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Maxent modelling for predicting climate change effects on the potential planting area of tuber mustard in China

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Abstract

Potential planting area for tuber mustard was simulated using the Maxent model under current and future conditions based on 591 coordinates and 22 environmental layers. Model accuracy was excellent, with area under the receiving operator curve values of 0.967 and 0.958 for model training and testing, respectively. Dominant factors were mean diurnal range, mean temperature of the coldest quarter, annual mean temperature and minimum temperature of the coldest month, with thresholds of 6.5–7.5, 5.5–9, 16–19 and 2.0–6.5 °C, respectively. Under current conditions, suitable habitat areas (2.16% of total land in China) were concentrated mainly in Central, Southwest and East China, which can be defined as three occurrence and diffusion centres. In the 2050s and 2070s, suitable habitat areas are predicted to change to 3.72 and 3.92%, and 3.60 and 3.73% under scenarios RCP4.5 and RCP6.0, respectively, indicating that suitable habitat areas will increase slightly. However, future distribution of tuber mustard was predicted to differ among provinces or cities, i.e. predicted suitable habitat areas in Sichuan Province increased up to the 2050s but remained relatively unchanged between the 2050s and 2070s; in Chongqing city they first increased and then decreased; in Hunan, Anhui, Jiangsu, Zhejiang and Fujian Provinces they increased continuously; and in Guizhou, Hubei, Jiangxi Provinces and Shanghai city they first decreased, and then increased. The results from the current study provide useful information for management decisions of tuber mustard.

Introduction

Tuber mustard (*Brassica juncea* var. *tumida* Tsen & Lee) is endemic to China and belongs to a variation of the species *B. juncea* of the family Cruciferae. It is an agricultural and economic crop in China (Chen *et al*., 2011) and its swollen fleshy stem is used as a raw material and processed to form a delicious pickled food, named Fuling hot pickled tuber mustard. To date, it has been cultivated along the Yangtze River in China including Chongqing, Sichuan, Zhejiang, Fujian, Jiangsu, Hubei, Hunan, Shanghai and Guangxi province/city of China (Liu, 1996; Fan *et al*., 2017). At present, it is famous for its unique sweet and crisp taste, produced by wind dehydration and the processing technology. Fuling hot pickled tuber mustard, as well as the European pickled vegetable and Japanese pickle, are the three most famous pickled vegetables worldwide (Chen *et al*., 2011). In recent years, with the development of the market both at home and abroad, demand for tuber mustard products has increased greatly and increasing its production base has become the most fundamental problem in the development of the pickle industry. In addition, climate change, especially with regards to temperature, rainfall and humidity, affects physiological and ecological characteristics, as well as phenology of tuber mustard, which has certainly influenced some changes in its geographical distribution (Tao and Zhang, 2011; Li *et al*., 2018). The detailed potential distribution of this species in China is unclear under current and future environmental conditions except from related data from Chongqing municipality (Li *et al*., 2018). Therefore, it is very important to determine the current and/or future potential area of this species for scientific planning of agricultural production and formulating policies to cope with climate change.

To simulate species' geographical distribution effectively, detailed and reliable information about the geographic coordinates of the species is required. However, species-occurrence data are often sparse for the vast majority of species. Recently, researchers have created several techniques to model species distribution with only small sample sizes or presence-only data (Phillips *et al*., 2006; Pearson *et al*., 2007; Wang *et al*., 2010). Species distribution models are algorithmic tools that can relate the occurrence of a species to the environmental characteristics of its location (Guisan and Thuiller, 2005; Jaryan *et al*., 2013). Of the available species distribution models (e.g. Bioclim, Domain, Maxent and Garp), the Maxent model is a maximum entropy based machine-learning program, by means of which the probability map of a species' occurrence can be computed by assessing the probability distribution based on the principle of maximum entropy (Xu *et al.*, 2014). The method has many advantages to make it suitable for species distribution modelling (Phillips *et al.*, 2006; Liao *et al.*, 2017; Qin *et al.*, 2017). For example, the Maxent model can utilize both continuous and categorical data, incorporates interactions between different variables (Phillips *et al.*, 2006; Wang *et al.*, 2010) and has been proven to perform better than other models in forecasting species distribution with small sample sizes or presence-only data (Elith *et al.*, 2006; Hu *et al.*, 2015). Additionally, the probability distribution obtained from the Maxent model has a concise mathematical expression and is amenable for studying the obtained results. The model can also identify environmental factors that limit species distribution. Therefore, the Maxent model originating from the statistical mechanics (Jaynes, 1957) is very popular for accurately forecasting species distribution (Elith *et al.*, 2006; Wang *et al.*, 2010; Qin *et al.*, 2017).

In the current study, the Maxent model was adopted to simulate the planting area of the tuber mustard species by combining a set of known geo-coordinates together with layers of environmental variables in China under current and future environmental conditions. The aims of the study were to: (1) determine the potential planting area of tuber mustard under current environmental conditions; (2) identify dominant environmental variables associated with the distribution of its potential planting area and (3) analyse distribution trends of tuber mustard in the future, which will be of benefit to the government and relevant departments for undertaking regional layout and scientific planning of tuber mustard plantations in China.

Materials and methods

Species distribution samples

The occurrence locations of tuber mustard were obtained partly via on-the-spot investigation using a Global Positioning System (GPS) receiver with ± 5 m positional accuracy in Chongqing Municipality. The majority of occurrence records for this species were gathered from two databases, the Plant Specimen Database (http://mnh.scu.edu.cn) and the Chinese Digital Plant Specimen Database (http://www.cvh.org.cn), which only provide the names of small places where this species has been recorded, without GPS information. Then, the coordinates of known locations were acquired when occurrence records lacked exact geo-coordinates using the Geographic Names Database (http://www.geonames.org/) and Google Earth (http://ditu.google.cn/). Spatial autocorrelation among the predictor variables has been identified as a source of error (Jaryan *et al.*, 2013); therefore, duplicate and neighbouring records were deleted, so only one occurrence record per grid cell was retained. Finally, the data set was reduced from 671 to 591 occurrence points from the sources mentioned above. The known coordinates of this species were then reorganized into a database based on the requirements of the Maxent model.

Current environmental parameters

In general, the geographical distribution of species is affected by environmental factors, such as climate, terrain and so on (Phillips and Dudík, 2008; Wang *et al.*, 2010; Xu *et al.*, 2014). Consequently, environmental factors including 19 bioclimatic parameters and three topographic variables were selected for use in the current study. These bioclimatic parameters with 30 s spatial resolution (*c.* 1 km^2 at the ground level) were downloaded from the WorldClim database (http://www.worldclim.org), which expresses a combination of annual trends, seasonality and extreme environmental conditions in terms of temperature and precipitation (Hijmans *et al.*, 2005). Elevation (digital elevation model) information with the same spatial resolution as described above, also obtained from the WorldClim website, was utilized to produce the slope degree, aspect and altitude data layers. Finally, Chinese environmental data in GCS-WGS-1984 were obtained from the above global raster data overlaid by the administrative boundary maps of China in ESRI shape format in ArcGIS 10.2 and then converted into 'asc' format based on the requirements of the Maxent model. Additionally, the analysis base map (China 1:4 000 000) was downloaded from the national fundamental geographic information system (http://mail.nsdi.gov.cn/).

Future environmental parameters

The representative concentration pathways (RCPs), published by the Intergovernmental Panel on Climate Change (IPCC) in the fifth IPCC assessment report (AR5), express the full bandwidth of possible future emission trajectories. The RCPs (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) were named based on the possible range of radiative forcing values in the year 2100 compared with pre-industrial values (Hu *et al.*, 2015). For simplification, the intermediate stable paths were selected for simulation, such as RCP4.5-2050 and RCP6.0-2050, which represent the average values for the years 2041–2060, whereas RCP4.5-2070 and RCP6.0-2070 represent the average values for the years 2061–2080. The two future bioclimatic data selected were downloaded from the WorldClim website (Hijmans *et al.*, 2005). Other environmental parameters such as slope degree, aspect and altitude data were unchanged for the Maxent model analyses under the future environmental conditions. In total, there were 22 environmental factors used directly by the Maxent model, which were similar to the above environmental parameters.

Predicting potential distribution and evaluation

The potential geographic distribution of tuber mustard was simulated using the Maxent model Version 3.4.1 (http://www.cs.princeton.edu/~schapire/maxent/) (Phillips *et al.*, 2006; Qin *et al.*, 2017). In the current model, 25% of the data was utilized randomly for model testing and the other 75% was used for model training (Phillips *et al.*, 2006; Qin *et al.*, 2017). To avoid over-fitting of the test data, the regularization multiplier value was set as 0.1. Meanwhile, 'do jack-knife to measure variable importance' and 'create response curves' commands were checked in the model with the default used for the other settings. The output result generated by the Maxent model predicted the suitability of a habitat in logistic format and asc types. Further, this result was transformed into a raster format and the grade classification was completed based on the suitable values using Jenks' natural breaks in the ArcGIS 10.2. Simultaneously, all habitat areas were calculated after projection conversion.

The area under the receiving operator curve (AUC) has often been utilized to evaluate the goodness-of-fit of a model (Yang *et al.*, 2013; Qin *et al.*, 2017), with the range for the AUC value being from 0.5 to 1.0 (Kumar *et al.*, 2014). An AUC value of 0.5 demonstrates that the model performance was no better

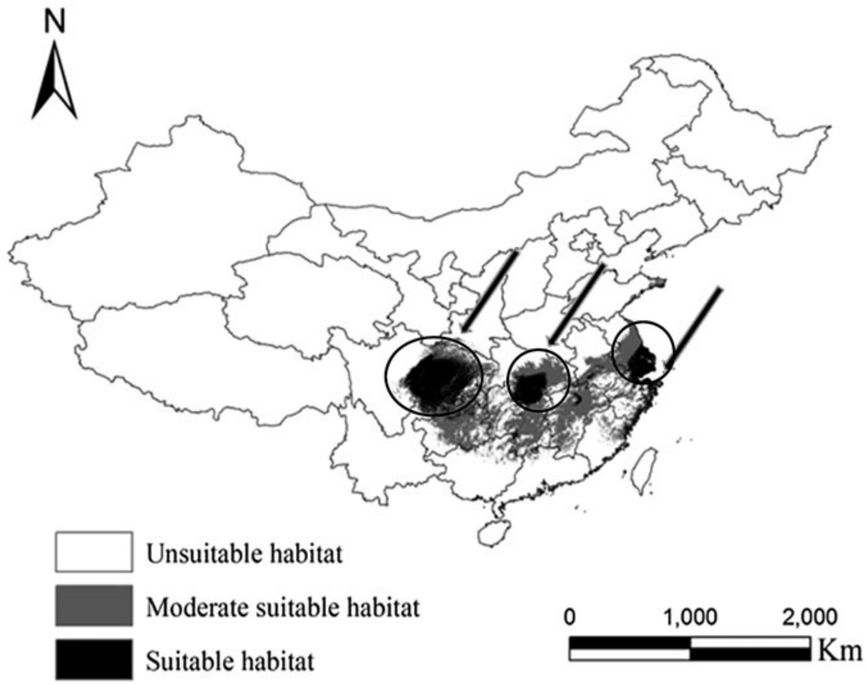

Fig. 1. Current potential geographic distribution of *B. juncea* var. *tumida*.

than random, whereas a value of 1.0 demonstrates excellent discrimination (Jaryan *et al*., 2013; Xu *et al*., 2014). The model with the greatest AUC value is commonly regarded as the best performer.

Determining important variables and threshold values

The jack-knife test was then utilized for *B. juncea* var. *tumida* to evaluate the relative importance of the individual environmental variables in the prediction procedure (Kumar *et al*., 2014; Qin *et al*., 2017). In addition, by using Maxent-produced curves, the relationships between habitat suitability for tuber mustard and environmental variables were analysed to obtain the appropriate ranges of dominant factors (Hu *et al*., 2015).

Results

Current geographic distribution and evaluation

Based on occurrence coordinates and current environmental data, the potential geographical distribution of tuber mustard in China was simulated using the Maxent model. In the current study, the value of AUC was 0.967 for model training and 0.958 for model testing, indicating that Maxent modelling for *B. juncea* var. *tumida* provided satisfactory results. Based on a previous study (Li *et al*., 2018), the final potential species distribution map was grouped into three classes (0–1 range), namely 'suitable habitat' (>0.5), 'moderately suitable habitat' (0.15–0.5) and 'unsuitable habitat' (<0.15). The suitable habitats for tuber mustard are concentrated in southwest China, central China and east China, i.e. three occurrence and diffusion centres (Fig. 1). Specifically, the suitable habitat distribution areas are mainly in eastern Sichuan, western and north-western Chongqing, southern Hubei, northern Hunan, south-eastern and eastern Zhejiang, northern Guizhou, eastern Jiangsu and a few regions in Fujian, Jiangxi and Anhui. The moderately suitable habitat areas are mainly in certain regions of Sichuan, Chongqing, Hubei, Hunan, Guangxi, Jiangxi, Anhui, Fujian and Zhejiang Provinces. The unsuitable habitat regions are in the majority of provinces except for the above-mentioned suitable and moderately suitable habitat regions. Based on statistical analysis after the projection conversion, the percentages of suitable, moderately suitable and unsuitable habitat areas of tuber mustard in China are 2.16, 6.31 and 91.53%, respectively.

Importance of environmental variables and threshold values

From the jack-knife procedure, the mean diurnal range had the highest gain when it was used alone (Fig. 2), i.e. it was the most significant environmental variable that affected the distribution of tuber mustard. In addition, the mean temperature of the coldest quarter, annual mean temperature and minimum temperature of the coldest month also affected the geographical distribution of tuber mustard to a certain extent. Subsequently, using individual response curves for different variables (Fig. 3), the following thresholds were obtained for the main environmental parameters (probability of presence >0.5): mean diurnal range (bio-02) ranged from 6.5 to 7.5 °C, mean temperature of coldest quarter (bio-11) ranged from 5.5 to 9 °C, annual mean temperature (bio-01) ranged from 16 to 19 °C and minimum temperature of the coldest month (bio-06) ranged from 2.0 to 6.5 °C.

Future changes in suitable habitat areas

The future distribution was forecast using the Maxent model with future environmental parameters. Based on the same classification standard and projection coordinates as those discussed previously, the potential species distribution map was divided into three categories and each type of area was calculated. The predictive distribution map (Fig. 4) showed that under future environmental parameters, tuber mustard could be potentially distributed in southwest China, central China and east China. The moderately suitable habitat areas were mainly in parts of Sichuan,

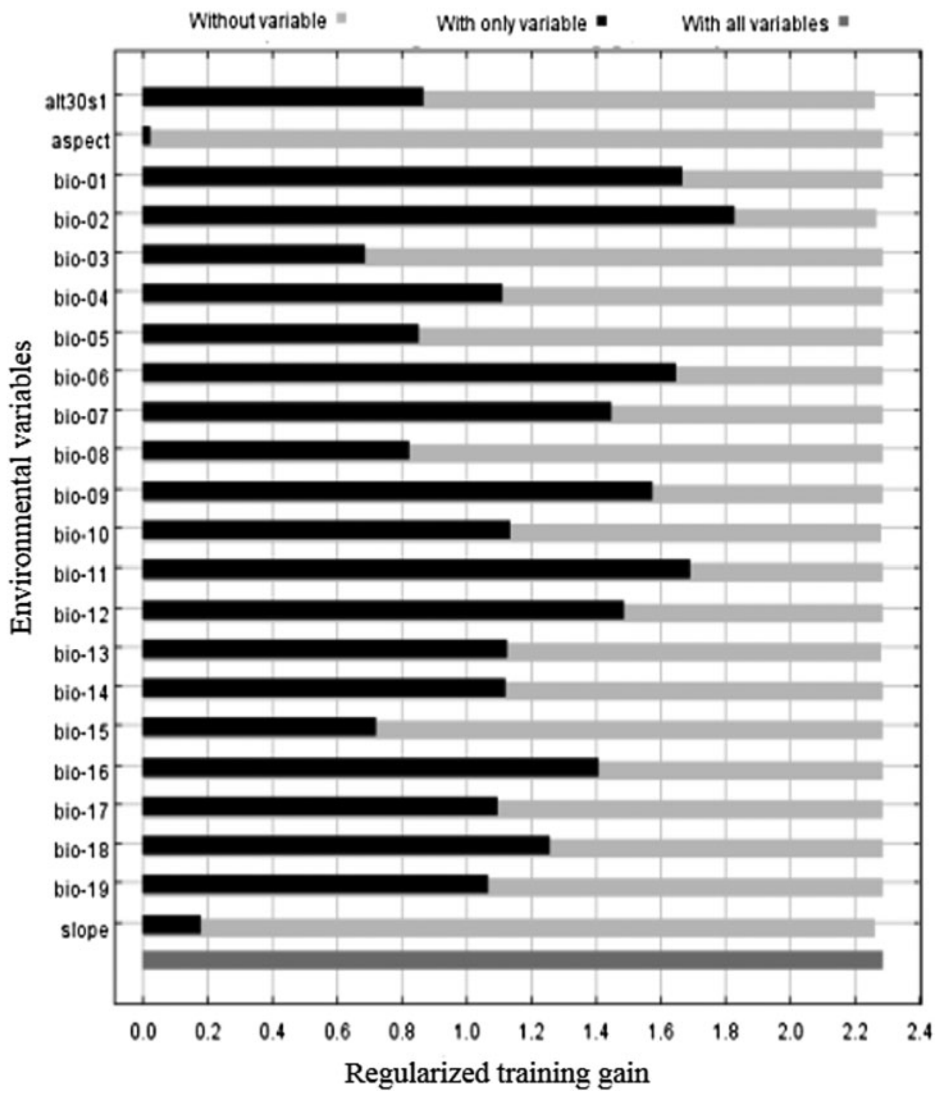

Fig. 2. Jack-knife test evaluating the relative importance of environmental variables for *B. juncea* var. *tumida* under current environmental conditions.

Chongqing, Hubei, Hunan, Jiangxi, Anhui, Fujian and Zhejiang Provinces. However, the percentage of the three habitat areas had a certain amount of change. Under the current conditions, 2.16% of the areas were identified as suitable habitat areas for tuber mustard, whereas 6.01% was identified as moderately suitable habitat areas. In the 2050s and 2070s, the percentage of suitable habitat areas changed to 3.72 and 3.92%, and 3.60 and 3.73%, in the two scenarios of RCP4.5 and RCP6.0, respectively, whereas the percentage of the moderately suitable habitat areas was 6.93 and 6.88%, and 7.59 and 7.45%, respectively. The results showed that in the 2050s and 2070s, the suitable and moderately suitable habitat areas were predicted to increase slightly. However, for different provinces or cities (Table 1), the distribution of tuber mustard is different. For example, suitable habitat area in Sichuan Province increased up to the 2050s and 2070s; however, it remained approximately unchanged between the 2050s and 2070s; suitable habitat in Chongqing city increased at first, and then decreased; suitable habitats in Hunan, Anhui, Jiangsu, Zhejiang and Fujian Provinces increased continuously to the 2050s and 2070s; and suitable habitat in Guizhou, Hubei, Jiangxi Provinces and Shanghai city decreased first, but then increased.

Discussion

Tuber mustard belongs to an economically important crop in China. To date, it has been cultivated in provinces along the Yangtze River including Chongqing, Shanghai, Sichuan, Hubei, Zhejiang, Fujian, Jiangsu, Hunan and Guangxi Provinces (Liu, 1996; Chen *et al*., 2011). Analysis of the relationship between species and environment parameters has become an important issue in ecology and biogeography (Yang *et al*., 2013). With the development of applied ecology, species distribution models are regarded as an important tool for evaluating and forecasting changes in a species' potential distribution and have been compiled into software tools (Wang *et al*., 2010; Qin *et al*., 2017). Compared with other species distribution models, the Maxent model is popular for accurately forecasting species distribution in a certain region (Phillips *et al*., 2006; Jaryan *et al*., 2013; Qin *et al*., 2017). The principle of the design of the Maxent model is that species are present in areas with suitable environmental conditions and absent in unsuitable climates (Guisan and Zimmermann, 2000; Hu *et al*., 2014), and there are only minor deviations from biological routes of transmission and interactions between organisms (Svenning *et al*., 2008; Hu *et al*., 2014). In the

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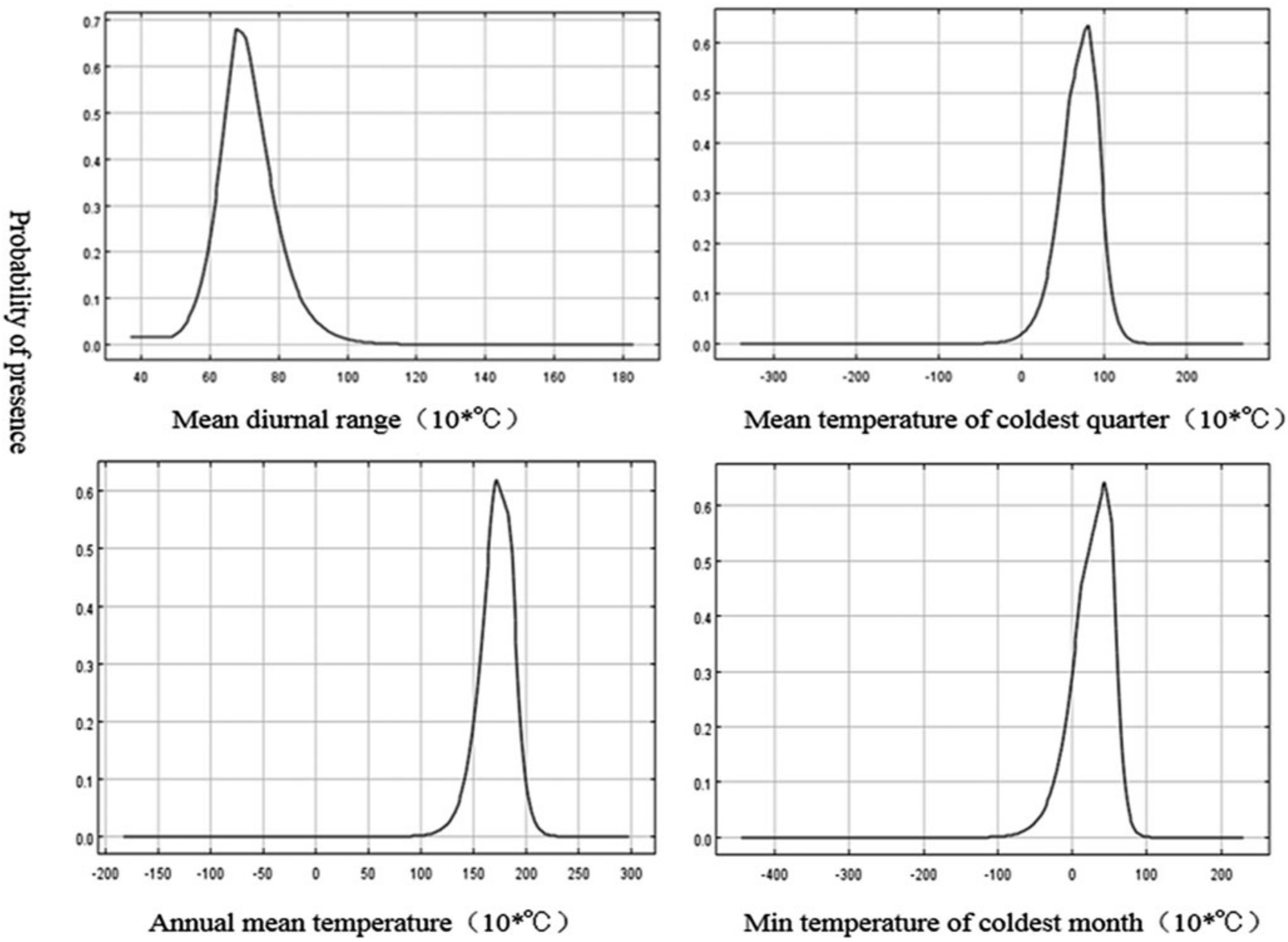

Fig. 3. Relationship of each dominant factor and the distribution probability of *B. juncea* var. *tumida* under current environmental conditions.

current study, human cultivation activities of tuber mustard have overcome these two restrictions; therefore, the accuracy of the Maxent model is excellent in predicting potential planting areas for tuber mustard. In addition, the value of AUC was 0.967 and 0.958 for model training and testing, respectively, indicating that the model performance was excellent. Furthermore, climate change, especially temperature, rainfall and humidity modifications, have significant effects on the physiological and ecological characteristics, phenology and geographical distribution of tuber mustard (Li *et al*., 2018). Compared with current environmental variables, the suitable habitats of tuber mustard in the future were found to be concentrated mainly in southwest China, central China and east China, i.e. three occurrence and diffusion centres. Fortunately, in the 2050s and 2070s, the suitable distribution areas are predicted to increase gradually, and a new suitable area is expected to appear in central China including southern Hubei and northern Hunan. This trend is in agreement with the development of the pickle industry in China. However, for different provinces or cities, the distribution of this species is different, for example, the suitable habitat area in Chongqing city increases first, but then begins to decrease, whereas the suitable habitat area in Guizhou, Hubei, Jiangxi Provinces and Shanghai city decreases first, but then begins to increase. Therefore, management of suitable planting areas of tuber mustard must be strengthened and, for the reduced area of suitable planting regions, suitable local varieties should be bred and domestication increased in the moderately suitable habitat to ensure that the total volume will not decrease in the future.

Many studies have indicated that the main factors restricting geographical distribution of plants are cold tolerance, energy supply needed to complete life-cycles and available water (Woodward, 1987; Jia *et al*., 2017). The results in the current study are in agreement with these viewpoints. In the current study, the mean diurnal range, mean temperature of the coldest quarter, annual mean temperature and minimum temperature of the coldest month made the largest contributions to the model for tuber mustard compared with the other parameters. These key factors are all related to temperature, suggesting that this is one of the decisive factors affecting the distribution of suitable habitat areas for tuber mustard. This is in agreement with previous studies (Li *et al*., 2015, 2018). Among them, mean diurnal range made the largest contribution, with the threshold ranging from 6.5 to 7.5 °C. For tuber mustard, the winter mean diurnal range from 6.5 to 7.5 °C may guarantee local minimum temperature over 0 °C, thus avoiding frostbite, because in Chongqing the daytime temperature is 4–15 °C (Li *et al*., 2015). The mean temperature of the coldest quarter is from 5.5 to 9 °C and the minimum temperature of the coldest month is from 2.0 to 6.5 °C, which might also guarantee the avoidance of frostbite for tuber mustard. The annual mean temperature from 16 to 19 °C coincides with the optimum temperature of tuber mustard tuber (Li *et al*., 2015). Previous studies have shown that

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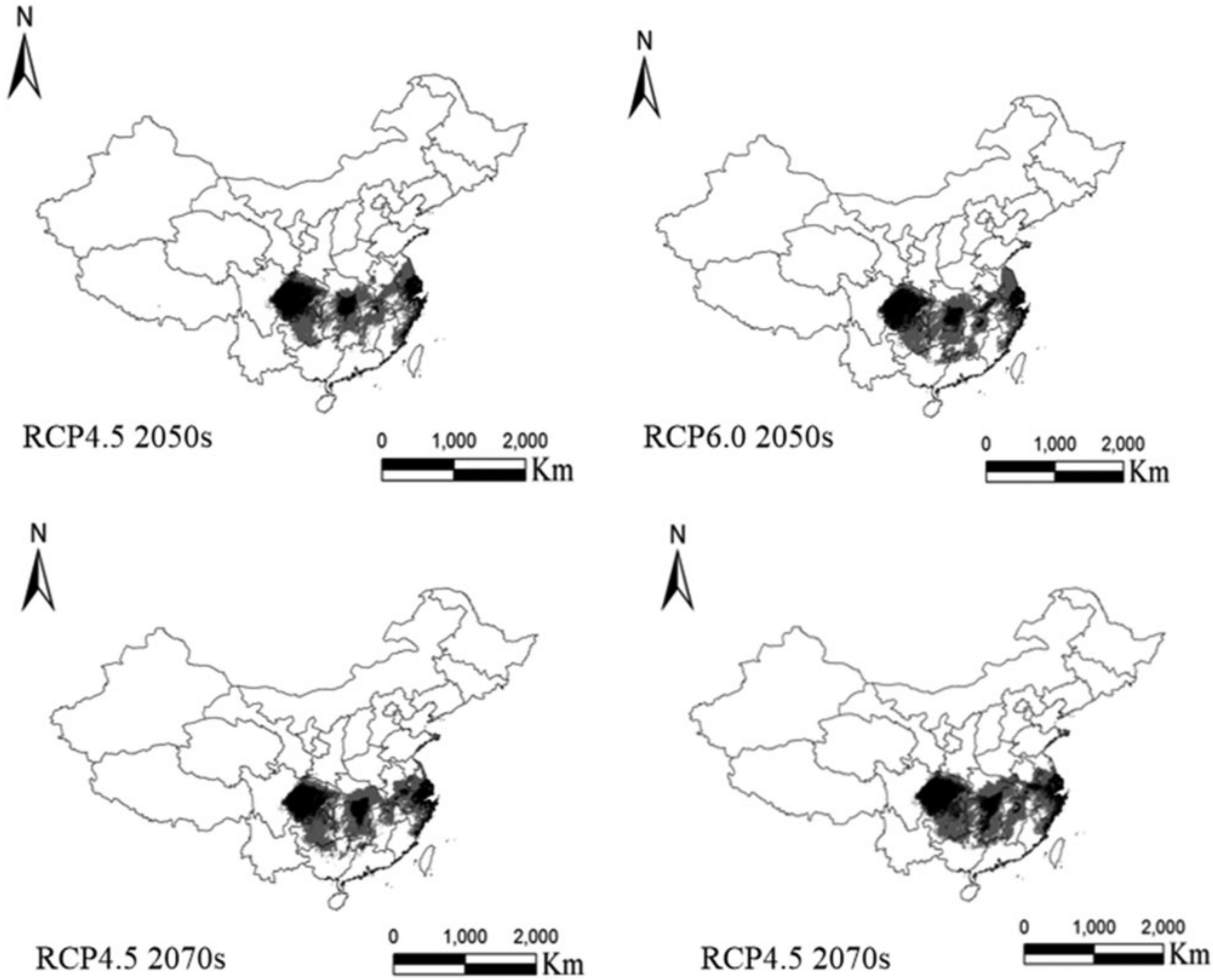

Fig. 4. Distribution of habitat suitability for *B. juncea* var. *tumida* under different climate change scenarios.

Table 1. Percentage of suitable habitat distribution of *B. juncea* var. *tumida* under current and future environmental conditions in different provinces or cities

		2041–2060		2061–2080	
Region	1970–2000	RCP4.5	RCP6.0	RCP4.5	RCP6.0
Sichuan	21.32	23.93	24.20	23.34	23.24
Chongqing	41.60	50.36	51.59	47.99	45.46
Guizhou	5.95	4.01	4.41	6.98	8.98
Hubei	11.01	8.68	8.37	14.10	17.04
Hunan	13.61	14.31	16.15	17.04	21.01
Jiangxi	2.16	1.25	1.38	3.15	3.57
Anhui	1.67	3.92	5.81	7.34	7.15
Jiangsu	19.62	22.95	21.17	23.08	23.89
Zhejiang	22.62	27.56	31.34	29.95	35.77
Fujian	1.52	1.79	2.65	2.91	3.59
Shanghai	99.98	84.13	93.89	99.69	99.93

precipitation is the dominant factor affecting plant growth, regeneration, nutrient cycle and community productivity in different habitats (Hu *et al*., 2014; Fu *et al*., 2016). However, the growth period of tuber mustard is from August to late February of the following year (Fan *et al*., 2017; Li *et al*., 2018). Since winter occurs in the dry season in China, tuber mustard grows relatively slowly; therefore, precipitation becomes less important for this species.

Conclusions

(1) The suitable habitats of tuber mustard in China under current environmental conditions are concentrated mainly in central China, south-west China and east China, i.e. there are three occurrence and diffusion centres. (2) The dominant factors were mean diurnal range, mean temperature of the coldest quarter, annual mean temperature and minimum temperature of the coldest month, which had the threshold of 6.5–7.5, 5.5–9, 16–19 and 2.0–6.5 °C, respectively. (3) By the 2050s and 2070s, the predicted suitable and moderately suitable habitat areas increased slightly. However, the suitable habitat area in Sichuan Province increased up to the 2050s and 2070s yet remained reasonably unchanged between the 2050s and 2070s; suitable habitat area in Chongqing city increased at first and then decreased; suitable habitats in Hunan, Anhui, Jiangsu, Zhejiang and Fujian Provinces increased continuously; and suitable habitat areas in Guizhou, Hubei, Jiangxi Provinces and Shanghai city decreased first, but then began to increase.

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Conflict of interest. The authors declare that there is no conflict of interest.

Ethical standards. Not applicable.

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