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Potential Impact of Climate Change on the Distribution of the Pinewood Nematode *Bursaphelenchus xylophilus* in Chongqing, China

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***Bursaphelenchus xylophilus*, Climate change, Potential geographical distribution, Maxent model.**

ABSTRACT

Pine wilt disease, caused by pine wood nematode, is one of the most dangerous biological hazards which leads to great economic losses and ecological damage in the invaded range. Here the geographical distribution of potential pine wilt disease was analyzed by using the Maxent model in the current and future conditions. Our results indicated that Maxent model provided satisfactory result with the AUC value of 0.871 and 0.841 for the model training and testing, respectively. The most significant factors were maximum temperature of hottest month, mean temperature of hottest quarter, altitude, annual mean temperature and minimum temperature of coldest month, with the thresholds 30.5~31.8°C, 27.5~28.7°C, ≤ 400 m, ≥ 17.5°C, and ≥ 2.3°C, respectively. Under the current conditions for the years 1950-2000, 9.22% of total areas, located in the central district of Chongqing, were identified as the suitable areas including increased three districts of Jiangbei, Dadukou and Jiulongpo for the nematode while 29.27% of the areas as the moderately suitable areas. During the periods of 2041-2060s and 2061-2080s, proportion of the optimum suitable areas in Chongqing were expected as 12.59%~15.44% and 12.10%~16.84%, with the proportion of moderately suitable areas as 23.00%~25.11% and 24.34%~25.00%, respectively. Altogether, the results shows that the optimum suitable areas will increase while moderately suitable ones decrease, however, the optimum and moderate ones almost not change between the 2050s and 2070s in the future. So forestry activities related to Pinus trees must be intensively controlled and "pine replacement project" may be implemented. Moreover, insect vector control actions should be conducted on suitable and moderate suitable habitats.

INTRODUCTION

Pine wood nematode (*Bursaphelenchus xylophilus*), listed as the top quarantine forestry pest in the world (Cheng *et al*., 2015), heavily damages pines in amount of countries such as Mainland and Taiwan of China, Japan, South Korea in Asia (Togashi and Shigesada, 2006; Robinet *et al*., 2011; Ikegami and Jenkins, 2018). It usually causes the pine wilt disease transmission between trees by the Japanese pine sawyer (*Monochamus alternatus*) (Fu *et al*., 2010) resulting in the fastest death of the infected *Pinus* trees within 40 days (Liu *et al*., 2017; Robinet *et al*., 2011). The whole pine forest can wilt and die within 3~5 years after being infested, so the disease is known as the "cancer" of pine and the "bird flu" of pine forest (Cheng *et al*., 2015). Changes, above all climate change in the spatio-temporal pattern, will have a potential effect on plant phenology, plant diseases and pests, and the characters of forest ecosystems (Hu *et al*., 2015; Qin *et al*., 2017). Based on the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the average temperature of each year on the planet will have risen by 0.3–4.5°C or so at the end of the 21st century (Hu *et al*., 2015). Therefore, it is of great urgency to forecast the potentially geographic distribution of *B. xylophilus* in the future climatic environment.

In China, pine wood nematode was first discovered in 1982 in Nanjing city, Jiangsu Province (Liu *et al*., 2017). Since then, it has rapidly expanded to Jiangsu, Chongqing, Zhejiang, Anhui, Hongkong, Taiwan and so on, and already caused the death of 500 million of the pines (Fu *et al*., 2010). The disease has caused great economic losses and ecological damage to the invaded regions, and is still spreading to other suitable habitats. However, few

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effective methods have been studied to predict and control it, though the situation is getting worse. At present, pine wilt disease has posed a serious threat to the ecological safety of Mountain Lu, Mountain Huangshan and the Three Gorges Reservoir Area in China (Liu *et al*., 2017). The State Forestry Bureau in China (2018) showed that the disease had extended to 12 districts of Chongqing belonging to the Three Gorges Reservoir Area, such as Banan, Wanzhou, Fuling, Changshou, Jiangjin, Kaizhou, Qianjiang, Tongliang, Wansheng, Qijiang, Yunyang, Zongxian *etc*. Thus, it is necessary to estimate the potential risk of the nematode invasions in Chongqing, and propose appropriate solutions for controlling the invasion.

At present, one of the most important ways to stop the damage is to formulate various measures to prevent the invasive species from entering the suitable areas (Ju *et al*., 2010). Only the invaded and potentially diffused areas are detected as early as possible, the potential hazards could be reasonably estimated and effectively controlled (Cheng *et al*., 2015; Robinet *et al*., 2011). Studies have shown that early prevention of the invasive alien species is more effective and economical for hazard mitigation than that after a large invasion outbreak (Waage and Reaser, 2001; Puth and Post, 2010). Thus, predicting and understanding the invasion processes is very necessary for the management. The species distribution model (SDM) is one of the most current means to evaluate the species-surroundings relationship and define the potentially suitable habitat for the species (Elith and Leathwick, 2009). However, among numerous species distribution models (SDMS), the Maxent model, a computer learning program has proven to be better compared with other model methods (Phillips *et al*., 2006; Qin *et al*., 2017). The Maxent method has several characteristics: it requires the presence-only occurrence data together with environment variables, and take advantage of the continuous and categorical data, and integrates the interactions between the variables (Phillips *et al*., 2006). In addition, the results of the Maxent model are more stable, and the requirements for computer configuration are lower, and the operation time is shorter, and so the operation is more convenient. In the previous study, we estimated potential distribution of *B. xylophilus* in Chongqing using the Maxent model by known occurrence records at Fuling District and found only seven districts of Chongqing in the infested area, while in 2018, twelve districts invaded by the nematode were announced by the State Forestry Administration in China (http://www.forestry.gov.cn/). Furthermore, the climate change in the future will promote the invasion of non-native species and threat biological diversity all over world (Bethanya *et al*., 2010; Bertrand *et al*., 2011). Here, the Maxent model was further performed to simulate the geographical distribution of the pine wood nematode by combining 247 known locations from 12 different districts and 22 environmental layers in Chongqing in the current and future environment conditions. The aim of this study was to analyze the potential effect of environment change on the distribution of the pinewood nematode *B. xylophilus* and gain some insights into the factors controlling the invasion in Chongqing.

MATERIALS AND METHODS

Species distribution samples

Chongqing is situated on the upstream of the Yangtze River between 105.18°–110.18°E and 28.17°–32.22°N in the southwest of China. The study area has a mountainous and subtropical humid climate and experiences an average annual temperature of 19.2°C, with the highest summer temperature averaging between 27 and 29°C. Vegetation is mostly evergreen broad-leaved forest, warm coniferous forests (mainly *Pinus massoniana* parasitized by pine wood nematode), bamboo forests and evergreen broad-leaved shrubs, and percentage of forest cover amounts to 43.15% or so. The occurrence data of *B. xylophilus* were collected in Chongqing from *Chongqing Forest* Disease and *Pest Control Station*, which only provides the names of small towns and villages in infested areas. The longitude and latitude of each location were obtained by using the Geographic Names Database (http://www.geonames.org/). Additionally, the geographical coordinates of sampling localities were recorded from our field studies using a Global Positioning System receiver. In order to avoid spatial autocorrelation, duplicate database records were deleted and the exclusive one record per grid cell was allowed, so the 247 unique records including twelve out of 39 districts or counties in Chongqing city was retained after checking their locations. According to the Maxent software demands, the points were saved in csv format according to species name, longitude, and latitude in order.

Environmental data

Because the geographical distribution of species depends mainly on its adaptability to environmental factors, such as climate and terrain (Tang *et al*., 2016), the environmental factors including 19 bioclimatic parameters and 1 topographic variable were selected. These bioclimatic parameters for the years 1950-2000 with 30 seconds (ca.1km^2 at ground level) spatial resolution were downloaded from the worldclim database (http://www.worldclim.org), representing a combination of annual trends, seasonality, and extreme environmental surroundings of temperature and precipitation (Hijmans *et al*., 2005). Elevation (DEM) with the same spatial resolution was also obtained from the WorldClim website The Representative Concentration Pathways (RCPs) were derived from a new set of scenarios described by the fifth IPCC Assessment Report (AR5). Four RCPs (RCP2.6, RCP4.5, RCP6.0, RCP8.5) were numbered in accordance with a possible range of radiative forcing values in the year 2100 relative to preindustrial data (Hu *et al*., 2015). In addition, compared with the previously used emission scenarios (Special Report on Emissions Scenarios, SRES), the RCPs scenario is more scientific and closer to the real change of climate (Tang *et al*., 2016), so PCRs-2050 (average value for the years 2041–2060) and PCRs-2070 (average value for the years 2041–2060) were downloaded from the same database (http://www.worldclim.org/) (Hijmans *et al*., 2005), and the elevation variable were remained unchanged for the Maxent analysis in the future environment conditions. Finally, all above-obtained environmental data under GCS-WGS-1984 frame were overlaid by the administrative boundary maps of Chongqing in ESRI shape format in ArcGIS 10.2 and be converted into 'asc' format in order to be compatible with the Maxent format. Additionally, the 1:400 million maps of province and country boundaries used here were obtained from the national fundamental geographic information system (http://nfgis.nsdi.gov.cn/).

Predicting potential distribution

Potential distribution of *B. xylophilus* in Chongqing was simulated by the Maxent model (Version 3.4.1) (http://www.cs.princeton.edu/~schapire/maxent/). In this study, owing to un*considering* the correlation between the variables (Phillips *et al*., 2006), the presence-only occurrence data together with the predictor variables can be directly imported into the Maxent model. In our models, 75% of the species records were randomly chosen for model training and the other 25% were hold for model testing (Phillips *et al*., 2006; Xu *et al*., 2014). Meanwhile, the model commands of "do jackknife to measure variable importance" and "create response curves" were also checked and other model parameter values were kept as default settings. For display and further analysis, the model prediction for the presence of *B. xylophilus* were imported into ArcGIS 10.2. Based on a document to the classification adjusted slightly (Yang *et al*., 2013; Qin *et al*., 2017), three classes of potential habitats were grouped: unsuitable (0–0.25), moderate suitable (0.25–0.54) and highly suitable (0.54–1.0). Finally, all kinds of habitat area are calculated after projection conversion (WGS_1984_UTM_Zone_48N).

Model performance and influencing factors

The area under the curve (AUC) stemming from the receiver operating curve (ROC) was used to estimate model's goodness-of-fit (Phillips *et al*., 2006), and the value of AUC ranged from 0.5 to 1.0. It is now generally believed that AUC = 0.5 shows model predictions not better than random, and the predictions are poor, useful, good and excellent for 0.70 > AUC > 0.50, 0.80 > AUC > 0.70, 0.90 > AUC >0.80 and AUC > 0.90, respectively (Simpson and Prots, 2013; Hu *et al*., 2015).

Based on the jackknife procedures in the Maxent model, the main impact factors were able to be identified for habitat suitability in *B. xylophilus* (Yang *et al*., 2013; Qin *et al*., 2017). In addition, using Maxent-produced response curves, the relationships between habitat adaptation and surrounding variables can be obtained (Hu *et al*., 2015).

RESULTS

Model evaluation

Based on the Maxent model, the relationship between the geographical distribution of pine wood nematode and environmental variables was simulated, and AUC values are often used to access the ability of the models to accurately forecast independent points. In this study, the AUC value reached 0.871 for model training and 0.841 for model testing, both are higher than 0.5 of a random model and up to good performance, suggesting that the Maxent model worked well and the results of the potential distribution for pine wood nematode were quite accurate.

Importance of surrounding variables

Using by the jackknife test of variable importance, the results showed that maximum temperature of hottest month (bio-05), mean temperature of hottest quarter (bio-10), altitude (Alt), annual mean temperature (bio-01) and min temperature of coldest month (bio-06) had the great contribution to the distribution of *B. xylophilus* relative to other variables (Fig. 1). Furthermore, in order to further clarify the environmental characteristics of this species' distribution under the current conditions and eliminate the correlation of environmental factors, the above 4 leading factors were alone imported into the MaxEnt model, and the results of individual response curves showed that the thresholds for the main environmental parameters (probability of presence >0.5) were: maximum temperature of hottest month (bio-05) ranged from 30.5 to 31.8°C, mean temperature of hottest quarter (bio-10) from 27.5 to 28.7°C, altitude less than 400 m, annual mean temperature (bio-01) greater than 17.5°C and temperature of coldest month (bio-06) greater than 2.3°C (Figures are not shown).

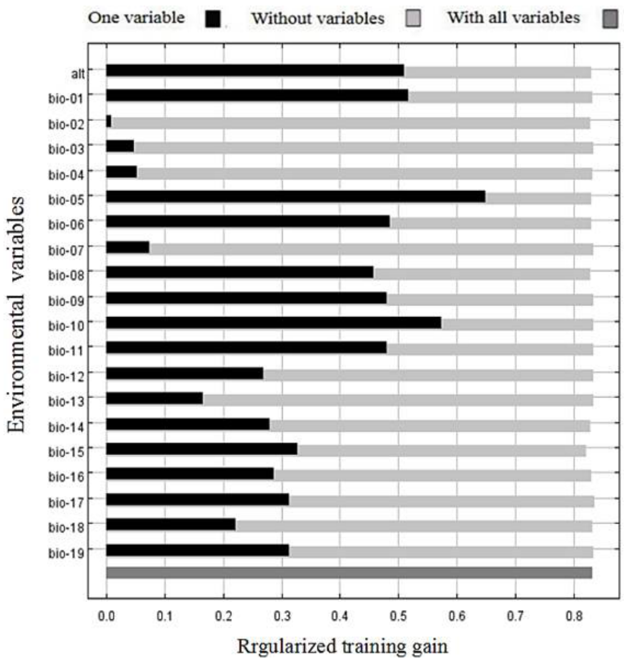

Fig. 1. Effects of environmental variables on the gain of distribution using Jackknife test.

Trend of potential habitat distribution of pine wood nematode

Current potential distribution

The current suitable habitats of *B. xylophilus* were evaluated by the Maxent model. the suitable habitats of *B. xylophilus* are mainly concentrated in the central districts of Chongqing and the Three Gorges Reservoir Area (Fig. 2). Specifically, the suitable distribution areas are mainly in some parts of Yubei, Jiangbei, Banan, Nanan, Dadukou, Jiulongpo, Qijiang, Jiangjin, Wanshou, Fuling, Fengdu, Zongxian, Changshou, Yunyang and Kaixian. The moderate suitable areas are mainly in some parts of Hechuan, Tongliang, Bisan, Yongchuan, Baibei, Nanchuan, Wulong, Pengshui, Jianjiang, liangping and Fengjie. Whereas unsuitable regions are located in Tongnan, Rongchang, Shizhu, Qianjiang, Youyang, Xiushan, Wuxi, Wushan, and Chengkou. According to the statistical analysis after projection conversion, the proportion of the suitable, moderate and unsuitable habitat area of pine wood nematode in Chongqing are 9.22%, 29.27% and 61.51%, respectively. Therefore, under the current circumstances, the area of the suitable habitats for the nematodes in Chongqing is large relative to most of other cities (Ju *et al*., 2010).

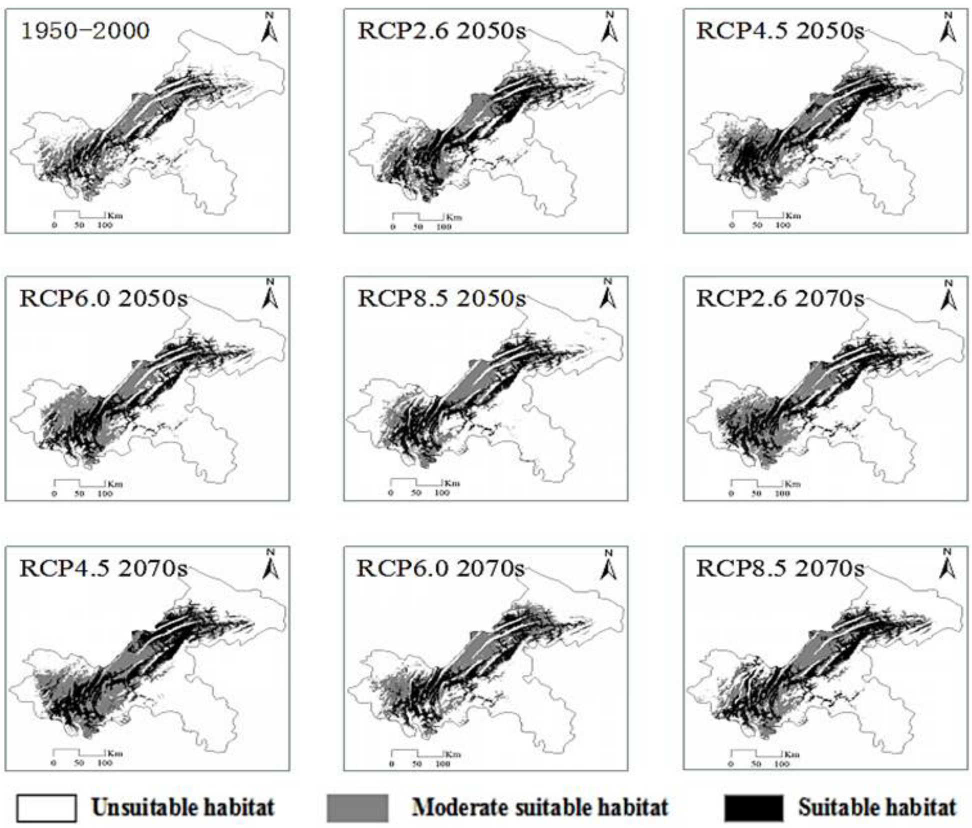

Fig. 2. Distribution of habitat suitability for *B. xylophilus* in Chongqing under different climate change scenarios.

Future potential distribution

The Maxent model is also used to predict future distribution of *B. xylophilus* for the periods of 2041-2060s (2050s) and 2061-2080s (2070s) under the climate change scenarios of RCP 2.6, RCP 4.5, RCP 6.0, and RC P8.5. The 4 kinds of habitats are classified in the same way as the previous section. As shown in Table I and Figure 2, *B. xylophilus* could be potentially distributed in a similar geographic pattern under the future environmental parameters, but it has a gradual spread to the periphery of the suitable habitats compared with the distribution areas under the current conditions. In 4 RCP climate change scenarios, proportion of the best suitable areas in Chongqing are 14.11%, 15.44%, 13.23% and 12.59% for 2041-2060s, and 14.02%, 16.84%, 12.10% and 14.34% for 2061-2080s, while proportion of moderate suitable areas are 23.97%, 24.89%, 25.11%, 23.01% and 24.34%, 25.63%, 24.97%, 25.00% for 2041-2060s and 2061-2080s. The results show that the suitable distribution areas are coming to increase in the future environment conditions, suggesting the promotion of future nematode invasion by the projected environmental variation.

DISCUSSION

Pine wood nematode (*B. xylophilus*), as one of the most dangerous forestry pests, results in the great economic losses and ecological damage in the invaded range. In the past, we predicted only seven districts of Chongqing in the infested area using by the Maxent model under the current conditions (Liu *et al*., 2017). However, twelve districts invaded by the nematode were announced by the State Forestry Administration in China in 2018. The difference between the prediction in 2017 and the announcement in 2018 could be resulted from the selected model, the resolution of the environmental variable, or sampling bias (Xu *et al*., 2014). Many studies have shown that the number of occurrence localities may be too low to reliably estimate the parameters of the model (Li and Ding, 2015). By comparing the above three reasons that lead to the difference, there is only a difference in the size of the sample. It is concluded that bias in presence samples only from Fuling district, Chongqing (Liu *et al*., 2017), induces an incomplete relationship between bioclimatic variables and presence samples, thus producing incomplete predictions when the relationship is applied over a study area.

In the present study, the Maxent model is used to simulate the distribution of the species by combining 247 known occurrence records from the announced twelve districts/counties and 22 environmental variables. The models' output provided excellent results, with the AUC value of 0.871 for model training and 0.841 for model testing. As shown in Figure 2, three districts including Jiangbei, Dadukou, and Jiulongpo were predicated as the high infestation areas, besides the announced twelve districts/counties, indicating that the actual invasive range of *B. xylophilus* was far narrower than ones that the model predicted, further suggesting that these three districts are coming to be invaded by the nematode. Closely monitoring these three districts in the future will provide evidences to verify the model prediction. In addition, in 2041-2060s and 2061-2080s, even if the locations of the future potential distribution for *B. xylophilus* are resemble to the current one, our results predicted that the species

Table I.- Areas and percentages of suitable habitats for different grades of *B. xylophilus* in Chongqing under different climate change scenarios.

Climate change scenarios	Year	Percentage of area (%)			Area (km^2)		
		Suitable habitat	Moderate suitable habitat	Unsuitable habitat	Suitable habitat	Moderate suitable habitat	Unsuitable habitat
Current	1950–2000	9.22	29.27	61.51	7626.94	24219.2	50885.9
RCP26	2041–2060	14.11	23.97	61.92	11671	19833	51228.1
	2061–2080	14.02	24.34	61.63	11604.9	20139.4	50987.8
RCP45	2041–2060	15.44	24.89	59.67	12773	20592.8	49366.3
	2061–2080	16.84	25.63	57.53	13929.4	21203.3	47599.3
RCP60	2041–2060	13.23	25.11	61.66	10944.6	20775.6	51011.9
	2061–2080	12.10	24.97	62.93	10008.3	20656.6	52067.2
RCP85	2041–2060	12.59	23.01	64.41	10412.7	19033.5	53285.9
	2061–2080	14.34	25.00	60.66	11865.4	20683	50182.9

distribution will expand under the assumed environment change (Table I; Fig. 2). For example, the suitable habitat areas predicted for 2050s and 2070s by using four different climatic models are larger than those under the current climate conditions (Table I; Fig. 2). Therefore, it can be concluded that the projected environmental variation will promote future invasion of the nematode in Chongqing without regards for human-mediated activities. This view is consistent with the past result all over world (Ikegami and Jenkins, 2018). However, the pine wood nematode, which has almost no dispersal ability by itself, is transmitted between trees by the Japanese pine sawyer over relatively short distances (Robinet *et al*., 2011). Consequently, periodic surveys and insect vector control actions, *e.g.* some traps of capturing the vector, should be conducted on suitable and moderate suitable habitats, which have a large number of susceptible host tree density. Moreover, the human-mediated spread plays important roles in the long-distance spread of the terrestrial invertebrates (Robinet *et al*., 2009, 2011; Haack *et al*., 2010). So, trees with symptoms of pine wilt disease must be felled and burned in the infective area, and forestry activities such as transportation of infested logs, lumber or wood packaging, especially relating to *Pinus* trees, should be strictly controlled, because the existence of the nematode in a tree doesn't always express the symptoms of pine wilt disease.

In the past, Robinet *et al*. (2009) had taken advantage of the climatic conditions to predict the potential distribution of the exotic pinewood nematode, such as July mean temperature of ≥ 21.3°C and January mean temperature of ≥ -10°C (Ma *et al*., 2006). Here, using by the jackknife test, maximum temperature of hottest month (bio-05), mean temperature of hottest quarter (bio-10), altitude (Alt), annual mean temperature (bio-01) and temperature of coldest month (bio-06) with thresholds of 30.5~31.8°C, 27.5 ~ 28.7°C, ≤ 400 m, ≥ 17.5°C, and ≥ 2.3°C, respectively, had the great contribution to the distribution of *B. xylophilus* relative to other variables. By comparison, partly results are consistent with the previous studies (Robinet *et al*., 2009; Cheng *et al*., 2015). For example, mean temperature of hottest quarter and maximum temperature of hottest month are approximately similar to a July mean temperature (≥ 21.3°C), resulting in the potential spread for the vector of the nematode (Ikegami and Jenkins, 2018). With a temperature rise of 3°C, the area suitable for the disease spread could run up to 40% in China (Robinet *et al*., 2009, 2011). The reason is probably that high temperature and seasonal drought can cause water evaporation in the host trees to facilitate disease development (Evans *et al*., 2008). Annual mean temperature of Chongqing (≥ 19.2°C), named as one of the 4 fire furnaces in China, is obviously higher than that of the whole country, and could probably explain why numbers of the high infestation increased from six in 2015 to twelve in 2018 in Chongqing (http://www.forestry.gov.cn/). In addition, suitable habitat for *B. xylophilus* is mainly distributed in area of a very low altitude (≤ 400 m asl). Previously, some authors have reported that *B. xylophilus* occurs only at lower altitude in Japan (Rutherford *et al*., 1990). Here, human population density in these regions is thought to be a good index of the risk for the accidental transport of infective woods. When temperature of coldest month drops to 2.3°C at the lowest point and temperature in Forest is less than 2.3°C (covered by ice and snow often), the growth potential of *Pinus* trees reduces and its resistance declines. This is favorable for Japanese pine sawyer to lay eggs on the weak wood and its numbers are multiplied to facilitate the nematode to spread. The situation is in accordance with previous investigation that the numbers of *Monochamus* increased after the ice disaster in southern China (Dai *et al*., 2010).

In addition, pine wilt disease caused by pine wood nematode, is currently getting worse and worse, and has resulted in the great economic losses and ecological damage in Chongqing of China (Liu *et al*., 2017). Up to now, few effective methods have been adopted to control and eliminate it. For some main factors influencing its geographical distribution, it is difficult for us to change them; and to 2050s and 2070s, percentage of the suitable areas is coming to increase in the future environment conditions in Chongqing. Therefore, for pine wood nematode, besides taking some effective measures for prevention and warning efforts, "pine replacement project" implemented by Fuling forestry bureau, Chongqing is another method for prevention and control.

CONCLUSION

1. Maximum temperature of hottest month (bio-05), mean temperature of hottest quarter (bio-10), altitude (Alt), annual mean temperature (bio-01) and temperature of coldest month (bio-06) made a major contribution to the Maxent model compared with other variables. 2. The potential distribution of *B. xylophilus* by using the Maxent model in Chongqing was predicted to add three districts of Jiangbei, Dadukou and Jiulongpo relative to twelve known infested area under current environmental conditions. 3. The optimum suitable distribution areas are expected to be 16.84% at utmost in the future climate scenarios compared with 9.22% under the current environmental conditions, suggesting the promotion of future nematode invasion by the projected environmental variation.

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Statement of conflict of interest

The authors have declared no conflict of interests.

REFERENCES

Bethanya, B., Davids, W. and Michael, O., 2010. Climate change increases risk of plant invasion in the Eastern United States. *Biol. Invas.*, **12**: 1855-1872. https://doi.org/10.1007/s10530-009-9597-y

Bertrand, R., Lenoir, J., Piedallu, C., RiofríoDillon, G., de Ruffray, P. and Vidal, C., 2011. Changes in plant community composition lag behind climate warming in lowland forests. *Nature*, **479**: 517-520. https://doi.org/10.1038/nature10548

Cheng, G., Lu, Q., Feng, Y.M., Li, Y.X., Wang, Y.L. and Zhang, X.Y., 2015. Temporal and spatial dynamic pattern of pine wilt disease distribution in china predicted under climate change scenario. *Sci. Silvae. Sin*., **51**: 119-126.

Dai, L.X., Liu, Y.J. and Zhang, Q., 2010. Influence of ice and snow disasters on the population of *Monochamus alternatus* and its counter-measures. *Forest Pest Dis.*, **29**: 32-34.

Elith, J. and Leathwick, J.R., 2009. Species distribution models: Ecological explanation and prediction across space and time. *Annu. Rev. Ecol. Evol. S.*, **40**: 677-697. https://doi.org/10.1146/annurev.ecolsys.110308.120159

Evans, S., Evans, H. and Ikegami, M., 2008. Modelling PWN-induced wilt expression: A mechanistic approach. In: *Pine wilt disease : A worldwide threat to forest ecosystems (eds.* M.M. Mota and P. Vieira). Springer, Netherlands.

Fu, D.Y., Hu, S.J., Ye, H., Robert, A.H. and Zhou, P.Y., 2010. Pine wilt disease in Yunnan, China: Evidence of non-local pine sawyer *Monochamus alternatus* (Coleoptera: Cerambycidae) populations revealed by mitochondrial DNA. *Insect Sci*., **17**: 439-447. https://doi.org/10.1111/j.1744-7917.2010.01329.x

Haack, R.A., Hérard, F., Sun, J.H. and Turgeon, J.J., 2010. Managing invasive populations of Asian longhorned beetle and citrus long-horned beetle: A worldwide perspective. *Annu. Rev. Ent*., **55**: 521-546. https://doi.org/10.1146/annurev-ento-112408-085427

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G. and Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. *Int. J. Climatol*., **25**: 1965-1978. https://doi.org/10.1002/joc.1276

Hu, X.G., Jin, Y., Wang, X.R., Mao, J.F. and Li, Y., 2015. Predicting impacts of future climate change on the distribution of the widespread conifer *Platycladus orientalis*. *PLoS One*, **10**: e0132326. https://doi.org/10.1371/journal.pone.0132326

Ikegami, M. and Jenkins, T.A.R., 2018. Estimate global risks of a forest disease under current and future climates using species distribution model and simple thermal model – pine wilt disease as a model case. *Forest Ecol. Manage*., **409**: 343-352. https://doi.org/10.1016/j.foreco.2017.11.005

Ju, Y.W., Li, M.Y. and Wu, W.H., 2010. Predictive methods of pine wilt disease in Jiangsu Province. *Sci. Silva. Sin.,* **46**: 91-96.

Liu, X.M., Pu, Y.L., Li, H.Q., Liu, X.L., Yang, Q.Y. and Ding, S.M., 2017. A study on potential biotope of pine wilt disease in Chongqing by using Maxent model. *Ecol. environ. Monit. Three Gorges*, **2**: 75-80.

Li, Y.L. and Ding, C.Q., 2015. Effects of sample size, sample accuracy and environmental variables on predictive performance of MaxEnt Model. *Pol. J. Ecol.*, **64**: 303-312. https://doi.org/10.3161/15052249PJE2016.64.3.001

Ma, R.Y., Hao, S.G., Kong, W.N., Sun, J.H. and Kang, L., 2006. Cold hardiness as a factor for assessing the potential distribution of the Japanese pine sawyer *Monochamus alternatus* (Coleoptera: Cerambycidae) in China. *Annls. Forest Sci.*, **63**: 449-456. https://doi.org/10.1051/forest:2006025

Phillips, S.J., Anderson, R.P. and Schapire, R.E., 2006. Maximum entropy modelling of species geographic distributions. *Ecol. Model.*, **190**: 231-259. https://doi.org/10.1016/j.ecolmodel.2005.03.026

Puth, L.M. and Post, D.M., 2010. Studying invasion: have we missed the boat? *Ecol. Lett*., **8**: 715-721. https://doi.org/10.1111/j.1461-0248.2005.00774.x

Qin, A., Liu, B., Guo, Q., Bussmann R.W. and Pei, S.,

2017. Maxent modeling for predicting impacts of climate change on the potential distribution of *Thuja sutchuenensis*, Franch. an extremely endangered conifer from southwestern China. *Glob. Conserv. Ecol.*, **10**: 139-146. https://doi.org/10.1016/j.gecco.2017.02.004

Robinet, C., Opstal, N.V., Baker, R. and Roques, A., 2011. Applying a spread model to identify the entry points from which the pine wood nematode, the vector of pine wilt disease, would spread most rapidly across Europe. *Biol. Invasions*, **13**: 2981-2995. https://doi.org/10.1007/s10530-011-9983-0

Robinet, C., Roques, A., Pan, H.Y., Fang, G.F., Ye, J.R., Zhang, Y.Z. and Sun, J.H., 2009. Role of human-mediated dispersal in the spread of the pinewood nematode in China. *PLoS One*, **4**: e4646. https://doi.org/10.1371/journal.pone.0004646

Rutherford, T.A., Mamiya, Y. and Webster, J.M., 1990. Nematode-induced pine wilt disease: Factors influencing its occurrence and distribution. *Forest Sci*., **36**: 145-155.

Simpson, M. and Prots, B., 2013. Predicting the distribution of invasive plants in the Ukrainian Carpathians under climatic change and intensification of anthropogenic disturbances: Implications for biodiversity conservation. *Environ. Conserv.*, **40**: 167-181. https://doi.org/10.1017/S037689291200032X

Tang X.P., Song, N., Chen, Z.F. and Wang, J.L., 2016. Spatial and temporal distribution of ET0 under main climate scenarios in future across Huang-Huai-Hai Plain. *Trans. CSAE*, **32**: 168-176.

Togashi, K. and Shigesada, N., 2006. Spread of the pinewood nematode vectored by the Japanese pine sawyer: modeling and analytical approaches. *Popul. Ecol.*, **48**: 271-283. https://doi.org/10.1007/s10144-006-0011-7

Waage, J.K. and Reaser, J.K., 2001. A global strategy to defeat invasive species. *Science*, **292**: 1486. https://doi.org/10.1126/science.292.5521.1486a

Xu, Z., Peng, H., Feng, Z. and Abdulsalih, N., 2014. Predicting current and future invasion of *Solidago canadensis*: A study from China. *Pol. J. Ecol.*, **62**: 263-271. https://doi.org/10.3161/104.062.0207

Yang, X.Q., Kushwaha, S.P.S., Saran, S., Xu, J.C. and Roy, P.S., 2013. Maxent modeling for predicting the potential distribution of medicinal plant, *Justicia adhatoda*, L. in Lesser Himalayan foothills. *Ecol. Eng*., **51**: 83-87. https://doi.org/10.1016/j.ecoleng.2012.12.004