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RESEARCH

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Estimation of the potential geographical distribution of invasive peach fruit fly under climate change by integrated ecological niche models

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Abstract

Climate change and biological invasions of insect pests are interlinked global concerns that drive shifts in the distribution of invasive insects. The peach fruit fly, *Bactrocera zonata* Saunders, is one of the most economically important Tephritidae species that attack several host plants and causes serious damage in Asia and Africa. Currently, *B. zonata* is absent from many countries and regions but has a risk of invasion. Therefore, it is crucial to investigate the impact of climate change on the global potential distribution of *B. zonata*. In this study, we used MaxEnt and CLIMEX models to estimate the risk area for *B. zonata* under near current and future climate conditions. The MaxEnt and CLIMEX results showed that the south of North and Central America was suitable for *B. zonata*. The European countries were slightly suitable for *B. zonata*. In Asia, the highly suitable regions of *B. zonata* included Saudi Arabia, United Arab Emirates, Oman, Iran, Pakistan, India, Nepal, Bangladesh, Bhutan, Myanmar, Thailand, Vietnam, and Laos. Moreover, China, Philippines, Indonesia, and Japan showed highly climate suitability for *B. zonata*. The climate suitability of *B. zonata* was increasingly high in the projection under climate change. The result of the two models showed that the climatic suitability for *B. zonata* will increase under climate change in China. Taken together, these predictive results support the quarantine of *B. zonata* for high-risk countries and provide in-depth information on how climatic changes may affect its possible geographic range.

Keywords Tephritidae, Ecological management, Climatic change, Invasive pest, Potential geographical distribution

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Introduction

Invasive insect species can have significant negative effects on ecosystems and economies Worldwide (Hulme and Trade 2009; Desneux et al. 2011; Ragsdale et al. 2011; Kenis et al. 2023; Mondino et al. 2022; Weinberg et al. 2022). These invasive insects were projected to cost at least 70.0 billion USD annually throughout the world (Bradshaw et al. 2016). Fruit flies are regularly introduced into new locations by human activities, whether purposefully or accidentally (Gutierrez et al. 2021; Lin et al. 2020). Tephritidae is among the largest families of Diptera and also among the most damaging invasive insects (Jiang et al. 2018; Qin et al. 2015; Zhu et al. 2022; González-Núñez et al. 2021). According to White and Elson-Harris, frugivorous Tephritid fruit flies, in particular, have caused large losses (White and Elson-Harris 1992). Fruit fly damage usually results in crop losses of 80–100% (Hendrichs et al. 2015).

The peach fruit fly, *Bactrocera zonata* (Saunders), is one of the most economically important invasive pests of Tephritidae. This polyphagous pest attacks almost 40 species of fruits and vegetables worldwide (White and Elson-Harris 1992). In Pakistan, *B. zonata* can cause 25–50% guava loss, while it causes 25–100% losses in peaches, apricot, guava, and figs in India (Ahmad et al. 2003). *Bactrocera zonata*, native to South and South-East Asia, is now spread in more than 20 countries, including India, Bangladesh, Bhutan, Laos, Myanmar, Nepal, Pakistan, Sri Lanka, Thailand, and Vietnam. In the 1980s, *B. zonata* began to spread over the Arabian Peninsula, including Iran, Iraq, Israel, Oman, Saudi Arabia, the United Arab Emirates, and Yemen (White 2006). After the initial invasion of *B. zonata* in Egypt in 1997, this species spread to neighboring countries, including Sudan, Libya, and Israel (Ekesi et al. 2016). *B. zonata* has great quarantine significance in international trade owing to their wide host range, reproductive potential, and dispersal ability following high climatic suitability in tropical and subtropical environments (Zingore et al. 2020). European Union (EU) regulation choose *B. zonata* as a high-priority fruit fly pest. Currently, *B. zonata* is absent from China and is one of the most economically important quarantine pests, despite reports that it was previously discovered in Yunnan Province, which have not been confirsmed (Li et al. 2016).

Climatic change and biological invasion are two major worldwide concerns that are linked with each other. The average temperature is projected to increase by 1.8 to 4 ℃ by the end of the 21st century (Skendžić et al. 2021). Insects are expanding their ranges due to climate change (Hulme 2017; Taheri et al. 2021). Many species, however, may have trouble adjusting to changing environments, mainly if they depend on other species for certain periodic needs (Wilson et al. 2007). Climatic change is key in establishing invasive insects in new environments (Hulme and Trade 2009). The invaded areas may suffer serious ecological and economic consequences from these invasive species (Hulme 2017). Insects adapted to temperature stress to survive and develop in their temperature range (Cornelissen et al. 2019; Ullah et al. 2022a, b). Qin et al. examined how climate change may affect the geographic spread of insects, emphasizing the negative impacts of these invasive insect pests on agriculture (Qin et al. 2019).

Different models based on species distribution data and environmental conditions in specific locations were used to forecast the areas that would be ideal for the target insect species (Hijmans 2012). These models included Species Distribution Models (SDMs), climate envelopes, ecological niche models (ENMs), habitat models, and resource selection functions (RSFs). Maximum entropy (MaxEnt) is a well-known and commonly used species distribution model that uses algorithms and entropy maximization to correlate species occurrences with known distributions (Zhao et al. 2020). The MaxEnt offers details on how climate change may affect the future distribution of insect species (Zhan et al. 2022). CLIMEX is a semi-mechanistic modeling tool that may fit biologically significant parameters while considering more than just distribution points and climatic factors (Kriticos et al. 2015). According to the CLIMEX model, *B. zonata*was expected to spread over most of the tropics and subtropics, including some regions of the USA, southern China, southeastern Australia, and northern New Zealand (Zingore et al. 2020; Ni et al. 2012).

In this study, we used two models, MaxEnt and CLIMEX, to investigate the optimal locations for invasive *B. zonata* under climate change scenarios. These results will provide in-depth information about the favorable areas for *B. zonata* under climate change scenarios.

Materials and methods

Occurrences of species were used to conduct models. The distribution data of *B. zonata* were extracted from Global Biodiversity Information Facility (GBIF, http://www.gbif.org/), the Centre of Agriculture and Bioscience International (CABI, http://www.cabi.org/) dataset, EPPO Global Database (https://gd.eppo.int/) and published literature (Ni et al. 2012). The replicates were removed by R package spThin. There were 201 points left (Fig.1a). Furthermore, to minimize spatial autocorrelation, the location records were spatially filtered specifying in a 5×5 arcminutes grid, the same as environmental variables' resolution. Host data were downloaded from FAOSTAT (https://www.fao.org/faostat/zh/#data/QCL). Item was "Peaches and nectarines", the production for

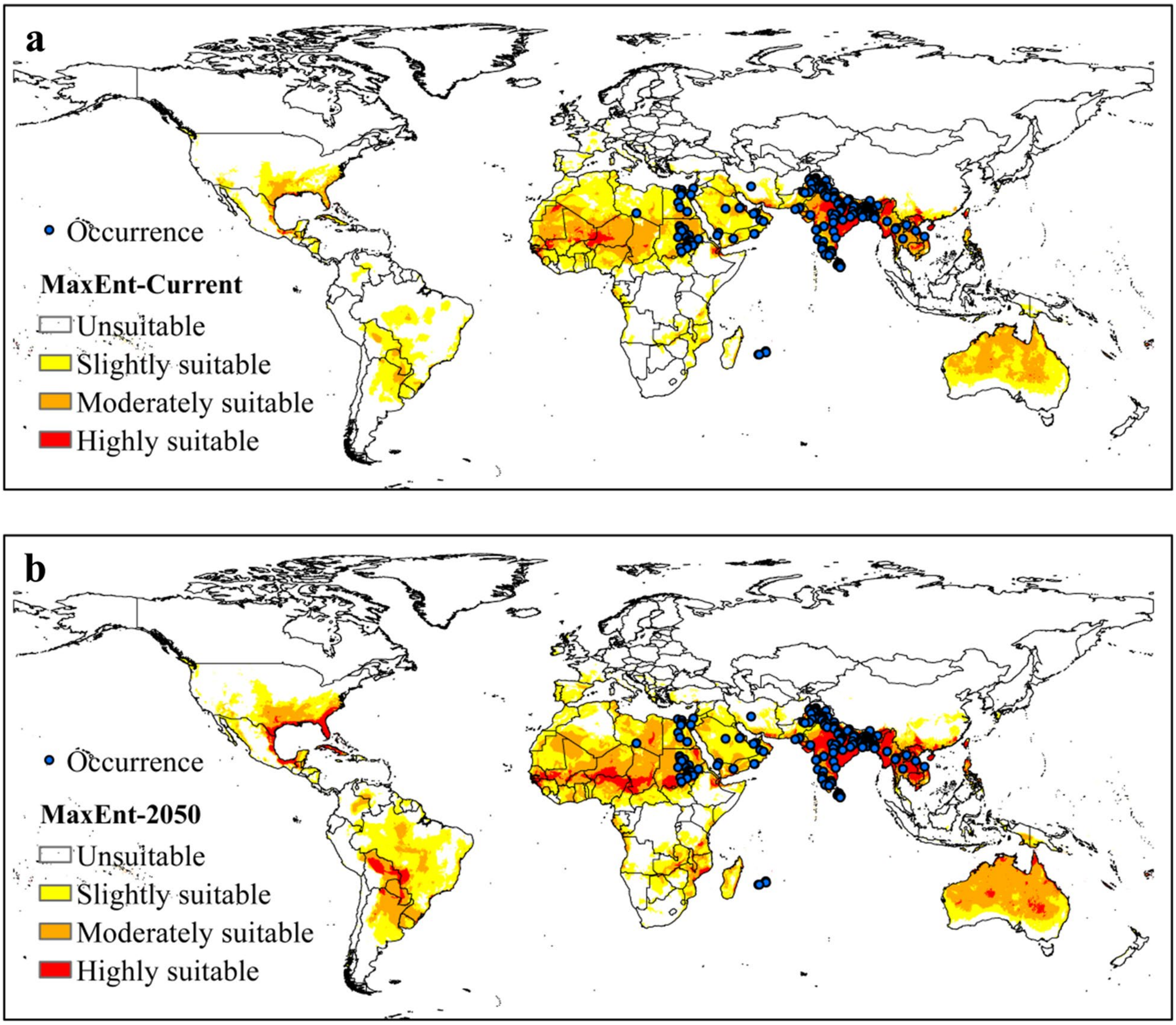

Fig. 1 Based on MaxEnt to predict the potential geographical distribution of *Bactrocera zonata* under **a** current; **b** 2050 (SSP585), the blue points are occurrence data used to build and evaluate the model

each country were averaged from 2017 to 2021 (data of latest two years were absent).

MaxEnt

Environmental variables

The current bioclimatic variables were obtained in version 2.1 with a resolution of 5 arc minutes from the Worldclim database (https://worldclim.org/,1970-2000). These variables represent yearly climatic ranges and limiting factors that affect species' geographic distribution, making them frequently utilized in the research of ecological niche modeling (Slater and Michael 2012). Prediction accuracy may be impacted by environmental factors' multicollinearity (Qin et al. 2019). A set of variables with Pearson correlation coefficients having absolute values < 0.8 that are uncorrected (Figure S1) and eco-physiologically relevant for modeling were chosen using principal component analysis (PCA) and correlation analysis (IBM SPSS Statistics version 21) (Qin et al. 2021b).

Modeling and evaluation

In this study, we used MaxEnt 3.4.4 to simulate the optimum regions for *B. zonata*. MaxEnt is easily overfitted and sensitive to sample variance (Zhu et al. 2014). The MaxEnt parameters had to be adjusted to avoid overfitting and enhance transferability. We applied the R package "ENMeval" to minimize model overfitting (Kass et al. 2021; , Wei et al. 2020). Adjustment of the MaxEnt variables, including the regularization multiplier (RM) value and feature combinations (FCs, linear, quadratic,

Table 1 Principal component analysis (PCA) performed on 19 bioclimatic variables to model distribution of *Bactrocera zonata (*Six uncorrelated variables used in the analysis, values in bold were above 0.8 explaining more variance)*

Bioclimatic variables	Principal components			
	1	2	3	4
Annual mean temperature (bio1)	0.596	− 0.071	0.755	0.193
Mean diurnal range (bio2)	− 0.231	− 0.632	0.317	0.468
Isothermality (bio3)*	**0.891**	− 0.041	− 0.131	− 0.134
Temperature seasonality (bio4)	**− 0.852**	− 0.351	0.095	0.206
Max Temperature of Warmest Month (bio5)	0.002	− 0.46	0.706	0.442
Min Temperature of Coldest Month (bio6)*	**0.924**	0.183	0.281	− 0.1
Temperature Annual Range (bio7)	− 0.722	− 0.451	0.253	0.374
Mean Temperature of Wettest Quarter (bio8)*	0.032	0.118	**0.876**	0.039
Mean Temperature of Driest Quarter (bio9)	0.678	− 0.272	0.298	0.227
Mean Temperature of Warmest Quarter (bio10)*	0.13	− 0.351	**0.802**	0.362
Mean Temperature of Coldest Quarter (bio11)	**0.87**	0.113	0.449	0.041
Annual Precipitation (bio12)	0.154	**0.937**	− 0.074	− 0.235
Precipitation of Wettest Month (bio13)	0.152	0.092	− 0.111	**− 0.89**
Precipitation of Driest Month (bio14)	0.148	**0.928**	− 0.088	0.139
Precipitation Seasonality (bio15)	0.049	0.107	0.45	0.656
Precipitation of Wettest Quarter (bio16)*	0.128	**0.962**	− 0.048	0.066
Precipitation of Driest Quarter (bio17)*	0.131	0.164	− 0.127	**− 0.89**
Precipitation of Warmest Quarter (bio18)	− 0.246	0.717	0.147	− 0.414
Precipitation of Coldest Quarter (bio19)	0.395	0.371	− 0.346	− 0.087

Six uncorrelated variables used in the analysis, values in bold were above 0.8 explaining more variance

product, threshold, and hinge). The RM value ranged from 0.5 to 4 in steps of 0.5 for the six feature categories such as L, LQ, H, LQH, LQHP, and LQHPT. Akaike information criterion (AICc) values were estimated using "checkerboard2" (Santana et al. 2019). The final model was chosen to match RM value 1.5 and LQHPT using the lowest delta AICc model (Warren et al. 2014) (Additional file 1: Figure S2). The response curves and jackknife analysis were conducted to assess variable relevance; Cloglog output format and *.asc output file type were chosen. There could be a maximum of 5000 iterations (Swets 1988). The subsample with 10 replications comprised the repeated run type. The maximum test sensitivity plus specificity threshold rule was included, and the random test percentage was set to 25%. In this study, suitability for the peach fruit fly were divided into four classifications, the Maximum Test Sensitivity Plus Specificity Threshold was used to determine the suitability, Jenks Natural Breaks Classification (NBC) was employed to divide the other three suitable levels. By reducing variance within each range, this method makes each range's areas as comparable in value to one another as is feasible. NBC selected possible places into four categories based on the MaxEnt result plots (Arabameri et al. 2020). Model evaluation was done using AUC values averaged over replicated runs (Plowright et al. 2015). Based on their performance, the models can be categorized into four groups: predictions that perform worse than the chance ($AUC < 0.5$), predictions with poor performance ($0.5 \leq AUC < 0.7$), predictions that perform moderately or reasonably ($0.7 \leq AUC < 0.9$), and predictions that perform well ($AUC \geq 0.9$)(Swets 1988).

Climate change projection

Future climate conditions were assessed with global climate model (GCM) data downscaled form Coupled Model Intercomparison Projections (CMIP) 6 with WorldClim v2.1 as the baseline climate, four GCMs in 2050 (averaged from 2041-2060) were selected to reduce the uncertainty arose from different model projections, BCC-CSM2-MR (BCC), IPSL-CM6A-LR (IP), CNRM-CM6-1 (CN) and MIROC-ES2L (MI), separately. One shared socio-economic pathway that with very high greenhouse gas emissions (SSP5-8.5) was used in this study.

CLIMEX

Meteorological databases

The 30′ CliMond climate dataset (https://www.climond.org/) (1981–2010) was used within CLIMEX, the dataset accompanied CLIMEX version 4.0 and consists of 30-year averages from 1981 to 2010 with 67,420 climate stations worldwide (Kriticos et al. 2012).

Fitting parameters

With its semi-mechanistic methodology, CLIMEX implies that it may be possible to estimate the climatic conditions that a species may withstand from the locations where it is recorded. It lessens the seasons that are detrimental to the development of the species and increases the seasons that are favorable (Sutherst et al. 2007; , Araújo et al. 2022). The parameters were manually and iterativedly 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. In this study, the EI classification is 0.00–0.49 (Unsuitable), 0.5–9.99 (Slightly suitable), 10.00–19.99 (Moderately suitable) and above 20 (Highly suitable). The CLIMEX parameters was cited by (Ni et al. 2012). The full parameter table can be found in Additional file 1: Table S1 referred to (Wilson et al. 2007). Specifically, Egypt has a tropical desert climate, agriculture is completely dependent on the water of the Nile for irrigation, for that reason, 2.5 mm irrigation (summer) was set per day, and the setting had no significant influence on other areas.

Climate change projection

The climate data of CLIMEX were downloaded from the CliMond dataset. The future projection was 2050 under the A2 scenario from CSIRO. It describes a very heterogeneous world with a continuously increasing global population and regionally oriented economic growth that is more fragmented. This scenario assumed an increase in CO_2 concentrations by 846 ppm and predictions of a temperature increase of approximately 6 °C by the end of the century (Van Vuuren et al. 2014).

Results

MaxEnt performance and variables contribution

The average AUC under training for the model with the lowest AICc (FC = LQHPT, RM = 1.5) was 0.950 (Additional file 1: Figure S4), demonstrating the MaxEnt model's excellent performance in forecasting the potential distribution of *B. zonata*. Among 19 environmental variables, there are six different contributions to the MaxEnt models (Table 1). The jackknife results showed that the highest contribution variable was mean temperature of wettest quarter (bio8), mean temperature of warmest quarter (bio10), isothermality (bio3) and min temperature of coldest month (bio6) also have a greater impact on the model, then the two precipitation-related variables, precipitation of wettest quarter (bio16) and precipitation of driest quarter (bio17) (Fig. 2).

The response curve (Additional file 1: Figure S3) showed that the fitness potential of the peach fruit fly was highest when Isothermality was 38.60, then the mean temperature of coldest month should above − 16.8°C then the region can be suitable to the pest, the mean temperature of wettest quarter has one peak when it was 29.36 °C, the survival probability increased sharply when the mean temperature of warmest quarter in 22.89 °C, reached peak when it is 32.45 and 34.18 °C, and the probability increase when the precipitation of wettest quarter exceeds 3.12 mm, from the response of bio17, it has little impact to the pest's survival.

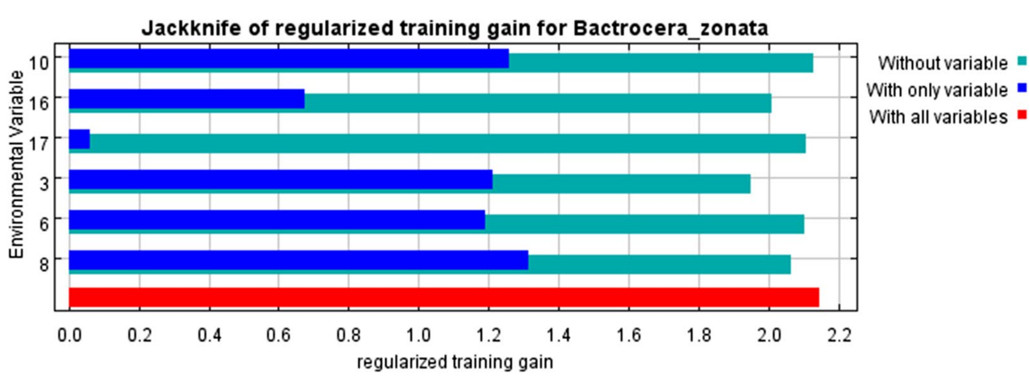

Fig. 2 Jackknife analysis result showing the most influential environmental variables predicting potential geographical distribution of *Bactrocera zonata*

MaxEnt projection of *B. Zonata* under climatic change

The results showed that the south of North and Central America was suitable for *B. zonata* (Fig. 1a), including the Southern United States, Eastern Mexico, Northern Guatemala and Honduras, most part of Nicaragua and Cuba. For South America, countries such as Brazil, Argentina, Uruguay, Paraguay, Bolivia, Peru, and Venezuela are with suitable areas of *B. zonata*. Eastern Europe and the Mediterranean coast were slightly suitable for the peach fruit fly. Northern Africa showed more suitable for *B. zonata*. There are few countries in Southern Africa also suitable for the pest.

In Asia, the current available region of the peach fruit fly, such as Saudi Arabia, United Arab Emirates, Oman, Iran, Pakistan, India, Nepal, Bangladesh, Bhutan, Myanmar, Thailand, Vietnam, and Laos are highly suitable for it. Besides, China, the Philippines, Indonesia, Japan also have climatic suitability for *B. zonata*. Oceania has no occurrence record yet, but Northern Australia, part of Papua New Guinea, Fiji and New Caledonia were suitable for *B. zonata*.

Under climate change (Fig. 1b), the suitable area for *B. zonata* increased generally. Compared with the current scenario, a suitable area of North America, the eastern coastal area has become more suitable for the peach fruit fly, Europe and west of Asia has a trend to expand north. As for South America, Africa, and Oceania, their southern border of the suitable region was further south. Besides, the climate suitability of *B. zonata* was increasingly high in the projection under climate change.

CLIMEX projection of *B. Zonata* under climatic change

There was a high risk of *B. zonata* becoming established in North America, south of the United States, and in countries further south (Fig. 3a). The region around the Andes was predicted to be unsuitable for the peach fruit fly. The rest of South America has high climatic suitability for the pest. In Europe, France, Spain, the United Kingdom, Italy, Albania, and Greece were at potential risk. Except for the Sahara and its vicinity, most African regions are potentially suitable climatic zones for the peach fruit fly. Most of the region south of 40°N was at risk, especially in India and its surrounding countries where the peach fruit fly now occurs. In Oceania, the model projected areas with high climatic suitability for *B. zonata* over a wide area. The suitable area of *B. zonata* decreased in specific regions under climate change (Fig. 3b), mainly in the north of Africa and the north of Oceania. The other three continents showed a slight expansion in the northern and southern.

Host availability of *Bactrocera zonata* in climatically suitable regions

There is agreement (two mode shows climate suitability are consistent) and disagreement (one model shows suitable whereas the other shows not) between the MaxEnt and CLIMEX results (Fig. 4). The most disagreement part under current scenario is in Central America, Northern South America, Southern Africa, part of Eastern Asia and Oceania (Fig. 4a). Northern Africa and Northern America turned to be more differentiated under climate change (Fig. 4b).

The average host production (2017–2021) including peaches and nectarines for *B. zonata* in 92 countries is shown on the map (Fig. 4a). The countries with highest production are China, Spain, Italy, Turkey, Greece, the United States of America, Iran, Egypt, Chile and Brazil (Table 2), all these countries have suitable climatic areas for *B. zonata.*

Discussion

Biological invasions are considered one of the main drivers of biodiversity loss and species extinction in the world's major plant and animal taxa (Gentili et al. 2021). SDMs are broadly used to estimate the global distribution pattern of invasive species. In this study, a semi-mechanistic modeling software, CLIMEX, and a machine learning model, MaxEnt, were used to realize and create the spatial distribution of potential areas for the invasion of *B. zonata*.

The main environmental factor limiting the pest's range is temperature, precipitation contributes less. The results also indicate that the peach fruit fly is likely spreading further north and south. Both models describe the survival environment of the peach fruit fly in general agreement, with a maximum temperature of about 36 °C. The probability of survival increases with increasing temperatures from the coldest month, with the pest reaching its highest probability of survival in this location when temperatures reach about 12 °C. It is predicted that temperatures will increase by 1.8-4 °C by the end of the century and that climatic conditions suitable for the survival of the peach fruit fly can be easily achieved in places that are currently unsuitable for it, as has been demonstrated previously: Egypt was considered unsuitable for the survival of the peach fruit fly due to lower temperatures than the existing distribution sites (Ullah et al. 2019) but was established after its introduction in the late 1990s (Ni et al. 2012; Delrio 2010). In addition to climate, other factors can also infect the distribution range of *B. zonata*. Abiotic factors such as land type and soil condition can also influence the distribution of species, and biotic

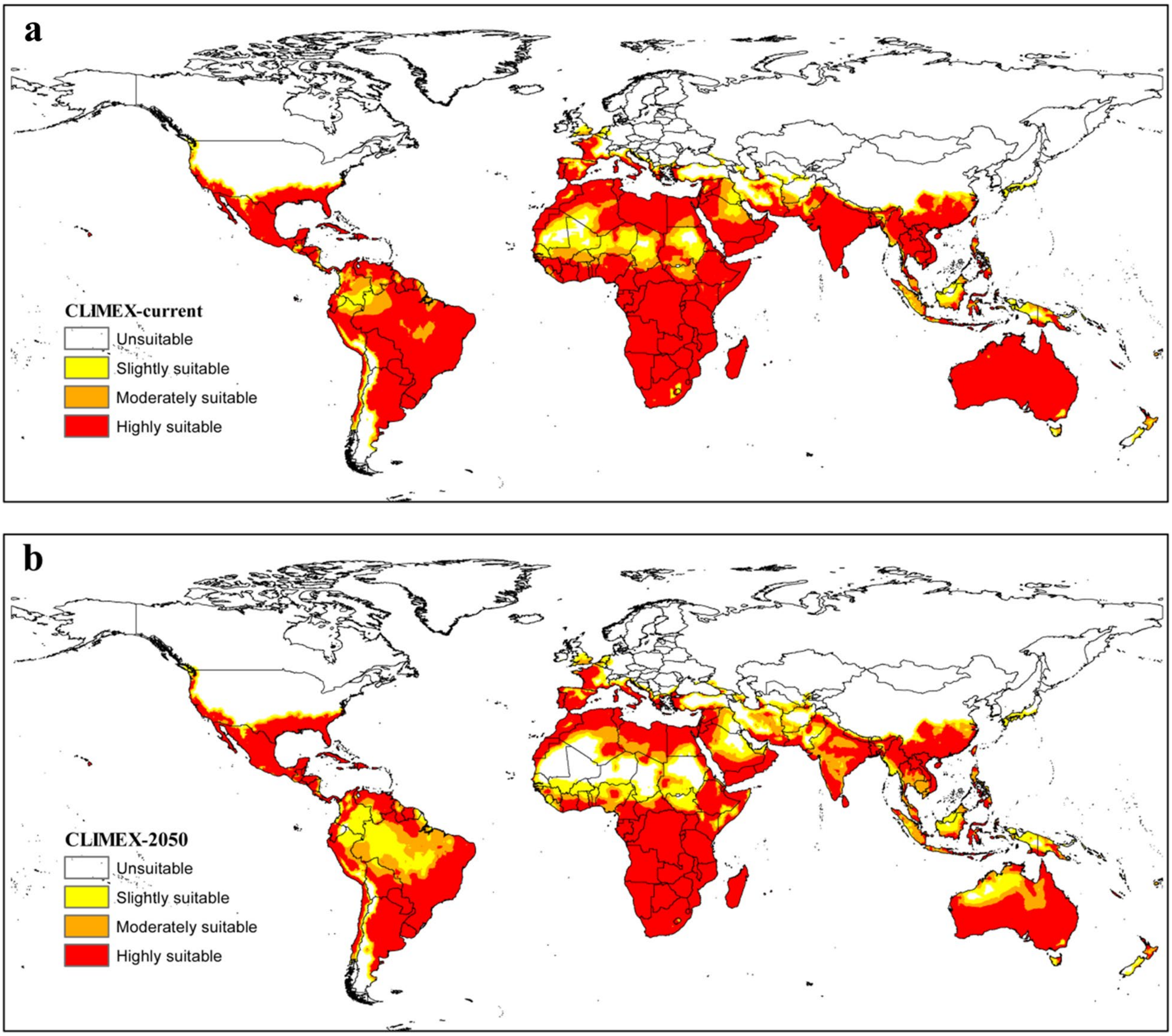

Fig. 3 Based on CLIMEX to predict the potential geographical distribution of *Bactrocera zonata* under **a** current; **b** 2050 (CSIRO A2)

factors such as species interactions can affect the distribution of species at smaller spatial scales (Darwell et al. 2017; Martínez et al. 2015), but they were not used in this study.

The results suggest that *B. zonata* is expected to be able to establish in tropical and subtropical areas. Both two models (CLIMEX and MaxEnt) have a scene that the species is suitable in Sahara, it is coincided with the true distribution. Although the results suggested that the insect can survive in the desert, study (Khan and Naveed 2017) indicated that its survival is dependent on the presence of suitable hosts. There may be limited host availability in desert environments, so while climate and physiological indicators indicate its potential survival in the desert, the actual outcome depends on the presence of suitable hosts.

The present study examines peaches and nectarines as representative hosts and emphasizes the need for heightened vigilance in countries such as China, Spain, Italy, Turkey, etc. Although these countries have yet to experience any occurrences of the peach fruit fly, it is crucial for them to prioritize preventive measures. Once established, this pest has the potential to cause severe economic damage. A study (Qin et al. 2021a) used peaches as host example to simulate two management scenarios in China: (1) nil and (2) management when *B. zonata* was established, it shows that if the government ignore the pest, 0.82–3.07 billion dollars may loss. However, the

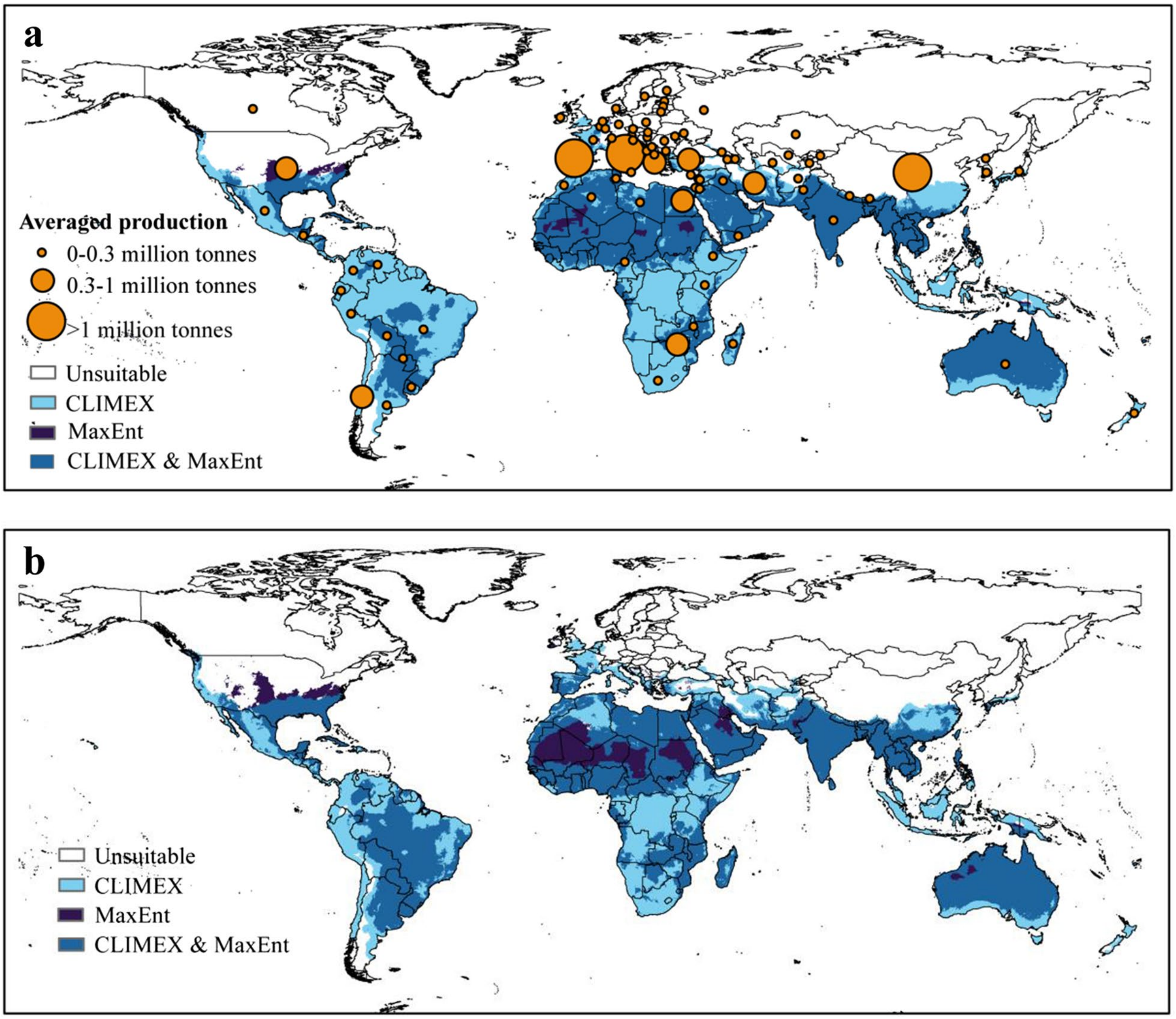

Fig. 4 Ensemble results of MaxEnt and CLIMEX worldwide under **a** near current, **b** 2050; Orange points are host production data averaged from 2017 to 2019

Table 2 Host (Peaches and nectarines) production data average from 2017 to 2019

Countries	Production / million tonnes
China	14.76
Spain	1.46
Italy	1.12
Turkey	8.35
Greece	8.04
United States of America	7.26
Islamic Republic of Iran	6.13
Egypt	3.34
Chile	3.23
Brazil	2.11

peach fruit fly is also a polyphagous pest, it can attack almost 40 species of fruit and vegetables (White and Elson-Harris 1992). Therefore, it is imperative for these countries to proactively address the potential threat posed by the peach fruit fly.

Considering these new factors, our study can be used as a basis for future work. In addition to natural migration, invasive species may be spread to other locations through human activities. In this study, southern China was predicted to be a suitable habitat for the peach fruit fly, and there is no current distribution of this pest in China. China borders countries where the peach fruit fly is currently distributed, and monitoring sites should be set up in suitable areas to prevent its natural spread and dispersal. Moreover, quarantine of this pest should be strengthened to prevent greater ecological and economic losses.

Conclusion

Taken together, MaxEnt results showed that south of North and Central America while in South America, the Brazil, Argentina, Uruguay, Paraguay, Bolivia, Peru, and Venezuela are suitable for *B. zonata*. In Asia, the current available region of the peach fruit fly, such as Saudi Arabia, United Arab Emirates, Oman, Iran, Pakistan, India, Nepal, Bangladesh, Bhutan, Myanmar, Thailand, Vietnam, and Laos are highly suitable while China, Philippines, Indonesia, Japan also have climatic suitability for *B. zonata*. The suitable area for *B. zonata* generally increased under climate changes. Compared with the current scenario, the North America and the Eastern coastal area has become highly suitable for the peach fruit fly. Besides, Europe and west of Asia has a trend to expand north. CLIMEX results showed a high risk of *B. zonata* becoming established in North America, and south of the United States. In Europe, France, Spain, the United Kingdom, Italy, Albania, and Greece were at potential risk of *B. zonata*. The average host production (peaches and nectarines) for *B. zonata* were highest from China, Spain, Italy, Turkey, Greece, the United States of America, Iran, Egypt, Chile and Brazil. All these countries have suitable climatic areas and are at potential risk for *B. zonata*. These results provided in-depth information about policy decisions and adaptive agricultural management plans for better monitoring and surveillance and support the quarantine measures to manage the spread of *B. zonata*.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s43170-023-00187-x.

Additional file 1: Table S1. CLIMEX parameters used to model the distribution of *Bactrocera zonata*. **Figure S1.** Pearson's correlation analysis of 19 environmental variables. **Figure S2.** The delta AICc-value of the model under user-specified range of regularization multiplier (RM) and feature combinations (FCs). **Figure S3.** The response curves of the six environmental variables. **Figure S4.** ROC and AUC values for the model.

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Author contributions
Conceptualization, ZL, YQ, FU and YZ; methodology, FU, and YZ; writing—original draft preparation, FU, and YZ; writing—review and editing, ZL, YQ, ND, HG, MH, FU and YZ; project administration, ZL; funding acquisition, ZL, amd YQ. All authors have read and agreed to the published version of the manuscript.

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Data availability
All data presented in this study are available in the article.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests

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