endangered wild resources of *B. Balsamifera* (Xie et al., 2017). In addition, habitat change caused by climate warming may also be one of the potential factors. Therefore, the study on the influence of climate change on the suitable habitat distribution of *B. balsamifera* will be helpful to the selection of introduction and domestication sites, the protection of germplasm resources, and the sustainable reproduction of this medicinal plant resources.

Research on *B. balsamifera* has mainly focused on its resource distribution and investigation (Yuan et al., 2011; Zheng et al., 2017), chemical composition analysis (Wang and Zhang, 2020; Hanh et al., 2021), breeding and cultivation techniques (He et al., 2005; Gu et al., 2016), pharmacological action (Agdamag et al., 2020; Ginting et al., 2020; He et al., 2020), basic genetic research (Guan et al., 2016; Zhang et al., 2016), and germplasm resources identification (Liu et al., 2016; Xiao et al., 2021); however, only a few scholars to date have examined its potential distribution. In 1999, Hu et al. (1999) analyzed the plant resources of *B. balsamifera* in Guizhou Province, and divided the most suitable growing area, suitable growing area and general distribution area. In 2010, Jiang et al. (Jiang et al., 2010) conducted a detailed survey of *B. balsamifera* resources in Red River region, Guizhou Province, and classified and statistically analyzed its ecological types and habitat characteristics. However, the limited research only focused on the suitable distribution area of *B. balsamifera* in Guizhou, and the climate, environment and suitability of other producing areas have not been reported. Under the background of climate change, it is still unknown whether the suitable distribution area of *B. balsamifera* will change.

Guizhou is the genuine production area of *B. balsamifera*, and the quality of *B. balsamifera* produced in Luodian, Qiandongnan Prefecture is the best. Luodian *B. balsamifera* is a national geographical indication protection product approved by AQSIQ (General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China), which is an important production area of *Blumea balsamifera* in China. Unfortunately, the construction of Longtan Hydropower Station in 2008 directly led to the inundation of a large area of *B. balsamifera* planting base, which severely damaged the industry. The destruction of the original area has led to the wild resources of the Annah being plundered and exploited wildly, which further aggravates the depletion of its resources. In this case, it is very important to find a suitable migration area for *B. balsamifera*. Hainan, as the only tropical island in China, is the main wild distribution area of *B. balsamifera*. Recently, researchers have carried out research on taking Hainan as a key candidate area for ex-situ conservation of *B. balsamifera*, which has been strongly supported by Hainan provincial government. However, the key to the success of ex-situ

protection of *B. Balsamifera* is whether the quality and yield of medicinal materials are significantly different from those in the original area.

In this study, we collected geographic location information of *B. balsamifera* by searching databases and the literature, downloaded climate variables from the WorldClim website, and used MaxEnt to simulate the potential suitable distribution of *B. balsamifera* in China. We evaluated the dominant environmental variables restricting the geographical distribution of *B. balsamifera* and the change of suitable distribution area in the future, determined the contents of L-borneol, total flavonoids and fresh leaf yield of *B. balsamifera* in different populations to provided theoretical and technical support for the ex-situ conservation of *B. balsamifera* production area in China.

Methods

Collecting occurrence data of *B. balsamifera*

Firstly, the distribution data of *B. balsamifera* were obtained by searching GBIF (Global Biodiversity Information Facility) and publications (Bai et al., 2020; Bao et al., 2020; He et al., 2020; Wang and Zhang, 2020; Wei et al., 2020; Xiao et al., 2021). Secondly, the longitude and latitude of distribution data were picked up by Google Earth 7.1.3 (Google, USA), and were converted into decimal after removing the repeated distribution points. Thirdly, the spatial analysis function of ArcGIS 10.0 (ESRI, USA) was employed to calculate the distance between the distribution points and the centre of the censored grid to ensure that each censored grid contains only one distribution point closest to the centre, so as to reduce the impact of spatial autocorrelation (Wang et al., 2020). Finally, a total of 228 distribution points were obtained (Fig. 1).

Environmental variables

The grid data of 19 bioclimatic variables with WGS84 coordinate system and 2.5 arc-minutes resolution were accessed through the Worldclim database (<https://www.worldclim.org/>), and the current climate data was obtained by interpolating the detailed meteorological information recorded by meteorological stations all over the world, with a time span of 1970-2000. The future climate data was based on BCC-CSM2-MR climate system model developed by National Climate Center, involving SSP5-8.5, SSP2-4.5 and SSP1-2.6 emission scenarios. The 1:16 million administrative division map of China was downloaded from the website of the Ministry of natural resources of the people's Republic of China (<http://bzdt.ch.mnr.gov.cn/index.html>).

The selection procedure of environment variables was divided into two steps. Firstly, all the 22 environmental variables (Table S1) were imported into MaxEnt model, and the variables with contribution rate of 0 were deleted after three operations. Secondly, all the environmental factors with percent contribution rate greater than 0 were selected for Spearman correlation analysis. Thirdly, the smaller

contribution rate of paired variables with correlation coefficient ≥ 0.8 was eliminated, and finally 11 environmental variables were selected for MaxEnt. (Table 1).

Table 1
Environmental variables used in MaxEnt model.

Environmental variables	Description
Bio3	Isothermality
Bio4	Standard deviation of temperature seasonality
Bio5	Max temperature of warmest month
Bio8	Mean temperature of wettest quarter
Bio11	Mean temperature of coldest quarter
Bio12	Annual precipitation
Bio15	Coefficient of variation of precipitation seasonality
Bio17	Precipitation of wettest quarter
Altitude	Altitude
Slope	Slope
Aspect	Aspect

Parameter setting of MaxEnt model

Based on the selected distribution data and environmental variables, the model was established and repeated 10 times. The proportion of test data was set as 'Random seed', the replicated run type was set as 'Crossvalidate', the maximum iterations was set to 500, the importance of climatic variables was measured by 'Jackknife test', the impact of variables on the distribution of *B. balsamifera* was analyzed by creating response curves, the output format was logistic, and other settings were set as the default values of the software (Narouei-Khandan et al., 2016).

Verification of model accuracy. The Receiver operating characteristic (ROC) curve output by MaxEnt was one of the effective methods to evaluate the accuracy of niche model. AUC (Areas under Roc curve) ≤ 0.8 indicated poor performance, $0.8 \leq \text{AUC} \leq 0.9$ indicated moderate performance, $0.9 \leq \text{AUC} \leq 0.95$ indicated good performance, and $0.95 \leq \text{AUC} \leq 1$ indicated excellent performance (Ortega-Huerta and Peterson, 2008; López-Collado et al., 2013).

Division of suitable grade. In the output file, the maximum value of 10 repetitions was selected as the prediction result of the present study. ArcGIS was used to convert the ASC file output by MaxEnt into raster format file. According to IPCC's explanation of the probability (P) of species' presence and combined with previous research results, the suitability grades were divided into four categories and

indicated by different colors, i.e., highly suitable habitat ($P \geq 0.66$, red), moderately suitable habitat ($0.33 \leq P < 0.66$, orange), poorly suitable habitat ($0.05 \leq P < 0.33$, yellow), and unsuitable habitat ($P < 0.05$, white) (Remya et al., 2015; Zou et al., 2015; Wang et al., 2018).

Determination of main effective components and fresh leaf yield of *B. balsamifera*

Determination of the weight of fresh leaves. After 6 months of transplanting, 15 plants with the same field performance were selected from each population. All leaves were picked and bagged in the laboratory and weighed with electronic balance. SPSS17.0 was used for data analysis.

Determination of L-borneol by GC(Agilent 7890A, Agilent Technologies, Inc). 1) Setting of chromatographic conditions. HP-5 quartz capillary (0.32 mm×30 m, 0.25 μm) was used as the chromatographic column. The initial temperature was set at 80 °C and kept for 2 min, then the temperature was raised to 100 °C at a rate of 5 °C/min and then raised to 200 °C at a rate of 20 °C/min. The temperature of injector and FID detector were set at 220 °C and 240 °C respectively, and the injection volume was 0.6 μL without diverting. 2) Preparation of internal and external standard solution. L-borneol (100mg) was added into a 100 ml volumetric flask, and ethyl acetate was used to fix its volume to obtain the L-borneol reference solution with a mass concentration of 1.000 mg/ml. Methyl salicylate (250mg) was added into a 250 ml volumetric flask, and the volume was fixed with ethyl acetate and shaken up to obtain an internal standard solution with a mass concentration of 1.000 mg/ml. 3) Preparation of test products. Leaves of *B. balsamifera* were put into a mortar and ground into powder with liquid nitrogen. 2 g of ground powder was accurately weighed and extracted for 30 min in a centrifuge tube containing 25 ml ethyl acetate under 40 kHz ultrasound. 1 ml of filtrate and 1 ml of internal standard solution were added into a 10 ml volumetric flask and diluted with ethyl acetate. After shaking, the filtrate was filtered with a 0.22μm microporous membrane. The filtrate obtained was the test sample. 4) Drawing of standard curve. 100 mg of L-borneol standard was placed in a 100 mL volumetric flask and ethyl acetate was added to determine the volume. The standard solution was obtained after shaking well. Measure 0.1, 0.2, 0.5, 1.0, 2.0 mL of standard solution into 10 mL volumetric flask, add 1 mL of internal standard solution at the same time, and measure volume to scale with ethyl acetate. The determination was carried out according to the above chromatographic conditions. Taking the mass concentration of L-borneol ($\text{mg}\cdot\text{ml}^{-1}$) as the abaxial axis (X) and the peak area ratio of L-borneol to the internal standard as the vertical axis (Y), the standard curve was plotted and the linear regression equation was obtained ($Y = 15.641X + 0.0158$, $R^2 = 0.9999$). The results showed that there was a good linear relationship between the mass concentration ($10.429\text{--}210.448\ \mu\text{g}\cdot\text{ml}^{-1}$) and peak area.

Determination of total flavonoids by UV. 1) Preparation of chromogenic agent. NaNO_2 (25g), $\text{Al}(\text{NO}_3)_3\cdot 9\text{H}_2\text{O}$ (88g) and NaOH (20g) were dissolved in H_2O and diluted to 500ml respectively to prepare 5% NaNO_2 solution, 10% $\text{Al}(\text{NO}_3)_3$ solution and 4% NaOH solution. 2) Preparation of rutin reference solution. The rutin reference substance (12.06 mg) dried to constant weight at 105 °C and ethanol (75% volume fraction) in 50 ml volumetric flask were slightly dissolved in water bath. Then, 75% ethanol was

added to the cooled solution for constant volume and shaking to obtain rutin reference solution with mass concentration of $\text{mg}\cdot\text{mL}^{-1}$.3) Preparation of test solution. *Blumea balsamifera* powder (0.5 g) and 75% ethanol solution (25 ml) were extracted by ultrasound at 400 W power and 40 kHz frequency for 40 min and then cooled. Then, 75% ethanol was used to make up the lost mass, and the test solution was obtained after shaking and filtering. 4) Drawing of standard curve. First, 75% ethanol was added into five 25 ml volumetric flasks containing rutin reference solution (1.00, 2.00, 4.00, 6.00, 8.00 ml) respectively, and the volume was adjusted to 10 ml. Then, 1 ml of 5% NaNO_2 solution was added and shaken well. After 5 min, 1 ml of 10% $\text{Al}(\text{NO}_3)_3$ solution was added and shaken well. After 5 min, 10 ml of 4% NaOH solution was added. After shaking well, the volume was fixed to the scale with 75% ethanol, and shaken well for 15 min. The absorbance was detected at 509 nm with the corresponding reagent solution as blank. The absorbance of rutin reference solution was detected, and the standard curve was drawn with the mass concentration of reference as abscissa X and the absorbance as ordinate Y . The linear regression equation $Y = 22.03X - 0.01015$ ($R^2 = 0.9992$) were obtained, which showed that the linear relationship was good in the range of 0.00482–0.03859 $\text{mg}\cdot\text{ml}^{-1}$.

Results

Model performance

The AUC values of training data and test data were 0.965 and 0.938 (Fig. 2), respectively, indicating the performance level of the model was “excellent”.

Analysis of the importance of environmental variables

The results showed that mean temperature of coldest quarter (42.8%) was the most important variable determining the distribution of *B. balsamifera*. Precipitation of driest quarter and annual precipitation explained 17.1% and 16.5% of the contribution. Altitude (0.9%), mean temperature of wettest quarter (0.7%), and aspect (0.6%) were the three variables with least impacts on *B. balsamifera* distribution (Table 2).

Table 2
Percent contribution of each variable to the potential distribution of *B. balsamifera* defined by MaxEnt.

Variables	Percent contribution / %
Mean temperature of coldest quarter	42.8
Precipitation of driest quarter	17.1
Annual precipitation	16.5
Temperature seasonality	9.3
Isothermality	6.2
Precipitation seasonality	3
Slope	1.5
Max temperature of warmest month	1.5
Altitude	0.9
Mean temperature of wettest quarter	0.7
Aspect	0.6

By comparing the regularized training gain with only variable (Fig. 3), it was found that mean temperature of coldest quarter (bio11) had the highest score (1.81), which was the most important climate variable affecting the distribution of *B. balsamifera*. The regularized training gain of precipitation of driest quarter (bio17), Annual precipitation (bio12) and temperature seasonality (bio4) were 1.48, 1.47 and 1.45, respectively, which were important for its distribution. The regularized training gain of the above four were significantly higher than other variables, which indicated that they contained unique information affecting the distribution of *B. balsamifera*.

Relationship between environmental variables and probability of presence

In order to clarify the relationship between key environmental variables and the probability of presence of *B. balsamifera*, we used MaxEnt to draw the response curve using only a single environmental variable (Fig. 4). The results showed that the suitable ranges of mean temperature of coldest quarter (bio11), precipitation of driest quarter (bio17), annual precipitation (bio12) and temperature seasonality (bio4) were 6.18-26.57 °C (Fig. 4-A), 22.46-169.7 mm (Fig. 4-B), 518.36-1845.29 mm (Fig. 4-C), and 291.31-878.87 (Fig. 4-D) respectively.

Potential distribution of *B. balsamifera* in China under current climate condition

Figure 5 showed the geographical distribution of *B. balsamifera* in China under current climate conditions predicted by MaxEnt. The results showed that the highly suitable habitats were mainly located in western Guangxi, southern Yunnan, most of Hainan, southwestern Guizhou, southwestern Guangdong, southeastern Fujian and western Taiwan, with a total area of $24.1 \times 10^4 \text{ km}^2$, accounting for 2.51% of China's land area. Among them, Guangxi had large areas, reaching $7.75 \times 10^4 \text{ km}^2$. The moderately suitable habitats were mainly located in central and southern Yunnan, central and eastern Guangxi, central and eastern Guangdong, southeastern Sichuan, southern Guizhou, western Chongqing and southeastern Fujian., with a total area of $27.57 \times 10^4 \text{ km}^2$, accounting for 2.87% of China's land area. Among them, Yunnan, Guangxi and Guangdong had larger areas, which were $8.12 \times 10^4 \text{ km}^2$, $7.56 \times 10^4 \text{ km}^2$ and $7.21 \times 10^4 \text{ km}^2$, respectively. The poorly suitable habitats were located in most of Yunnan, central and northern Guizhou, eastern Sichuan, most of Guangdong, northern Guangxi, eastern Chongqing, central and northern Fujian, western Hunan, western Hubei, southern Jiangxi and southeastern Tibet, with a total area of $42.43 \times 10^4 \text{ km}^2$, accounting for 4.42% of China's land area. Among them, the area of Yunnan was the largest, reaching $14.14 \times 10^4 \text{ km}^2$.

Figure 6 showed the suitable habitat of *B. balsamifera* under SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios in the future. The results showed that the areas of the highly, moderately, and poorly suitable habitats of *B. balsamifera* showed a significant increasing trend. By 2050s, the areas of the highly suitable habitats would increase to $68.73 \times 10^4 \text{ km}^2$ (SSP1-2.6), $57.25 \times 10^4 \text{ km}^2$ (SSP2-4.5) and $77.04 \times 10^4 \text{ km}^2$ (SSP5-8.5), and the moderately suitable habitats would increase to $49.06 \times 10^4 \text{ km}^2$ (SSP1-2.6), $47.34 \times 10^4 \text{ km}^2$ (SSP2-4.5) and $57.97 \times 10^4 \text{ km}^2$ (SSP5-8.5), and the poorly suitable habitats would increase to $81.19 \times 10^4 \text{ km}^2$ (SSP1-2.6), $93.79 \times 10^4 \text{ km}^2$ (SSP2-4.5) and $74.85 \times 10^4 \text{ km}^2$ (SSP5-8.5) (Figure 6). By 2070s, the areas of the highly suitable habitats would increase to $49.34 \times 10^4 \text{ km}^2$ (SSP1-2.6), $81.42 \times 10^4 \text{ km}^2$ (SSP2-4.5) and $106.08 \times 10^4 \text{ km}^2$ (SSP5-8.5), and the moderately suitable habitats would increase to $40.39 \times 10^4 \text{ km}^2$ (SSP1-2.6), $63.08 \times 10^4 \text{ km}^2$ (SSP2-4.5) and $67.89 \times 10^4 \text{ km}^2$ (SSP5-8.5), and the poorly suitable habitats would increase to $99.23 \times 10^4 \text{ km}^2$ (SSP1-2.6), $70.6 \times 10^4 \text{ km}^2$ (SSP2-4.5) and $62.18 \times 10^4 \text{ km}^2$ (SSP5-8.5) (Figure 6).

Figure 7 showed the changes of the total suitable habitats of *B. balsamifera* under different climate change scenarios. Compared with the current simulation, the newly gained suitable habitats were mainly located in most of Hunan, Jiangxi, most of Zhejiang, Anhui, central and eastern Hubei, central and southern Henan, western Jiangsu, southern Shaanxi and northeast Guangxi. The newly losted suitable habitats were relatively small.

Under SSP1-2.6, the areas of the gained area would be $80.59 \times 10^4 \text{ km}^2$ (2050s) and $70.48 \times 10^4 \text{ km}^2$ (2070s), accounting for 40.57% (2050s) and 37.38% (2070s) of the total suitable habitat. The areas of the stable area would be $118.07 \times 10^4 \text{ km}^2$ (2050s) and $118.08 \times 10^4 \text{ km}^2$ (2070s), accounting for 59.43% (2050s) and 62.62% (2070s) of the total suitable habitat.

Under SSP2-4.5, the areas of the gained area would be about $80.04 \times 10^4 \text{ km}^2$ (2050s) and $96.71 \times 10^4 \text{ km}^2$ (2070s), accounting for 40.42% (2050s) and 45.03% (2070s) of the total suitable habitat. The areas of the stable area would be $117.97 \times 10^4 \text{ km}^2$ (2050s) and $118.08 \times 10^4 \text{ km}^2$ (2070s), accounting for 59.58% (2050s) and 54.97% (2070s) of the total suitable habitat.

Under SSP5-8.5, the areas of the gained area would be about $91.45 \times 10^4 \text{ km}^2$ (2050s) and $117.92 \times 10^4 \text{ km}^2$ (2070s), accounting for 43.64% (2050s) and 49.97% (2070s) of the total suitable habitat. The areas of the stable area would be $118.1 \times 10^4 \text{ km}^2$ (2050s) and $118.07 \times 10^4 \text{ km}^2$ (2070s), accounting for 56.36% (2050s) and 50.03% (2070s) of the total suitable habitat.

Variations of the geometric center of the suitable habitats under climate change scenarios

Under SSP1-2.6, the geometric center of the total suitable habitats of *B. balsamifera* would move 262.23 km from Daxin (Current) to northeast to Rongshui (2050s), then 97.73 km to southwest to Hechi (2070s). By 2070s, the center would generally displaced 194.96 km to the northeast. Under SSP2-4.5, the geometric center of the total suitable habitats of *B. balsamifera* would move 210.69 km from Daxin (Current) to northeast to Huanjiang (2050s), then 50.19 km to northeast to Huanjiang (2070s). By 2070s, the center would generally displaced 260.81 km to the northeast. Under SSP5-8.5, the geometric center of the total suitable habitats of *B. balsamifera* would move 257.43 km from Daxin (Current) to northeast to Luo Cheng (2050s), then 142.14 km to northeast to Jingzhou (2070s). By 2070s, the center would generally displaced 397.78 km to the northeast (Fig. 8).

Main effective components and fresh leaf yield of *B. balsamifera* from Guizhou and Hainan

In order to clarify the feasibility of the migration of the producing areas of *B. balsamifera*, we measured the main effective components and fresh leaf yield in Luodian, Anlong, Xingyi and Wangmo (national geographical indication protected areas) in Guizhou and Baisha, Qiongzong, Danzhou and Wuzhishan in Hainan (areas with a large number of wild resources). Results showed that the L-borneol content of *B. balsamifera* from Luodian was the highest (6.58 mg/g), while that from Wangmo was the lowest (3.79 mg/g). In Hainan, the content from Baisha was the highest (6.97 mg/g), while that from Wuzhishan was the lowest (4.23 mg/g). For the yield of fresh leaves, the yield of Luodian (0.64 kg) in Guizhou was slightly higher than that in other regions, while the yield of Qiongzong (0.63 kg) in Hainan was higher. By comparison, the content of L-borneol and fresh leaf yield had no significant difference among populations ($P > 0.05$), and there was also no significant difference between Guizhou and Hainan ($P > 0.05$). The content analysis of total flavonoids showed that the content of total flavonoids in Danzhou was the highest (124.16 mg/g) in Hainan, while in Guizhou, the content of total flavonoids in Luodian was the highest (53.58 mg/g), and there was significant difference among populations ($P \leq 0.05$), but there was no significant difference between the average values of Hainan and Guizhou ($P > 0.05$) (Table 3).

Table 3
Comparison of the content of L-borneol, total flavonoids and fresh leaf yield of *B. balsamifera* in different populations

Province	Location	L-borneol (mg/g)	Total flavonoids (mg/g)	Fresh leaf yield (kg)
Guizhou	Luodian	6.58 ^a	53.58 ^b	0.64 ^a
	Anlong	5.57 ^a	28.69 ^{abc}	0.62 ^a
	Xingyi	4.36 ^a	25.41 ^{abc}	0.53 ^a
	Wangmo	3.79 ^a	13.27 ^c	0.58 ^a
	Mean	5.08 ^A	30.24 ^A	0.59 ^A
Hainan	Baisha	6.97 ^a	24.54 ^{abc}	0.60 ^a
	Qiongzhong	6.78 ^a	40.01 ^{abc}	0.63 ^a
	Danzhou	5.66 ^a	124.16 ^d	0.59 ^a
	Wuzhishan	4.23 ^a	27.33 ^{abc}	0.66 ^a
	Mean	5.91 ^A	54.01 ^A	0.62 ^A

Discussion

Key climatic variables affecting the occurrence of *B. balsamifera*

Climate factors are the key factors limiting the geographical distribution of species, and the study of the interaction between plants and climate is a hot spot in ecology (Ramachandran et al., 2020). As a special agricultural resource, the cultivation, growth, harvesting and distribution of traditional Chinese medicine resources will also be greatly affected by the climate (Xia et al., 2019). Studies have shown that the extreme value and variation range of temperature were closely related to the large-scale landscape geographical distribution of species (Renne et al., 2019). Zheng et al. (2016) considered that temperature was the key meteorological index affecting the cultivation of *B. balsamifera*. Based on five temperature indexes, a regression model was established to determine the planting area of *B. balsamifera* in Guizhou. The results showed that the mean temperature of coldest quarter had the highest percent contribution rate to the simulation (42.8%), which was the most critical variable affecting its distribution. When the mean temperature of coldest quarter was lower than 6.18 °C, the probability of presence of *B. balsamifera* was very low, indicating that it has poor cold resistance and needs to be planted in the area with higher temperature in winter. He et al. (2005) found that in warm winter years, even if the flower

shoots of *B. balsamifera* in December were frozen to death, the smooth overwintering of old stems would not affect the fruiting in the second year. This is in line with our view.

Water is the main factor to control the vegetation coverage level in most areas, but also the decisive factor to affect the formation and growth of medicinal plants. Our results showed that precipitation of driest quarter (bio17) and annual precipitation (bio12) were important factors affecting the distribution of *B. balsamifera*. Liu et al. (2019) pointed out that the drought resistance of *B. balsamifera* was poor, and the water content should be kept as high as 40% in order to maintain the accumulation and growth of leaf biomass. Therefore, close attention should be paid to the precipitation in the cultivation region during the introduction and artificial cultivation, especially for the area with annual precipitation less than 518.36 mm, water management should be strengthened. Studies have shown that the slowly growth period of *B. balsamifera* is from February to April, and the water demand is not high at this stage. Our results showed that the suitable range of precipitation of driest quarter was 22.46-169.7 mm, which was consistent with its biological characteristics. The precipitation is 15, which is consistent with its biological characteristics (He et al., 2005). However, this does not mean that water management can be ignored at this stage, but it needs to be strengthened, especially for the plants planted in that year. This is mainly due to the weak water absorption capacity caused by the shallower root system of the seedlings, and the artificial intervention can better promote the growth and development of the seedlings.

In addition to climate factors, topography, soil, light, interspecific competition, human disturbance and other factors also affect the geographical distribution of vegetation (Douda et al., 2016; Xu et al., 2019; Meng and Gao, 2020). However, the existing technical conditions are not mature enough, and there is still no model that can integrate all the impact factors into one model to simulate the potential distribution of species. Therefore, our study still has important reference value for the distribution of potential suitable habitats and the introduction and cultivation of *B. balsamifera* under the background of climate change.

Potential distribution of *B. balsamifera* in China

In this study, the simulation results showed that, under current climate condition, the highly suitable habitat of *B. balsamifera* in China was mainly located in western Guangxi, southern Yunnan, most of Hainan, southwestern Guizhou, southwestern Guangdong, southeastern Fujian and western Taiwan. According to field investigation and literature review, *B. balsamifera* mainly grows in Hainan, Guizhou, Guangxi, Guangdong, Fujian, Taiwan and other provinces south of the Yangtze River (Xie et al., 2017).. In terms of climate types, the distribution area extends from the Emei mountains in Sichuan to the dry hot valley in Guizhou, and then to the subtropical and tropical regions in Yunnan, Guangxi and Guangdong. It is also widely distributed in Hainan Island, Leizhou Peninsula and Taiwan Island, and sporadically distributed in Fujian, Jiangxi, Zhejiang and Hunan. In contrast, the distribution frequency, abundance and relative coverage of *B. balsamifera* in Guangdong, Guangxi, Hainan and Southern Guizhou were higher (Yuan et al., 2011). All the above areas were located in the suitable habitats predicted in this paper, which showed that the results were reliable.

In 2008, the construction of Longtan Hydropower Station directly led to the inundation of a large area of *B. balsamifera* planting base, which severely damaged the industry (Fig. 9-A, C). Based on the investigation results of its germplasm resources from 2009 to 2011, *B. balsamifera* is distributed in Baisha, Danzhou, Qiongzong, Wanning, Wuzhishan and other cities and counties in Hainan, covering mountains, hills, Plains, paddy fields, residential areas and other types. In addition, Hainan Island has suitable climatic conditions, rich land resources, sound science and technology service system, and good policy support, so it is considered as the key area for the migration of *B. balsamifera*. The results of this paper also showed that the area of the highly suitable habitat in Hainan was extremely high, accounting for 94.66% of the total area of the whole province (Fig. 9-B). For this, in the early stage, we have collected 82 germplasm resources of *B. balsamifera* from five provinces in China, and systematically compared and analyzed the content of active components after they migrated to Hainan. The results showed that the quality and disease resistance of the resources from Guizhou were significantly better. Moreover, the content of active components of Guizhou materials decreased slightly after they were introduced into Hainan, but the difference was not significant (Huang et al., 2016). At present, our research group has initially established a gap demonstration area in Hainan, and established a Pilot-Plant for its extraction and processing, which has laid a solid foundation for the migration of *B. balsamifera*-growing regions.

In order to further evaluate the feasibility of ex-situ conservation of *B. balsamifera* resources from Guizhou to Hainan, the contents of L-borneol, total flavonoids and fresh leaf yield of *B. balsamifera* in different populations were determined. The results showed that the content of L-borneol in Baisha and Qiongzong in Hainan was slightly higher than that in Luodian, Guizhou, although the difference was not significant. However, for a long time, in Hainan, *B. balsamifera* has been mostly used by the Li people for daily use, such as postpartum bathing and mosquito repellent, so its planting area is small. With the destruction of the genuine producing area of *B. balsamifera* in Guizhou and the continuous reduction of its suitable planting area, the ex-situ protection and ex-situ planting were imperative. In addition, in Hainan, *B. balsamifera* can be harvested twice a year, that is, the yield can be doubled under the condition of little difference in L-borneol content. Therefore, we believe that so far, Hainan is the best choice for ex-situ protection of *B. balsamifera*.

Potential distribution of *B. balsamifera* in China in the future

We quantitatively analyzed the area changes of suitable habitats of *B. balsamifera* in 2050s and 2070s under SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios. The results showed that the areas of the suitable habitats would increase. The impact of climate change on the distribution pattern of different species is different. Some species are threatened by climate change and are endangered or even extinct, while some species will benefit from climate change and continue to expand their distribution areas (Ma and Jiang, 2005). According to our results, *B. balsamifera* obviously belongs to the latter case. Many studies have confirmed that the changes of plant geographical distribution caused by global warming are mostly related to the changes of temperature and precipitation in the growing season of this species. (Root et al., 2003; Guo et al., 2014; Zhu and Xu, 2019). In the future, the suitable habitats of *B. balsamifera* would expand significantly in most of Hunan, Jiangxi, most of Zhejiang, Anhui, central and eastern Hubei,

central and southern Henan, western Jiangsu, southern Shaanxi and northeast Guangxi, and the annual precipitation in these areas was expected to show a significant growth trend (Wu et al., 2015; A et al., 2016). Compared with the simulation under current climate situation, the stable area of the total suitable habitat, that was, the area less affected by climate change, accounted for a relatively high proportion (50.03%-62.62%), which could be used as an ideal candidate for large-scale cultivation of *B. balsamifera*.

Studies have shown that there are regional and latitudinal differences in the change of plant phenology under the background of temperature rise. Some studies have shown that under the influence of climate change in the future, the suitable habitats of many medicinal plant would move northward. Peng and Guo (2017) explored potential impacts of climate change on the suitability of *Astragali Radix* by MaxEnt, and the results showed that by the 2050s and 2070s, the suitable habitats would move forward to north. Tan et al. (2020) simulated the ecological suitability of *Gentiana macrophylla* Pall..under current and future scenarios of global climate and found that its distribution center would shifted to the northeastern China. Xiong et al. (2019) analyzed the potential distribution of *Sorbus tianschanica*, an important ethnomedicinal plant, and the results showed that the suitable distribution habitats would move to high latitudes under climate warming in the future. Fan et al. (2021) simulated the potential geographical distribution of *Rosa roxburghii* under future climate scenarios and demonstrated that the suitable region tended to move to high latitude area. Referring to the methods of Yue et al. (2011), we calculated the geometric center of the suitable habitat with the area as the weight, and the results showed that the geometric center of the total suitable habitat would move to the northeast. There may be two reasons for this phenomenon. First, climate warming has a positive impact on the expansion of thermophilic plants (Araujo et al., 2010), which makes the suitable habitat of *B. balsamifera* expand. Secondly, the climate warming may lead to the increase of precipitation intensity in the middle and high latitudes of the northern hemisphere and the drought days in the middle and low latitudes of the northern hemisphere, resulting in its movement to high latitudes, which is consistent with its living habits of warm and humid climate, tolerance to a certain degree of low temperature and weak drought resistance.

Conclusions

Based on the MaxEnt model and species distribution data, it was concluded that the highly suitable habitats of *B. balsamifera* were mainly located in western Guangxi, southern Yunnan, most of Hainan, southwestern Guizhou, southwestern Guangdong, southeastern Fujian and western Taiwan. The key environmental variables affecting the potential distribution of *B. balsamifera* were mean temperature of coldest quarter (6.18-26.57 °C), precipitation of driest quarter (22.46-169.7 mm), annual precipitation (518.36-1845.29 mm) and temperature seasonality (291.31-878.87). Under the three climate change scenarios, the areas of the highly, moderately, and poorly suitable habitats of *B. balsamifera* showed a significant increasing trend, the geometric center of the total suitable habitats of *B. balsamifera* would move to the northeast. Our results can provide theoretical and technical support for the migration of *B. balsamifera* production area. As a medicinal plant, the quality of medicinal materials must be valued, but this study only investigated the suitability of climate factors for the growth of *B. balsamifera*. Therefore,

in the next work, we need to further study the effects of different climatic factors on the active components of *B. balsamifera* and the quality differences in different regions.

Declarations

Author contribution

Lingliang Guan and Yuxia Yang provided relevant data of *Blumea balsamifera* and required funds for the experiment. Yingwen Xu and Rulin Wang planned and supervised the project. Pan Jiang, Qiuyu Mou, Yunsha Gou and Xueyan Zhu analyzed the data and performed simulations.

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Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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Figures

Figure 1

Distribution data of *B. balsamifera*.

Figure 2

ROC curve and AUC values for the model.

Figure 3

Importance of environmental variables to *B. balsamifera* by jackknife analysis.

Figure 4

Response curves of presence probability of *B. balsamifera* to mean temperature of coldest quarter (A), annual precipitation (B), precipitation of wettest quarter (C) and temperature seasonality (D).

Figure 5

Potential distribution of *B. balsamifera* in China under current climate condition.

Figure 6

Potential distribution of *B. balsamifera* in China under climate change scenarios.

Figure 7

Changes of the total suitable habitats of *B. balsamifera* under different climate change scenarios.

Figure 8

Variations of the centroids of the total suitable habitats of *B. balsamifera* under climate change scenarios in the future.

Figure 9

Potential distribution of *B. balsamifera* in Guizhou (A) and Hainan (B).