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RESEARCH ARTICLE

Modeling the Potential Geographic Distribution of Black Pepper (*Piper nigrum*) in Asia Using GIS Tools

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Abstract

Known as the "king of spices", black pepper (*Piper nigrum*), a perennial crop of the tropics, is economically the most important and the most widely used spice crop in the world. To understand its suitable bioclimatic distribution, maximum entropy based on ecological niche modeling was used to model the bioclimatic niches of the species in its Asian range. Based on known occurrences, bioclimatic areas with higher probabilities are mainly located in the eastern and western coasts of the Indian Peninsula, the east of Sumatra Island, some areas in the Malay Archipelago, and the southeast coastal areas of China. Some undocumented places were also predicted as suitable areas. According to the jackknife procedure, the minimum temperature of the coldest month, the mean monthly temperature range, and the precipitation of the wettest month were identified as highly effective factors in the distribution of black pepper and could possibly account for the crop's distribution pattern. Such climatic requirements inhibited this species from dispersing and gaining a larger geographical range.

Key words: *Piper ngirum*, ENM, bioclimatic distribution, Maxent

INTRODUCTION

Piper nigrum L. is a medicinally and commercially important member of the giant genus *Piper* (Piperaceae). This species is often called "black pepper" because of the color of its peppercorn, and is considered to be the "king of spices" because of its huge trade share in the international market (Mathew *et al*. 2006; Srinivasan 2007). The fruits of the black pepper contain 1.0-2.5% volatile oil and 5-9% alkaloids, of which the major ones are piperine, chavicine, piperidine, piperetine, and resin (Navickene *et al*. 2000). Its fruits have been widely used as flavoring agents in India since ancient times. In various traditional systems of medicine, the fruits of the black pepper have been used in the treatment of cholera and dyspepsia, as well as a variety of gastric ailments and arthritic disorders (Scott *et al*. 2008; Umit *et al*. 2009). Geographically, the Western Ghats of the South Indian Peninsula is the primary center of the black pepper cultivation, and domestication is believed to have taken place in this area many centuries ago. Since then, black pepper cultivation has been introduced to other countries in South and Southeast Asia

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(Ravindran *et al*. 1994; Ravindran 2000; Nair *et al*. 2003). Currently, this crop is chiefly cultivated in the tropical regions of the world, such as India, Vietnam, Malaysia, Indonesia, China, and Brazil, and, on a smaller scale, in Sri Lanka and in the West Indies (Howard 1973). According to statistics from the Food and Agriculture Organization, black pepper was cultivated on 553 144 ha of land to produce 433 238 t of peppercorns in 2008. China is the fifth largest producer in the world, with an estimated annual production of 27 210 t, and with the province of Hainan producing nearly 90% of the country's black pepper (Food and Agriculture Organization of the United Nations 2009).

Although having been cultivated for thousands of years, black pepper has not been introduced and cultivated in many regions. Thus, determination of whether those regions are suitable for its cultivation would be a necessary and important premise. Geographic distributions of plant species and their relation to environmental variables have been probed for centuries and have long fascinated scientists and naturalists (Krishtalka *et al*. 2000). New distributional modeling techniques provide an improvement over the broad-stroke maps typical of field guides and other faunal and floral treatments. Essentially, those new techniques aim to predict areas that describe where environmental conditions (e.g. bioclimate) are suitable for the survival of the species, that is, fundamental niche (Hutchinson 1957; Anderson *et al*. 2003; Peterson 2003; Guisan and Thuiller 2005). This approach has recently been explored under the rubric of "ecological niche modeling" (ENM; Soberón and Peterson 2005), and refers to reconstruction of ecological requirements of species that are analogous to the Grinnellian ecological niche (Grinnell 1917). ENM is a good tool to assess potential geographic distributions of species (Guisan and Thuiller 2005; Elith *et al*. 2006), and has been applied to problems in biogeography, conservation, evolutionary ecology, and invasive-species management (James and McCulloch 2002; Anderson *et al*. 2004; Solano *et al*. 2007; Giovanelli *et al*. 2008). ENM may provide a new and powerful predictive framework for targeting additional suitable regions for crop plantation, while the application on modeling bioclimatic distribution of black pepper has been reported rarely (Parthasarathy *et al*. 2006).

In this study, we modeled the bioclimatic distribution of black pepper in Asia using WorldClim bioclimatic data and Maxent software. The aims of this study were to (1) estimate its bioclimatic distribution using the selected algorithm, and (2) detect the probable bioclimatic factors that might explain its distribution pattern, and (3) explore the additional potential distributions for this crop. Such a study could be expected to provide sound scientific rationale for understanding distribution pattern of this crop and thereby give rise to a reliable decision-support for crop introduction and cultivation.

RESULTS

Evaluation of modeling algorithm

Results showed that maximum entropy gained low omission rates (0.61%) and high commission rates (5.42%), indicating that the algorithm was not over-omitting but over-predicting its bioclimatic distribution. Guisan and Thuiller (2005) thought that commission error likely results from species that have not yet colonized all climatically suitable locations and from dispersal limitations. This conclusion is mainly applicable to widespread species, but not to restricted plant species (Anderson *et al*. 2003). Black pepper has been cultivated in Asia, Africa, and Latin America, making it a widespread species. Therefore, a high commission rate is acceptable. The AUC (area under the curve) value of maximum entropy was 0.988, which was significantly better than random performance (0.5). Based on the results above, maximum entropy is suitable for modeling the bioclimatic distribution of black pepper.

Analysis of suitable bioclimatic distribution

Modeling predictions for this species were mapped in terms of the cumulative probability over the region of study at ~5 km spatial resolution. As shown in Fig. 1, bioclimatic distributions were mostly distributed in the eastern and the western coasts of the Indian Peninsula, the east of Sumatra Island, some areas in the Malay Archipelago, and the southeast coastal areas of China. Black pepper covers a huge geographic area and has expanded to almost every country in South and Southeast Asia, except for Pakistan and Bhutan.

The role of environmental variables

Jackknife evaluation was applied to analyze the importance of the variables used in the modeling process (Fig. 2). Bio6,

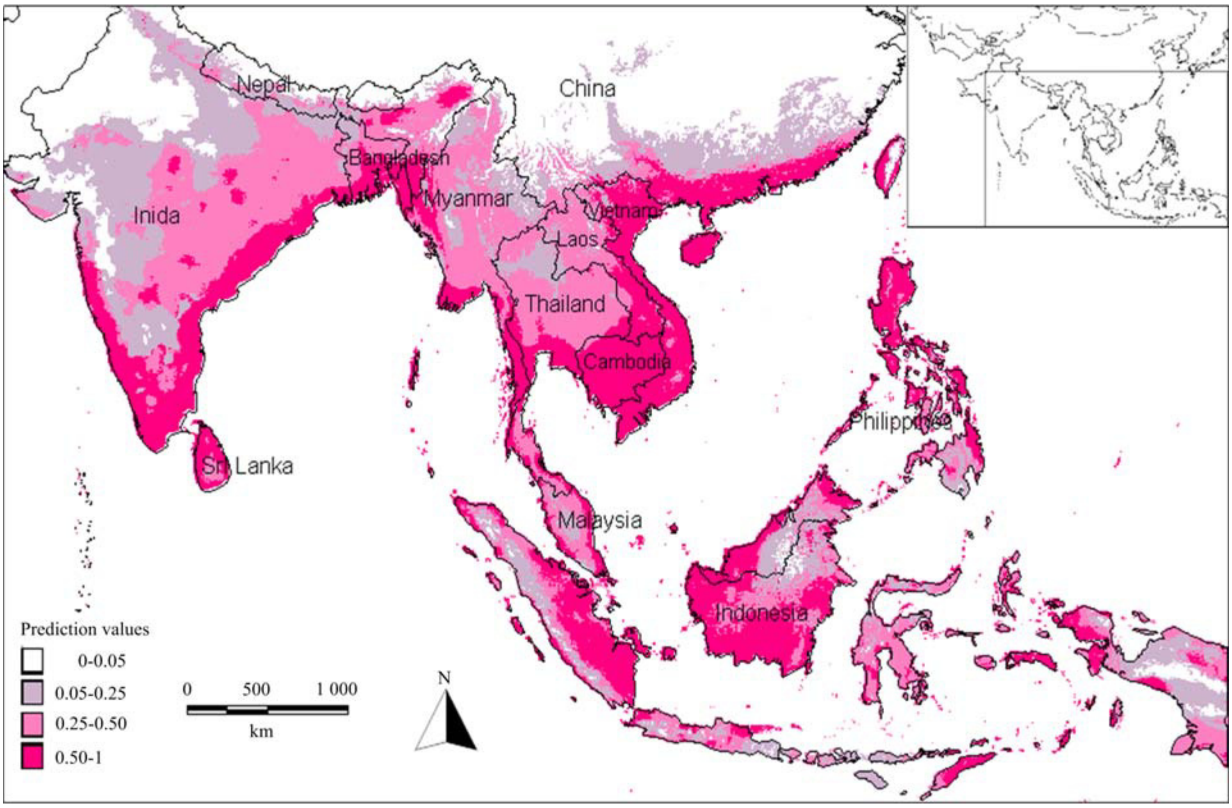

Fig. 1 Predicted bioclimatic distribution of black pepper in Asia resulting from maximum entropy algorithm in Maxent.

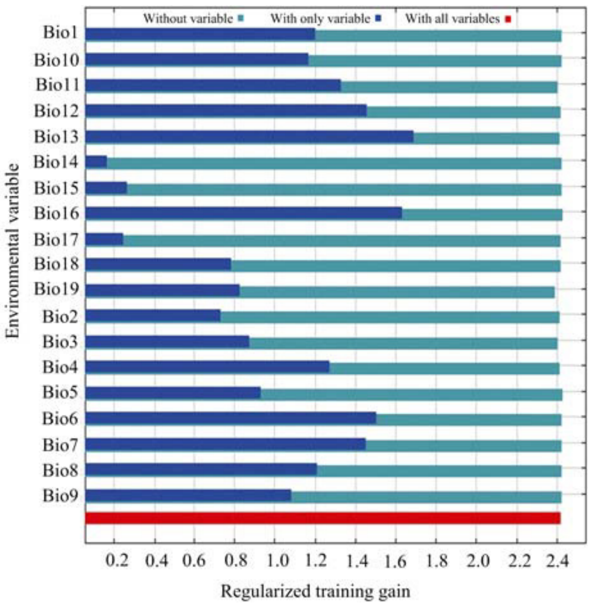

Fig. 2 Jackknife of training gain of different climatic variable for black pepper. Output generated by Maxent software. See Environmental data sources section for environmental variables details.

Bio7, Bio12, Bio13 and Bio16 presented higher gain (contained more information) compared with other variables , and were the most important predictors of black pepper. Some variables, such as Bio2 and Bio5, were the next contenders in defining habitat. Bio14, Bio15 and Bio17, on the other hand, were not important indicators for habitat, except for the evaluation. The heuristic test showed that Bio13, Bio2, Bio6, and Bio7 were the four most important predictors of black pepper distribution, and their percent contributions in the modeling were 38, 20.2, 19.5, and 8.1%, respectively.

DISCUSSION

ENM is a useful tool in outlining and understanding the distributions in geographical and ecological locations of crops, and is useful in a variety of applications on species introduction, conservation, and any application that requires detailed information on species' geographic distributions. Maxent was selected because it had been used in ENM development for crops (Peterson *et al*. 2007; Phillips 2008), and had undergone intensive analysis of performance.

This algorithm predicted that areas with the highest probabilities (>50%) were mainly in the east and the west coasts of the Indian Peninsula, the east part of Sumatra Island, some areas of the Malay Archipelago, and the southeast coastal areas of China. The foregoing was based on known occurrences. Some undocumented areas were also predicted as suitable. Visual inspection of the predicted areas matched the biological characteristics of this species. In India, the Malabar Coast is the center of origin of the black pepper. From this area, black pepper was taken to Indonesia, Malaysia, and, subsequently, to other pepper-growing countries. The modeling showed that areas with higher probabilities were located almost throughout India, especially East, South and West India. With more than 2 000 yr of cultivation history, black pepper in India has been given sufficient time to expand its geographical range, so it is easy to understand that the bioclimatic distributions of black pepper are basically similar to its current distributions. Vietnam is the largest producer in the world, where black pepper is cultivated mainly in the south region, in which Binh Phuoc Province is the center of production. However, the crop was difficult to find in North Vietnam, and we doubted whether these areas were suitable for the plantation of black pepper. The current study answered this problem. The modeling results showed that some provinces in North Vietnam are suitable for black pepper plantation, so local farmers could carry out the introduction and the trial plantation of black pepper in the future. We also wanted to know why black pepper was distributed in such a large geographic area. Thus, we analyzed 19 bioclimatic variables based on known occurrence points (Table). Based on the Table, the changing ranges of these climatic variables are large, which indicates the black pepper's wide adaptability to various environmental conditions.

The minimum temperature of the coldest month, the mean monthly temperature range, and the precipitation of the wettest month were identified as highly influential in the distribution of black pepper. This species prefers hot and humid environments, which limit this crop from spreading to higher latitudes. Precipitation during the wettest period plays an important positive role in defining the geographic distribution of the black pepper, whereas precipitation during the driest month does not. During June to October (wettest period), this crop flowers, fills grain, and ripens. Thus, physiological activities are at their maximum, and there is a higher demand for water during this period. To some extent, our conclusions were consistent with those of previous studies (Indian Institute of Spices Research 2008; Li *et al*. 2010). Black pepper is a plant found in humid tropics, requiring adequate rainfall and humidity. The hot and humid climate of submountainous tracts is ideal for its cultivation, and black pepper can grow successfully between 20° North and South latitudes. Black pepper tolerates temperatures between 10 and 40°C. Such ecological requirements limit this species from dispersing and gaining larger geographical range.

In China, Hainan Province produces about 90% of the country's black pepper. Guangdong, Fujian, Guangxi, and Yunnan produce the remaining 10%. Our results indicate that areas with higher probabilities are located on the southeast coast of China, and are related with known occurrences. The pepper in China comes

Table Bioclimatic variables of black pepper based on the known occurrence points

Code of climatic variable	Mean	SE	Range	Code of climatic variable	Mean	SE	Range
Bio1	256.23	20.77	171-292	Bio11	235.34	33.98	139-270
Bio2	82.92	14.58	51-135	Bio12	2 369.72	951.54	546-4 771
Bio3	62.94	14.73	25-94	Bio13	525.69	355.90	145-1 619
Bio4	1 599.60	1 286.51	108-5 906	Bio14	36.24	51.91	0-230
Bio5	325.35	20.90	244-421	Bio15	76.94	31.09	17-155
Bio6	187.38	39.18	53-239	Bio16	1 278.37	762.60	271-3 580
Bio7	137.96	40.80	73-323	Bio17	134.51	171.46	0-816
Bio8	258.14	17.54	178-289	Bio18	452.35	200.49	18-1 238
Bio9	245.12	34.75	139-305	Bio19	697.40	776.82	4-3 005
Bio10	276.19	18.93	189-330				

mainly from Hainan because of the weather condition there. Hainan, one of the rainiest areas among those found in the same latitude, is classified into the tropical maritime monsoon climate zone. The average high temperature is between 22.5 and 25.6°C, and the annual average rainfall is up to 1 640 m. Such climatic conditions are especially suitable for black pepper cultivation because of low management cost, high output and great efficiency. Consequently, the cultivated area and the output of pepper production in Hainan are over 90% of that of the whole nation. Modeling also predicted the south, the west, and the east coastal strips of Taiwan of China as suitable areas for plantation of the pepper species, where wild populations or plantations of black pepper have not been documented yet. Using modeling as guide, the authors carried out a preliminary investigation in Taiwan of China and found black pepper plantations in the Xinfa Village of Kaohsiung (23°01´36´´N, 120°39´29´´E), which, to some extent, illustrates the authenticity of the results.

CONCLUSION

Modeling the geographic range of a crop holds promise in introduction and cultivation as an important improvement over subjective, broad-stroke, shaded, and outlining maps. Fine scale resolution of environment data is always desirable to develop accurate species distribution pattern to address ecological limiting factors. In this study, maximum entropy was successfully applied to modeling the suitable bioclimatic distribution of black pepper. The algorithm predicted that areas with the highest probabilities were mainly in the east and west coasts of India Peninsula, the east part of Sumatra Island, some areas of Malay Archipelago, and southeast coastal areas of China. Minimum temperature of coldest month, mean monthly temperature range, and precipitation of wettest month were three important factors determining its distributions. This conclusion would help in outlining and understanding the distributions in geographic and bioclimatic spaces of black pepper, and proves useful in a variety of applications to crop introduction, conservation, and any application that requires detailed distribution information.

MATERIALS AND METHODS

Collection of occurrence points

In the current research, a lot of resource were used to search for the present sites of black pepper production from various data sources around the world (e.g., natural history museums, published literature, and reliable observational data) to understand the current distribution of this crop. Most of the information we found focused on habitat description and local name, but did not include numerical latitude and longitude. We found the present points in the gazetteer of different countries and recorded geographic coordinates. Only points with clear geographical information were accepted. Specific information on each observation (e.g., data, locality, coordinate and state) was recorded and detailed in the 1:4 000 000 maps downloaded from the National Fundamental Geographic Information System of China (http://nfgis.nsdi.gov.cn/nfgis/chinese/c_xz.htm). We found a total of 328 spatially unique point locations from 17 countries, such as India, Malaysia, Vietnam, Indonesia, China, Brazil, Cambodia, Thailand, Philippines, and Sri Lanka. The longitude and the latitude of all unique points were converted to decimal degree.

Environmental data sources

We used the 19 bioclimatic variables based on the global climate data sets developed by Hijmans *et al*. (2005). These bioclimatic variables were obtained from WORLDCLIM (ver. 1.3, http://www.worldclim.org), which is explained in detail in Hijmans *et al.* (2005). The 19 bioclimatic variables were as follows: annual mean temperature (Bio1), mean monthly temperature range (Bio2), isothermality (Bio3), temperature seasonality (Bio4), maximum temperature of warmest month (Bio5), minimum temperature of coldest month (Bio6), temperature annual range (Bio7), mean temperature of wettest quarter (Bio8), mean temperature of driest quarter (Bio9), mean temperature of warmest quarter (Bio10), mean temperature of coldest quarter (Bio11), annual precipitation (Bio12), precipitation of wettest month (Bio13), precipitation of driest month (Bio14), precipitation seasonality (Bio15), precipitation of wettest quarter (Bio16), precipitation of driest quarter (Bio17), precipitation of warmest quarter (Bio18), and precipitation of coldest quarter (Bio19). Those bioclimatic variables have important biological significance and have been widely applied for the modelling of ecological niches and potential distribution (Graham *et al.* 2006; Wang *et al.* 2007; Thorn *et al.* 2009). Those bioclimatic layers were genetic grid format and should be transformed to American standard code for information interchange in DIVA-GIS.

Modeling algorithm and software used

Maximum entropy is a machine-learning method for making predictions or inferences from incomplete information, and it has been found to perform best among many different modeling methods (Elith *et al*. 2006). It requires only species presence data (not absence) and environmental variable (continuous or categorical) layers for the study area. Maxent software (ver. 2.3) is selected to operate maximum entropy algorithm, and further information are available from http://www.cs.princeton.edu/~schapire/maxent (or see Phillips *et al*. 2006). The GIS software, ArcView GIS (ver. 3.2), was also used to display and analyse the modeling results. The estimated map was produced as continuous predictions with values ranging from 0 to 100. Although it would be better if we use continuous data, we need to categorize the data for many practical applications like planting place selection. Therefore, prediction map were categorized on four classes (0-5%, 5-25%, 25-50%, and 50-100%), and assigned a gradient of colors to facilitate visual inspection of the predicted areas.

Threshold-dependent and threshold-independent evaluation

Threshold-dependent tests and threshold-independent tests are two kinds of methods commonly used to evaluate the prediction results of different algorithms. Omission test and commission test both are threshold-dependent measure. After applying a threshold, model performance can be investigated using the extrinsic omission rate (under prediction), commission rate (over prediction) and the proportional predicted area. Receiver operating characteristic (ROC) test has become a dominant tool in evaluating the accuracy of models predicting distributions of species (Peterson *et al*. 2008). As a threshold-independent measure, ROC does not require decisions regarding thresholds of what constitutes a prediction of presence versus absence (Fielding and Bell 1997). The area under the curve (AUC) of ROC measures the ability of a model to discriminate between sites where a species is present versus those where it is absent (Fielding and Bell 1997; Elith *et al*. 2006). Many facets of this test method and its application have been examined in detailed analyses (Stockwell and Peterson 2003; Guisan and Thuiller 2005; Peterson *et al*. 2007). In this paper, the evaluation was carried out by characteristics in term of omission and commission error statistics and ROC test. The model was trained with 75% of the presence data and tested with the rest, 25%.

Jackknife evaluation of bioclimatic variables

Jackknife evaluation was applied to analyze the importance of the variables used in the modeling process. Each variable was excluded and a model was reconstructed using the remaining ones. Thus, a new model was created using each variable in isolation. The jackknife test provided gain values for two scenarios, namely, identifying the environmental variable with the highest gain when used in isolation that predicts distribution and the bioclimatic variable that decreased the gain when it was omitted. As with the jackknife, variable contributions should be interpreted with caution when predictor variables are correlated. Therefore, a heuristic estimate of relative contributions of variables was conducted. To determine this estimate, in each iteration of the training algorithm, increase in regularized gain was added to the contribution of the corresponding variable, or subtracted from it if the change to the absolute value of lambda was negative.

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