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Abstract: The solanum fruit fly, *Bactrocera latifrons* (Hendel), is a major pest throughout South and South East Asia, including very few parts of southern China, and has invaded Hawaii and recently the continent of Africa (Tanzania and Kenya). With the development of international trade in fruits and vegetables, *B. latifrons* has become a potential threat to Chinese agriculture. In this study, CLIMEX 3.0 and ArcGIS 9.3 were used to predict the current and future potential geographical distribution of *B. latifrons* in China. Under current climatic conditions, its projected potential distribution includes most parts of southern China (about 32.2% of all 748 meteorological stations), from 16.544°N to 32.442°N. Optimal climate conditions occur in most areas of Yunnan, Guizhou, Sichuan, Chongqing, Hunan, Hubei, Jiangxi, Zhejiang, Fujian, Guangdong, Guangxi, Hainan, Taiwan, Hong Kong and Macao. The factors limiting the boundary of its suitability range are mainly the cold and dry stress. Climate change scenario for the 2020s indicates that the future potential geographical distribution will be increased by 5% of the total land areas of China, and the northern distribution boundary will move from 32.442°N to 33.408°N. There are 34 non-suitable climate sites change into suitable, mainly in Jiangsu, Anhui, Henan, Shanxi, Gansu, Sichuan and Tibet, because of China is likely to become hotter and wetter in the 2020s. In order to prevent the introduction and spread of *B. latifrons*, the present plant quarantine and monitor measures should be enhanced more where are projected to be suitable areas under current as well as future climatic conditions. At the same time, we should strengthen education for the public's awareness of plant protection.

Key words: ArcGIS, *Bactrocera latifrons* (Hendel), climate change, CLIMEX, potential geographical distribution

1. Introduction

The solanum fruit fly, *Bactrocera latifrons* (Hendel) (Diptera:Tephritidae), native to South and South East Asia [1], is known as a pest of solanaceae crops, and some cucurbitaceae plants were also reported as host fruits in Hawaii [2]. Now, it is widespread in South and South-East Asia, such as Brunei Darussalam, China (Guangdong, Guangxi, Hainan, Hong Kong, Yunnan, Taiwan), India (Karnataka, Tamil Nadu and West Bengal), Indonesia, Japan (Ryukyu Archipelago), Laos, Malaysia (Peninsular Malaysia and Sabah), Pakistan, Singapore, Sri Lanka, Thailand, Vietnam [3]. It is a very damaging pest wherever it occurs [4], for example, 60–80% of red pepper was lost in Malaysia due to *B. latifrons* [5]. As well as being a serious pest in South and South-East Asia, *B. latifrons* has established in a number of other regions. In Hawaii, *B. latifrons* was first discovered on Oahu in 1983 [6] and became sequentially distributed throughout the major islands [2]. Recently, it has invaded Africa, being detected in Tanzania in 2006 [7] and in Kenya in 2007. Surveys were conducted in different parts of Tanzania during 2006~2007, the species was widespread throughout the country but most abundant in the north-eastern region close to the border with Kenya [8]. They also indicated that the population of *B. latifrons* based on infestation rates and incidence in host fruits, seems to be relatively high during the wet seasons, probably because of availability of many hosts; the surveys further indicated that *B. latifrons* is more abundant in low to medium altitude areas compared to high altitude areas [8].

B. latifrons has been intercepted in China from 1994 [9], and the frequency of interception of *B. latifrons* in China in recent years increased annually. For example, from 2003 to 2008, according to the intercepted fruit flies information provided by Chinese Academy of Inspection and Quarantine, China had intercepted *B. latifrons* a total 2156 times, most of which came from the fruit carried by incoming travelers. Ministry of Agriculture of the People's Republic of China (PRC) had listed *B. latifrons* and all other *Bactrocera spp.* on the entry plant quarantine pest list of the PRC in 2007. Predictably, with the increase of Chinese-foreign trade in agricultural products and the further opening of China's agricultural market, the risk of introduction of these fruit flies from abroad as well as further spread in our country will continue to increase. In addition, pest ranges are likely to shift in response to changes in temperature, soil moisture and humidity patterns. Therefore, the effects of climate change should also be taken into account when we are assessing the likely climatic suitability of *B. latifrons*.

CLIMEX is professional biological software that is widely accepted worldwide and used to estimate the potential geographical distribution and seasonal abundance of a species in relation to climate. It was first described by Sutherst and Maywald [10], and has been used successfully to describe the potential distribution of other Tephritid fruit fly species, such as *Ceratitis capitata* (Wiedemann) [11-12], *B. tryoni* (Froggatt) [13-14], *Carpomya vesuviana* Costa [15], *B. tsuneonis* (Miyake) [16]. This model also has previously been used to predict the effects of climate change on species' potential distributions using both global climate model (GCM) [17] and synthetic climates [18-19]. Examples of studied subject species are *B. dorsalis* (Hendel) [20], *Melaleuca quinquenervia* [21] and *Nassella neesiana* [22]. In this study, the CLIMEX 3.0 model was used to infer the response of *B. latifrons* to climate and to predict its potential distribution in China under current climate and future climate scenario out to the 2020s.

The Geographic Information System (GIS) is a space information system, a way of collecting, storing, managing, analyzing, describing the data of the Earth surface and geographical distribution. From the 60's of 20th century up to now, the development of the world GIS experienced four stages: Expanding period consolidating period, development period and the consumers' period. It is widely used in almost all areas nowadays. In this article, the CLIMEX outputs were processed and visualized by using ArcGIS 9.3.

2. Materials and Methods

2.1 Overview of The CLIMEX Model and ArcGIS

CLIMEX is a dynamic model [23] that integrates the weekly responses of a population to climate using a series of annual indices, which is based on the assumption that if you know where a species lives, you can infer what climatic conditions it can tolerate [24]. The model combines the growth index (GI) and the stress indices (SI) into an overall ecoclimatic index (EI) which is scaled from 0 for locations where the species is unable to persist to 100 for environments that provide perfect habitat all year round. In this study, EI is classified into four classes of climatic suitability for *B. latifrons*: unsuitable (EI = 0), marginal (0＜EI≤10), suitable (10＜EI≤20) and optimal (EI＞20).

ArcGIS provides the integrated environment of mapping, display, edit and output maps, has powerful graphics editing features. Preparation of maps using ArcGIS, we must first get the map data in digital form. Then, symbolic the data and place map annotation. Finally, follow the application needs to produce a complete map, which includes the paper size settings, mapping scope and scale identification, map name, legend, grid reference, a compass and a series of elements placed. We made the maps of special subject display that the current and future potential geographical distribution of *B. latifrons* in China, and carried out the space distribution and analysis that comparing the different suitable degrees of areas projected under current and future climatic conditions by processing the CLIMEX outputs using ArcGIS 9.3.

2.2 Meteorological databases and Climate change

Two climate databases were used in this modeling exercise. Firstly, the CLIMEX standard meteorological dataset was used to create an initial fit. This dataset that comes with CLIMEX 3.0 consists of 30-year averages from 1961 to 1990 for an irregularly spaced set of 2500 climate stations. Subsequently, the relevant climate data for 748 weather stations from China as used in previous studies [15, 16, 25-27] were appended to the CLIMEX 3.0, which were acquired from the National Weather Bureau of China and include minimum temperature, maximum temperature, relative humidity, and rainfall for each month for each station (average values of 30 years from 1971 to 2000).

Due to the impact of human activities, the significant warming in China might continue. Comparing with the 30 years mean over 1961 to 1990, according to the projections [28], the nationwide annual mean temperature might increase by a range of 1.3~2.1℃ and the annual mean precipitation might increase by 2%~3% in 2020.

The electronic map of national boundary, province boundary and the distribution of national forest land used in this study were downloaded from http://nfgis.nsdi.gov.cn/ with the scale 1:4,000,000.

2.3 Fitting CLIMEX parameters

To fit the CLIMEX model of *B. latifrons*, the parameters were manually and iteratively adjusted until the simulated geographical distribution as estimated by the EI values coincided with the species known native distribution and the reported description of its range. The parameters were then validated using data from regions where *B. latifrons* has invaded or established. Parameters used in the CLIMEX model are presented in Table 1.

Table 1. Parameters used in the CLIMEX model for the solanum fruit fly, *B. latifrons*.

Parameter	Mnemonic	Value
Lower threshold temperature	DV0	15.70
Lower optimum temperature	DV1	18.00
Upper optimum temperature	DV2	33.00
Upper threshold temperature	DV3	36.00
Degree-days to complete one generation	PDD	415.40
Lower threshold of soil moisture	SM0	0.10
Lower limit of optimum soil moisture	SM1	0.50
Upper limit of optimum soil moisture	SM2	1.00
Upper threshold of soil moisture	SM3	1.80
Cold stress temperature threshold	TTCS	2.00
Cold stress accumulation rate	THCS	-0.10
Heat stress temperature threshold	TTHS	36.00
Heat stress accumulation rate	THHS	0.005
Dry stress soilmoisture threshold	SMDS	0.10
Dry stress accumulation rate	HDS	-0.005
Wet stress soil moisture threshold	SMWS	1.80
Wet stress accumulation rate	HWS	0.002

Degree-days per generation (PDD)

PDD is degree days required for a generation. The Parameter PDD for *B. latifrons* was reported 415.397 degree days [29]; we adjusted it to 415.4 degree days used for the CLIMEX model.

Temperature index

The lowest overwintering temperature, the highest over summering temperature and lower threshold temperature of *B. latifrons* were reported as -3.7, 36 and 15.68℃, respectively [29]. At 16℃, reproduction was completely suppressed and the survival rate of larvae was only 2.6% in *B. latifrons* [30-31]. So the minimum temperature and upper threshold temperature for development (DV0 and DV3) was set at 15.7 and 36℃, respectively. *B. latifrons* (Hendel) is native to South and South-East Asia, so the lower and upper temperature optima (DV1 and DV2) were set at 18 and 33℃, respectively.

Moisture index

The moisture requirements of *B. latifrons* are mediated through their host plants. The lower soil moisture limit for development (SM0) was set to 0.1 to indicate the permanent wilting point, which is normally about 10% of soil moisture. The lower and upper limits for optimal growth (SM1 and SM2) were set to biologically reasonable levels for many host plants; and *B. latifrons* like moist environment, so SM1 and SM2 were adjusted to be slightly higher, but also ensures distribution of *B. latifrons* in North Asia to Pakistan border. The selected value for SM3 was a compromise determined from fitting the threshold soil moisture wet stress threshold (SMWS). A lower value of SMWS would have made it more difficult to achieve a satisfactory fit to the known distribution in southern Asia.

Cold stress

TTCS was set to 2.0℃. The northern Asian boundary of *B. latifrons* is indistinct. Pakistan are suitable; in China, *B. latifrons* was detected in Tianlin and Baise in Guangxi [32], Wanting and Ruili in Yunnan province [33]. Accordingly, parameters were adjusted to allow suitable in some areas of Pakistan, persistence in Yunnan and Guangxi provinces of China and at higher altitudes in Hawaii.

Heat stress

According to the highest over summering temperature *B. latifrons* is 36℃ [29] and the upper tolerable temperatures for egg development and hatching of *B. latifrons* was 46 to 48℃ [34], TTHS was set to 36℃ to account for the averaging effect of climate, whereby several days where temperatures exceed 40℃ may be expected in a long-term climate record where the monthly average of daily maximum temperature is 36℃.

Dry stress

To be consistent with SM0, SMDS was set to 0.1 to indicate the permanent wilting point, which is normally about 10% of soil moisture.

Wet stress

Wet stress was adjusted to limit the southerly distribution in Asia. According to CABI [3] records, in the south, the critical fitting considerations were the reported presence of the fly in Malaysia (Peninsular Malaysia and Sabah), Singapore and Indonesia. SMWS and HWS were adjusted to ensure that the distribution has been reported in Asia in the southern border.

3. Results

3.1 Potential geographical distribution under current climate

Under current climate, considering the parameters in Table 1, the potential geographical distribution of *B. latifrons* in China was predicted and mapped. The predictive distribution map (Fig 1) suggested that, from 16.544° N to 32.442° N, about 241 meteorological stations (about 32.2% of all stations) in most parts of southern China are projected to be suitable for *B. latifrons*. Optimal climate conditions occur in most areas of Yunnan, Guizhou, Sichuan, Chongqing, Hunan, Hubei, Jiangxi, Zhejiang, Fujian, Guangdong, Guangxi, Hainan, Taiwan, Hong Kong and Macao. Climatic conditions are projected to be marginal in parts of Jiangsu, Anhui, Henan, Shaanxi, Gansu, Sichuan and Tibet, where the principle range-limiting factor is likely to be cold stress and reduction in rainfall. The remaining 507 meteorological stations in northwest, northeast and central China were unsuitable for the establishment of *B. latifrons*.

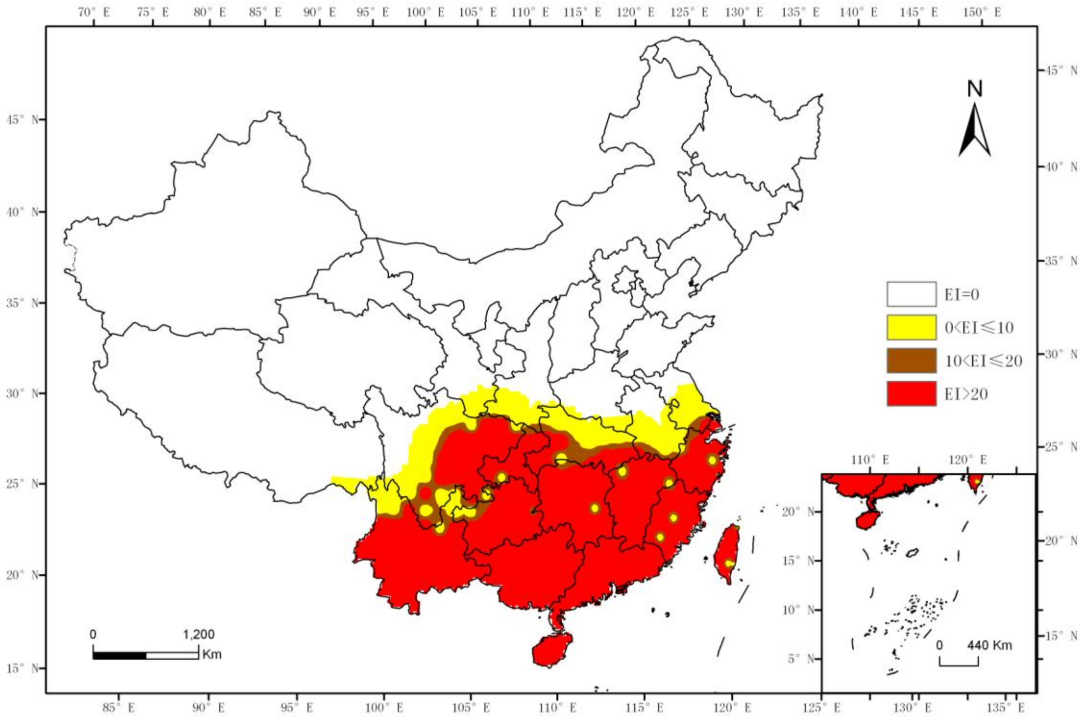

Fig.1. The climate suitability (EI) for the solanum fruit fly under the current climate (1961–1990 averages) projected using CLIMEX3.0 (□, unsuitable (EI=0); ■, marginal (0＜EI≤10); ■, suitable (10＜EI≤20); ■, optimal (EI＞20))

3.2 Potential geographical distribution under future climate

Climate change scenario indicates that China is likely to become hotter and wetter in the 2020s. As a result of these changes, the potential range for *B. latifrons* is projected to include most areas of southern China and extends into parts of central China (Fig 2). It will be increased by 5% of the total land areas of China compared with the current potential geographical distribution, and the northern distribution boundary will move from 32.442° N to 33.408° N. High suitable areas for *B. latifrons* will increase from 232 meteorological stations to 265, and the expansion is mostly in Guizhou, Sichuan, Hubei, Anhui, Jiangsu. There are 34 non-suitable climate sites change into suitable, mainly in Jiangsu, Anhui, Henan, Shanxi, Gansu, Sichuan and Tibet.

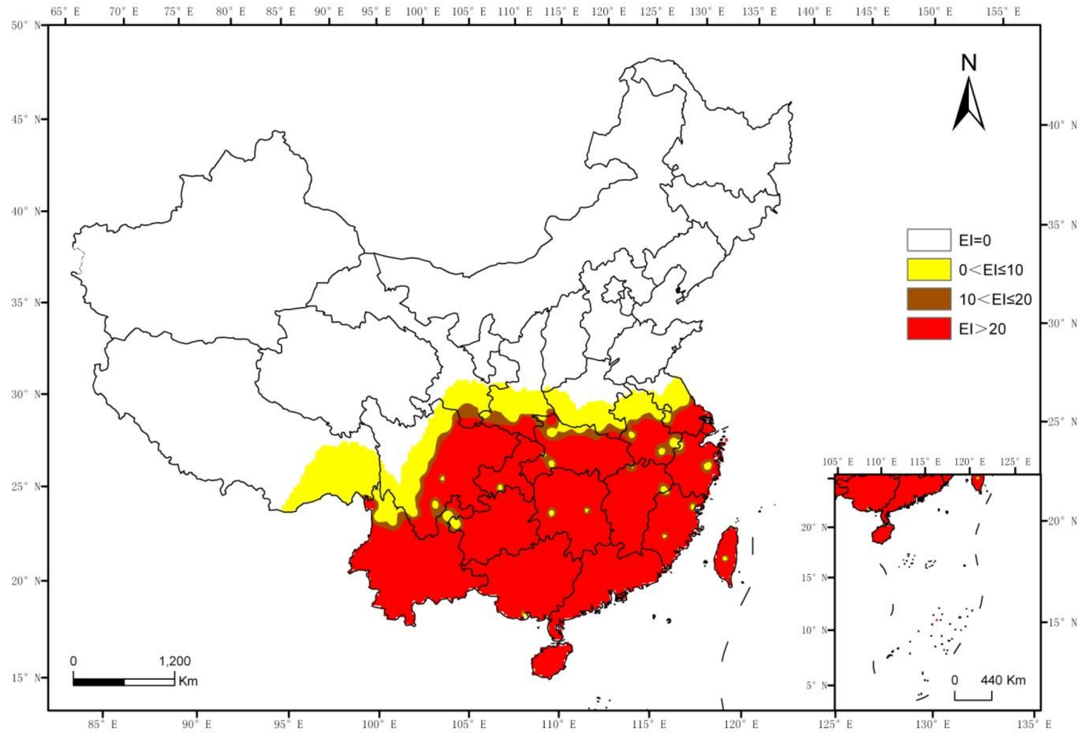

Fig.2. The climate suitability (EI) for the solanum fruit fly in the 2020s projected using CLIMEX3.0 (□, unsuitable (EI=0); ■, marginal (0＜EI≤10); ■, suitable (10＜EI≤20); ■, optimal (EI＞20))

In order to visually see the difference in the potential geographical distribution for *B. latifrons* under current and future climatic conditions, the suitable areas of different degrees projected under current and future climate scenarios were calculated by ArcGIS 9.3 software, respectively. Then, these suitable areas' different proportions of the total land areas of China were displayed in the line graph (Fig. 3). To the 2020s, it was shown that unsuitable areas' proportion of the total land areas of China will fall 5% from 76% to 71%, marginal areas' proportion will increase 2% from 5% to 7%, suitable areas' proportion will maintain at 2% and optimal areas' proportion will rise 3% from 17% to 20%. Therefore, all suitable areas will be increased by 5% when it comes to 2020s.

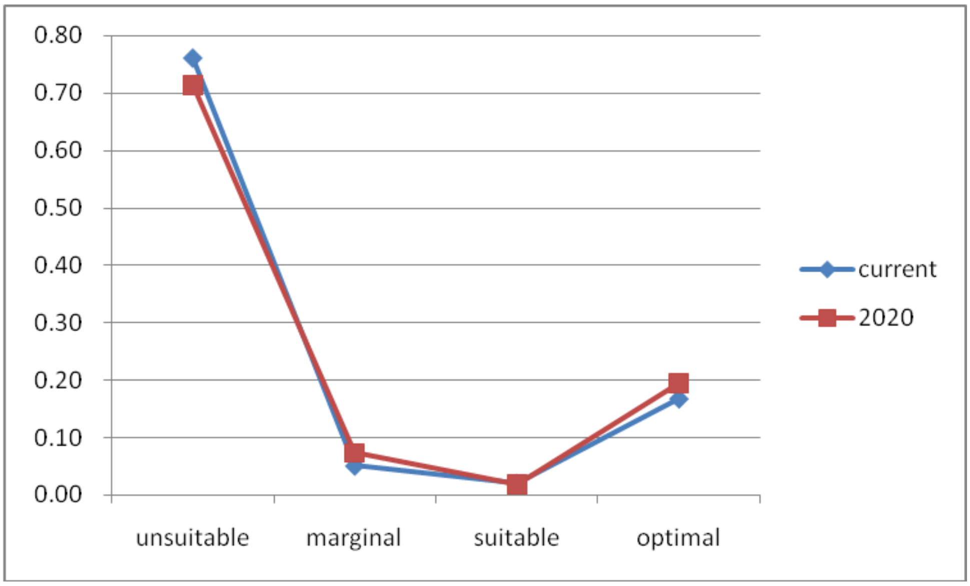

Fig.3. The proportions of the suitable areas of different degrees of the total land areas of China under the current and future climate conditions

4. Discussion

Analysis of limiting factors for distribution of pests

Ecoclimatic factors, such as temperature, humidity and light, are the most direct factors in limiting the potential geographical distribution of pest, in addition, other factors, especially soil types, geographical features, natural barriers, vegetation types should also be considered. Due to the CLIMEX model only taking these ecoclimatic factors into account, there is no doubt that the predicted results have practical restrictions. Therefore, in order to get more scientific predictions, we should take all of the above factors into consideration.

The most important thing is that the relationships between species and human activities will greatly affect the actual distribution of pest in their potential geographical distributions. For example, the development of international trade in fruits and vegetables and the increasing incoming travelers carried fruit will remarkably raise the risk of introduction of pest into a new area. Consequently, these are the starting point and foothold, and then, all of the above factors should be considered when we are framing prevention and control measures.

Development of prevention and control measures

The significant increases in the potential distribution of *B. latifrons* is projected under the climate change scenario in the 2020s suggest that the biosecurity authorities should consider the effects of climate change when undertaking pest risk analysis. Of course, establishing invasive alien species risk assessment system, improving early warning and rapid response mechanisms, strengthen international exchanges and cooperation, and the establishment of data sharing are very important in preventing the invasion of alien species is important.

In order to prevent the introduction and further spread of *B. latifrons*, the airline passengers must be strictly prohibited from bringing fruits or vegetables into China; Quarantine licensing system for imported fruits should be strictly implemented; we must step up port inspection and surveillance work. Last but not least, strengthen the public education is the most basic and most effective measures in limiting the introduction and spread of this fruit fly.

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