

# Modeling the Ecological Niche of *Bactrocera Carambolae* Drew & Hancock (Diptera: Tephritidae) for Climate Change Scenarios

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## Research Article

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# Abstract

*Bactrocera carambolae* Drew & Hancock (Diptera: Tephritidae), is a significant pest in fruit farming, native to Asia. To assess the impact of climate change on the global distribution of *B. carambolae* at the end of the twenty-first century, an ecological niche model of the pest species was developed. Using the CLIMEX modeling software, suitable habitats for *B. carambolae* were mapped under current (2022) and future (2100) climate conditions, considering a 3°C increase in global temperature by 2100. The model was developed based on the climate parameters that the pest species tolerates and was projected for the world. The results highlighted that part of the tropics will be climatically suitable for the carambola fruit fly in a future scenario, including Central and South America, Sub-Saharan Africa, the coast of Australia, and Asian countries. However, the areas suitable for the species will be reduced, according to the model, compared to the suitability in 2022. This result reflects the importance of cold stress that will affect the pest in the cold seasons of the year. Therefore, monitoring the areas where the pest is not present should also consider the impacts of global climate changes on the potential geographic distribution.

## INTRODUCTION

According to diverse organizations, including the World Health Organization (WHO), climate changes and global warming are the biggest challenges for humanity in the twenty-first century because they threaten all aspects of life, World Health Organization (2018). Climate changes have been described as transformations in the temperature and climate patterns in general that occur gradually over time and can occur in a natural manner and/or under the effects of human activity, El-Sayed & Kamel (2020). Therefore, global warming is a consequence of these climate changes, indicating that the temperature of the Earth is increasing, Robinson (2020).

Since the time of the Industrial Revolution, in the middle of the 1800s, human activity has intensively shared in increasing the temperature of the planet, mainly due to the burning of fossil fuels, Conti (2011). Deforestation, landfills, industries, means of transportation moved by fossil fuels, and crop and livestock raising are some of the main sources of methane greenhouse gas emissions, contributing to climate changes, Albritton & Dokken (2001). As a result, the Earth continues to warm, with an increase of 1.1°C recorded from 2011 to 2020 in relation to the temperature at the end of the nineteenth century, Nações Unidas Brasil 2022. Perspectives for coming years indicate that the temperature of the Earth may increase from 1.6 to 6.0°C (Albritton & Dokken 2001; Jiménez-Clavero 2012; Masson-Delmotte et al. 2018; Nações Unidas Brasil 2022).

The Intergovernmental Panel on Climate Change (IPCC) indicates that the warming of the planet in 2100 will likely be from 1.5 to 4°C above the pre-industrial levels, Masson-Delmotte et al. (2018). The CSIRO-Mk3 global climate model considers a future of rapid economic growth, low population growth, and an increase in greenhouse gas emissions up to 2050. From 2050 to 2100, an increase in the use of predominantly clean energy sources is projected and, consequently, reduction in the emission of

pollutant gases. Thus, the projection results in an increase of 2.1°C in global temperature up to 2100 (Gordon et al. 2002).

Among the consequences of this increase in global temperature are intense droughts; large wildfires; water shortages; melting of polar ice sheets, which results in an increase in sea level, flooding, and catastrophes; and, finally, a decline in biodiversity, Qin et al. (2019). Therefore, the pressure of insect pests and of diseases will likely increase, reducing yield in many regions, Masson-Delmotte et al. (2022).

In addition, the natural spread of insects may be affected by changes in the environment, whether caused by climate changes or changes in the composition of the agroecosystem, resulting in possible introductions of new pest species (Sutherst et al. 2007; Garrett et al. 2013). These environmental changes are expected to affect even the balance between biological control agents and their hosts and prey, and may affect natural biological control, as well as an applied biological control (Guisan et al. 2013). Therefore, understanding the response of insect pests in the face of climate changes is important for planning control strategies, considering local, regional, and global scales, projecting attack scenarios and thus implementing preventive measures (Ehrlén & Morris 2015; Nurhayati & Koesmaryono 2017).

A prominent pest in fruit farming is the carambola fruit fly, *Bactrocera carambolae* Drew & Hancock (Diptera: Tephritidae), which is one of the most destructive and polyphagous species of fruit flies, with more than 100 species of host plants already reported (Danjuma et al. 2014). Citrus fruits are good hosts for fruit flies, and these plants are grown in more than 140 countries (Louzeiro 2017). Brazil, the USA, India, Mexico, and Spain together produce more than two-thirds of the worldwide total of citrus crops and derivatives (Lv et al. 2015). China is the largest worldwide producer of fruit, especially citrus fruit, apple, pear, grape, and banana, AQSIQ Association 2007, and some of these types of fruit are hosts of *B. carambolae*. In addition, many types of fruit-bearing plants, such as carambola, *Averrhoa carambola* L.; guava, *Psidium guajava* L.; and mango, *Mangifera indica* L., are grown throughout the world, and their fruit is suitable for the development of *B. carambolae* (Iwaizumi 2004; Danjuma et al. 2014; Fujii et al. 2016; Koswanudin et al. 2018).

In general, an increase in global temperature may modify the environment so as to become suitable for *B. carambolae*, creating problems due to the spread of the pest (Marchioro 2016). Considering current (2022) conditions, species of *Bactrocera* spp. do not find good climate conditions, due to low temperatures recorded in the winter in Chinese production regions, for example. However, the increase in global temperature may expand the ecological niche of this pest species, as well as of other fruit fly species, (Biosecurity Australia 2009).

Thus, the aim of this study was to project the future (2100) geographic distribution of *B. carambolae*, considering modifications of the climate brought about by climate change. For that purpose, ecological niche models (ENM) were used to consider the impact of climate change on the potential future spread of the species (Araújo & Peterson 2012; Giannini et al. 2017; Silva et al. 2018) and also to evaluate the possible establishment of exotic species (Jiménez-Valverde et al. 2011; Silva et al. 2018).

## MATERIAL AND METHODS

Evaluation of climate suitability for *B. carambolae* throughout the world, considering a future scenario for 2100, was based on current climate conditions (reference year 2022). CliMond 10' was used in that evaluation, collecting five climate variables in the period of 1950 to 2000. The following variables were used: mean monthly minimum temperature (Tmin), mean monthly maximum temperature (Tmax), mean monthly precipitation (Ptotal), and relative humidity at 9:00 a.m. (RH09:00) and at 3:00 p.m. (RH15:00), Kriticos et al. 2012. To make estimates, the scenario proposed by the Intergovernmental Panel on Climate Change (IPCC) was used as a basis, where no reduction in net radiation emitted was considered, but an increase of 3°C in worldwide temperature in 2100 (Masson-Delmotte et al. 2018).

Using the CLIMEX software, with the function and the modeling suitable for *B. carambolae*, the current (2022) scenario was considered, using the climate parameters that best represent the known distribution of the species (Table 1).

Table 1  
Description of the climate parameters of CLIMEX and values used for *Bactrocera carambolae* Drew & Hancock (Diptera: Tephritidae)

| Index            | Parameter                    | Abbrev. | Values | Unit    |
|------------------|------------------------------|---------|--------|---------|
| Temperature      | Lower limit of temperature   | DV0     | 11.2   | °C      |
|                  | Optimal lower temperature    | DV1     | 25     | °C      |
|                  | Optimal upper temperature    | DV2     | 27     | °C      |
|                  | Upper limit of temperature   | DV3     | 35     | °C      |
| Soil moisture    | Lower limit of soil moisture | SM0     | 0.1    | A       |
|                  | Optimal lower soil moisture  | SM1     | 0.5    | A       |
|                  | Optimal upper soil moisture  | SM2     | 1      | A       |
|                  | Upper limit of soil moisture | SM3     | 1.5    | A       |
| Stress – Cold    | Temperature threshold        | TTCS    | 11     | °C      |
|                  | Stress accumulation rate     | THCS    | -0.012 | Week-1  |
|                  | Degree day threshold         | DTCS    | 10     | °C days |
|                  | Stress accumulation rate     | DHCS    | 0      | Week-1  |
| Stress – Heat    | Temperature threshold        | TTHS    | 36     | °C      |
|                  | Stress accumulation rate     | THHS    | 0.005  | Week-1  |
| Stress - Drought | Soil moisture threshold      | SMDS    | 0,1    | A       |
|                  | Stress accumulation rate     | HDS     | -0.024 | Week-1  |
| Stress - Water   | Soil moisture threshold      | SMWS    | 1.5    | A       |
|                  | Stress accumulation rate     | HWS     | 0.007  | Week-1  |
| Degree days      | Degree days per generation   | PDD     | 371.4  | °C days |

The parameters provided information in respect to the response of the species in relation to climate variations and were obtained in the scientific literature available for carambola fruit fly and for other species of the genus *Bactrocera*. However, some parameters that were not located in the domains consulted were estimated empirically, using tests on the model until all known points of location were included. The points of real occurrence of *B. carambolae* are available on international data bases that aim at disseminating information on the species.

After developing the projection model for the current scenario, an increase of 3°C was included for temperature across the globe to be able to predict the geographic distribution of the carambola fruit fly under these “new” environmental conditions. We considered that the biological parameters of the pest

species in regard to its response to the climate did not change or had minimal change up to the year 2100.

In addition, for the results to be more representative, an irrigation scenario was added, where the water application depth was established at  $2.5 \text{ mm.day}^{-1}$  for regions where there is irrigation (GMIA5) (Siebert et al. 2005). For the other locations, only the rainfall scenario was considered.

## RESULTS

Potential geographic distribution for *B. carambolae* in 2100, based on the Ecoclimatic Index (EI), indicates that there will be a reduction in the areas suitable for the species compared to projections of distribution in the current (2022) scenario.

The increase of 3 °C in global temperature as a result of climate changes is expected to bring about greater suitability for *B. carambolae* in the northwest part of South America and in Central America (Fig. 1). On the African continent, the Sub-Saharan region remains environmentally suitable, especially at the coast. The biggest changes were observed in Asia and in Oceania, where the suitable areas will likely decline, although most of the countries currently suitable maintain the perspective of remaining suitable in 2100, with a lower EI and fewer marked areas (Fig.1). The coast of Australia remains suited to development of the carambola fruit fly, though at fewer points and with an EI considered low (Fig.1). Asian countries, from which the species originated, also remain favorable for it, though with reduction in the level of suitability and in points of probable occurrence. It is estimated that continental India will have a considerable reduction in areas suitable for *B. carambolae* in 2100, as well as Myanmar, Thailand, and some islands of the Indian Ocean (Fig. 1).

Fig. 1 Ecoclimatic Index (EI) for *Bactrocera carambolae* Drew & Hancock (Diptera: Tephritidae) modeled in a global manner by CLIMEX in a climate change scenario (increase of 3 °C)

The reduction in the areas climatically suitable for this pest is due to the increase in temperature in the tropical and subtropical zones; however, an increase in the suitable zone was not observed for equatorial regions. This response is likely due to a more rigorous winter in the regions near the poles, which would hinder the establishment of the carambola fruit fly.

However, the growth index (GI), which corresponds to the potential for population growth of the species considering the reproduction of at least one generation, indicates that many areas will become suitable for population growth of *B. carambolae* by the end of the twenty-first century (Fig. 2). However, the GI estimates only the most favorable season or period of the year, not taking the hot, cold, dry, or wet periods into consideration.

With the scenario of climate change resulting in global warming of 3 °C, many countries previously unsuitable for establishment of the pest will come to have areas prone to the establishment of *B. carambolae* (Fig. 2). In the Americas, increased probability is observed in a large part of the United

States, Canada, Chile, and Argentina, areas where the limiting factor for the carambola fruit fly is the cold in some period of the year (Fig. 2). The same occurs in European countries, which exhibited high GIs (Fig. 2).

Fig. 2 Growth index (GI) for *Bactrocera carambolae* Drew & Hancock (Diptera: Tephritidae) modeled in a global manner by CLIMEX in a climate change scenario (increase of 3 °C)

To explain the high GI in these areas, the cold stress, heat stress, drought stress, and water stress indexes should also be analyzed. These stress indexes limit the population growth of the carambola fruit fly in these regions. Many points where the growth index is observed in the ideal scenario coincide with points of cold stress (Fig. 3), indicating that cold is a limiting factor for *B. carambolae*.

The highest levels of cold stress (CS) were expressed in regions of Europe, North America, the south of Africa, the south of Australia, and the south and west of North America (Fig. 3). That explains why the population of *B. carambolae* does not find good environmental suitability in these regions, even with the rise of possible new habitats brought about by global warming.

Fig. 3 Cold stress (CS) index for *Bactrocera carambolae* Drew & Hancock (Diptera: Tephritidae) modeled in a global manner by CLIMEX in a climate change scenario (increase of 3 °C)

The heat stress (HS) index estimates the areas when the heat will be a limiting factor in 2100 during at least one period of the year (Fig. 4). This index explains the lack of suitability for carambola fruit fly in the north of Africa and regions of large deserts, just as in the desert part of North America and of Australia (Fig. 4), characterized by high temperatures.

Fig. 4 Heat stress (HS) index for *Bactrocera carambolae* Drew & Hancock (Diptera: Tephritidae) modeled in a global manner by CLIMEX in a climate change scenario (increase of 3 °C)

The dry stress (DS) index indicates the regions where the lack of water in the soil may affect the survival of *B. carambola* at the end of the twenty-first century (Fig. 5). The points with higher DS coincide with desert regions, where the moisture is extremely low, and they are not areas of fruit production (Fig. 5).

Fig. 5 Drought stress (DS) index for *Bactrocera carambolae* Drew & Hancock (Diptera: Tephritidae) modeled in a global manner by CLIMEX in a climate change scenario (increase of 3 °C)

However, points with a light to moderate drought stress index are found in regions where the carambola fruit fly already occurs, as in Asian countries (Fig. 5), indicating that in some period of the year, the lack of water will be a limiting factor for this species of fruit fly in other regions (countries) considered suitable. It should be emphasized that known irrigated areas were considered; nevertheless, the increase in new production areas with irrigation may change the result of DS, because it would increase the moisture in periods in which drought stress would be fatal under natural conditions.

The water stress (WS) index identifies excess water in the soil; excess water makes it difficult for the pest to enter the soil during the pupal stage. Even so, studies indicate that *B. carambolae* can transform itself into pupae above the soil under high moisture conditions (Danjuma *et al.* 2014). Therefore, this stress index does not have the greatest impact on the establishment of *B. carambolae*. A low level of water stress is seen for the world in 2100 (Fig. 6).

Fig. 6 Water stress (WS) index for *Bactrocera carambolae* Drew & Hancock (Diptera: Tephritidae) modeled in a global manner by CLIMEX in a climate change scenario (increase of 3 °C)

## DISCUSSION

Climate change is related to extreme climate events, such as droughts and flooding, and it impacts the global ecosystem, including sea level increase, Lee (2010), and change in agricultural production areas and distribution of species (Pearson & Dawson 2003; Kwak *et al.* 2008). Plant pathogens and arthropod pests are among the first indicators of the effects of climate changes because of their population and growth characteristics, and they may increase their range and cause damage to means of human subsistence (Gullino *et al.* 2022). It is estimated that in the United States, around 13 billion dollars in agricultural production is lost due to the invasion of exotic insect pests, and in Europe, this loss can exceed 20 billion euros per year (Pellicciotto *et al.* 2012).

To predict the response of populations of insect pests in the face of climate changes, a common approach is ecological niche modeling for future scenario (Jiménez-Valverde *et al.* 2011; Giannini *et al.* 2017; Silva *et al.* 2018). Studies involving modeling of climate change scenarios often show an increase in the niche projections of exotic pests (Bradley *et al.* 2010; Duursma *et al.* 2013). An example of this is the study for modeling the future distribution of *Bactrocera zonata* (Saunders) (Diptera: Tephritidae), a noxious species that causes damage to fruit-bearing plants in Asia and threatens many countries located along or near the Mediterranean Sea. The climate mapping program, CLIMEX 3.0, was used to model the current and future potential geographic distribution of *B. zonata*. Climate change scenarios for 2070 indicate that the potential distribution of *B. zonata* will expand in the direction of the poles into areas that currently are considered cold (Ni *et al.* 2012).

CLIMEX was also used to model the potential global distribution of another species of fruit fly, *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae), in current and future climate scenarios. The oriental fruit fly, *B. dorsalis*, is a significant pest throughout Southeast Asia and on various Pacific islands, with wide distribution, invasive ability, and potential impact on access to import markets. In a future climate scenario, as affected by climate changes, the potential global range for *B. dorsalis* is projected to extend even more in the direction of the poles as the limits of cold stress diminish. However, the potential interval contracts in areas where precipitation is projected to substantially decline, indicating that low soil moisture could be quite a limiting factor (Stephens *et al.* 2007).

The results obtained show that global climate suitability for *B. carambolae* will likely decline significantly in many regions of the world in the face of the effects of climate changes. There are studies for climate

change scenarios in India for the species *Bactrocera papayae* (Drew & Hancock) (Diptera: Tephritidae) and *B. dorsalis* using the CLIMEX software that corroborate the results of the present study. These studies foresee gradual reduction in climate suitability for both species due to the increase in various stress factors (Sridhar *et al.* 2014; Sridhar *et al.* 2017). It is estimated that for *B. dorsalis*, Central and Western India become progressively less suitable by 2030 and 2050, and completely unsuitable by 2090. In the south of India, there will be a slight reduction in climate suitability for the pest over the years, but the northeast of that country, in contrast, will become highly suitable by 2090 (Sridhar *et al.* 2014). For *B. papayae*, the climate similarity for establishment of the species also fell gradually throughout the country with the increase in temperature of 3 °C, except in the states of Karnataka and Maharashtra (Sridhar *et al.* 2017). The modeling of the ecological niche of *B. carambolae* estimates that its response is the same as expected for *B. papayae* and *B. dorsalis* for India, with reduction in climate suitability for most of the country. The state of Karnataka is an exception, because it shows high suitability for carambola fruit fly, *B. carambolae*, and for *B. papayae*.

A large part of Central America and South America, Africa, Asia, and Oceania, which currently (2022) have climate suitability, should remain suitable in the future (2100) in the scenario of a 3 °C increase in global temperature. However, the level of suitability, indicated by the ecoclimatic index, declined throughout the world. Locations with high environmental suitability are projected to have moderate to low suitability. This reduction may be related to the increase in drought stress, considering the projection of reduction in rainfall of around 14% up to 2100 and, consequently, an increase in evaporation, Gordon *et al.* (2002), as well as an increase in heat stress due to warming of the planet.

Drought stress or dry stress occurs from reduction in soil moisture and relative humidity, which works against mating, oviposition, the viability of pupae, and the emergence of fruit fly adults, Vayssières *et al.* 2009. Heat stress can cause temporary or permanent aestivation, impeding the insects from performing their normal activities, such as feeding and reproduction. For *B. carambolae*, aestivation occurs as of 35 °C, a temperature at which emergence of adults was not observed, Danjuma *et al.* 2014. Thus, global warming works against the incidence of the species in equatorial and tropical regions where the temperature easily reaches 30 °C under current (2022) conditions and is expected to increase by 3 °C up to 2100, Bastos & Ferreira 2000.

For temperate regions, cold stress is indicated as the main factor limiting the establishment of carambola fruit fly, even with a 3 °C increase in temperature. This is owing to the temperatures being so low, especially in the winter, that even with the foreseen increase in global temperature, they will not yet be favorable for the species.

Certainly, the occurrence of *B. carambolae*, just as of other species of the genus, will remain associated with the intertropical zone, where it is estimated that the climate conditions will remain favorable in 2100. Although the future projection models involving other species of *Bactrocera* appear divergent, one must take into consideration that the stress factors are variable, considering each species, and that the projections for the climate change scenarios used in the studies are not standardized.

It should be noted that in the present study, the effect of irrigation on the current scenario was evaluated, without which many crops would not be possible in some regions. Irrigation excludes the water limitation, creates suitable microclimates, and makes the growing of host plants possible, allowing the persistence of fruit flies in areas in which they might not exist without irrigation (Sutherst & Yonow 1998). In that case, it is possible that the projections of suitability presented may undergo modifications if irrigation is not considered. In addition to climate, other factors can affect occurrence of the species, such as the seasonality of the host fruits, the presence of natural enemies, and the use of control measures and eradication programs. Modeling of the future ecological niche of *B. carambolae* based on the climate carries information that guides the development of strategies for containing the pest throughout the world. Modeling can assist in the formulation of strategies for controlling the advance of the pest to regions where it does not yet occur, collaborating with the implementation or exclusion of quarantine barriers.

## Declarations

### 8. FUNDING DECLARATION

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### 9. AUTHOR CONTRIBUTIONS

Luiza N. Braga; Ruan Carlos de M. Oliveira and Patrik L. Pastori performed the experiments, analyzed the data, prepared figures and tables. Luiza N. Braga and Ruan Carlos de M. Oliveira conducted the statistic, data analysis. All authors analyzed the data, reviewed drafts, contributed to reviews critically the manuscript and approved the final version.

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## Figures

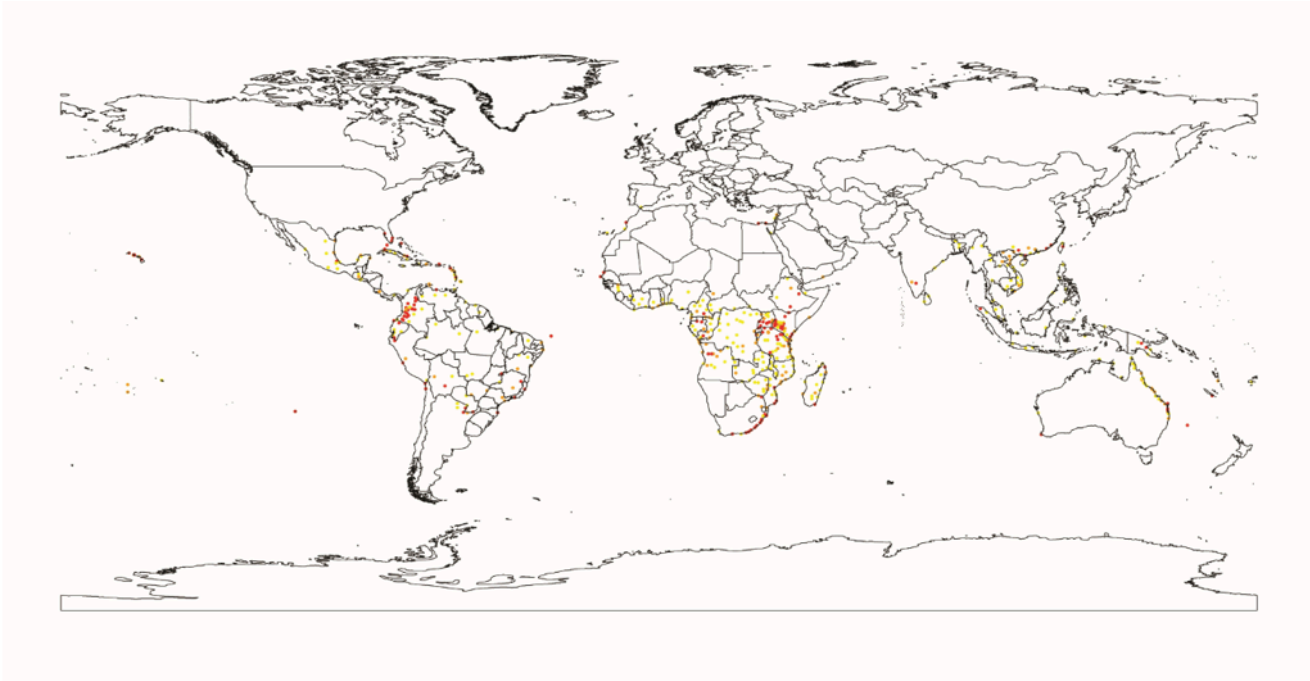


**Figure 1**

Ecoclimatic Index (EI) for *Bactrocera carambolae* Drew & Hancock (Diptera: Tephritidae) modeled in a global manner by CLIMEX in a climate change scenario (increase of 3 °C)

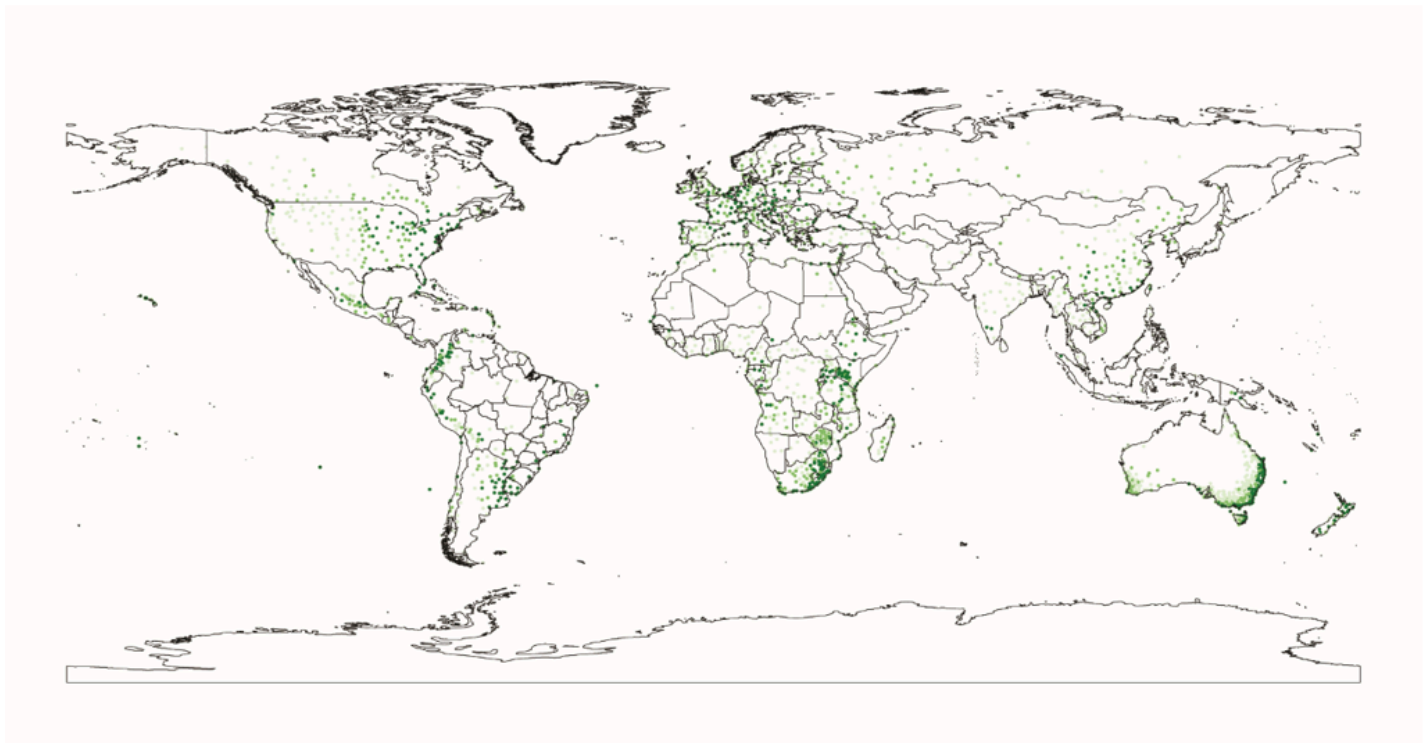


Figure 2

Growth index (GI) for *Bactrocera carambolae* Drew & Hancock (Diptera: Tephritidae) modeled in a global manner by CLIMEX in a climate change scenario (increase of 3 °C)

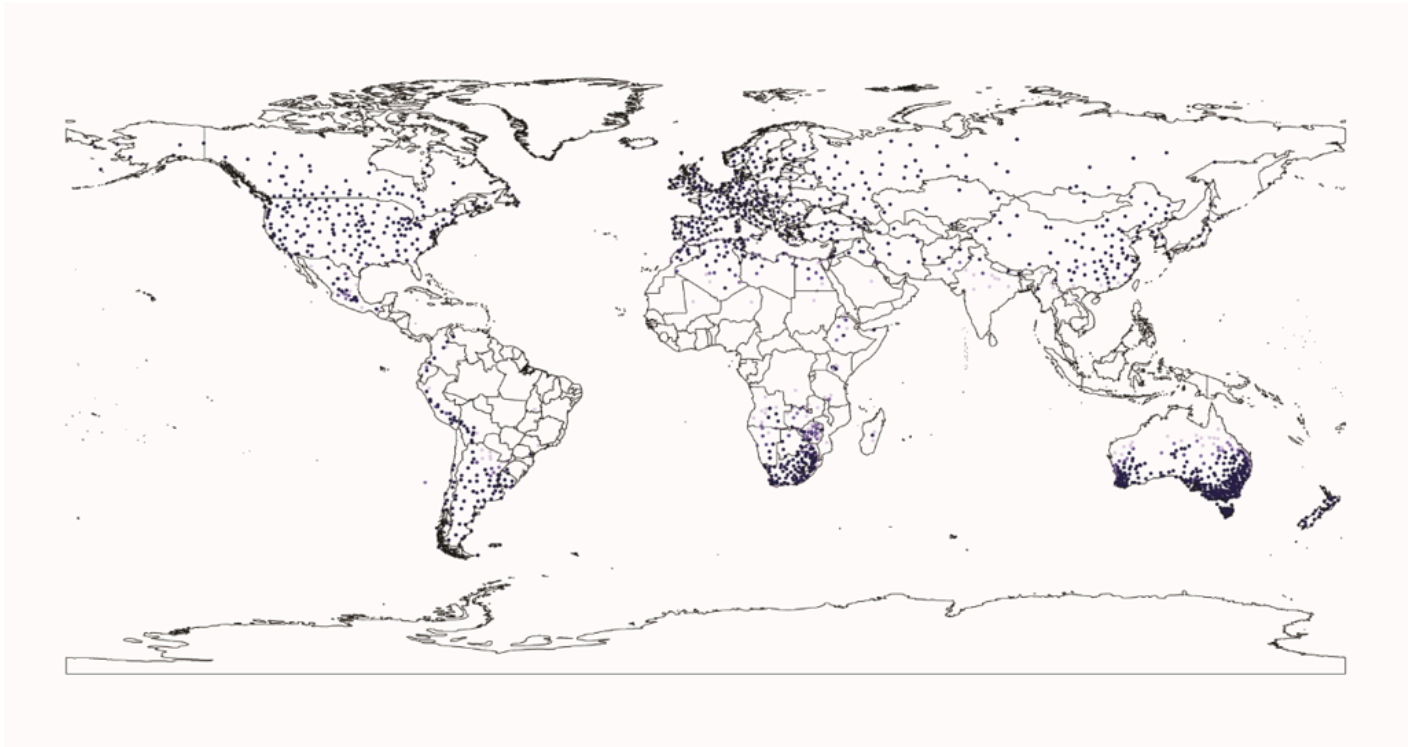


**Figure 3**

Cold stress (CS) index for *Bactrocera carambolae* Drew & Hancock (Diptera: Tephritidae) modeled in a global manner by CLIMEX in a climate change scenario (increase of 3 °C)

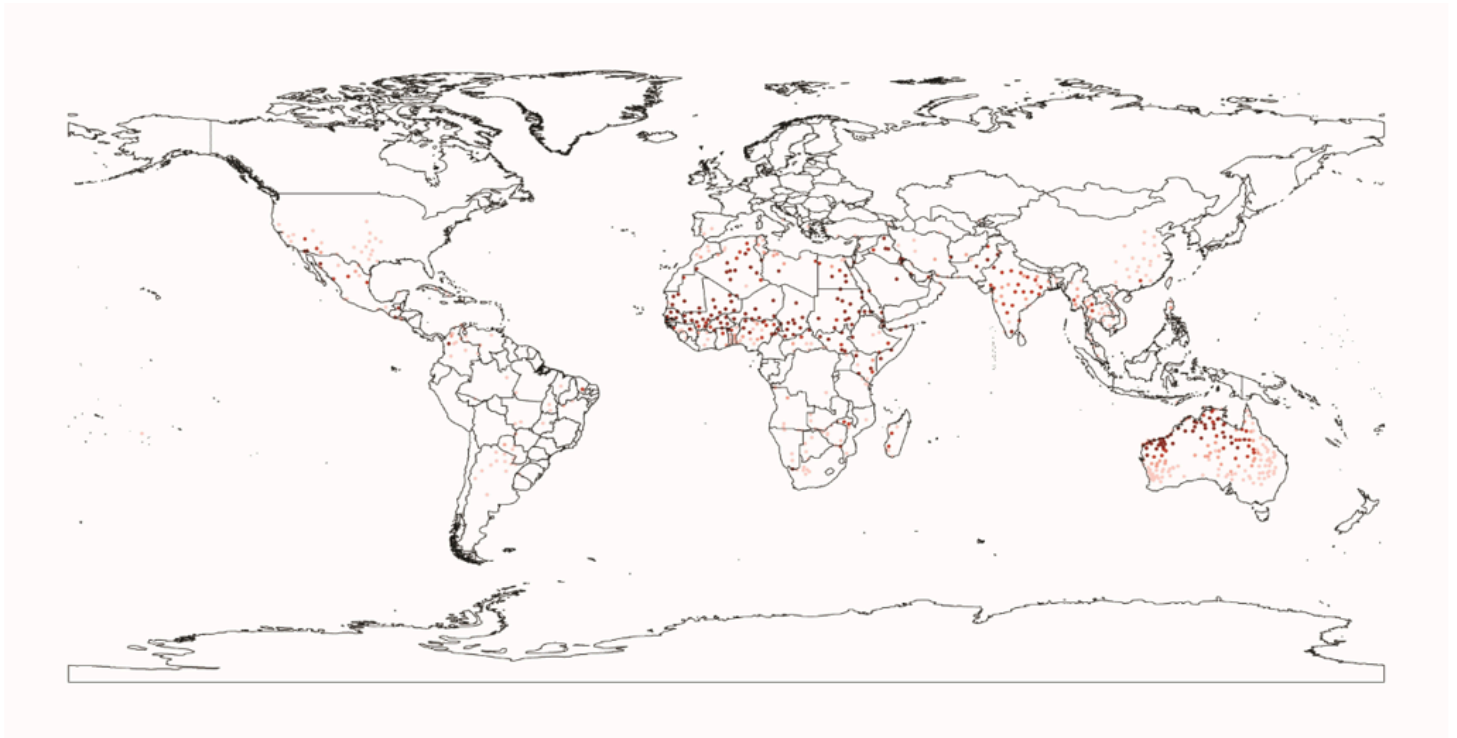


**Figure 4**

Heat stress (HS) index for *Bactrocera carambolae* Drew & Hancock (Diptera: Tephritidae) modeled in a global manner by CLIMEX in a climate change scenario (increase of 3 °C)

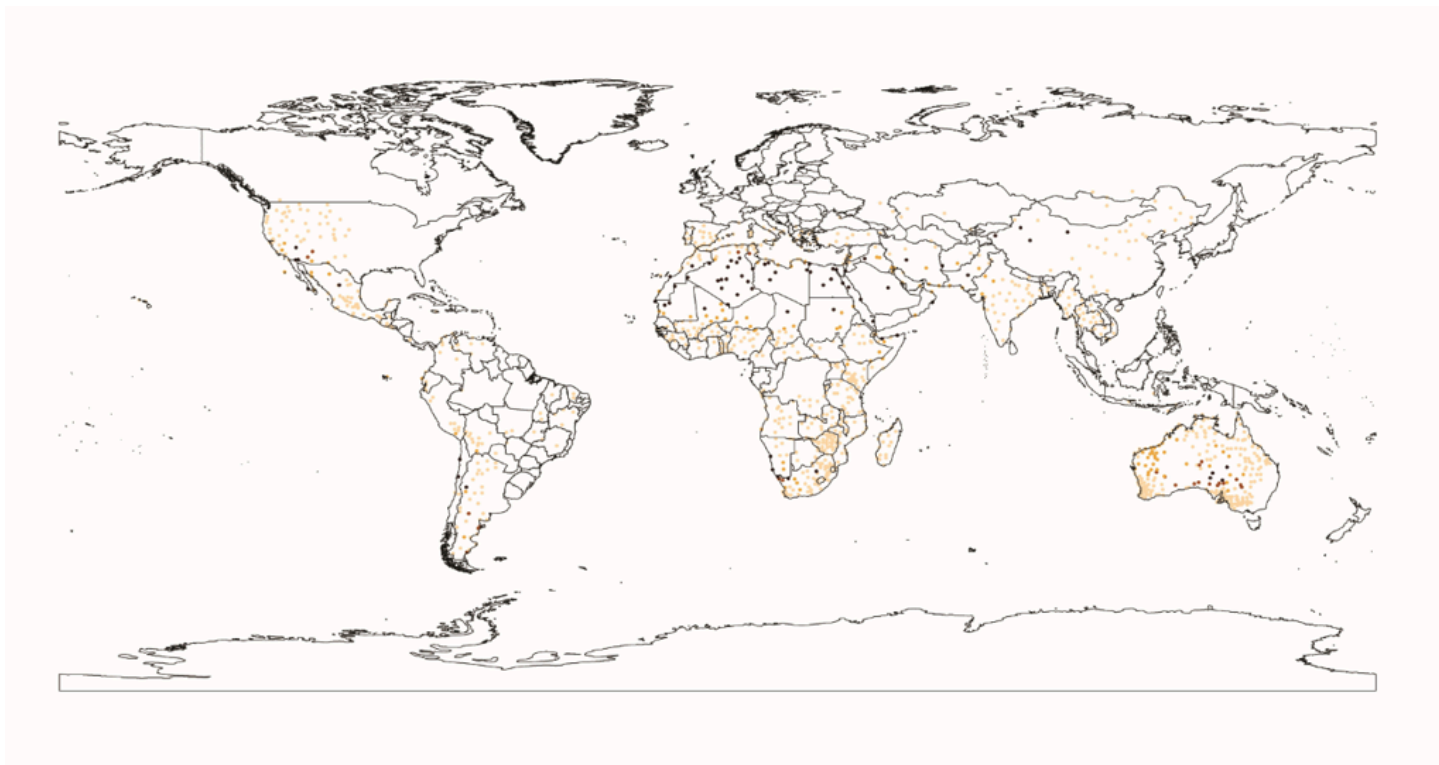


**Figure 5**

Drought stress (DS) index for *Bactrocera carambolae* Drew & Hancock (Diptera: Tephritidae) modeled in a global manner by CLIMEX in a climate change scenario (increase of 3 °C)

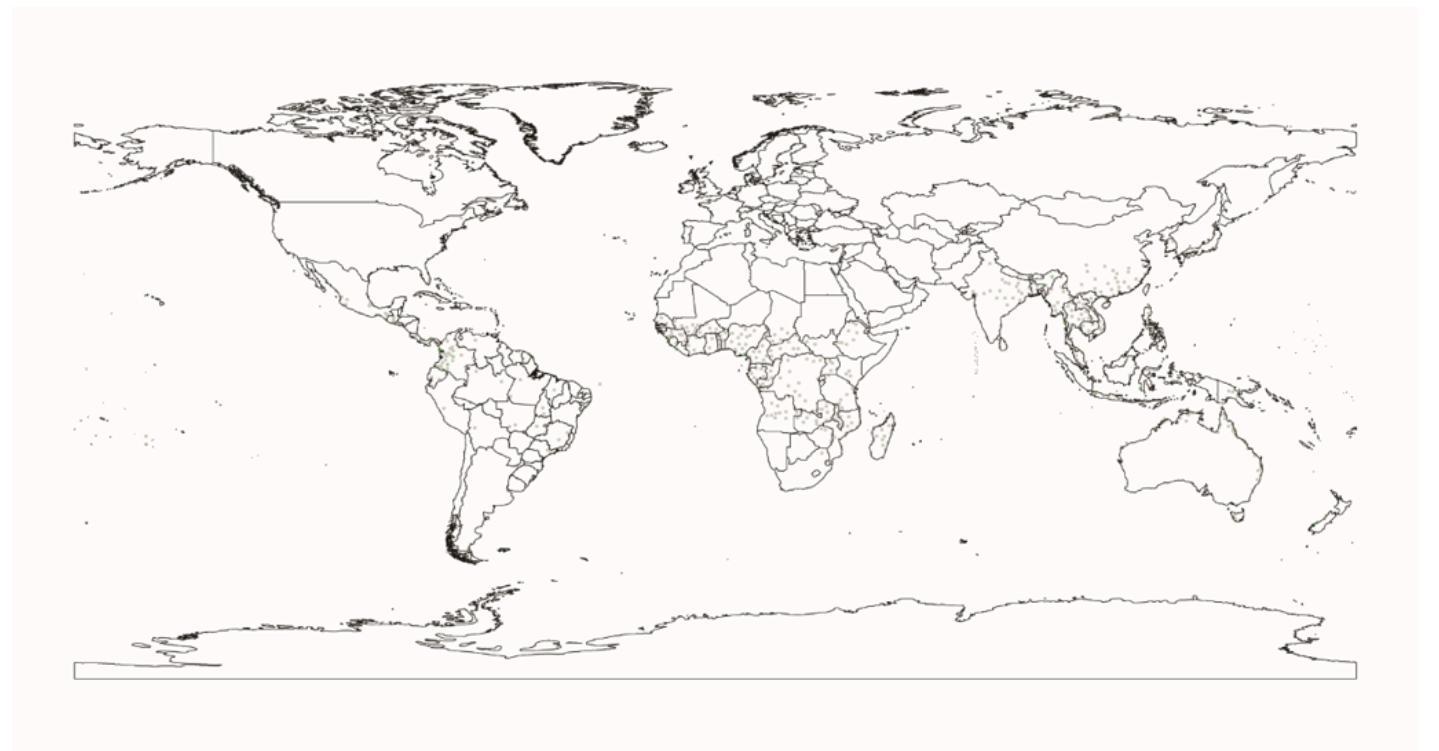


**Figure 6**

Water stress (WS) index for *Bactrocera carambolae* Drew & Hancock (Diptera: Tephritidae) modeled in a global manner by CLIMEX in a climate change scenario (increase of 3 °C)