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Abstract. The melon fruit fly, *Bactrocera cucurbitae* Coquillett (Diptera: Tephritidae), is one of the important insect pests of fruits and vegetables. In order to monitor and control it effectively, it is necessary to know the potential geographical distribution of this pest. The ER (Eclosion rate) model was constructed from empirical biological data, and analyzed with ArcGIS. Based on the soil temperature and moisture data of Chinese meteorological stations, the potential geographical distribution of *B. cucurbitae* from January to December in China was predicted. Six categories were used to describe different levels of suitability for *B. cucurbitae* in China. The potential geographical distribution and suitable levels for every month in China were obtained and showed that almost all locations were suitable from May to September. Further analysis showed that monitoring measures should be taken in Guangdong, Guangxi, Yunnan, and Hainan provinces throughout the year.

Key words: *Bactrocera cucurbitae*, potential geographical distribution, ArcGIS, eclosion rate model, plant quarantine

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1 INTRODUCTION

The melon fruit fly, *Bactrocera cucurbitae* Coquillett (Diptera: Tephritidae), originated from India [1], spread throughout Southeast Asia in the 1990s, and then spread to other regions. At present, *B. cucurbitae* is found in some areas of Asia, Africa, and the Pacific Islands, including more than 30 tropical and subtropical countries and regions [2-3]. In China, *B. cucurbitae* was mainly distributed in Guangdong, Guangxi, Hainan, Fujian, Yunnan (the geographic distribution in Yunnan can be divided into year-round distribution and seasonal distribution. The year-round distribution area was located at the South of latitude 24°), Taiwan, and Hong Kong. In addition, *B. cucurbitae* was found in Sichuan, Chongqing, Guizhou, Zhejiang, Jiangsu, Hunan, and other places in recent years [4-10]. *Bactrocera cucurbitae* has been reported to attack more than 100 species of fruits and vegetables, and has been listed as an important quarantine pest by many countries including China [11-12]. *Bactrocera cucurbitae* often caused losses of 30% to 90%. According to the reports, *B. cucurbitae* had caused a reduction in production of watermelon of India, bitter gourd of Nauru, and towel gourd and pumpkin of Solomon by 28.55%, 95%, 90% and 87%, respectively [1]. Japan had spent 20.4 billion yen to eradicate *B. cucurbitae* in Okinawa islands [13].

Population fluctuation of *B. cucurbitae* not only has been correlated with the temperature, but also with the relative humidity and rainfall [14].Temperature had a significant impact on *B. cucurbitae* [15], under laboratory conditions; when the temperature was below 14℃, all instars of *B. cucurbitae* did not develop normally [16-17]. The low temperature of developmental threshold for pupae was 11.14℃, developmental temperature range was 11-36℃ [17], and the optimum developmental temperature range was 22-30℃ [18]. When the temperature was greater than 32.2℃, the mortality rate to increased, and under the condition of 34℃ pupae mortality rate was 95.27%±0.35% [18]. Soil moisture also affected the pupae greatly. In India, the report showed two peak period of melon flies attacking the fruits -- the one is in June with the relative humidity 72.0% -84.0 % and rainfall 53.3-61.5 mm, the other is the second and third weeks in July with the relative humidity 85.0% and rainfall 114.1-247.5 mm [19]. Mature larvae of *B. cucurbitae* pupated in the soil of 0.5-15 cm depth [20-21], and it is favorable for the mature larvae to pupate with higher eclosion rate when the soil moisture is less than 25%. When the soil moisture is greater than 30%, both the pupation rate and eclosion rate are lower [18].

The potential geographical distribution study of fruit flies started with, climate maps, ecological niche modeling software, technical methods, etc. and involved several species (e.g., *Ceratitis capitata* Wiedemann, *B. dorsalis* (Hendel), *B.* (*Daculus*) *oleae*). In 1924, Cook (1925) used climate maps predict the pest potential geographical distribution, and then this technology was further developed [22]. Messenger (1972) used artificial climate chambers to simulate a dozen typical weather conditions of the United States, to study the growth and development of the *C. capitata* Wiedemann, *B. dorsalis* (Hendel) and *B. cucurbitae* under different climatic conditions. Combined with climate analysis, the suitable geographical distribution of the three fruit fly species in the United States was described [23]. Yonow applied CLIMEX to study the potential geographical distribution of the *B.* (*B.*) *tryoni* in Australia [24].

The potential geographical distribution study of fruit flies started later in China，but there are many papers in recent years, including the Multiple Indicator fuzzy comprehensive evaluation technology, agro-climatic similarity distance technology, geographic information systems (GIS) technology and ecological niche modeling software, among others. Many fruit flies were involved such as *B. dorsalis* (Hendel), *B. cucurbitae* Coquillett, *Anastrepha ludens* Loew and *Rhagoletis pomonella* Walsh. Zhou (2005) built the lethal temperature model and the effective accumulated temperature model of *B. cucurbitae* Coquillett in 2005, and used 30 years' climate data of the 670 meteorological stations in China to run the model. The prediction results showed that the melon fly could occur in 36.27% of China, the northern boundary of the distribution is about 31 °±2 °N. It could produce 2-10 generations/year, and mainly produced 4-7 generations/year [25]. Kong et al. (2008) analyzed the potential geographical distribution of *B. dorsalis* (Hendel) and *B. cucurbitae* Coquillett in China and world by combining the CLIMEX and DIVA-GIS in 2008. The highly suitable areas of *B. cucurbitae* Coquillett in China included Guangdong, Guangxi, Hainan, southern of Fujian, southern of Yunnan, western of Taiwan, and the Sichuan Basin, while moderate to low suitable areas include parts of Jiangxi, Hunan, Guizhou, Chongqing, Shanghai and Sichuan, Yunnan, Fujian, Zhejiang, Jiangsu, Anhui, Hubei, Shaanxi, Henan, and Gansu [26].

The purpose of this study was to establish the ER (eclosion rate) model of B. cucurbitae, and analyze the potential geographical distribution and suitability levels using the ER model and displaying distribution patterns using soil temperature and soil moisture of past years in China by ArcGIS.

2 MATERIALS AND METHODS

The *B. cucurbitae* samples collected from Huangpu in Guangdong province were selected for the eclosion experiment. Eggs of *B. cucurbitae* were obtained from adults that had been reared for four generations on an artificial diet. Mature larvae (6 days after egg hatch) were placed in moist sand (75% relative humidity) at 29℃ for pupation. All 6480 pupas were gathered after 24h under and held at 25℃.

The eclosion rate (ER) data were collected by placing pupae in a plastic box (high 7cm, diameter 12.5cm) containing medium soil (Guangdong, DaHan) in an Artificial Climate box (Germany Binder Kbwf240). Data were analyzed using SPSS13.0 (http://www.seekbio.com/soft/1492.html) and ArcGIS 9.0 (Environmental Systems Research Institute, ESRI). Soil temperature and moisture (2001-2003) were obtained from China Meteorological Administration.

The ER model, based on soil temperature and relative humidity was obtained from a crossover design experiment conducted at the plant quarantine laboratory of Guangdong Entry-Exit Inspection and Quarantine Bureau. The design specified six soil temperature grades: 9℃, 14℃, 19℃, 24℃, 29℃, and 34℃. Six relative humidity grades included 0%, 20%, 40%, 60%, 80%, and 100%. Experiments consisted of 36 treatments and 3 replications during about 25 days and every box had 60 pupas. All pupas were placed 2 cm under the soil and held in artificial climate boxes. Water was added as needed [27].The ER of *B. cucurbitae* was obtained and the ER model was derived by stepwise regression (SPSS 13.0)

Geographic distribution and suitability was calculated for each month of the year for all of China and displayed as maps by ArcGIS. Soil temperature and moisture data were limited, but at data for a minimum of 10 days per month were obtained. Since values were obtained from different locations in different months, the full data set is presented in Table 4. The suitability of *B. cucurbitae* was analyzed on the basis of these data and ER model results. The ER of *B. cucurbitae* for every location in China was obtained. For each location, suitability was categorized into 6 levels; negligible (where the *B. cucurbitae* is unable to occur and survive) (ER=0), extremely low ($0 < ER \leq 0.1$), low（$0.1 < ER \leq 0.2$), moderate ($0.2 < ER \leq 0.3$), high ($0.3 < ER \leq 0.4$) and extremely high ($0.4 < ER \leq 1$). Suitability maps were plotted for each month using the inverse distance weight (IDW) raster interpolation.

3 RESULTS

3.1 ER model

SPSS was used to build the modelas it is convenient, fast, and reliable. The binary model was not significant ($p>0.05$) and the binary cubic model is too complicated to explain, so we chose binary quadratic regression model as the eclosion rate model of *B. cucurbitae*. After XY was dropped, the model chosen for eclosion rate was as follows:

$$Z=-0.0041X^2-0.00005Y^2+0.17976X+0.01044Y-1.618$$

Z is the ER (eclosion rate) of *B. cucurbitae*

X is the soil temperature

Y is the soil moisture

Table 1 shows the regression model summary, and four constants are available including XX, X, Y and YY. Table 2 shows the analysis of variance of regression. Stepwise regression ordered the independent variables according to their explanatory power. Analysis showed that XY did not contribute to the explanatory power of the model significantly ($p>0.05$), so it was dropped. By regression analysis, after XY was dropped, t=0.107, P>0.01(Table 3). The model was reliable because of $R^2=0.706$, $F=48.991>F0.05$ and $P<0.01$. The regression analysis of the ER showed that P was significant on 0.01 level.

Table 1. Regression model summaries

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.840（a）	0.706	0.692	0.206

a Predictors:(Constant), xy, xx, yy, y, x

Table 2. Analysis of variance of regression

Model		Sum of squares	Df	Mean square	F	Sig.
1	Regression	10.396	5	2.079	48.991	1.31E-25
	Residual	4.329	102	0.042		

	Total	14.725	107
a	Predictors: （Constant）, xy, xx, yy, y, x		
b	Dependent Variable: z		

Table 3. Excluded variables of regression model

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	（Constant）	-1.618	0.158		-10.218	2.69E-17
	x	6.112	0.485	4.157	12.593	1.68E-22
	y	1.004	0.253	0.928	3.961	0.0001
	xx	-4.743	0.367	-4.138	-12.906	3.59E-23
	yy	-0.539	0.199	-0.519	-2.713	0.0078
	xy	0.025	0.231	0.018	0.107	0.9152
a	Dependent Variable: z					

3.2 Potential geographical distribution of B. cucurbitae in China

After the suitable range and suitable level analysis of *B. cucurbitae* in China monthly the results showed that the percent of suitable locations was about 11% in January and February, then it increased to 37.14% quickly in March, and it was 76.19% in April. Almost all locations were suitable from May to September, but it was 61.76% in October, and then decreased to 19% in November, and it was 12.28% in December. For the most part, it was basically the same in December, January and February, and there was a turning point in March and April with the suitable locations increasing. May to September was the most suitable period, and there was another turning point in October and November with the suitable locations decreasing. Finally, it accomplished an alternating cycle of the four seasons. Combined with the change of the different suitable level locations, May and September took the largest proportion of extremely high and high suitable level locations, followed by them was April, June, August and October, and then it was July, November, December, February and January. The percentage of extremely high level locations was the lowest and the percent of extremely low locations was the highest in January. The percentage of extremely high and high level locations increased linearly from January to May, and then it decreased from May to July. It increased from July to September, and then decreased from September to December. It was the lowest in July because the soil temperature exceeded the eclosion threshold temperature of *B. cucurbitae*.

The distribution of *B. cucurbitae* diffused towards north in March. Guangdong, Guangxi, Yunnan and Sichuan came to be the extremely high or high suitable level locations. We must pay attention that Shannan prefecture of Tibet, Juxian and Laiyang of Shandong came to be the extremely high or high suitable level locations in March. Ba county of Hebei Province (latitude 39.07°, longitude 116.23°) was the northern boundary of the suitable regions in March. The eclosion of *B. cucurbitae* occurred at Ba county in March when monthly average soil temperature was 10.89℃, the monthly average soil relative humidity was 16.90% (Fig. 1).

As a turning point, we can clearly see the division of the potential geographical distribution of *B. cucurbitae* in October. Extremely high and high suitable area concentrated in the southern provinces of China, in which we must pay attention to the Nuomuhong of Qinghai and Tianjin. Yili of Xinjiang (latitude 43.57°, longitude 81.20°) was the northern boundary of the suitable regions in October. Monthly average soil temperature was 10.93℃, and the monthly average soil relative humidity was 17.01% (Fig. 2).

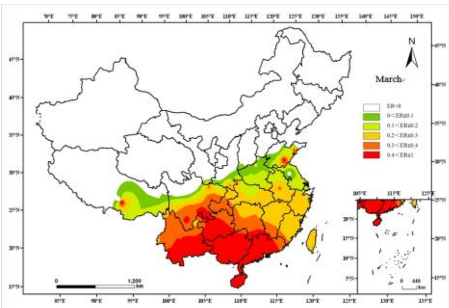

Fig. 1. The potential geographical distribution of *B. cucurbitae* in March

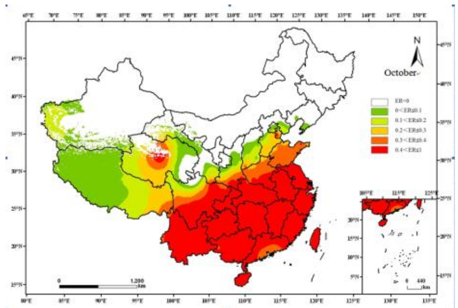

Fig. 2. The potential geographical distribution of *B. cucurbitae* in October

3.3 Conclusions

The results indicated that soil temperature and soil moisture affected the potential geographical distribution of *B. cucurbitae* in China and suitable areas changed with the seasons. From the coefficients of the variables in the model, the soil temperature affected the eclosion of *B. cucurbitae* more than soil moisture. In winter, the potential geographical distribution of *B. cucurbitae* was concentrated in the south of China, such as Yunnan, Guangxi, and Guangdong. In March, *B. cucurbitae* started to spread from south to north. Almost all locations were suitable from May to September.

By the analysis month by month, the suitable range and level of *B. cucurbitae* of the 12 months in China were obtained, and the causes of its distribution were analyzed in detail. It is useful for the quarantine departments to determine the distribution of the density of monitoring locations, the monitoring time according to the local conditions and the pest management time.

4 DISCUSSION

4.1 Monitoring and trapping periods

This study indicated four monitoring and trapping periods for fruit fly eclosion in China. If continuous two months are not suitable, monitoring should be suspended. Monitoring measures should be taken throughout the year in Guangdong, Guangxi, Yunnan, and Hainan. The second period was from March 1 to November 30 and included Hubei, Hunan, Sichuan, Chongqing, Guizhou, Jiangxi, and Fujian. The third period, from March 1 to October 31 included Shandong, Jiangsu, Shanghai, Zhejiang, Anhui, Tibet. and Taiwan. The last period was from April 1 to October 31, and monitoring areas included Liaoning, Heilongjiang, Jilin, Inner Mongolia, Qinghai, Beijing, Tianjin, Hebei, Henan, Shaanxi, Shanxi, Gansu, Ningxia, and Xinjiang.

In summary, the two important natural factors (soil temperature and moisture) determined the potential geographical distribution of *B. cucurbitae* over 12 months in China were reported, and the ER model can be used to predict where and when these conditions are suitable for eclosion. This model also can be applied to other countries and will be improved with the development of the future research.

4.2 Potential geographical distribution of B. cucurbitae in China

Almost all suitability analysis methods of fruit flies include the main natural factors that affect the occurrence of fruit flies, and temperature and humidity often is the key to determine fruit fly outbreaks. Under the situation that meteorological data are relatively limited, how to make full use of these data is particularly important; however, we often encounter data substitution or conversion problems (e.g., temperature and soil temperature data conversion), as well as the relationships among atmospheric humidity, rainfall, and soil moisture, which are very important to the adaptability analysis research of fruit flies.

In addition, the mode of ‘biological experiments + biological model +GIS analysis’ was suitable for suitability analysis of invasive fruit flies. To date, pest suitability analysis techniques use models combined with software analysis as its main analysis methods; thus, models and software for medical and military fields can be used to analyze the pest suitability. Once related environmental meteorological data are available, we can analyze the suitability of any instars of the invasive species year by year, month by month, even ten days by ten days and day by day, and a detailed study can increase the accuracy of suitability analysis and forecast. Detailed and completed information obtained from the literatures and biological experiments is very important for the potential geographical distribution research. We also need to explore how to combine the results of quantitative analysis and graphics, as the analysis of the species turns from qualitative methods towards quantitative methods.

4.3 Management countermeasures

Quarantine measures should be strengthened domestically as well as at the borders (inspection and quarantine). The critical tasks of border inspection and quarantine are port inspection and quarantine from May to September, because many areas of China are suitable for *B. cucurbitae* during this time. Especially from imports of these continents in which the *B. cucurbitae* distributes: Asia (Oman, Bangladesh, Brunei, Cambodia, India, Indonesia, Japan's Ryukyu Islands, Laos, Malaysia, Myanmar, Nepal, Pakistan, Philippines, Sri Lanka, Thailand, Vietnam), Africa (Egypt, Kenya, Tanzania, Mauritius, some areas of Reunion), and Solomon Islands, Mariana Islands, Papua Island, Hawaii of USA and other parts of the Pacific Islands[1,3,28]. In addition, domestic inspection and quarantine should monitor the transport of fruits and vegetables from south to north in China, such as Guangdong, Guangxi, Hainan, Fujian, Yunnan, Taiwan, Hong Kong, Sichuan, Chongqing, Guizhou, Zhejiang, Jiangsu, Hunan, and other places [4-10]. Quarantine measures ought to be reinforced to prevent the infestations of fruits and vegetables.

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REFERENCES

1. Dhillon, M.K., Singh, R., Naresh, J.S., *et al*.: The melon fruit fly, *Bactrocera cucurbitae*: A review of its biology and management. Journal of Insect Science. 5, (2005)
2. Animal and Plant Quarantine Administration of the People’s Republic of China and Plant Quarantine Institute of Ministry of Agriculture: A Selection of the entry plant quarantine pests of China. China Agriculture Press, Beijing, (1997) (in Chinese)
3. EPPO. Distribution Map of Quarantine Pests for Europe *Bactrocera cucurbitae*. http://pqr.eppo.org/datas/DACUCU/DACUCU.pdf. (2006)
4. Wang, X.J.: Overview about important fruit fly pests of fruits and vegetables. Plant Quarantine, 9, 20--30 (1995) (in Chinese)
5. Wang, X.J.: Diptera Tephritidae insects of East Asia. Acta Zootaxonomica Sinica, 331--338(1996) (in Chinese)
6. Zhou, Y.S., Zhao, H.P.: Biology and other comprehensive prevention and control of *B. dorsalis* for mangos. Journal of Southwest Agricultural University, 3, 210 (1996) (in Chinese)
7. Jiang, X.L., Ren, L.Q., Xiao, S., He, W.Z., Sun, B.Z.: Study on the biology of *Bactrocera cucurbitae.* Plant Quarantine, 17,74--76 (2003) (in Chinese)
8. Jiang, C.M., Ai, H.M., Zhao, S.X.: Pest Risk Analysis of *Bactrocera cucurbitae*. Entomological Journal of East China, 14, 256--259 (2005) (in Chinese)
9. Jiang, C.M., Ai, H.M., Zhao, S.X.: Life tables of the melon fly laboratory population reared on various host fruits. Journal of Fujian Agriculture and Forestry University(Natural Science Edition, 35, 24--28 (2006) (in Chinese)
10. Zhu, Z.H., Ye, H., Zhang, Z.Y.: Genetic relationships among four *Bactrocera cucurbitae* geographic populations in Yunnan Province. Chinese Journal of Applied Ecology, 16, 1890--1892(2005) (in Chinese)
11. Chen, H.D., Zhou, C.Q., Yang, P.J., Liang, G.Q.: On the seasonal population dynamics of

melon and oriental fruit flies and pumpkin fly in Guangzhou area. Journal of Plant Protection, 22, 348--354 (1995) (in Chinese)
12. Li, R.K.: Damage and Control of *Bactrocera cucurbitae*. CHINA VEGETABLES, 26--27(1997) (in Chinese)
13. Koyama, J., Kakinohana, H., Miyatake, T.: Eradication of the melon fly, *Bactrocera cucurbitae*, in Japan: importance of behavior, ecology, genetics, and evolution. Annual Review of Entomology. 49, 331--349(2004)
14. Zaman, M.: Assessment of the male population of the fruit flies through kairomone baited traps and the association of the abundance levels with the environmental factors. Sarhad Journal of Agriculture. 11, 657--670 (1995)
15. Manzar, A., Srivastava, J.P.: Population fluctuation of fruit flies, *Bactrocera* spp. infesting bitter gourd in Central Uttar Pradesh. Progressive Horticulture. 36, 146--149 (2004)
16. Keck, C.B.. Effect of temperature on development and activity of the melon fly. Journal of Economic Entomology. 44, 1001--1002(1951)
17. Liang, G.Q., Liang, G.Z., Lin, M., *et al*.: Fruit fly and its Control. Guangdong Science and Technology Press, Guangzhou (1993) (in Chinese)
18. Yuan, S.Y., Kong, Q., Xiao, C., Chen, B.,Yang, S.S., Zhang, J.B., Sun, W., Li, Z.Y.: Influence of Temperature on Development, Survival and Fecundity of *Bactrocera dorsalis* Hendel. Journal of Huazhong Agricultural, 24, 588--591 (2005) (in Chinese)
19. Ingoley, P., Mehta, P.K., Verma, K.S.: Seasonal occurrence of fruit fly, *Bactrocera cucurbitae* Coq., on cucumber in midhills of Himachal Pradesh. Himachal Journal of Agricultural Research. 28, 48--53 (2002)
20. Jackson, C.G., Long, J.P., Klungness, L.M.: Depth of pupation in four species of fruit flies (Diptera: Tephritidae) in sand with and without moisture. Journal of Economic Entomology. 91, 138--142 (1998)
21. Pandey, M.B., Misra, D.S.: Studies on movement of Dacus cucurbitae maggot for pupation. Shashpa. 6, 137--144(1999)
22. Cook, W.C.: The distribution of the alfalfa weevil Phytonomus Posticus Gyll. A study in physical ecology. Journal of Agricultural Research, 30, 479--491 (1925)
23. Messenger, P.S.: Bioclimatology and prediction of population trends. Pro.FAO conf: ecology in relation to plant pest control, Rome, 21--45(1972)
24. Yonow, T., Sutherst, R.W.: The geographical distribution of the Queensland fruit fly, *Bactrocera* (*Dacus*) *tryoni*, in relation to climate. Australian Journal of Agricultural Research. 49, 935--953 (1998)
25. Zhou, W.C.: Research on geographic distribution model of *Bactrocera cucurbitae*. Entomological research progress, 36--40 (2005) (in Chinese)
26. Kong, L.B., Lin, W., Li, Z.H., Huang, G.S., Liang, Y.B.: Effects of climatic factors on the growth and geographical distribution of Oriental fruit fly, *Bactrocera dorsalis*. Chinese Bulletin of Entomology, 45,528--531(2008) (in Chinese)
27. Wu, Q.H., Shao, Z.X., Su, D.M.: Insect ecology experiments. Fudan University Press, Shanghai (1991) (in Chinese)
28. Stonehouse, J.M., Stravens, R., Dacambra, P.: The Melon Fly *Bactrocera cucurbitae* in the Republic of Seychelles. In: Proceedings of the Indian Ocean Commission, pp. 211--213. Regional Fruit Fly Symposium. (2000)