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Climate warming affects phenology of *Bactrocera dorsalis*: a case study of Fujian and Guangxi, China

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Abstract

Climatic warming is promoting change of a very diverse nature in the biological events of an array of insect species, including alterations in phenology. Based on collected historical data, the potential impacts of climate warming on the phenology of *Bactrocera dorsalis* (Hendel) (Diptera Tephritidae) in Fujian and Guangxi, China were investigated by analysing the four phenological parameters including the date of first occurrence, end occurrence, population initial growth and population peak. Results showed that, during a period of last three decades (1990-2020), the annual and seasonal mean temperatures of Guangxi and Fujian have shown increasing trends at different levels. During these studied periods, the end occurrence date and population peak of *B. dorsalis* in Fujian significantly advanced, and first occurrence of *B. dorsalis* in Guangxi also significantly moved earlier. Pearson correlation analysis suggested that the mean temperature in winter and spring were the key temperature variables affecting the occurrence and population growth of *B. dorsalis* in Fujian and Guangxi, respectively. This research provides valuable implications for understanding the effects of climate warming on insect pests and theoretical guidance for prediction and control of fruit fly pests in the future.

Key words: climate warming, oriental fruit fly, occurrence, population dynamic, phenology.

Introduction

As demonstrated in particular by meteorological observations of rising surface air temperature, environmental warming is a well-established fact, which is expected to have many abiotic and biotic impacts on agricultural ecosystems (Allen *et al.*, 2010). Insects are essentially poikilothermic animals with their physiological processes exhibiting a high level of sensitivity to environmental temperatures. Thus, they are possibly to respond very quickly to elevated temperature, that is, they are also inevitably influenced by global warming (Logan *et al.*, 2003). To date, researches addressing the long-term effects of climate warms on insects have mainly concentrated on butterflies (Roy *et al.*, 2000; Dell *et al.*, 2005), which was considered as good organisms for investigating this environment scientific questions, and other insects species such as dragonflies, damselflies (Hassall *et al.*, 2007; Dingemanse *et al.*, 2008), moths (Martín-Vertedor *et al.*, 2010), aphids (Bell *et al.*, 2015), beetles (Berg *et al.*, 2006), flies and bees (Gordo *et al.*, 2005), due to the existence of adequate phenological records of these species.

The available evidence suggested that environmental warming can speed up the growth, development and the completion of the insect reproductive cycle, resulting in advanced occurrence, longer life cycle and more generations (Raza *et al.*, 2015). For example, several researches concerned the impacts of climatic warming on the life cycle of lepidopterans, broadly suggest that an advanced tendency in the occurrence of adult butterflies and moths, and species-specific alterations in migratory potential (Sparks *et al.*, 2007), altitudinal distribution (Wilson *et al.*, 2007), voltinism (Braune *et al.*, 2008), and population decline (Halsch *et al.*, 2021). In recent paper, Wu *et al.* (2020) demonstrated that three aphid pests including *Myzus persicae* Sulzer, *Aphis gossypii* Glover, and *Sitobion avenae* (F.) in China have advanced their occurrence dates and their migration seasons had been prolonged over recent four decades due to complex effects of rising temperature. One general consensus is that environmental warms might change the fitness and geographical ranges of pest and the interactions of “insect pests -host plants -natural enemies”, and ultimately resulting in the enhancement of crop damage caused by insect pests (Weed *et al.*, 2013; Pureswaran *et al.*, 2018). Therefore, understanding the possible mechanisms induced these changes is becoming increasingly urgent now that gathering evidence is displaying that climate warming can pose spatiotemporal effects on the life-cycle events of insect pests, which is of great significance in both science and application.

As one of fruit fly pests of economic importance, *Bactrocera dorsalis* (Hendel) (Diptera Tephritidae) originated from Asia and is capable of devastating diverse fruit species distributed among 46 different plant families (Vargas *et al.*, 2007). First documented in Hainan island in mainland China in 1934, this polyphagous pest has gradually enlarged its geographical distribution from southern to northern China due to global warming and its excellent ability for rapid reproduction and strong diffusion potential (Cai *et al.*, 2020). So far, this pest has been recorded as causing serious economic losses in more than 10 provinces in China, where it threatens local agricultural industries; in southern China alone, these losses amount to three billion USD every year (Ji *et al.*, 2016). The phenology and seasonal occurrence patterns of this notorious pest have been widely explored in many regions of China, such as Fujian (Zheng, 2013), Guangxi (Sun *et al.*, 2020), Yunnan (Ye *et al.*, 2005; Chen *et al.*, 2007), Jiangxi (Li *et al*., 2019), Guangdong (Lv *et al.*, 2008), and Hubei Provinces (Han *et al.*, 2011). Most of these researches highlighted that local infestation patterns of *B. dorsalis* reportedly reflect local temperatures, that is, the population dynamic of *B. dorsalis* was mainly determined by air temperature (Ye *et al.*, 2005; Chen *et al.*, 2007). Thus, there are of great scientific significance in investigating how this pest have responded to climate warming, in order to facilitate interpretation of how they may occur in future as the development of environmental warms. In India, Jayanthi *et al*. (2011) explored the scope of using weather variables such as temperature, humidity, wind speed and rain and host-plant (*Psidium guajava* L.) phenology variables to develop a comprehensive prediction model for timing *B. dorsalis* activity, which possessing good potential for improving the effectiveness of current IPM programs.

To reduce the damage from *B. dorsalis*, a series of area-wide Integrated Pest Management (IPM) were established, including: (1) field sanitation (Vargas *et al.*, 2010), (2) male annihilation technology (Vargas *et al.*, 2012), (3) sprays of environmentally friendly protein bait (Wang *et al.*, 2021), (4) mass release of sterile insect (Cai *et al.*, 2018a; Zhang *et al.*, 2021), (5) augmentative release of parasitoids (Cai *et al.*, 2017; 2018b; Yang *et al.*, 2018). Moreover, extra control measures have been developed for suppressing the population of *B. dorsalis*, such as chemical insecticides (Zhang *et al.*, 2014), cultural approaches (Klungness *et al.*, 2005) and soil drenches (Stark *et al.*, 2014). Within the background of global warming, the issue that whether the control timeline required some adjustments to fit the shifts of *B. dorsalis* population dynamic across different geographical scales is urgently needed to enhance the control effectiveness to this pest.

However, the long-term impacts of climate warming on the timing of the life cycles of fruit fly pests remained largely unknown due to the lack of long-term historical data related to phenological monitoring. For these species that have no current population monitoring, inspection of historic data from literature may be the important avenue to understand this issue (Sparks *et al.*, 2007; Halsch *et al.*, 2021). Moreover, the collection of past population monitoring data was time-consumed and costly, thus, the full exploitation of these data is highly desirable. Based on our preliminary investigation, the most phenological records of *B. dorsalis* in China have been reported from Guangxi Province and Fujian Province, which giving us a chance to examine spatial heterogeneity of the impact of climate warming across different geographical scales. Located in south China, Guangxi has the subtropical and tropical climate with hot and wet summer and relatively mild winter, while Fujian possesses the subtropical climate with the similar weather condition with Guangxi. Given the favourable conditions, these two provinces are not only the major regions for tropical fruits production and but also the suitable areas for the growth and development of *B. dorsalis*. Making utilization of long-term dataset from literature, this research investigated alterations in phenology of *B. dorsalis* in Guangxi and Fujian Province over last three decades (1990 to 2020). This study quantified the correlation between several phenological parameters (the first and end of occurrence, the initial growth and peak date of population) and seasonal temperature variables (spring, summer, autumn and winter temperature) and tested whether observed changes in phenology are caused by changes in these temperature variables over the years.

Materials and methods

Phenological data

Based on CNKI database (http://www.cnki.net), phenological data of adult *B. dorsalis* in this research were extracted and organized from historical literature. The approach of subject word retrieval was selected, and the common name and Latin name of oriental fruit fly were utilized as subject words. Afterwards, the related literature documented the occurrences, distributions and population dynamics of *B. dorsalis* in Guangxi and Fujian Province were consulted from January 1991 to March 2021 (supplemental material table S1). A total of 36 relevant papers were collected, of which 20 were recorded in Guangxi Province and 16 were recorded in Fujian Province. Up until April 2022, total of 146 valid data were extracted from collected literature. Among these, 51 valid data were recorded in Fujian Province and 95 data were recorded in Guangxi Province (supplemental material tables S2 and S3). The specific time and geographic information on phenophase parameters were extracted and a databank was constructed. All data collection sites derived from the collected literature were georeferenced into geographical maps by the ArcGIS 10.2 (ESRI Inc., Redlands, CA, USA) (supplemental material figures S1 and S2).

The complied data were arranged in terms of four phenophase parameters, which were the most frequently noted indicators in collected articles, including the first occurrence date, the end occurrence date, the population initial growth date and the population peak date. In this study, we defined the time when adult flies were first detected in field as the first occurrence date, the time when no adult flies were detected in field as the end occurrence date, the time when population of adult flies began to grow rapidly as the population initially growth data, the time when the capturing amount of adult flies reached the highest levels in field as the population peak date.

These phenological parameters existed some ambiguous time descriptions in some articles, such as “the beginning (middle or end) of the month”, and “the first (middle or last) ten days”. Therefore, such time information without specific dates were specifically quantified. For instance, the description about and the first, middle, and last ten days of a month were quantified as 5th, 15th, and 25th of that month respectively, and the beginning of a month was quantified as the first day of that month while the end of a month was quantified as the last day of that month. In some articles, the same locations might have different phenological values, and the average of these values was taken as the observation value in this location and used in the analysis.

Temperature data

Meteorological data were available as annual means and seasonal means of temperatures from Guangxi and Fujian Province for the period 1990-2020. Temperature records were obtained from Chinese meteorological websites (http://data.cma.cn/). The trend and process of annual and seasonal temperature changes in Guangxi and Fujian Province were analysed by a simple linear regression method in the past 30 years.

Statistical analysis

All analyses were performed using SPSS for Windows version 20.0 (SPSS Inc., Chicago, IL, USA). A normal examination for all quantified data sets was conducted by Shapiro-Wilk test, which showed that all data sets were under normal distributions. The phenological responses of *B. dorsalis* were analysed by plotting changes of the aforementioned phenological parameters including the date of the first occurrence, the end occurrence, the population increase, and the population peak. Change of days were quantified by calculating the differences (number of days) between the dates of each life cycle parameter recorded in our database and 1 January of that year. For each phenophase parameter, the change of days was taken as the Y-axis, and the occurrence year was taken as the X-axis. Linear regression analysis was utilized to construct regression equations and analyse the trends of the four parameters over time. Additionally, Pearson correlation analysis was performed to verify the correlation between seasonal mean temperature and the phenological parameters of *B. dorsalis*.

Results

Temperature changes in Guangxi and Fujian Province over time

There was a strong warming trend in Fujian Province in the period 1990-2020, the annual mean temperature (referred as AMT hereafter), spring (March-May, referred as SPMT hereafter), summer (June-August, referred as SUMT hereafter), autumn (September-November, AUMT) and winter (December-February, referred as WMT hereafter) all exhibited the significant upward trend with fluctuations. The linear regression analysis indicated that AMT, SPMT, SUMT, AUMT and WMT in Fujian Province increased about 0.04409 ± 0.00653 °C year^{-1}, 0.05352 ± 0.01405 °C year^{-1}, 0.04013 ± 0.00793 °C year^{-1}, 0.05223 ± 0.01076 °C year^{-1}, 0.03713 ± 0.01736 °C year^{-1}, respectively (all $p < 0.05$, figure 1).

In Guangxi Province, significant warming occurred in whole year and seasonal sequences between 1990 to 2020, except WMT. The linear regression analysis indicated that AMT, SPMT, SUMT, AUMT and WMT in Guangxi Province increased about 0.02703 ± 0.00693 °C year^{-1}, 0.04393 ± 0.0131 °C year^{-1}, 0.02624 ± 0.00664 °C year^{-1}, 0.0259 ± 0.01047 °C year^{-1} (all $p < 0.05$), 0.01774 ± 0.02167 °C year^{-1}, respectively (figure 2).

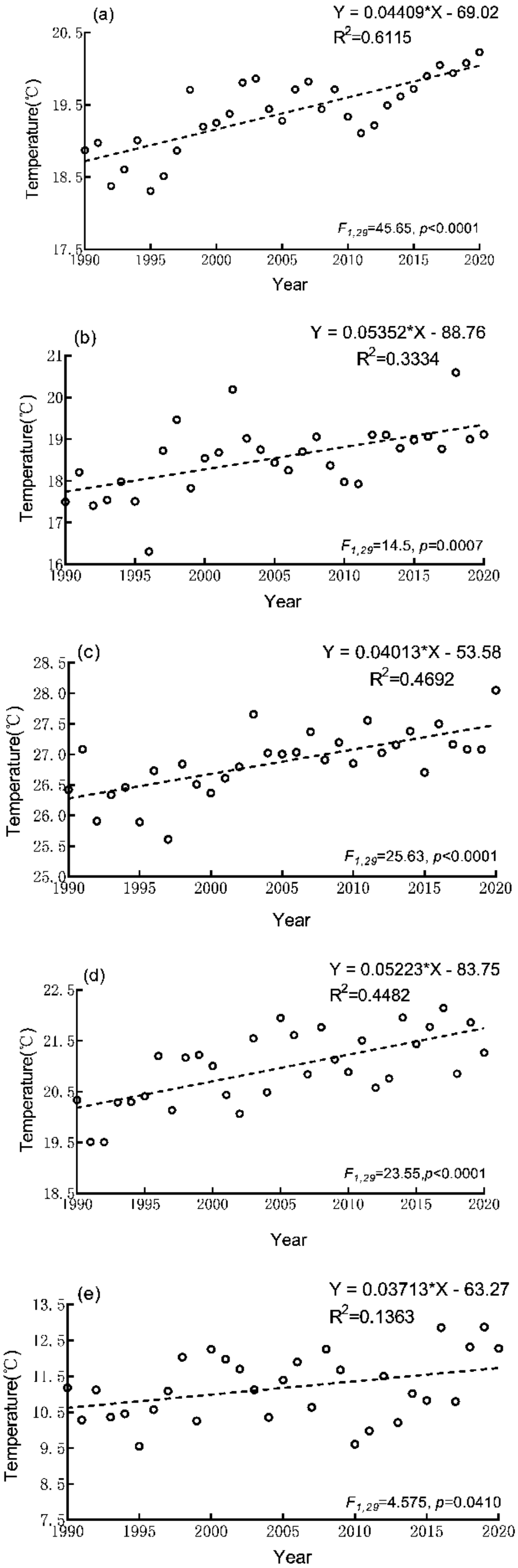

Figure 1. Temperature rise pattern during the last three decades at Fujian Province, China: (**a**) annual mean temperature; (**b**) spring mean temperature; (**c**) summer mean temperature; (**d**) autumn mean temperature; (**e**) winter mean temperature. The small circle indicates temperature record in a specific year and the dashed line represents the trend of temperature change.

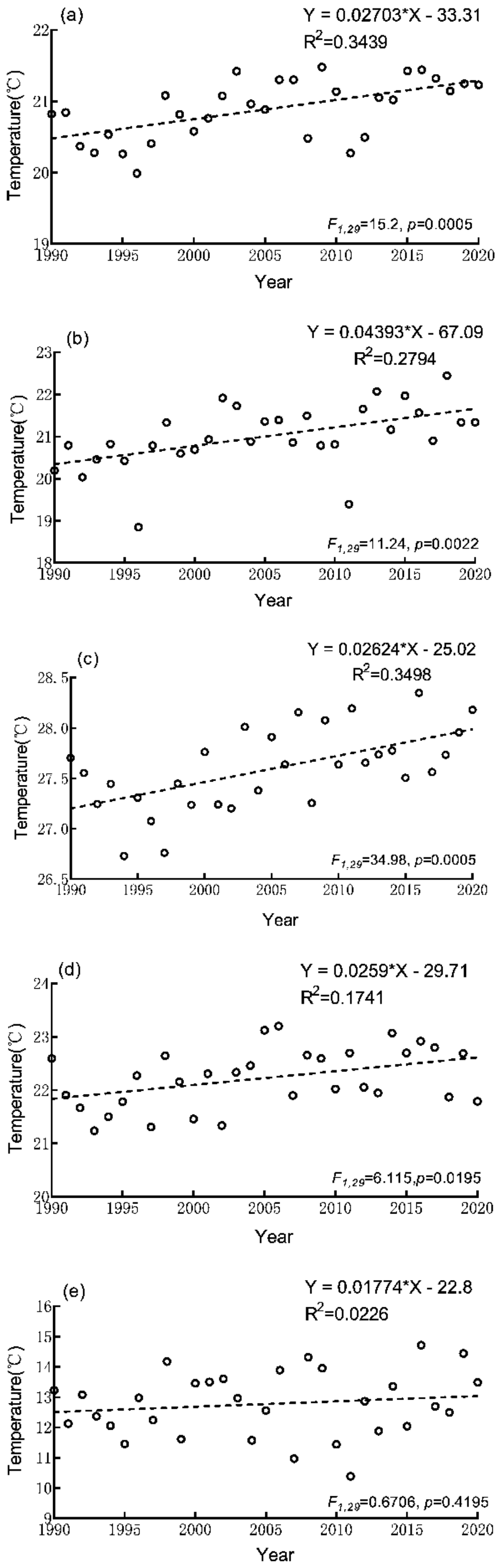

Figure 2. Temperature rise pattern during the last three decades at Guangxi Province, China: (**a**) annual mean temperature; (**b**) spring mean temperature; (**c**) summer mean temperature; (**d**) autumn mean temperature; (**e**) winter mean temperature. The small circle indicates temperature record in a specific year and the dashed line represents the trend of temperature change.

Temporal trend of *B. dorsalis* population phenology in Fujian and Guangxi

As shown in figure 3ac, the first appearance and population initial growth of *B. dorsalis* in Fujian Province followed an upward tendency over the years, indicating that the date of first occurrence and population initial growth of oriental fruit flies moved later by 8.947 ± 6.19 days year^{-1} and 2.999 ± 1.607 days year^{-1}, respectively. The alterations of the first occurrence date and population initial growth date of *B. dorsalis* in Fujian Province were not statistically significant, while the end occurrence date and population peak date were significantly advanced, and the change rates varied by −13.66 ± 2.411 days year^{-1}

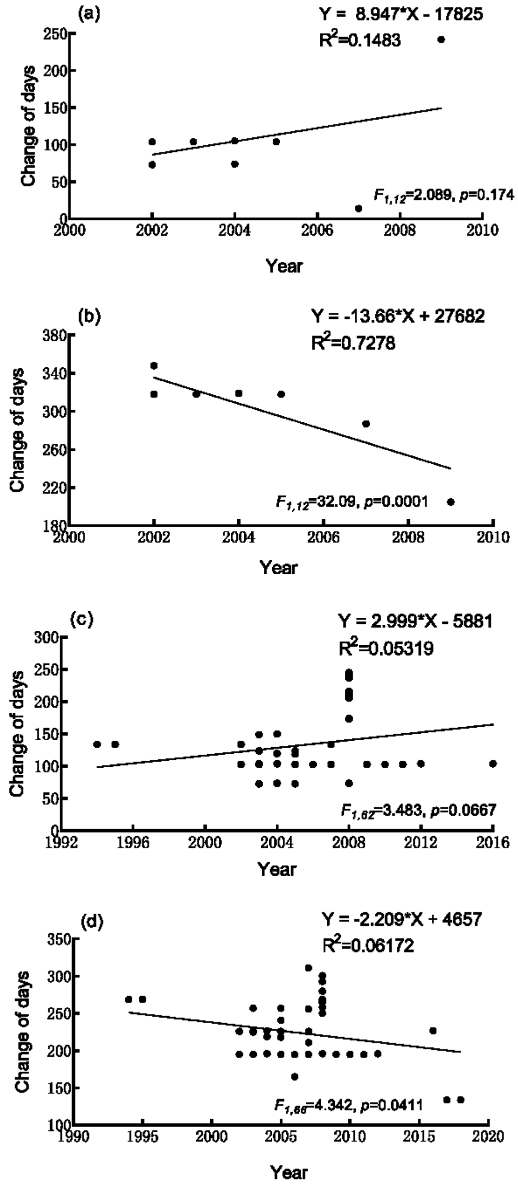

Figure 3. Linear regressions between population phenological parameters [first occurrence date (**a**), end occurrence date (**b**), population initially growth date (**c**) and population peak date (**d**)] and time (years) for *B. dorsalis* in Fujian Province. The solid lines represent the changing trends of the phenophase parameters and the dots indicate different phenological records.

and −2.209 ± 1.06 days year^{-1}, respectively (figure 3bd).

Based on the collected long-term historical data, the time of first occurrence, end occurrence date, population initially growth date and population peak of *B. dorsalis* in Guangxi Province both shown advanced tendencies at different levels, with the changing rates of −8.226 ± 0.8725 days year^{-1} (figure 4a), −2.011 ± 0.4658 days year^{-1} (figure 4b), −0.7734 ± 0.9228 days year^{-1} (figure 4c) and −0.5195 ± 0.4152 days year^{-1} (figure 4d), respectively. In this area, only the first appearance advancements of *B. dorsalis* were statistically significant, while another three phenological parameters were not significant.

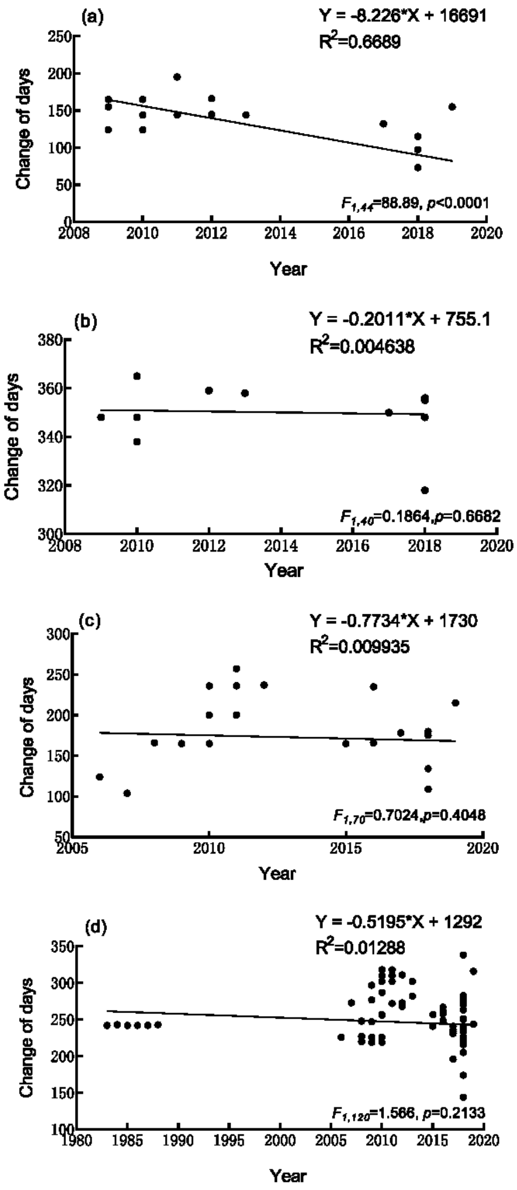

Figure 4. Linear regressions between population phenological parameters [first occurrence date (**a**), end occurrence date (**b**), population initially growth date (**c**) and population peak date (**d**)] and time (years) for *B. dorsalis* in Guangxi Province. The solid lines represent the changing trends of the phenophase parameters and the dots indicate different phenological records.

Response of *B. dorsalis* phenophase to seasonal temperature

As a result, the date of the initial growth of oriental fruit fly population in Fujian was significantly negatively correlated with the summer mean temperature (Pearson correlation coefficient = −0.2949, p = 0.0180) and significantly positively correlated with winter mean temperature (Pearson correlation coefficient = 0.4564, p = 0.0002, figure 5a). Moreover, there is a significant positive correlation between winter mean temperature and population peak date (Pearson correlation coefficient = 0.3016, p = 0.0131, figure 5a). In Guangxi Province, the date of the first occurrence of *B. dorsalis* population was significantly negatively correlated with spring mean temperature (Pearson correlation coefficient = −0.8233, p < 0.0001) and significantly positively correlated with autumn mean temperature (Pearson correlation coefficient = 0.6666, p < 0.0001, figure 5b). Furthermore, there were significant negative correlations between spring mean temperature and the date of population growth (Pearson correlation coefficient = −0.3874, p < 0.0001) or population peak (Pearson correlation coefficient = −0.2883, p = 0.0013, figure 5b).

Discussion

Global climate change is currently undeniable fact, involving simultaneous and complicate alterations of many environmental factors, especially increasing surface air temperature (Robinet *et al.*, 2010). This research corroborated that the occurrence of an apparent trend towards environmental warming in two provinces heavily infested by *B. dorsalis* in China, with increases in annual temperature of 1.3598 ℃ (Fujian) and 0.4085 ℃ (Guangxi) throughout the last three decades (1990-2020). Furthermore, the seasonal mean temperatures of these two provinces exhibited similar increasing trends. Under the context of environmental warming, the date of end occurrence and population peak of *B. dorsalis* in Fujian Province moved significantly earlier and the time of first occurrence of *B. dorsalis* in Guangxi Province became significantly earlier. Our findings were well in line with the general prediction which expressed that climate warming would result in the advancement of the phenology of insect groups (Harrington *et al.*, 2001; Robinet *et al.*, 2010; Raza *et al.*, 2015).

This observed advancement appears to have been caused by the interplay of complicate impacts of temperature regimes on the timing of the life-cycle events of fruit fly adults and the complex alterations in the temperature regimes of these two provinces. Previous research has demonstrated that influences of temperature regimes were complex because spring, summer, autumn and winter temperature had both quantitatively and qualitatively different effects on the insect phenology (Dingemanse *et al.*, 2008). Pearson correlations analysis in present study indicated that the first occurrence, initial growth and population peak of *B. dorsalis* in Guangxi Province had a significantly negative correlation with spring mean temperature, while the initial growth and peak of *B. dorsalis* population in Fujian Province had a significantly positive

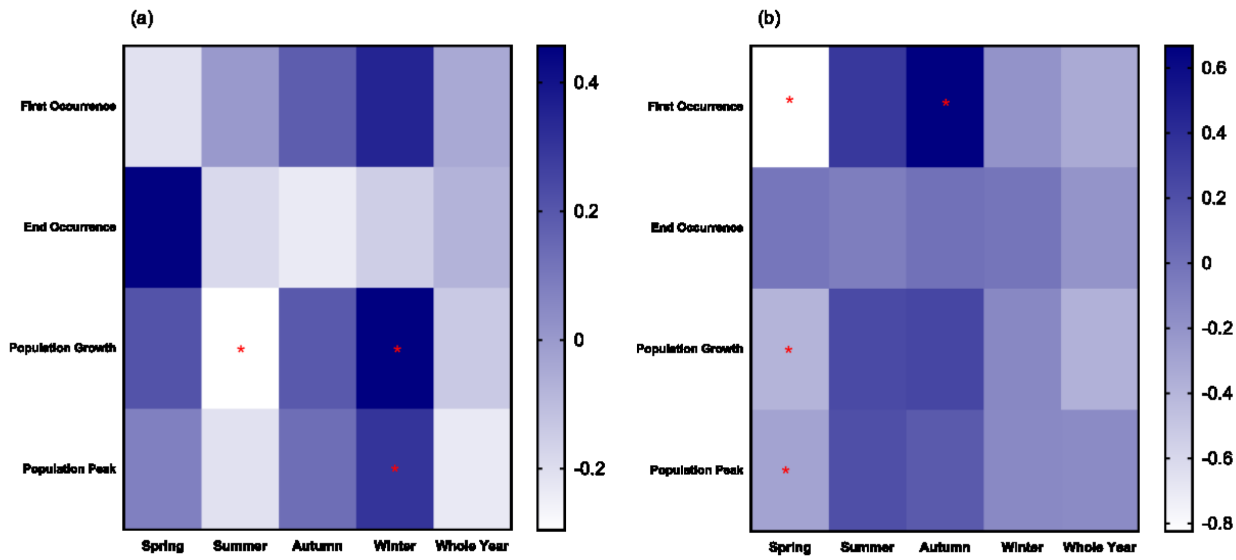

Figure 5. The correlations between the phenological parameters of *B. dorsalis* and temperatures in Fujian (**a**) and Guangxi (**b**) Province. The red asterisk indicated the Pearson correlations were significant at the levels of $p < 0.05$.

correlation with winter mean temperature. Increased spring temperatures advanced the first occurrence of *B. dorsalis* in Guangxi Province, which is possibly to have resulted from elevated springtime temperatures accelerated the preimaginal development, consequently allowing the pupae to emergence at an earlier date. Together with advanced first occurrence, there is a concurrent advancement of population initial growth and population peak date. However, winter warming retarded the date of population initially growth and peak of *B. dorsalis* in Fujian Province. Winter temperature might not directly influence the phenology of *B. dorsalis* in the focal year because adult flies were very difficult to detect during winter season in these two provinces, whereas reductions in winter chilling tend to enhance the amount of thermal requirement subsequently for insect emergence (Forrest *et al.*, 2011; Stålhandske *et al.*, 2016), thus postponing their phenology in the following year.

Moreover, this research also revealed that the first occurrence dates and population initial growth dates of *B. dorsalis* in Fujian Province showed slight postponement. Besides ambient temperature, which was regarded as a key factor influencing the occurrence of *B. dorsalis* (Vargas *et al.*, 1996; Sun *et al.*, 2020), other abiotic and biotic variables like atmospheric humility, rainfall, sunlight hours, host plant availability, natural enemies etc. may also affect the phenology of fruit flies. For instance, in Yulin city, Guangxi Province, the times of *B. dorsalis* population peak in different orchards were quite different due to differences in the phenology of host fruits. In lemon (*Citrus limon* L.) orchards, *B. dorsalis* population peaked on late-May, while on late-August in longan orchards (*Dimocarpus longan* Lour.) (Huang *et al.*, 2021). Additionally, soil moisture, closely related to the frequency of precipitation, was considered as an important factor affecting pupation and emergence of *B. dorsalis* (Duyck *et al.*, 2006). Alyokhin *et al.* (2001) indicated that when soil moisture was more than 30%, *B. dorsalis* would fail to emerge from pupae. The observed changes in phenology appears to be caused neither by a general elevation in the overall temperature over times 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 (Dingemanse *et al.*, 2008). Thus, other factors not included in this research might modify the impact of climate change towards insect phenology to some degree.

Moreover, our data in these two provinces in China have suggested that spatial heterogeneity of phenological responses to climate warming at a regional scale, as was also found in a previous research concerning three aphid species (*M. persicae*, *A. gossypii*, and *S. avenae*) in Xinjiang, China (Wu *et al.*, 2020). Firstly, due to the differences of the annual mean temperature in different regions in China, the field phenophase of oriental fruit flies in these two provinces existed differences. For instance, the mean population peak date of fruit flies in Guangxi was around early September, while that of in Fujian were around mid August. The data for the other three phenological parameters in these two provinces also suggested geographical variation. Secondly, the long-term changing trends of population dynamic of *B. dorsalis* displayed different patterns between these two provinces. For example, tested four phenological parameters in Guangxi were became earlier, while the first occurrence and population initial growth of *B. dorsalis* were slightly delayed.

Climate warming not only could change the phenology of *B. dorsalis*, but also could enlarge their distributions and facilitate this insect pest to invade and colonize new territories (Liu *et al.*, 2019), which are the challenges for detecting and suppressing fruit flies in the future. Understanding the long-term effect of climate warming on insects is an urgent question that is significant in both science and application. Not only may the pest problems alter in response to climate change, but the effectiveness of prevention and control measures may also adjust (Harrington *et al.*, 2001). The control timeline in these two regions may need some modifications in the future to satisfy the alteration of *B. dorsalis* population occurrence dynamics under nature conditions. Due to the lack of long-term dataset, evidence related to this issue is still limited (Matsuda *et al.*, 2018; Hu *et al.*, 2019). It is worth noting that certain uncertainty could occur in the process of quantification of time data due to the vagueness of time information mentioned in some literature. Therefore, careful and thorough data collection, standardization, and cautious analyses are essential to minimize the influence of uncertainty in such historical literature data. In the future, a more elaborated examination of the long-term effect of climate warming exert on fruit flies and other pests and the construction of standard detection network are urgently needed in China.

Conclusion

By collecting and analysing the historical data of *B. dorsalis* in two provinces from China, this study revealed the long-term impacts of climate warming on phenology of this pest across large temporal and spatial scales. Results exhibited that the annual and seasonal mean temperatures of Guangxi and Fujian have shown increasing trends at different change rates over the past three decades. Under the situation of climate warming, the end occurrence date and population peak of *B. dorsalis* in Fujian significantly advanced, and first occurrence of *B. dorsalis* in Guangxi also significantly moved earlier. This study proves the value of historical literature data for revealing temporal and spatial impact of climate warming on insect phenology, and provides valuable implications for future monitoring, prediction and prevention of insect pests.

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