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ORIGINAL RESEARCH ARTICLE

Phenological responses of *Bactrocera dorsalis* (Hendel) to climate warming in China based on long-term historical data

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Abstract

It is well accepted that the phenology of insects whose life activities are closely related to temperature is changing in response to global climate warming. To investigate the impacts of climate warming on the phenology of *Bactrocera dorsalis* (Hendel) across large temporal and spatial scales, this study collected historical data on the occurrence and population dynamic of this pest in China, and systematically explored its phenological responses. The results showed a delayed trend for the dates of first occurrence, end occurrence, population initial growth, and population peak of *B. dorsalis* in China during 40 years, and the changes of the latter two phenological parameters were significant. The mean temperature in spring and summer were the key climatic factors affecting the occurrence and population growth of *B. dorsalis* in China, respectively. Moreover, the *B. dorsalis* data in eastern, southern, central, and southwestern China showed spatial heterogeneity of phenological responses to climate warming at a regional scale. *B. dorsalis* phenology and their changing patterns with climate warming varied by geographical location. This study provides valuable information for future monitoring, prediction, and prevention of the oriental fruit fly in the context of climate warming.

Keywords Global warming · Oriental fruit fly · Occurrence · Population dynamic · Phenology

Introduction

Climate change, the most debated issue of time, threatens many organisms. The Intergovernmental Panel on Climate Change (IPCC) reported that the average global temperature had increased by 0.72 °C with a mean increase rate of 0.012 °C per year from 1880 to 2012 (IPCC 2014). The global temperature rise significantly impacts individual development, population dynamics, phenology, and the geographical range of organisms, including insects, which has recently attracted much attention (Wu et al. 2020). Insects, a large group of poikilotherms, are highly sensitive to climate warming. The life activities of insects, including growth and development, survival, reproduction, and mobility, are closely associated with ambient temperature, thus, are inevitably influenced by climate warming (Meglitsch 1972; Bale et al. 2002; Meineke et al. 2014). Thus, understanding the proximate mechanisms resulting in these shifts becomes increasingly urgent now that accumulating evidence exhibits that climate change can significantly impact individual survival and the population development of species.

Many studies have demonstrated that climate warming accelerates insects' growth and development rates, resulting in a shorter life cycle and earlier occurrences (Harrington et al. 2001; Robinet and Roques 2010; Raza et al. 2014). It has been demonstrated that increasing temperature could accelerate the reproductive cycle of insects, such as butterflies, dragonflies, damselflies, flies, aphids, bees, and beetles, to produce more generations (Gordo and Sanz 2005; Harrington et al. 2001). For instance, rising temperatures

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halved *Dendroctonus rufipennis* Kirby's breeding time in northwestern North America (Berg et al. 2006). Based on the data of the British Butterfly Monitoring Schemes (BMS), from 1976 to 1998, the first occurrence of most British butterflies advanced and the period of their mean flight was prolonged due to the increasing temperatures in spring and summer in central England. Similar results were observed for the butterflies in Spain (Stefanescu et al. 2010) and California, USA (Forister and Shapiro 2003), and 37 Odonata species in the Netherlands (Dingemanse and Kalkman 2008). In China, three aphid pests, *Myzus persicae* Sulzer, *Aphis gossypii* Glover, and *Sitobion avenae* Fabricius are occurring earlier, and their migration seasons have become longer due to climate warming (Wu et al. 2020).

Bactrocera dorsalis (Hendel), commonly known as the oriental fruit fly, is a highly polyphagous species, which attacks more than 300 host plants of commercially grown vegetables and fruits, and is thus regarded as a major pest worldwide (Clarke et al. 2005; Vargas et al. 2009). First recorded in Kaohsiung of Taiwan, China, in 1912 (Drew and Hancock 1994), *B. dorsalis* spread beyond tropical Asia over the following years, due to their adaptability to diverse climatic conditions (Clarke et al. 2005; Aketarawong et al. 2007). This pest has recently caused serious economic losses in more than 10 Chinese provinces. These losses in southern China amount to around three billion dollars annually (Ji et al. 2016).

Severe crop damage caused by *B. dorsalis* prompted research on this pest's biology and population ecology in subtropical and tropical regions (Uchida et al. 2007; Piñero et al. 2009; Vargas et al. 2008a, b). The phenology and population dynamics of this pest have been extensively investigated in eastern, southern, southwestern, and central China, such as Fujian (Zheng 2013), Jiangxi (Li et al. 2019), Guangdong (Lv et al. 2008), Yunnan (Chen and Ye 2007; Ye and Liu 2005), and Hubei Provinces (Han et al. 2011). These researches demonstrated that the seasonal occurrence of *B. dorsalis* was determined by factors, such as temperature, rainfall, and host plant availability. Particularly, the temperature was considered as a crucial factor affecting the occurrence of this pest (Vargas et al. 1996; Michel et al. 2021; Manrakhan et al. 2022). *Bactrocera dorsalis* development and reproduction permitting temperature range is 15–34 °C, and the optimal temperature range for development is 20–28 °C. The threshold temperature ranges for eggs, larvae, and pupae are 11–12 °C, 9–11 °C, and 9–11 °C, respectively. Many adults and larvae die when the temperature is $>$ 34 °C or $<$ 15 °C (Chen and Ye 2007). Moreover, the low winter temperatures restrict the expansion and establishment of *B. dorsalis* in the newly invaded regions (Stephens et al. 2007). Han et al. (2011) overwintering experiments in Wuhan, Hubei province, showed that only a small proportion of *B. dorsalis* pupae might survive the cold winter and bridge the gap between winter and spring, giving a small initial number of viable adults early in the season. In the context of climate change, it is not yet known how climate warm affects population dynamics and the phenology of fruit flies. It is important to investigate the effects of climate warming on the occurrence of fruit flies over a long historical period, which can provide valuable information for forecasting and comprehensive control of this pest.

To limit *B. dorsalis* damage, a series of area-wide Integrated Pest Management (IPM) were implemented in recent years. This IPM program is based on biological and sustainable technologies, including (1) trapping adults using methyl eugenol (ME) and other lures (Uchida et al. 2007; Vargas et al. 2008b; Gu et al. 2018; Lin et al. 2022), (2) protein bait sprays (Wang et al. 2021), (3) promptly removal of infested fruits, (4) elimination of overwintering pupae by turning soil, (4) bagging fruit to prevent fly infestation (Mau et al. 2007; Vargas et al. 2008a), (5) application of parasitoids (Cai et al. 2017, 2020, 2022; Yang et al. 2018), (6) mass release of sterile insect (Cai et al. 2018; Lin et al. 2020; Zhang et al. 2021). However, whether climate warming would influence the timeline of when and how to perform these effective control methods across different geographical scales remained unknown. Therefore, exploring this issue with this notorious pest from different geographical regions is urgently needed.

With vast territory, varied topography, and various climate types, China is also significantly influenced by global warming, with a temperature growth rate of 0.026 ℃/a over the past 70 years, which is significantly higher than that in the world or the northern hemisphere (Climate Change Center of China Meteorological Administration 2022). However, the long-term impacts of climate warming on fruit fly pests remained largely unknown due to the absence of long-term population monitoring data. To address this research need, historical data extracted from the literature may provide insight into this issue (Tian et al. 2010; Hu et al. 2019; Matsuda et al. 2018). Thus, our research thoroughly collected historical data on the seasonal occurrence and population dynamics of *B. dorsalis*, rated as the TOP 10 invasive pests in China (Wan et al. 2017). Based on the collected historical data, the effects of long-term climate change on *B. dorsalis* were determined by analyzing changes in several phenological parameters.

Materials & methods

Phenological data

Bactrocera dorsalis phenological data were extracted and compiled from historical literature, most of which originated from the CNKI database (http://www.cnki.net), the most extensive and comprehensive database of Chinese periodicals (Tu et al. 2017), and Web of Science (http://www.webofknowledge.com/). Firstly, the common and Latin names of this fruit fly specie were used as subject words and searched by subject word retrieval. Afterward, the related literature from January 1980 to March 2022 recording the occurrences, geographical distributions, and population dynamics of *B. dorsalis* in diverse areas of China was consulted. The specific time and geographic information on life cycle parameters were extracted and a database was constructed. All data collection sites documented in the *B. dorsalis* collected literature were georeferenced into geographical maps utilizing ArcGIS 10.2 (ESRI, Inc., Redlands, CA, USA).

The collected data were organized based on the four most frequently recorded life cycle parameters, the first occurrence date, the end occurrence date, the population peak date, and the population initial growth date. In this study, the first occurrence date was defined as the time when adult flies were first detected in the fields, the end occurrence date was the time when no adult flies were detected in the field, the population peak date as the time when the trapping amount of adult flies reached the highest levels in the field, and the time when the population of adult flies began to grow rapidly as the population initially growth data. For each parameter, "change of days" was quantified by calculating the differences (number of days) between the dates of first occurrence, end occurrence, population peak or population increase records in our dataset, and January first of that year. In some literature, time descriptions of these parameters were vague, such as "the beginning of the month", "the middle of the month", "the end of the month", "the first (middle or last) ten days". Thus, such time information without specific dates was specifically approximated. For instance, the description about the beginning of a month was set as the first day of that month while the end of a month was set as the last day of

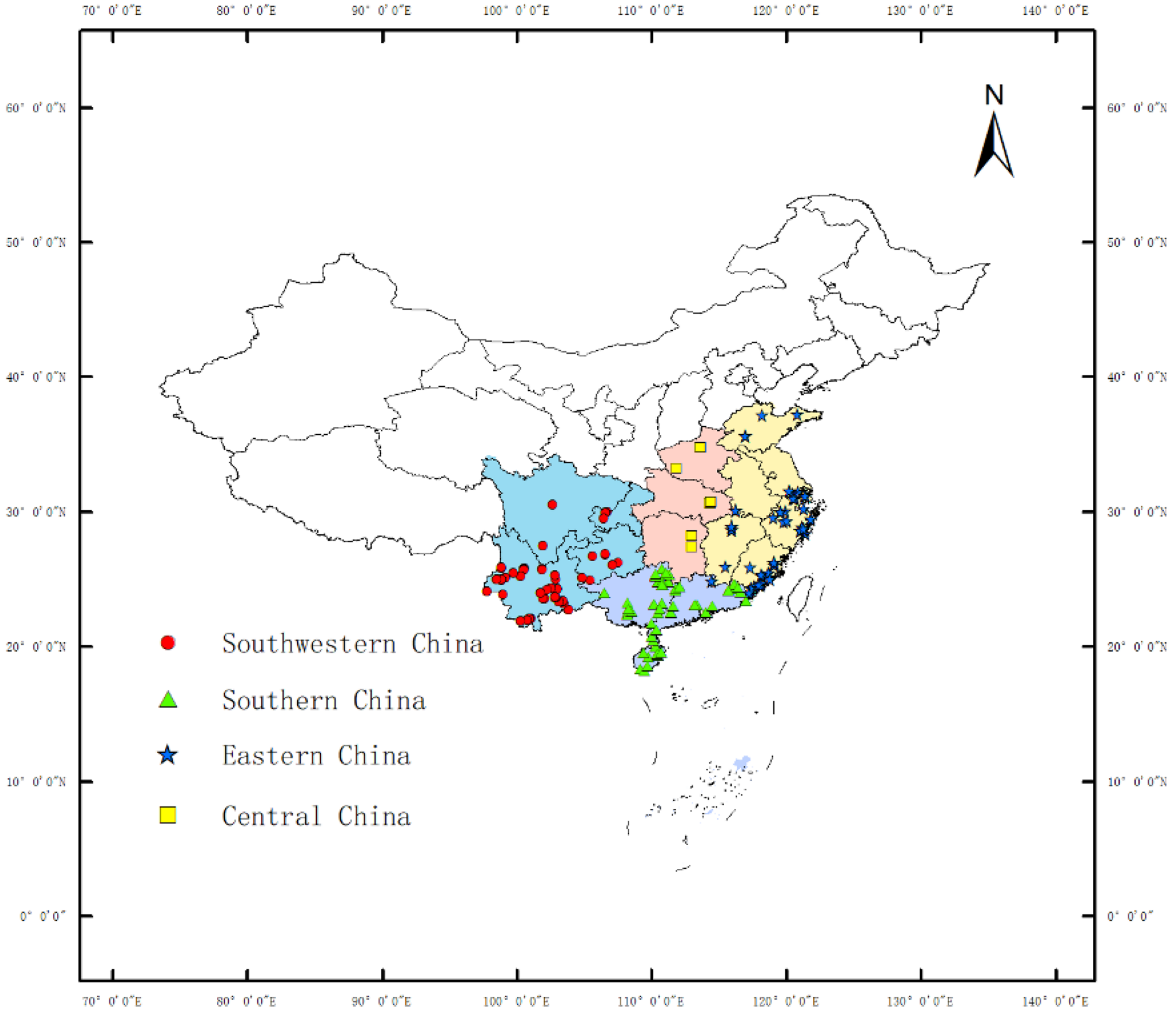


Fig. 1 The collection sites of phenological data of *B. dorsalis* used in this study

that month, and the first, middle, and last ten days of a month were set as 5th, 15th, and 25th of that month, respectively.

Meteorological data

The annual and seasonal mean temperatures of each province in China from 1980 to 2020 were obtained. Temperature records were downloaded from Chinese meteorological websites (http://data.cma.cn/). According to the collected literature, the annual mean temperature of southern China, eastern China, central China, southwestern China, and whole China where had phenological records of *B. dorsalis* were calculated and analyzed the overall change rates by a simple linear regression method to clarify the trend and temperature change about the past 40 years, respectively.

Statistical analysis

All analyses were conducted using SPSS for Windows version 20.0 (SPSS Inc., Chicago, IL, USA). The phenological responses of *B. dorsalis* were analyzed by plotting changes of the phenological parameters described above (the first occurrence, the end occurrence, the population increase, and the population peak). The change in days for each parameter was taken as the Y-axis, and the occurrence year was taken as the X-axis. Linear regression analysis was used to construct regression equations and reveal the trends of the four parameters in the time series. A normal test for all estimated data sets was performed, showing that all data sets were under normal distributions. Pearson correlation analysis was performed to verify the correlation between the phenological parameters of *B. dorsalis* and seasonal mean temperature.

Results

Phenological records of *B. dorsalis* in China

In March 2022, 150 pieces of literature that documented the phenological records of *B. dorsalis* in China were found in the CNKI and Web of Science databases (see supplemental files Table S1), involving 4 regions namely, southern China (Guangdong, Guangxi, and Hainan provinces), southwestern China (Sichuan province, Guizhou province, and Yunnan province), central China (Hubei, Hunan, and Henan provinces), eastern China (Shanghai city, and the Jiangsu, Jiangxi Fujian, Anhui, Zhejiang, and Shandong provinces) (Fig. 1). The collected data on *B. dorsalis* were mainly concentrated in southwestern, southern, and eastern China. These provide data support for investigating the impacts of climate warming to *B. dorsalis* at different geographical scales. The most phenological records of *B. dorsalis* have been reported from Yunnan province, followed by Guangxi and Fujian provinces, as they are the major fruit-producing areas where climatic conditions are also favorable for the survival, growth, and reproduction of this pest (Table 1).

Temperature changes in *B. dorsalis*-infested areas in China over time

In the past 40 years, the annual mean temperature (AMT) in eastern (Jiangsu, Jiangxi, Fujian, Anhui, Shanghai, Zhejiang, and Shandong), southern (Guangdong, Guangxi, and Hainan), central (Hubei, Hunan, and Henan), and southwestern (Sichuan, Guizhou, and Yunnan) China exhibited a significant upward trend with fluctuations, with the temperature rising rates of 0.0485 ± SE

Table 1 Phenological records of *B. dorsalis* in different regions in China

Region	Province	Valid record number of each province	Valid record number of each region	Total
Eastern China	Fujian	70	191	628
	Zhejiang	60		
	Jiangsu	22		
	Anhui	6		
	Jiangxi	22		
	Shandong	5		
	Shanghai	6		
Southern China	Guangdong	54	201	
	Guangxi	125		
	Haihan	22		
Central China	Henan	9	24	
	Hubei	9		
	Hunan	6		
Southwestern China	Guizhou	11	212	
	Sichuan	20		
	Yunnan	181		

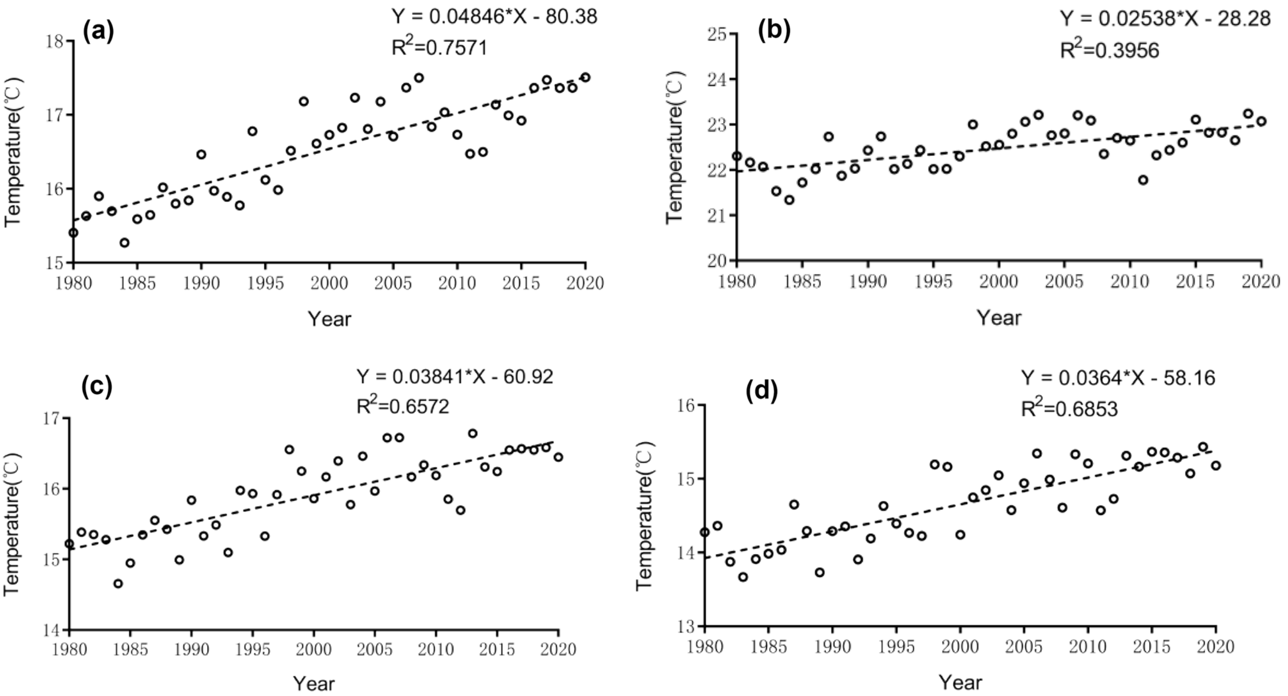


Fig. 2 The change of annual mean temperature (AMT) in eastern China (**a**), southern China (**b**), central China (**c**) and southwestern China (**d**). The small circle indicates AMT in a specific year and the dashed line represents the trend of temperature change

0.0044 ℃ year^{-1}, 0.0254 ± SE 0.0050 ℃ year^{-1}, 0.0384 ± SE 0.0044 ℃ year^{-1} and 0.0364 ± SE 0.0040 ℃ year^{-1}, as revealed by linear regression calculations (all $p < 0.0001$, Fig. 2).

Between 1980 and 2020, the spring (March–May, SPMT), summer (June–August, SUMT), autumn (September–November, AUMT), and winter (December-February, WMT) mean

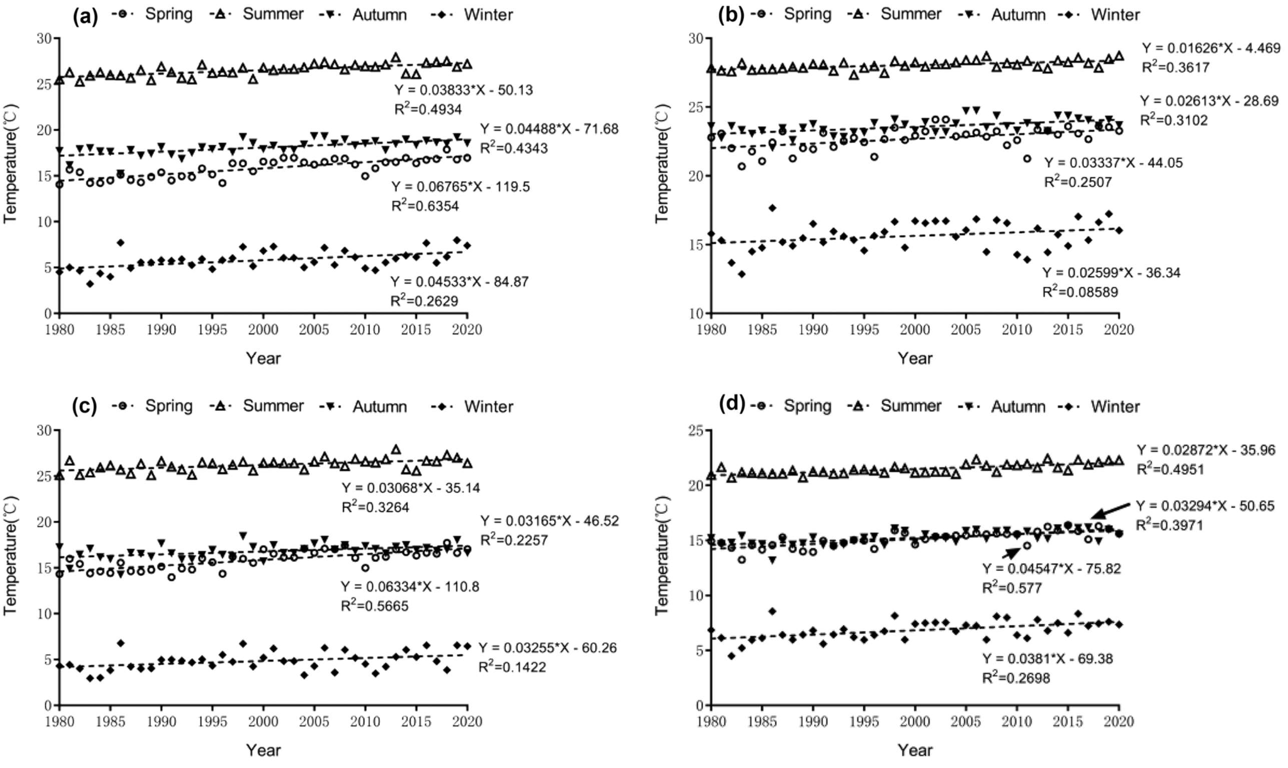


Fig. 3 The change of the seasonal mean temperature in eastern China (**a**), southern China (**b**), central China (**c**) and southwestern China (**d**). The dash lines exhibited the temperature change trend

temperatures in the areas infested by *B. dorsalis* in China had also increased over the years (Fig. 3). The linear regression analysis indicated that SPMT, SUMT, AUMT, and WMT in eastern China increased about $0.0677 \pm \mathrm{SE}0.0082$ ℃ year^{-1}, $0.0383 \pm \mathrm{SE}0.0062$ ℃ year^{-1}, $0.0449 \pm \mathrm{SE}0.0082$ ℃ year^{-1}, $0.0453 \pm \mathrm{SE}0.0122$ ℃ year^{-1}, respectively (all $p < 0.001$). Similar increasing trends of seasonal temperature parameters could be found in southern, central, and southwestern China. Still, the WMT in southern China did not show a significant rising trend ($p = 0.0629$).

The temporal trend of occurrence

Based on the collected long-term historical data, the first appearance of *B. dorsalis* in southern and central China followed an insignificantly downward tendency over the years, indicating that the first occurrence times of oriental fruit flies moved earlier by $-1.74 \pm \mathrm{SE}1.1$ days year^{-1} ($p = 0.1198$) and -1.822 ± 1.977 days year^{-1} ($p = 0.3684$), respectively (Fig. 4bc). However, the first occurrence date of *B. dorsalis* in eastern China and southwestern China were significantly

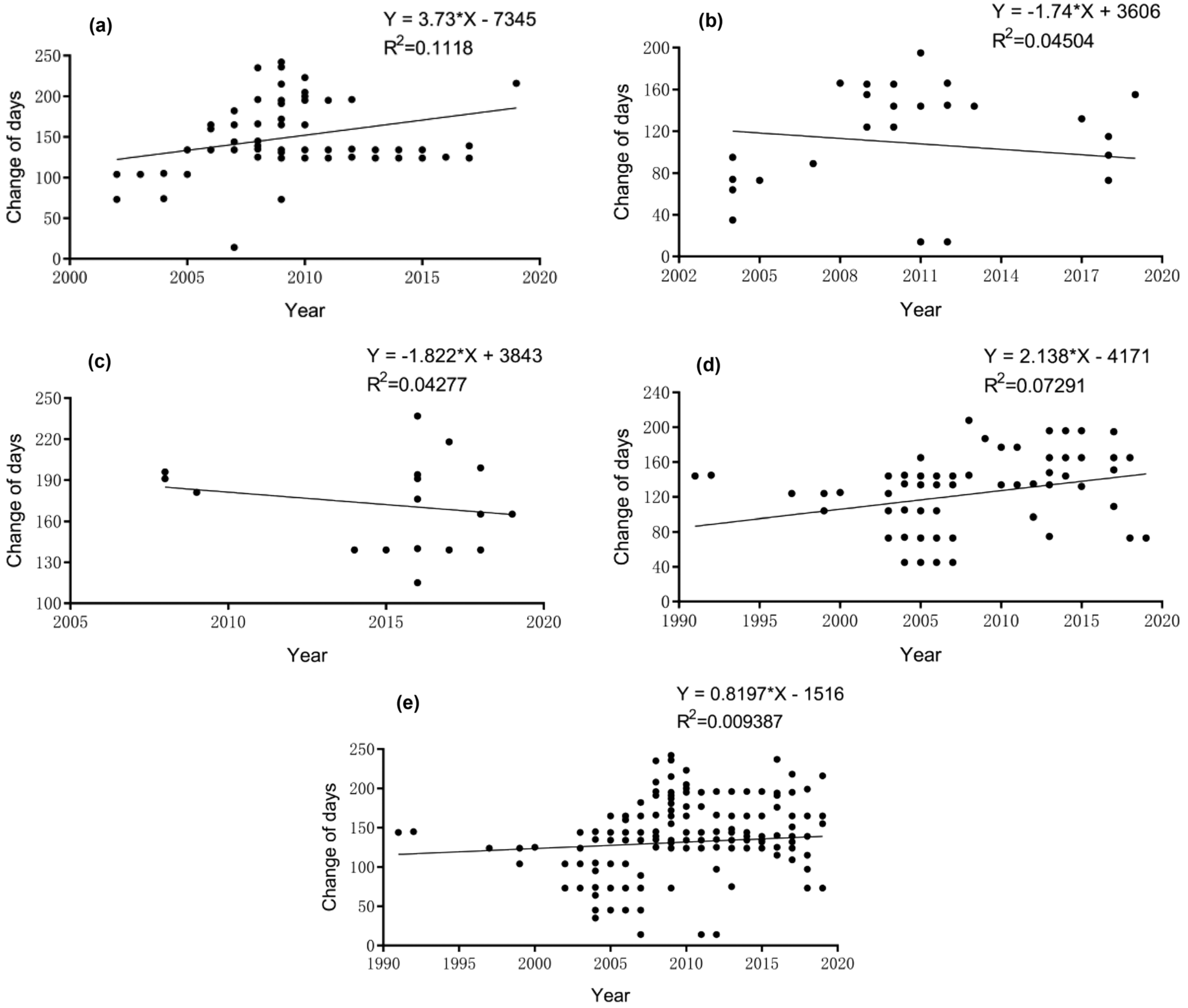


Fig. 4 First occurrence times of *B. dorsalis* in eastern China (**a**), southern China (**b**), central China (**c**), southwestern China (**d**) and whole China (**e**) for the period 1990–2020. The solid lines represent the trends of the beginning of occurrence and the dots indicate different phenological records

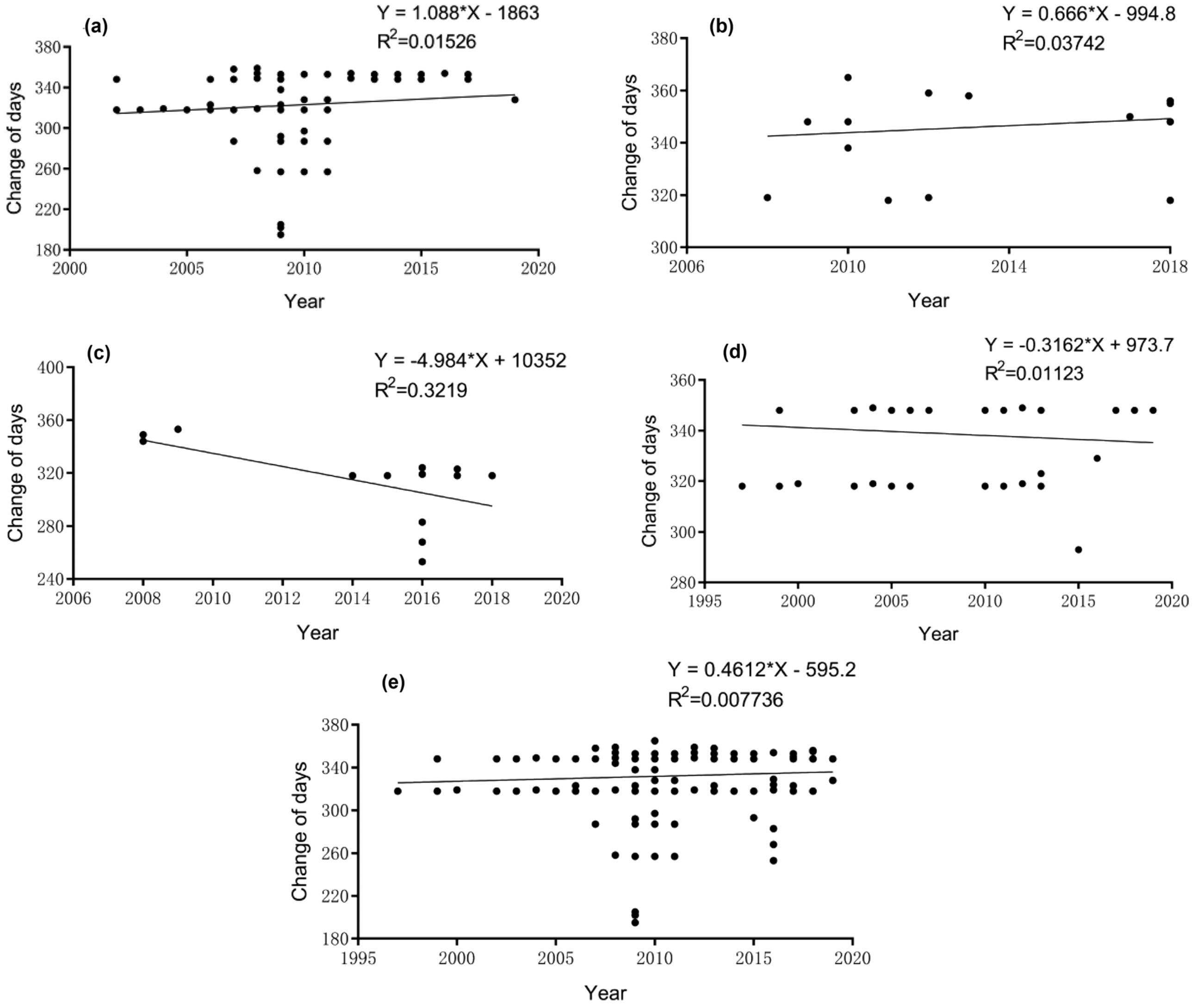


Fig. 5 End occurrence times of *B. dorsalis* in eastern China (**a**), southern China (**b**), central China (**c**), southwestern China (**d**) and whole China (**e**) for the period 1995–2020. The solid lines represent the trends of the end of occurrence and the dots indicate different phenological records

delayed by 3.73 ± SE1.062 days year^{-1} ($p = 0.007$) and 2.138 ± SE0.7702 days year^{-1}($p = 0.0066$), respectively (Fig. 4ad). For China as a whole, the scatter plots of the first occurrence change of *B. dorsalis* showed delayed tendency in the time series by 0.8197 ± SE0.5087 days per year ($p = 0.1083$, Fig. 4e).

For the end occurrence, the scatter plots of *B. dorsalis* in eastern and southern China showed a climbing trend over time, predicting that the end occurrence date was slightly delayed by 1.088 ± SE0.965 days year^{-1} ($p = 0.2629$, Fig. 5a) and 0.666 ± SE0.5151 days year^{-1} ($p = 0.2029$, Fig. 5b) respectively. However, this parameter of oriental fruit flies in central and southwestern China advanced by 4.984 ± SE2.006 days year^{-1} ($p = 0.0274$, Fig. 5c) and 0.3162 ± SE0.383 days year^{-1} ($p = 0.4123$, Fig. 5d), respectively. For China as a whole, the last occurrence times of *B. dorsalis* showed a slight upward shift, with a change rate of 0.4612 ± SE0.3657 days each year ($p = 0.2087$, Fig. 5e).

The temporal trend of population initial growth and peak

The current data collection revealed that the changes in population initial growth and peak of oriental fruit flies in central China exhibited significantly advanced tendencies

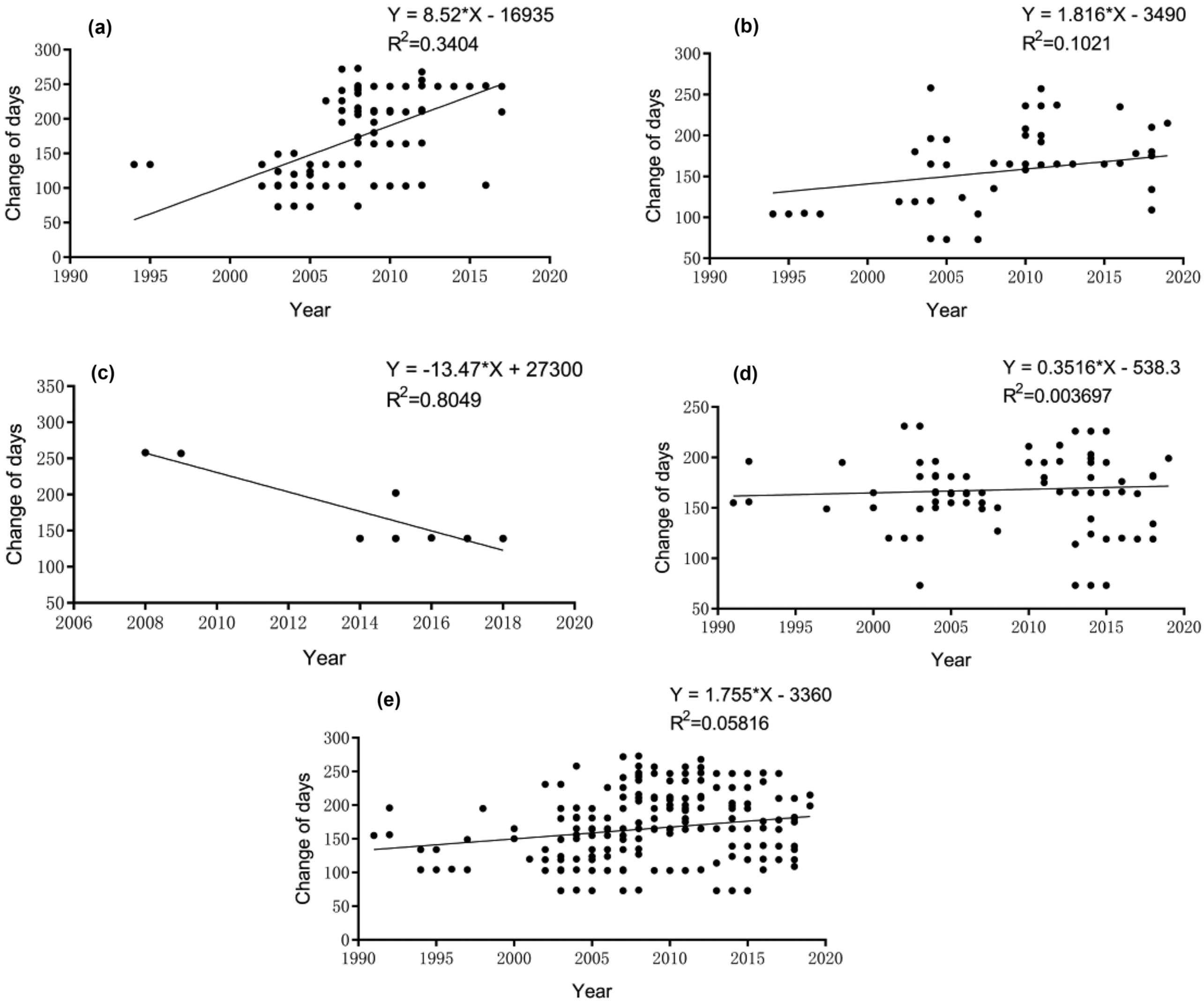


Fig. 6 The change of initially growth times of *B. dorsalis* population in eastern China (**a**), southern China (**b**), central China (**c**), southwestern China (**d**) and whole China (**e**) for the period 1990–2020. The solid lines represent the trends of the end of occurrence and the dots indicate different phenological records

by 13.47 ± SE2.707 days year^{-1} ($p = 0.0025$, Fig. 6c) and 3.563 ± SE1.599 days year^{-1} ($p = 0.0370$, Fig. 7c). In contrast, *B. dorsalis* population dynamics parameters in eastern, southern, and southwestern China were delayed. The population time change rates initially increased in the field were 8.52 ± SE1.152 days year^{-1} ($p < 0.0001$, Fig. 6a), 1.816 ± SE0.5468 days year^{-1} ($p = 0.0013$, Fig. 6b) and 0.3516 ± SE0.5528 days year^{-1}($p = 0.5261$, Fig. 6d), respectively. While the date of their population reached the maximum in the regions delayed by 1.356 ± SE0.6899 days year^{-1} ($p = 0.0509$, Fig. 7a), 1.033 ± SE0.3647 days year^{-1} ($p = 0.0051$, Fig. 7b) and 2.833 ± SE0.4133 days year^{-1} ($p < 0.0001$, Fig. 7d), respectively. For China as a whole, the initial increase date and peak times of the *B. dorsalis* population were both significantly delayed over the years and with the change rates of 1.755 ± SE0.3923 days each year ($p < 0.0001$, Fig. 6e) and 1.618 ± SE0.2525 days each year ($p < 0.0001$, Fig. 7e), respectively.

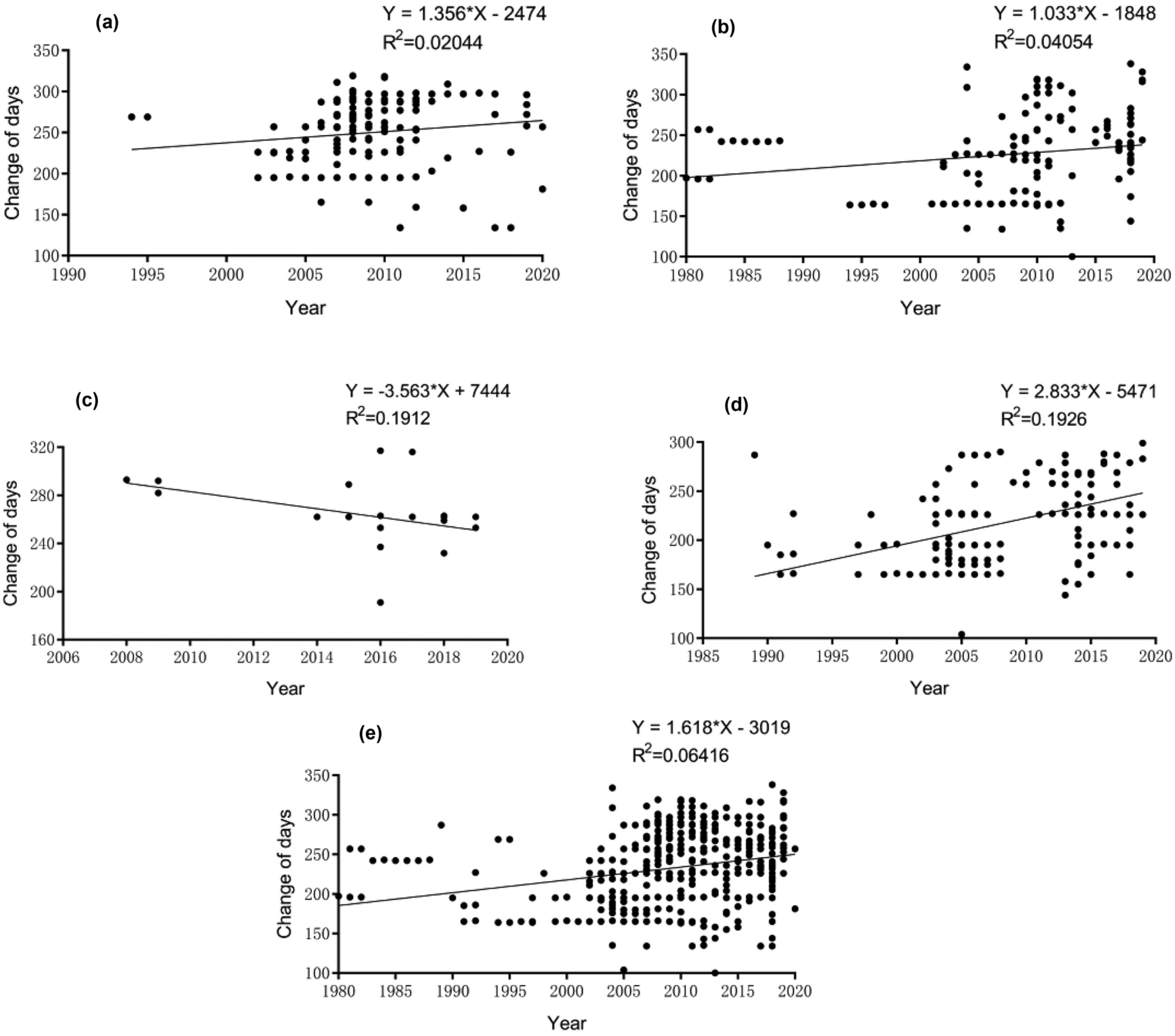


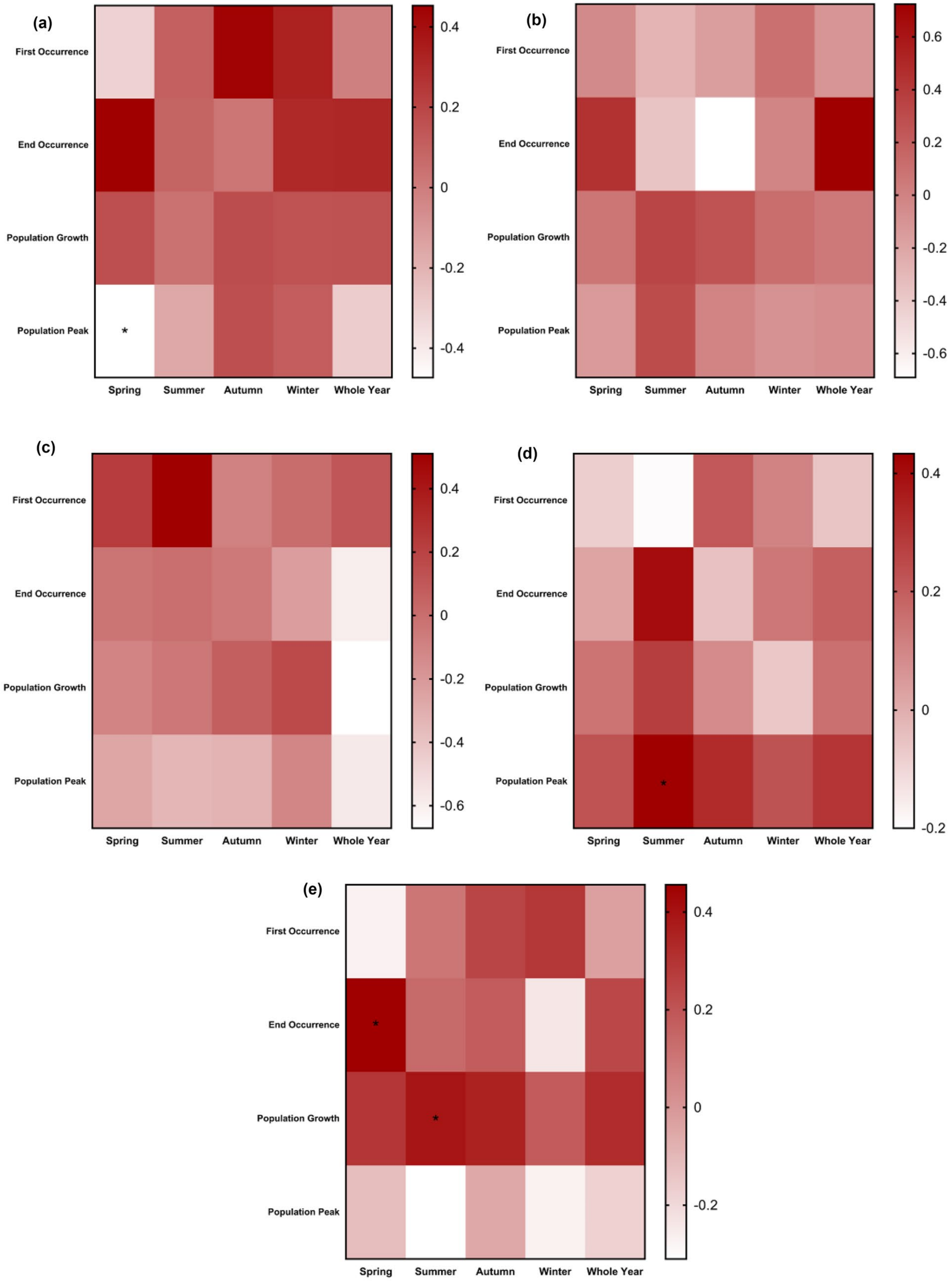
Fig. 7 The change of population peak times of *B. dorsalis* in eastern China (**a**), southern China (**b**), central China (**c**), southwestern China (**d**) and whole China (**e**) for the period 1990–2020. The solid lines represent the trends of the end of occurrence and the dots indicate different phenological records

Field phenology of *B. dorsalis* in relation to temperature

As a result, the date of the population peak of oriental fruit flies in eastern China was significantly negative correlated with the spring mean temperature (Pearson correlation coefficient = -0.4732, $p = 0.0302$, Fig. 8a). In southwestern China, there was a significant positive correlation between summer mean temperature and population peak date (Pearson correlation coefficient = 0.4332, $p = 0.0240$, Fig. 8d). For China as a whole, the date of the end occurrence and initial growth of *B. dorsalis* population were significantly positive correlated with spring mean temperature (Pearson correlation coefficient = 0.4556, $p = 0.0380$, Fig. 8e) and summer mean temperature (Pearson correlation coefficient = 0.3917, $p = 0.0433$, Fig. 8e).

Discussion

The analyses support several studies suggesting that, during four decades (1980–2020), the annual mean temperatures of the four regions infested by *B. dorsalis* in China have shown rising trends, as well as the seasonal mean temperatures of these regions. The population initial growth date and population peak date of *B. dorsalis* in China have been significantly delayed due to climate warming. The results of Pearson correlations analysis indicated that the initial growth of the *B.*


(a)
First Occurrence
End Occurrence
Population Growth
Population Peak
*
Spring
Summer
Autumn
Winter
Whole Year
0.4
0.2
0
-0.2
-0.4
(b)
First Occurrence
End Occurrence
Population Growth
Population Peak
Spring
Summer
Autumn
Winter
Whole Year
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
(c)
First Occurrence
End Occurrence
Population Growth
Population Peak
Spring
Summer
Autumn
Winter
Whole Year
0.4
0.2
0
-0.2
-0.4
-0.6
(d)
First Occurrence
End Occurrence
Population Growth
Population Peak
*
Spring
Summer
Autumn
Winter
Whole Year
0.4
0.2
0
-0.2
(e)
First Occurrence
End Occurrence
*
Population Growth
*
Population Peak
Spring
Summer
Autumn
Winter
Whole Year
0.4
0.2
0
-0.2

◂**Fig. 8** The correlations between the phenological parameters of *B. dorsalis* and annual and seasonal mean temperatures in eastern China (**a**), southern China (**b**), central China (**c**), southwestern China (**d**) and whole China (**e**). The asterisk indicated the Pearson correlations were significant at the levels of $p < 0.05$

dorsalis population had a significantly positive correlation with the summer mean temperature, implying that the initial growth of *B. dorsalis* population was similar to the summer mean temperature rising. The frequent appearance of extreme heat in the summer season may postpone the emergence of fruit flies to avoid exposure to high temperatures, leading to a delay in the initial growth date. With delayed population initial growth, there was a concurrent deferment of population peak occurrence. It is widely accepted that increased ambient temperature would generally accelerate the completion of the insect reproductive cycle to produce more generations in different insect species, ultimately leading to enhanced potential for insect pest outbreaks (Raza et al. 2014). Thus, *B. dorsalis* produced more generations due to rising temperature, resulting in more serious generation overlap, possibly explaining the delayed reaching of its maximum population size.

We also found that the first and end occurrence dates of *B. dorsalis* in China exhibited a slight delay. These findings did not agree with the general prediction that climate warming would lead to the advanced occurrence of insects (Harrington et al. 2001; Robinet and Roques 2010; Raza et al. 2014). Although the environmental temperature was considered as a crucial variable affecting the occurrence of *B. dorsalis* (Vargas et al. 1996; Su et al. 2020), other factors not included in this study such as atmospheric humility, rainfall, sunlight hours, and host plant availability. may also influence the phenology of fruit flies. For example, in Mengzi city, Yunnan province, the population peak date of *B. dorsalis* in different orchards was quite different due to differences in the phenology of host fruits. In peach orchards, *B. dorsalis* first occurred in mid-April, and in mid-March in jujube orchards, while on early-April in loquat orchards (Fang et al. 2017). Moreover, soil moisture, closely related to precipitation and rainfall frequency, was supposed to be an important factor influencing the pupation and emergence of *B. dorsalis* (Duyck et al. 2010). Previous research found it difficult for adults to emerge when soil moisture is more than 30% (Alyokhin et al. 2001). Thus, the observed changes in phenology appear to be caused neither by a general elevation in the overall temperature over time nor by a general response of fruit flies to temperature, but instead by the combined effects of changes in temperature regimes and other environmental variables that influence larval development and/or adult survival.

Additionally, our data in eastern, southern, central, and southwestern China show spatial heterogeneity of phenological responses to climate warming at a regional scale, as was found in previous research concerning three aphid species in Xinjiang, China (Wu et al. 2020). Firstly, the occurrence times of oriental fruit flies varied in different regions in China due to the existing differences in the annual mean temperature in different regions. For instance, the average first appearance date of fruit flies in southern China was around mid-April, while the average first occurrence date in eastern, central, and southwestern China were around late May, mid-late June, and early May, respectively. The data for the other three phenological parameters in different regions in China also suggested geographical variation at a regional scale. Secondly, the long-term trends of population occurrence and dynamic of *B. dorsalis* showed different patterns between four regions in China. For example, the first occurrence of *B. dorsalis* in southern China was slightly ahead of time and their end occurrence date slightly delayed, contrary to that of *B. dorsalis* in southwest China (Table S2). It is possible that this variation may be a real reflection of spatial heterogeneity of the effect of climate warming.

Considering that the phenology of fruit flies is temperature-dependent, there is a possibility that "noise" such as unusual values for the field phenological parameters may be introduced in a long-term data set due to weather anomalies in a specific year. For example, in 2008, the first and end occurrence dates of *B. dorsalis* in central China (data mainly originated from Wuhan city, Hubei province) were notably later than that of other years of this region (Han et al. 2011). According to literature records, low temperatures and heavy snow storms happened at the beginning of 2008 in Wuhan, which may postpone the occurrence of oriental fruit flies. Similarly, frost caused by a strong decreased temperature occurred in the Fujian province of eastern China in 2009. Thus, the first appearance date of *B. dorsalis* was deferred to mid-late August (Lin 2014).

Besides changing the phenology of *B. dorsalis*, a warming climate may facilitate range expansion of this pest and help them invade and colonize new territories (de Villiers et al. 2016). Previous research projected *B. dorsalis* to be capable of invading new territories and establishing persistent populations throughout the tropics and subtropics under predicted future climatic conditions (Stephens et al. 2007; de Villiers et al. 2016). It is worth noting that the time of *B. dorsalis* damage in China has been changed due to rising temperatures, which may result in a mismatch of phenological synchronicity between fruit flies and host plants or nature enemies (Visser 2008, 2017). If the pest emerges early, but the fruit of host plants does not germinate simultaneously, *B. dorsalis* females were finding less developed fruits during their oviposition period and this may have influenced their chances of reproduction (Gordo and Sanz 2005). Alternatively, *B. dorsalis* may shift to new plants for oviposition to maintain the population, expanding the host plant range. Moreover, the shift in fruit flies' occurrence may also influence the original phenological synchronization between pests and parasitoids, helping fruit flies avoid parasitoids' parasitism (Meineke et al. 2014). These are challenges to detecting and suppressing fruit flies in the future.

The long-term effect of climate warming on insects is a pressing issue for science and application. Due to the insufficiency of the long-term dataset, evidence concerning this issue remains limited (Hu et al. 2019; Matsuda et al. 2018). Though collecting a 40 years dataset on *B. dorsalis* population dynamics, this study reveals the long-term effect of climate warming on this notorious pest. It is worth noting that some uncertainty could happen in quantifying time data due to the vagueness of time information extracted from some literature. Thus, careful and thorough data collection, standardization, and careful analyses are essential to minimize the influence of uncertainty of historical literature data. In the future, a more detailed examination of the long-term effect of climate warming on fruit flies and other pests and the construction of a standard detection network are urgently required in China.

Conclusion

This research uncovered the long-term impacts of climate warming on the phenology of *B. dorsalis* in China across large temporal and spatial scales by collecting and analyzing historical data. The results showed that the annual and seasonal mean temperatures of four regions (eastern, southern, central, and southwestern China) infested by *B. dorsalis* have increasing trends at different change rates over the past 40 years. Under climate warming, the first and end occurrence date of *B. dorsalis* in China became later, and the initial growth and peak times of the *B. dorsalis* population were significantly delayed. The phenological date of *B. dorsalis* in eastern, southern, central, and southwestern China suggests spatial heterogeneity of the effect of climate warming at a regional scale. This research provides practical implications for understanding the effects of climate warming on insect pests, and theoretical guidance for future fruit fly pests' prediction and control.

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Author contributions Pumo Cai conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and tables, authored or reviewed drafts of the paper, and approved the final draft. Yunzhe Song collected the data, prepared figures and tables, revised the manuscript, and approved the final draft. Litao Meng analyzed the data, prepared figures and tables, and approved the final draft. Jia Lin collected the data, prepared figures and tables, and approved the final draft. Mengting Zhao collected the data, prepared figures and tables, and approved the final draft. Qingfeng Wu collected the data, prepared figures and tables, and approved the final draft. Chuanpeng Nie collected the data, prepared figures and tables, and approved the final draft. Yanyan Li collected the data and approved the final draft. Qinge Ji conceived and designed the experiments, authored or reviewed drafts of the paper, and approved the final draft. All authors have read and agreed to the published version of the manuscript.

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Data availability The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

Declarations

Competing interest The authors declare no conflict of interest.

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