INSTITUTO NACIONAL DE PESQUISAS DA AMAZÔNIA - INPA
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POTENCIAL DE DISTRIBUIÇÃO ESPAÇO-TEMPORAL DE *Anastrepha suspensa* (Diptera: Tephritidae) E DO PARASITOIDE *Diachasmimorpha longicaudata* (Hymenoptera: Braconidae) PARA AS AMÉRICAS VISANDO O CONTROLE BIOLÓGICO

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Manaus, Amazonas

Novembro de 2022

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Sinopse:

Foi determinado o potencial de distribuição atual e futura para *Anastrepha suspensa*.e o parasitoide *Diachasmimorpha longicaudata* utilizando a modelagem de nicho ecologico para as Américas, são fornecidos mapas de distribuição, dinâmica espaço-temporal, analise de sensibilidade de parâmetros e áreas de sobreposição entre as espécies e principais hospedeiros. Também foi destacado áreas com potencial de invasão.

Palavras-chave: climex, controle biológico clássico, praga agrícola.

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‘’Nossas vidas são fitas de Möbius, infelicidades e fascinação simultaneamente.
Nossos destinos são infinitos, e infinitamente recorrentes.’’
(Joyce Carol Oates – Figuras Fósseis)

RESUMO

A mosca-das-frutas *Anastrepha suspensa* (Lower, 1862) (Diptera: Tephritidae), presente na América Central e no Caribé, é uma praga ausente quarentenária em países da América do Sul, África e Oceania, principalmente por ataca comodities alimentares como goiaba, pêssego e citrus causando sérios prejuízos econômicos. *Diachasmimorpha longicaudata* (Ashmead, 1905) (Hymenoptera: Braconidae) é uma vespa parasitoide muito utilizada em programas de controle biológico de Tephritídeos incluindo *A. suspensa*. Por conta de o clima ser um fator limitante na distribuição dos insetos, nós utilizamos o CLIMEX para prever a distribuição potencial da praga e do parasitoide, as áreas de sobreposição entre as espécies e os efeitos das mudanças climáticas na distribuição futura de *A. suspensa*. Os dados foram coletados através de informações biológicas sobre os limites térmicos de cada espécies em bancos de dados científicos e dados de localização geográfica. Os dados foram utilizados para criar mapas de previsão do potencial de distribuição nas Américas e a futura no mundo. O modelo mostrou adequabilidade climática em todos os pontos de distribuição conhecido das espécies mostrando alta confiabilidade da modelagem, os resultados mostram adequabilidade semelhante para *A. suspensa* e *D. longicaudata* nas Américas, com áreas de sobreposição e principais hospedeiros presentes em áreas com adequabilidade climática. Os mapas de previsão futura para *A. suspensa* mostram diminuição nas áreas climaticamente adequadas, porém áreas no Caribe, Américas, África e Oceania mostram alta adequabilidade até o fim do século. O potencial de distribuição previsto pode ser útil para determinar os locais que apresentam maior risco de invasão de *A. suspensa* e determinar as áreas que medidas preventivas como monitoramento podem ser aplicadas. e em caso de invasão, como alternativa a utilização do controle biológico com a vespa parasitoide *D. longicaudata*.

ABSTRACT

The fruit fly *Anastrepha suspensa* (Lower, 1862) (Diptera: Tephritidae), present in Central America and the Caribbean, is a quarantine pest in countries in South America, Africa, and Oceania, mainly because it attacks food commodities such as guava, peach, and *citrus* spp., causing serious economic losses. *Diachasmimorpha longicaudata* (Ashmead, 1905) (Hymenoptera: Braconidae) is a parasitoid wasp widely used in biological control programs of Tephritids, including *A. suspensa*. Because the climate is a limiting factor in insect distribution, we used CLIMEX to predict the potential distribution of the pest and parasitoid, the areas of overlap between the species, and the effects of climate change on the future distribution of *A. suspensa*. Data was collected using biological information on the thermal thresholds of each species in scientific databases and geographic location data. The data was used to create predictive maps of potential distribution in the Americas and future distribution worldwide. The model predicted climatic suitability for *A. suspensa* and *D. longicaudata* in the Caribbean and the Americas, with areas of overlap and major hosts present in areas with climatic suitability. Future prediction maps for *A. suspensa* show a decrease in climatically suitable areas, but areas in the Caribbean, Americas, Africa, and Oceania show high suitability by the end of the century. The predicted distribution potential can be useful to determine the locations that are most at risk for invasion of *A. suspensa* and the areas where preventive measures such as monitoring can be applied. and, in case of invasion, as an alternative, the use of biological control with the parasitoid wasp *D. longicaudata*.

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INTRODUÇÃO GERAL

A taxa e magnitude das mudanças climáticas já resultam em uma resposta biológica em escala global. Organismos marinhos, de água doce e terrestres estão alterando suas distribuições para permanecer dentro de suas condições ambientais preferidas (Chen et al. 2011, Lenoir e Svenning 2014). Embora os limites de distribuição geográfica das espécies sejam dinâmicos e flutuem com o tempo, as mudanças climáticas estão impulsionando uma redistribuição universal da vida na Terra (Pecl et al. 2017).

A propagação espacial de muitas espécies de pequenos invertebrados é frequentemente restringida por extremos climáticos adversos (Overgaard et al. 2014). As espécies são afetadas pelo clima de várias maneiras. Os principais efeitos relacionam-se às mudanças de alcance, mudanças na abundância relativa nas áreas de distribuição das espécies e mudanças mais sutis no tempo de atividade e uso de micro-habitat (Bates et al. 2014, Ge et al. 2017). Com a mudança de clima, tais espécies podem migrar ou serem introduzidas em novas áreas, tornando-se com o tempo invasoras.

No entanto, o ambiente invadido também é de natureza dinâmica. Esta hipótese pode nem sempre ser verdadeira. As espécies invasoras são constantemente encontradas para preencher novas condições climáticas na faixa invasiva ou em ambientes artificiais (Guisan et al. 2014), devido à sua capacidade de adaptação local (Letnic et al. 2014, González-Bernal et al. 2016, Oduor et al. 2016), e plasticidade fenotípica em uma série de condições ambientais (Grewell et al. 2016, Li et al. 2016, Hoffmann 2017). O clima é o principal tema de estudo ao se abordar a distribuição de organismos, especialmente de ectodérmicos como insetos (Deutsch et al. 2008, Biber-Freudenberger et al. 2016, Shabani et al. 2016).

Em razão do aumento do número de informações sobre impactos negativos na biota regional e devido a espécies invasoras (Iacarella et al. 2015, Early et al. 2016, Bellard et al. 2017), a invasão biológica tornou-se um grave problema reconhecido globalmente. As espécies provavelmente estão mudando as distribuições mais rapidamente do que no passado e, por isso, esse fenômeno está no centro das atenções acadêmicas e, logicamente, é um tema recorrente das pesquisas científicas recentes (Lawing and Polly 2011).

As espécies conhecidas como exóticas invasoras ameaçam os ecossistemas locais, pois competem com as espécies nativas, ameaçando também os sistemas de manejo humano relacionados à agricultura, saúde animal e silvicultura. (Simberloff et al. 2013, Paini et al. 2016). Nos últimos anos, o impacto das mudanças climáticas sobre as pragas e espécies hospedeiras tem sido significativo (Wells and Tonkyn 2018), o que se correlaciona fortemente com a distribuição, fisiologia, fenologia, genética e comportamento de muitas espécies invasoras (Parmesan 2006).

A agricultura, produção, distribuição, marketing e consumo de alimentos contribuem com cerca de 30% do produto interno bruto global (Braun et al. 2017). Os insetos-praga são responsáveis por perdas da ordem de 18 a 20% da produção agrícola mundial, representando um valor superior a US$ 470 bilhões anuais; sendo essas perdas ainda mais acentuadas nos países em desenvolvimento (Sharma et al. 2017), comprometendo, assim, a segurança alimentar dessas regiões (Vigneron et al. 2019).

Apesar dos esforços para prevenir novas intrusões nas últimas décadas, os dados de registro coletados desde o século XVI até os dias atuais não mostraram nenhum sinal de desaceleração. Ao contrário, a velocidade de invasão da maioria dos grupos de táxons aumenta com o tempo (Seebens et al. 2017). A partir do século XX, a taxa registrada de invasões de insetos tem aumentado constantemente, provavelmente devido ao comércio global e à disseminação de plantas hospedeiras (Seebens et al. 2015). O custo global associado a insetos invasores foi estimado em US$ 77 bilhões anuais, equivalente ao custo combinado de todos os bens e serviços e saúde (Bradshaw et al. 2016).

As moscas-das-frutas estão entre os principais insetos invasores que ameaçam as atividades agrícolas no mundo. Dentre as espécies mais conhecidas, estão aquelas da família Tephritidae dos gêneros *Bactrocera, Ceratitis, Rhagoletis, Anastrepha* e vários outros gêneros particularmente prejudiciais para a agricultura. Por exemplo, apenas no Brasil a *Ceratitis capitata* (Wiedemann, 1824) é responsável por US$ 242 milhões/anuais em perdas econômicas (Oliveira et al. 2012).

Outro exemplo importante de moscas invasoras é do gênero *Anastrepha.* Esse gênero inclui 377 espécies descritas de moscas-das-frutas que são importantes devido aos seus efeitos nocivos nas culturas (Norrbom et al. 2015, GBIF 2021). Devido à sua capacidade de colonizar e se adaptar com sucesso à maioria dos habitats terrestres, são consideradas pragas (Vigneron et al. 2019).

Diversas espécies de *Anastrepha* são consideradas as principais pragas mundiais, com enorme impacto econômico sobre as commodities alimentares, como manga, frutas cítricas, goiaba, mamão e melão (Barr et al. 2017). O impacto econômico decorre em função do aumento dos custos com manejo para supressão ou erradicação das populações, além da consequente perda do mercado internacional em razão dos bloqueios sanitários. Por esses motivos, os prejuízos se devem tanto à oviposição de fêmeas adultas quanto à alimentação das larvas que aceleram a maturação promovendo a senescência do fruto (Adaime et al. 2018).

Dentre as espécies de *Anastrepha*, destaca-se a mosca-das-frutas-caribenha *Anastrepha suspensa* (Loew, 1862). Há registros de cerca de 100 hospedeiros para *A.suspensa*, havendo preferência por Myrtaceae, em especial *Psidium guajava* (goiaba), também é praga de *Annona* sp., infesta *Terminalia catappa* e eventualmente infesta frutos maduros de *Citrus* sp (EPPO 2018). Atualmente está distribuída por toda a região do Caribe, além do sul e centro da Flórida e Guiana Francesa (Adaime et al. 2018, CABI 2020).

Anastrepha suspensa exibe preferência por clima tropical, com temperatura média maior que 18°C e precipitação anual de até 1500 mm. Ocorre nos tipos climáticos: A - Clima tropical / megatermal; Af - Clima de floresta tropical; Am - Clima tropical de monções; As - clima de savana tropical com verão seco; Aw - clima tropical de savana úmida e seca; Cs - clima temperado quente com verão seco (CABI 2020). O período de desenvolvimento do ovo-adulto é diretamente correlacionado com a temperatura ambiente. Assim, em temperaturas baixas, o tempo de desenvolvimento do ovo-adulto é prolongado: à temperatura de 15°C, o período embrionário é de 243 horas, enquanto a 25°C é em torno de 57 horas (Prescott and Baranowski 1971).

A fêmea adulta de *A. suspensa* deposita seus ovos nos frutos. Após a eclosão, as larvas alimentam-se da polpa dos frutos, causando neles manchas, além de danos à qualidade. Após a queda dos frutos infestados, as larvas de terceiro ínstar em desenvolvimento migram para o solo e entram em fase de pupa, com duração de 14 dias, a uma profundidade de 0,7 a 3,3 cm, em seguida, o desenvolvimento do ovo dura em média de 22 a 31 dias conforme as condições de umidade e temperatura. Posteriormente a emergência, os indivíduos adultos de *A. suspensa* deixam o solo (Heve et al. 2017, Adaime et al. 2018) .

Os inimigos naturais fornecem um mecanismo essencial para o controle de pragas introduzidas, e o conhecimento das áreas que eles têm o potencial de ocupar em comum com o hospedeiro é necessário para o sucesso no controle biológico clássico em caso de invasão de pragas (Müller et al. 2019). Simplificando, o controle biológico é o uso de uma população de um organismo para reduzir a população de outro organismo (Lenteren et al. 2018). Portanto, a avaliação dos locais com áreas geográficas sobrepostas da praga e do inimigo natural são importantes para verificar o potencial de estabelecimento.

O parasitoide *Diachasmimorpha longicaudata* (Ashmead) (Hymenoptera: Braconidae), se estabeleceu em regiões infestadas por moscas-das-frutas do gênero

Anastrepha após introduções ordenadas por programas de controle biológico no sul da Flórida, Caribe, Ilhas do Pacífico e países da América Central e do Sul, entre outros (Schliserman et al. 2016, Thompson 2017). As vespas possuem o ovipositor de 2–4 mm e uma porcentagem maior de progênie feminina; ambas as características são altamente desejáveis para criação em massa (Paranhos et al. 2008)

Diachasmimorpha longicaudata oviposita seus ovos em larvas de mosca-das-frutas (quando em frutas), utilizando as entranhas de seus hospedeiros para o seu desenvolvimento e alimentação, ao final, emerge de pupas de mosca-das-frutas (quando no solo) (Simmonds et al. 2016, Thompson 2017).

Na última década, com as crescentes restrições ao controle químico das fruteiras, também aumentou a conscientização sobre a segurança alimentar (Paranhos et al. 2019). Portanto, as regulamentações fitossanitárias e de qualidade tornaram-se mais restritivas para exportação para países de primeiro mundo, causando uma carga maior aos exportadores e afetando negativamente os volumes exportados (Melo et al. 2014). Nesse contexto, o controle biológico deve ser mais valorizado e seu uso mais intensificado.

Numerosos estudos foram conduzidos para identificar de que forma espécies nativas se estabeleceram com sucesso em um ambiente novo e heterogêneo e se tornaram dominantes em comunidades invadidas (Callaway e Maron 2006). Estudos de modelagem de espécies no tempo atual e futuro em vários cenários aumentaram nos últimos anos, principalmente devido a maior necessidade de informações sobre os requerimentos de espécies invasoras para o seu estabelecimento.

O aumento exponencial no poder de processamento dos computadores, combinado com a disponibilidade de camadas ambientais digitais e dados primários sobre a distribuição de espécies, propagou um crescimento substancial de modelos de nicho ecológico (ENMs), que estão se tornando populares para prever a distribuição potencial de espécies invasoras (da Silva et al. 2017, García-Roselló et al. 2019). Estes modelos combinam dados empíricos sobre as ocorrências ou abundância de uma espécie, com dados sobre fatores ambientais relacionados (Shabani et al. 2016).

Muitos estudos têm mostrado que os modelos de distribuição de espécies podem ser usados para projetar as distribuições geográficas potenciais das espécies. Esses modelos incluem ANUCLIM / BIOCLIM, CLIMATE, CLIMEX, DOMAIN, GARP, HABITAT e MaxEnt (Phillips et al. 2006, Shabani et al. 2012, 2015, Ramirez-Cabral et al. 2016).

Entre modelos, o CLIMEX, utiliza parâmetros climáticos derivados de informações biológicas sobre as espécies. Usando dados de distribuição conhecidos, ele prevê e mapeia distribuições potenciais de ocorrência (Kriticos et al. 2015). O modelo CLIMEX, é amplamente usado para prever habitats adequados para bactérias, fungos, insetos e plantas.

Como um pacote de modelagem semi-mecanicista, o CLIMEX é especialmente adequado para estimar as distribuições potenciais de espécies ectodérmicas, como insetos (Kriticos et al. 2015). As previsões baseadas no modelo possuem algumas limitações, pois o CLIMEX considera apenas os fatores climáticos e não considera as interações entre as espécies, como ocorrência de pragas, doenças, ervas daninhas, tipos de solo e interações bióticas. Outros fatores de distribuição limitantes, como barreiras naturais e geográficas e atividades humanas, também afetarão a distribuição potencial de pragas (Shabani et al. 2012, Silva et al. 2017)

Estudos ecológicos por meio de modelagem podem ser uma ferramenta útil para aumentar o conhecimento dos padrões sazonais de insetos e colheitas de campo, bem como padrões sazonais de clima favorável para espécies (Allstadt et al. 2015, da Silva et al. 2017).

Até o momento, o aumento nas taxas invasivas anuais indica a necessidade de medidas preventivas adicionais, especialmente para grupos altamente invasivos (McGeoch et al. 2016). Identificar espécies com alto potencial de transmissão, determinar seus significativos danos ambientais e econômicos, e prever suas distribuições potenciais são os passos necessários para o desenvolvimento de políticas de prevenção (Seebens et al. 2017). Por reduzir o custo e a mão-de-obra necessários em estudos experimentais e de campo, é amplamente utilizado para fornecer uma visão inicial para determinação do local e o tempo adequados para prevenir a invasão e dispersão de pragas (He et al. 2012, Taylor e Kumar 2012, Kumar et al. 2016).

Quantificar esses impactos é essencial para dimensionar os custos da mudança climática global, e para projetar medidas de mitigação e adaptação ao clima. Os resultados podem ser usados para efetuar recomendações a organizações agrícolas e aos produtores de safras. Assim, os agentes destinatários das informações podem se preparar para a invasão de pragas, e obter vantagens econômicas significativas.

Desta forma, demonstraremos como utilizar os modelos incorporando dados de história de vida e clima para determinar o potencial de distribuição das populações de mosca-da-fruta-caribenha em locais onde as espécies não são nativas com o parasitoide, visando o controle biológico.

OBJETIVOS

Objetivo Geral

- Desenvolver modelos de clima utilizando o software Climex® para a previsão do potencial de distribuição no tempo atual e futuro para *Anastrepha suspensa* e *Diachasmimorpha longicaudata*.

Objetivos específicos

- Indicar as regiões mais suscetíveis através de mapas temáticos ao estabelecimento em relação à dinâmica atemporal nas Américas do com base nas mudanças climáticas globais projetadas para o período de 2050, 2080 e 2100.
- Estimar o número de gerações de cada inseto ao longo do ano.
- Estimar quais os períodos do ano têm maior adequação climática para a ocorrência da praga.
- Verificar as áreas de sobreposição entre a praga e o parasitoide.
- Verificar a presença dos principais hospedeiros em áreas de adequação climática para as espécies.

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Global potential distribution, climate dynamics, and essential climate variables for *Anastrepha suspensa* (Diptera: Tephritidae) using the CLIMEX model

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ABSTRACT

In economic terms, invasive species pose risks to human interests in management systems related to agriculture, animal health, and forestry, as they cause damage and change the composition of native species. Through modeling, ecological studies can help identify favorable climatic environments for species. Using biological factors and climate data, the CLIMEX software can forecast a species' seasonal phenology and dispersal locations across time. The Caribbean fruit fly, *Anastrepha suspensa* (Diptera: Tephritidae), was modeled using CLIMEX to assess the variables affecting its population and dispersal processes. The results show it exhibits climatic suitability in South America, Central America, Africa, and Oceania. The most important adaptation happens in the Caribbean and Central America between September and December, while it happens in South America between February and April. The sensitivity analysis showed that the species is more sensitive to temperature changes.Our results were validated through field data reports. Modeling has significant implications since it may be used to develop control and monitoring methods in situations and locations with favorable climates for *A. suspensa*, mainly when the pest is not present.

KEYWORDS: Climate change, Fruit fly, Climate modeling, Pest risk analysis, biosecurity

INTRODUCTION

Fruit flies (Diptera: Tephritidae) are the main invasive insects that threaten agricultural activities. Many species of *Anastrepha* are considered global pests, with high economic consequences for food commodities such as guava, mango, papaya, citrus, and melon (Barr et al. 2017). This genus includes 377 described species that are important in causing harmful effects on fruit production (Norrbom et al. 2015; CABI 2020). *Anastrepha* spp. successfully colonizes and adapts to most terrestrial habitats, but its immatures develop inside the fruits, destroying them (Vigneron et al. 2019).

The Caribbean fruit fly, *Anastrepha suspensa* (Loew), is a native pest to the Caribbean islands, which has been expanding its distribution. It is already found in Florida (USA) and Mexico. It's a threat to fruit production in South America, especially Brazil, where it is viewed as a prioritized absent quarantine pest (Adaime et al. 2018). This species has about 100 host plants, with a preference for species of the Myrtaceae family, especially *Psidium guajava* (Myrtaceae). Still, it is also a pest of *Annona* sp. (Annonaceae), *Terminalia catappa* (Combretaceae), and eventually *Citrus* sp. (Rutaceae) (EPPO 2018). The phase of egg-to-adult growth of *A. suspensa* is directly correlated with ambient temperature. The development time is prolonged at low temperatures, and at 15°C, the embryonic period is 243 hours, while at 25°C, it is around 57 hours (Prescott and Baranowski 1971).

The biological invasion has become a globally recognized problem, with increasing information on negative impacts on regional biota and cultivated species caused by the entry of invasive species into several countries (Iacarella et al. 2015; Early et al. 2016; Bellard et al. 2017). Despite quarantine procedures, several species of fruit flies have accidentally been introduced in different parts of the world, negatively impacting the fruit trade and causing economic losses (Barr et al. 2017). They indicated the need for additional forecasting, monitoring, and preventive measures, especially for highly invasive groups (McGeoch et al. 2016). Identifying species with high potential for dispersal and adaptation, determining their significant environmental and economic damage, and predicting their potential distributions are necessary for developing prevention policies.

Modeling techniques were developed and applied by reducing the cost and labor required in experimental and field studies and are widely used to provide initial insight and the appropriate location and timing to prevent pest invasion and dispersal (Taylor and Kumar 2012; He et al. 2012; Kumar et al. 2016). Through ecological studies, modeling can understand the seasonal patterns of insects and favorable climatic environments for the species (Allstadt et al., 2015; Silva et al., 2017).

According to numerous studies, species distribution models can project species' prospective geographic distributions. ANUCLIM/ BIOCLIM, CLIMATE, CLIMEX, DOMAIN, GARP, HABITAT, and MaxEnt are examples of these models (Phillips et al. 2006; Shabani et al. 2012, 2015; Ramirez-Cabral et al. 2016).

We chose CLIMEX because it is a model that predicts and maps the distributions of potential occurrences using available biological and distribution data (Kriticos et al., 2015) and is a widely used software to predict suitable habitats for different organisms.

This research aims to determine possible *A. suspensa* population growth and establishment in regions where the pest is absent using the CLIMEX model, which integrates life history and climate data.

MATERIAL AND METHODS

Current distribution *Anastrepha suspensa*

The current distribution data for *A. suspensa* was provided by the Compendium of Invasive Species (CABI 2020) and the Global Biodiversity Facility (GBIF 2021). The literature for *A. suspensa* was also searched in published scientific citation indexing services (Swanson and Baranowski 1972; Greany et al. 1977; Burk and Webb 1984; Sharp 1986; Nigg et al. 1994; Sivinski et al. 1996; Kendra et al. 2006; Schetelig and Handler 2012) obtaining 35 occurrence records.

The *A. suspensa* prefers a tropical climate with an average 18 °C and up to 1500 mm of yearly rainfall. It occurs in climatic types: A-tropical / mega_thermal climate; Af-tropical forest climate; Am-tropical monsoon climate; As-tropical savanna climate with dry summer; Aw-tropical climate of wet and dry savannah; Cs-hot temperate climate with dry summer. *A. suspensa*, considered of Puerto Rican origin, is currently found in the Caribbean and southern and central Florida (Adaime et al. 2018), postulated to be of Puerto Rican origin. The first record occurred in 1931 in Florida (USA) and remained until 1936, not observed anymore (Swanson and Baranowski 1972). Another infestation in the US was discovered in 1965 when more than 14,000 adults of *A. suspensa* were captured in Dade County (Miami) (Nigg et al. 1994).

CLIMEX

The modeling was performed using CLIMEX version 4.0 (Hearne Scientific Software, Melbourne, Australia), It uses mechanistic modeling to predict the potential development and persistence of organisms, including weeds, crops, and insects, funded by the observed responses to ecophysiological and climatic (Ramirez-Cabral et al. 2016).

The ecoclimatic index (EI) is a general equation that describes the climatic environment for pest population establishment and presence in a given location (Kriticos et al., 2015). The EI index ranges from 0 to 100 and represents the location's suitability for species in various climate scenarios (Bennett et al., 1998; Kriticos et al., 2007) according to EI categories (EI = 0: unsuitable, 0 < EI <30: suitable, EI>30: Optimal) to investigate how climate suitability has changed. Values near to 100 are only found under ideal conditions all year. Under these conditions, the area under analysis is considered ideal and of perfect similarity between the species' places of origin and introduction.

Weekly stress and grouth indices were computed and combined to produce an annual climate suitability index. When climatic conditions are favorable, the annual growth index (GIA) describes the potential for population growth. Four stress indices (cold, hot, wet, and dry) represent the population's probability of surviving unfavorable conditions.

The main port in Latin America and the Caribbean, the Port of Colón in Panama, was chosen for the climate suitability investigation. (ABTRA 2020) which is close to *A. suspensa* occurrences and thus an essential point of the potential global spread of the pest.

CLIMEX parameter values

Table 1 shows the climatic parameters used in the model. All initial parameters were obtained from previous records or biological data sets. The stress parameters were modified iteratively until the simulated geographic distribution indicated by the EI value corresponded to the species' distribution characteristics.

As requirements of CLIMEX, We used data on average monthly precipitation (P_{total}), relative humidity (RH) at 9:00 am and 3:00 pm, average monthly maximum temperature (T_{max}), and average monthly minimum temperature (T_{mim}) corresponding to 116 years (1901 to 2017) to characterize the historical climate.

Temperature index (TI.)

The *A. suspensa* prefers a tropical climate with the ideal air temperature range for development between 15 ° C (DV0) and 34 ° C (DV3), with 25 ° C being the optimal temperature for the development of all immature stages (Prescott and Baranowski 1971). The lowest ideal temperature (DV1) was defined according to the preference for an average temperature above 18°C of the *A. suspensa* (Adaime et al. 2018; CABI 2020). Lawrence (1979) identified that the optimal upper temperature (DV2) for the developing all stages of *A. suspensa* was 28 ° C. The weekly temperature index (TIw) was calculated using the parameters DV0-DV3 described by Kriticos et al. (2015).

The number of degree days per generation (PDD) was determined to be 152.6, according to Prescott and Baranowski (1971). When determining a theoretical "development zero", the generation variable number is calculated by dividing the annual total degree days by the PDD. When the accumulated degree days are less than the PDD, the EI is 0, indicating that the area is not suitable for persistence, although other indices are highly suitable.

Moisture index (MI.)

The *A. suspensa* is distributed in Central America, with values of Lower Soil Moisture Limit (SM0), Lower Soil Moisture Limit (SM1), Maximum Upper Soil Moisture (SM2), and Upper Soil Moisture Limit (SM3) adjusted to 0.35, 0.7, 1.5, 2.5, respectively, according to Kriticos et al. (2015), for wet tropical climate.

The MI can range from 0 to 1. Population growth is maximized when the soil moisture range is between SM1 and SM2. When soil moisture is less than SM0 or greater than SM3, a MI value of 0 corresponds to zero population growth.

Stress index (SI.)

During adverse seasonal conditions, the SI in CLIMEX describes the limits to population growth. A value of 0 indicates no stress at a given location. In contrast, values near 100 indicate that the conditions at that location harm the species and thus determine its geographic distribution (Kriticos et al., 2015).

Cold stress (CS.)

Prescott and Baranowski (1971) confirmed that the development of *A. suspensa* eggs is hampered at 11°C. This is the cold stress temperature (TTCS). The parameters of cold stress were manually adjusted, following the recommendations of Kriticos et al. (2015) for the wet tropical climate, to include the known distribution regions of *A. suspensa* in the Caribbean and Central America.

Heat stress (HS).

Physiological disturbances in insects can be caused by high temperatures (Ramos et al. 2019). The heat stress temperature ratio (THHS) and heat stress temperature threshold (TTHS) parameters were used as threshold temperatures to calculate heat stress (HS) and set to 0.002 week^{-1} and 40.56 ° C, as recommended by Sharp and Chew (1987) and Kriticos et al. (2015), respectively. The weekly HS was calculated by accumulating THHS when the mean weekly maximum temperatures (Tmax) exceeded the TTHS.

Dry Stress (DS.)

The dry stress rate (HDS) and dry stress threshold (SMDS) values were set at -0.01 week^{-1} and 0.25, respectively, supporting the occurrence of *A. suspensa* in Central America, as suggested by Kriticos et al. (2015). The weekly DS is calculated by multiplying the difference between SMDS and the weekly soil moisture level by HDS. When the soil moisture level falls below the SMDS, dry stress occurs (Kriticos et al., 2015).

Wet stress (WS.)

When the soil moisture level (SM) exceeds the wet stress threshold, wet stress occurs (SMWS). The WS result is obtained by multiplying the difference between SMWS and SM by the wet stress rate (HWS). The SMWS and HWS values were set at 2.5 and 0.002 week-1, respectively, to allow for more accurate forecasts for tropical and subtropical regions (Kriticos et al., 2015).

Sensitivity analysis

This analysis enables the identification of parameters where a variation in their value would influence model performance and is useful for adjustments considering suitability categories and regions according to species distribution (Silva et al., 2017).

The values were temperature +/-1°, soil moisture +/-10%, rate parameters +/-10%, and degree days (PDD) +/-20%. The parameters were set using the low and high values proposed by the software for sensitivity analysis (Kriticos et al., 2015). Sensitivity analysis was performed based on 13 CLIMEX parameters with the highest sensitivity in EI.

Results

The historical global potential distribution of *A. suspensa*

The potential distribution of *A. suspensa* under historical climatic conditions is shown in Fig. 2**.** It is possible to detect the model's adjustment to actual occurrence records (Fig. 1), which is necessary to confirm the reliability of the values chosen to generate the current model. All *A. suspensa* occurrence records were located within the projected potential distribution, showing high reliability (Fig. 3).

Southeast Asia, Sub-Saharan Africa, the Caribbean, and South, Central, and North America were predicted to be climatically suitable areas for establishing *A. suspensa*. In Southeast Asia, areas such as Hainan, Vietnam, Indonesia, India, and Sri Lanka presented suitable and optimal locations for establishing *A. suspensa*.

Côte d'Ivoire, Congo, Ghana, the Democratic Republic of the Congo, Uganda, and the southern coast of the Indian Ocean have a more significant number of optimal areas for pest establishment in Sub-Saharan Africa, indicating a severe threat of pest invasion. (Fig. 2)

The entire Caribbean region, where the pest originated, is ideal for the pest. In North America, areas of excellent suitability include Florida and southern Texas (USA), the Atlantic coast of Mexico, and the Yucatan Peninsula. *A. suspensa* can be found in Honduras, Nicaragua, Costa Rica, and Panama in Central America (Fig. 2).

Venezuela, Guyana, Suriname, French Guiana, Colombia, Ecuador, Peru's Amazon region, Paraguay, Argentina's Patagonian region, and the east coast and areas in the Midwest and South of Brazil have been identified as suitable and optimal. The annual accumulated temperature in North America (except for the states of Florida and Texas in the United States and Mexico), Europe, Asia, and a portion of Oceania couldn't sustain a generation's full growth (Fig. 2).

Climate suitability for the Caribbean, Central America, and South America

In the Caribbean, there is climate adaptation practically all year round (Fig. 4). Central America has climate adaptation almost every year, with the most significant adaptation being from September to December (Fig. 4).

From February to April, South America's most significant areas with climate suitability are the Amazon region, southern Brazil, Argentina, Uruguay, and Paraguay. From May to September, climatically favorable areas in the center of the west, southeast, and northeast (except for the coast) decrease. From June to August, climate suitability gradually decreases in northern Brazil, Peru, and Bolivia. We observed optimal climatic adequacy in the southern region of Brazil throughout the year, with greater intensity in October and November (Fig. 4).

The climatic variability for *A. suspensa* with the expanded area in the city of Colón (Fig. 5) shows that the greatest climatic adequability occurs between May and December, which is the last month with the greatest adequability in Colón. However, there was a gradual reduction in January and zero climatic adequacy in February and March. However, despite the growth rate being zero in both months, the surrounding areas are suitable for *A. suspensa*.

Model Sensitivity Analysis

In the A distribution, the parameters DV2, DV3, and SM2 were the most sensitive for *A. suspensa* in suitable and optimal areas, SMDS and HDS in unsuitable areas (Fig. ~~-~~6). When modifying the DV2 and DV3 parameters to the lowest value, suitable areas increased by 13.828% and 14.982%, respectively, and optimal areas decreased by 12.243 and 15.483, respectively. In contrast, when adjusted to the higher value, there was a decrease of 11.432% (DV2) and 7.229% (DV3) in suitable areas and an increase of 10.120% and 7.192% for DV2 and DV3, respectively, in optimal areas.

When the SM2 was adjusted to a low value (1.35), optimal areas decreased by -4.923%, while suitable areas increased by 5.618%. When the SM2 was adjusted to a high value (1.65), optimal areas increased by 3.275% and suitable areas decreased by 3.767%.

Changes in DV2, DV3, and SM2 using software default values and their impact on modeling for the Caribbean, South, Central, and North America (Fig. 7). When DV2 and DV3 are set to their maximum values, optimal areas expand, primarily in northern Brazil, Colombia, Peru, and Venezuela. In the Amazon region of South America, the suitable and optimal areas showed greater changes in the adjusted values for SM2.

Discussion

The Climex model claims that *A. suspensa* has a high potential for distribution expansion, as many areas of Southeast Asia, Sub-Saharan Africa, and Central and South America have climatic suitability for its establishment. Fruit transport and a diverse range of host plants in these uninvaded areas may contribute to their rapid spread (Seebens et al. 2015).

As a semi-mechanistic modeling package, CLIMEX is especially suited to estimating the potential distributions of ectodermal species, including insects (Kriticos et al., 2015). The model's predictions have some limitations. CLIMEX only considers climatic factors and does not consider the biotic interactions that can affect fruit fly species, including the presence of other pests, natural enemies, soil types, and host availability. Other limiting distribution factors, such as natural and geographic barriers and human activities, can all impact pest potential distribution (Shabani et al., 2012; Silva et al., 2017).

Due to its abundance of host plants, high environmental adaptability, and proximity to the pest's natural habitat, South America presents the greatest risk of *A. suspensa* invasion. The European Union, Brazil, Chile, Colombia, Paraguay, Uruguay, French Guiana, and other nations are exempt from the quarantine pest regulations because they do not have them (IPPC 2022).

In Brazil, *A. suspensa* is listed among the 20 high-risk pests for Brazilian agriculture (Fidelis et al. 2018). Due to their proximity to the Caribbean region, where the pest is widespread, the states of Amapá and Roraima would pose the greatest risks of introduction into Brazil (Adaime et al. 2018). Similar to what happened with the starfruit fly, *Bactrocera carambolae* (Drew and Hancock) can be repeated. This pest originated from Asia and was introduced to the American continent in 1975~~,~~ in Suriname, later dispersing to French Guiana and Guyana. In 1996, it arrived in Brazil, in Amapá, and in 2010 in Roraima (Malavasi, 2001; Midgarden et al., 2016). The great movement of people and fruits in this region facilitates the dispersion of fruit flies.

The northern part of South America has an almost year-round environment that is suitable, especially between February and September (Fig. 4).The pest can also disperse with the transport of infested fruits, requiring treatment strategies such as the proper packaging of fruits from infested regions through packaging that does not allow contact with the pest (Adaime et al. 2018), exposure to low (-2.22°C) and high (>43°C) temperatures (Sharp, 1986) and gamma radiation (50 Gy) (Gould and von Windeguth 1991).

The sensitivity analysis showed that the parameters regarding temperature (DV2, DV3) and soil moisture (SM2) changed the EI the most. By increasing DV2 to 29°C and DV3 to 35°C, the optimal development range is expanded (Fig. 7). Typically, these parameters exhibit a high sensitivity index for all EI categories (Byeon et al., 2018), indicating a high probability of range expansion.

Arthropod variety and abundance can be directly impacted by soil moisture levels, increasing the danger of desiccation (Harrison et al. 2012). The potential distribution changed by decreasing (1.35) and increasing (1.65) the value of SM2 (Fig. 7). Dry and wet stresses occur when soil moisture is too low or too high (Jung et al. 2017).

Due to chemical protection for both larvae and pupae in fruits and soil, managing *A. suspensa* is difficult (Heve et al. 2017). Monitoring through traps is essential as an early detection measure, guiding several integrated pest management strategies such as attractive baits based on torula (34.2%) and borax (57.2%) (Torres-Quezada et al. 2021), use of pheromones (Sivinski & Calkins, 1986) and removal of infested fruits (Adaime et al. 2018).

Biological control becomes a viable option for use in association with other management strategies, such as sterile insects. It can be permanent if the natural enemy establishes itself in the field (Paranhos et al. 2019). The use of nematodes such as *Steinernema feltiae* (Steinernematidae) and *Heterorhabditis bacteriophora* (Heterorhabditidae) reduces the development of larvae, pupae, and adults of *A. suspensa* (Heve et al. 2017).

Using the parasitoid *Diachasmimorpha longicaudata* (Ashemed) could be an alternative to the biological control of *A. suspensa*. The parasitoid established itself in regions infested by flies of the genus *Anastrepha* after introductions through biological control programs in South Florida, the Caribbean, the Pacific Islands, and Central and South American countries (Schliserman et al. 2016; Thompson 2017). Releases of *D. longicaudata* may be helpfulin suppressing *A. suspensa* populations in areas where more traditional methods, such as insecticidal baits and male sterile releases are impractical (Baranowski et al. 1993; Sivinski et al. 1996).

Conclusions

Projections can aid in developing preventative strategies, particularly in regions identified as ideal and with a high invasion risk. The critical factor restricting *A. suspensa* range is temperature. The estimated appropriateness can change depending on the sensitivity analysis and is specifically found in the tropical zone. Because of its proximity to locations where *A. suspensa* is known to occur, and South America offers favorable climatic conditions for it all year long.

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Authorship contributions: Conceptualization: GSS; Methodology and validation: GSS and RSS; Formal analysis: GSS and RSS; Investigation: GSS; Resources: GSS; Writing—original draft preparation: GSS; Writing—review and Editing: BRT, CMS, MAS, EGF, GA, GSS and RSS. All authors read and approved the final manuscript, and the author(s) did not report any potential conflicts of interest.

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Data availability Data supporting the findings of this study are available upon request from the author Santana G.

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Table 1. CLIMEX parameter values used for modeling *A. suspensa*.

Index	**Paramater**	**Values**	**Reference**
Temperature	DV0 = lower threshold	15 °C	Prescott and Baranowski (1993)
	DV1 = lower optimum temperature	18 °C	Adaime (2018); CABI (2020)
	DV2 = upper optimum temperature	28 °C	Lawrence (1979)
	DV3 = upper threshold	34 °C	Prescott and Baranowski (1993)
Moisture	SM0 = lower soil moisture threshold	0.35 *	Kriticos (2015)
	SM1 = lower optimum soil moisture	0.7 *	Kriticos (2015)
	SM2 = upper optimum soil moisture	1.5 *	Kriticos (2015)
	SM3 = upper soil moisture threshold	2.5 *	Kriticos (2015)
Cold stress	TTCS = Cold stress temperature limit	11 °C	Prescott and Baranowski (1993)
	THCS = Cold stress temperature rate	0 week^{-1}	Kriticos (2015)
	DTCS = degree-day threshold	15 °C dias	Kriticos (2015)
	DHCS = stress accumulation rate	-0.001 week^{-1}	Kriticos (2015)
Heat stress	TTHS = temperature threshold	40.56 °C	Sharp and Chew (1987)
	THHS = stress accumulation rate	0.0002 week^{-1}	Kriticos (2015)
	HDS = stress accumulation rate	-0.01 week^{-1}	Kriticos (2015)
Wet stress	SMDS = soil moisture threshold	0.25 *	Kriticos (2015)
	SMWS = soil moisture threshold	2.5 *	Kriticos (2015)
	HWS = stress accumulation rate	0.002 week^{-1}	Kriticos (2015)
Degree days	PDD = degree days per generation	152.6 °C days	Prescott and Baranowski (1993)

* Values without units are estimated soil moisture indices ranging from 0 (dry) to 1 (field capacity).

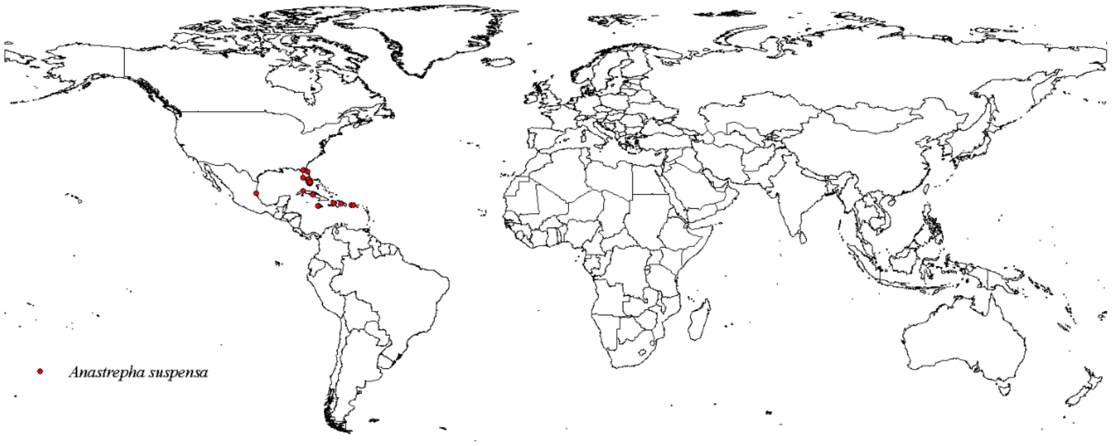


Fig. 1 Current global distribution of *Anastrepha suspensa*.

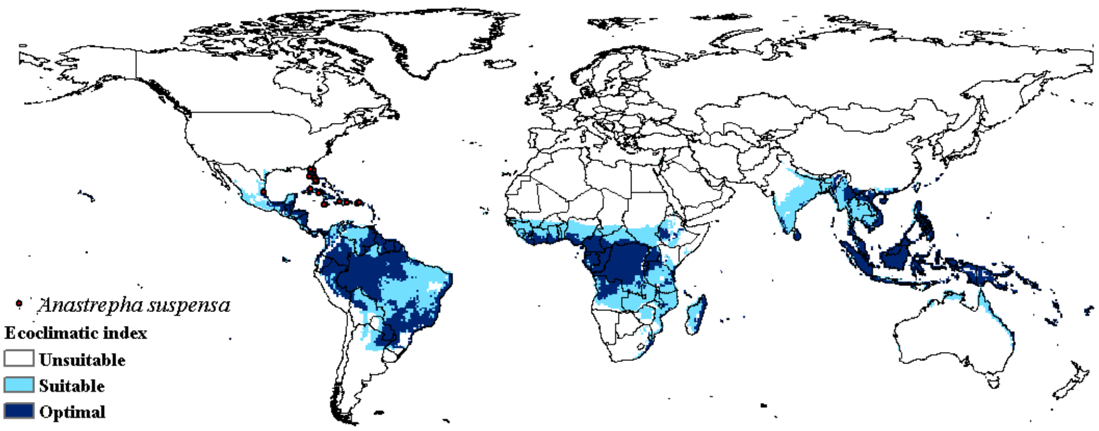


Fig. 2 The global climate suitability (E.I.) for *Anastrepha suspensa* under the reference climate (averages from 1901 to 2017) projected using CLIMEX, unsuitable (0=EI); suitable (0< E.I. <30); optimal (30< E.I. <100).

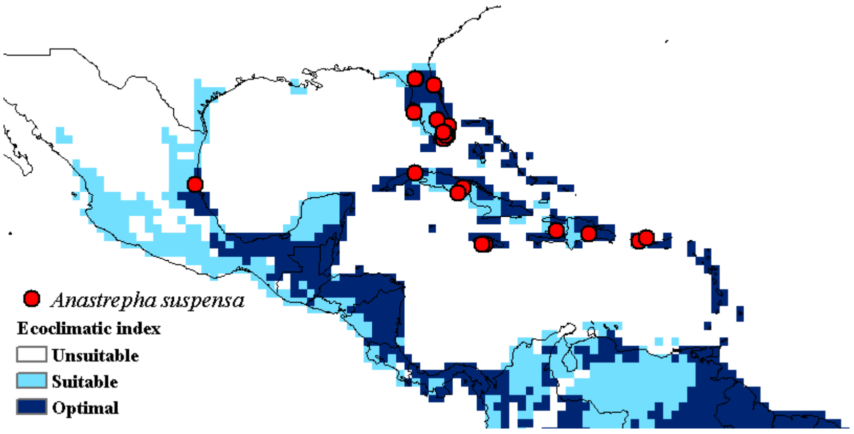
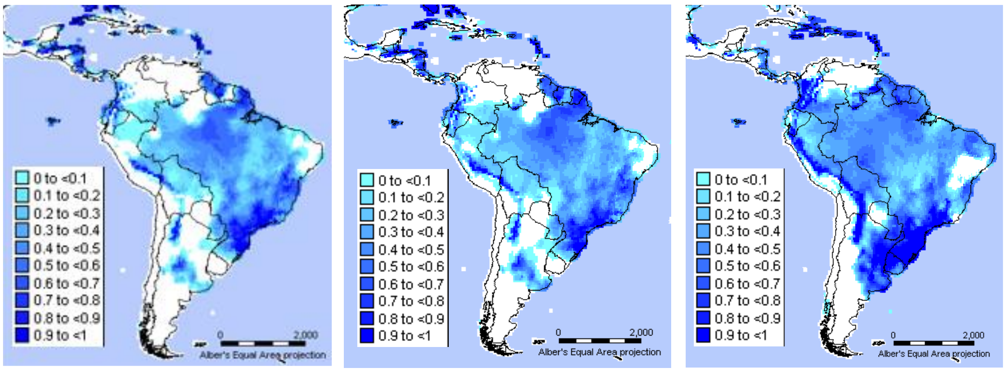
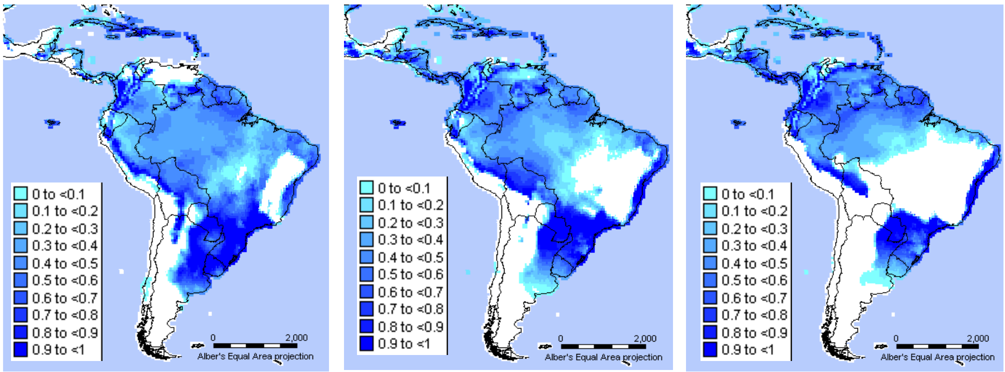


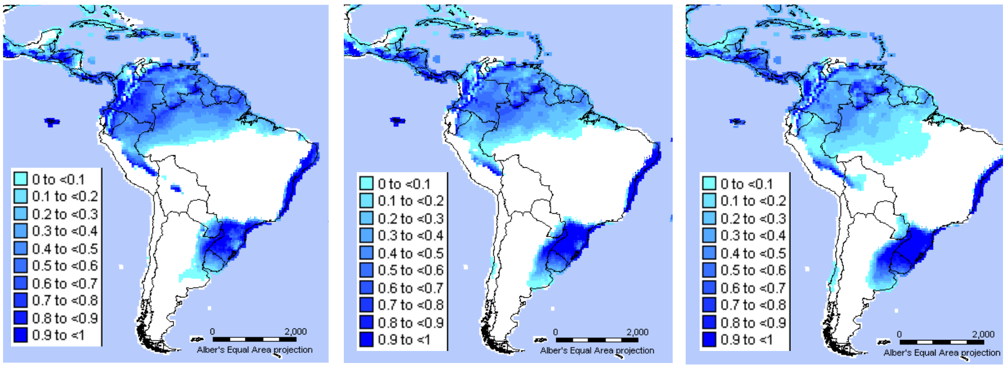
Fig. 3 Current and potential distribution of *Anastrepha suspensa* in the validation area based on the EI index. The areas in white (EI=0), light blue (0< EI <30), and dark blue (30<EI<100) indicate Unsuitable, suitable, and optimal areas, respectively.



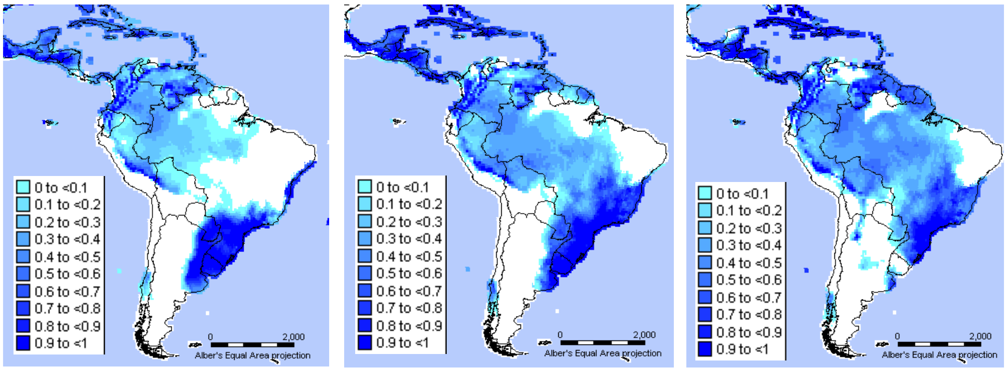
January **February** **March**



April **May** **June**



July **August** **September**



October **November** **December**

Fig. 4 Monthly climate variability based on growth rate (0 to 1) for *Anastrepha suspensa* for Caribbean, Central and South America.

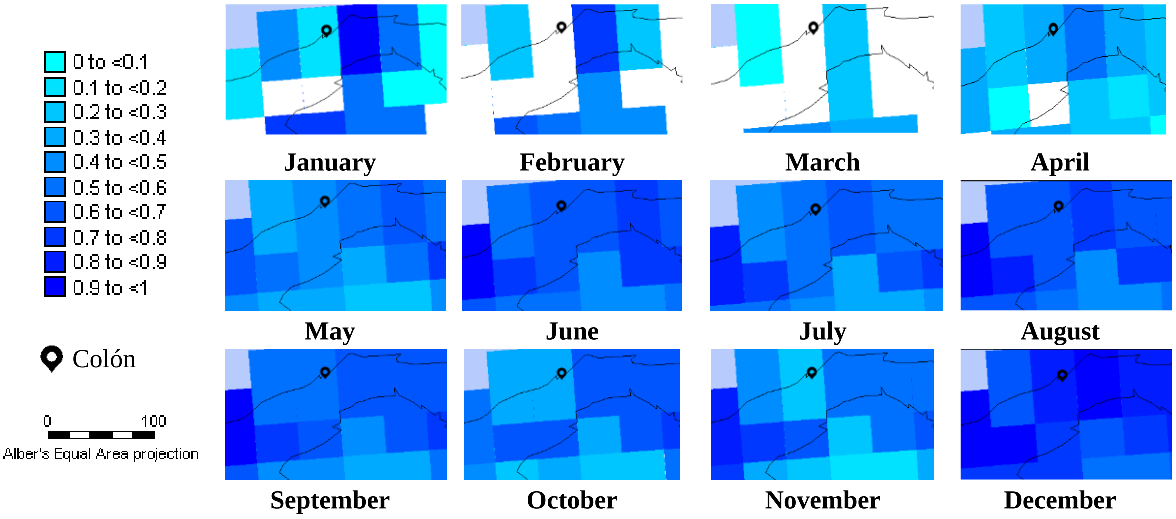


Fig. 5 Climate variability by month based on growth index (0 to 1) for *Anastrepha suspensa*, showing the location of the city of Colón in Panama. Areas in white color mean that the growth rate is equal to zero.

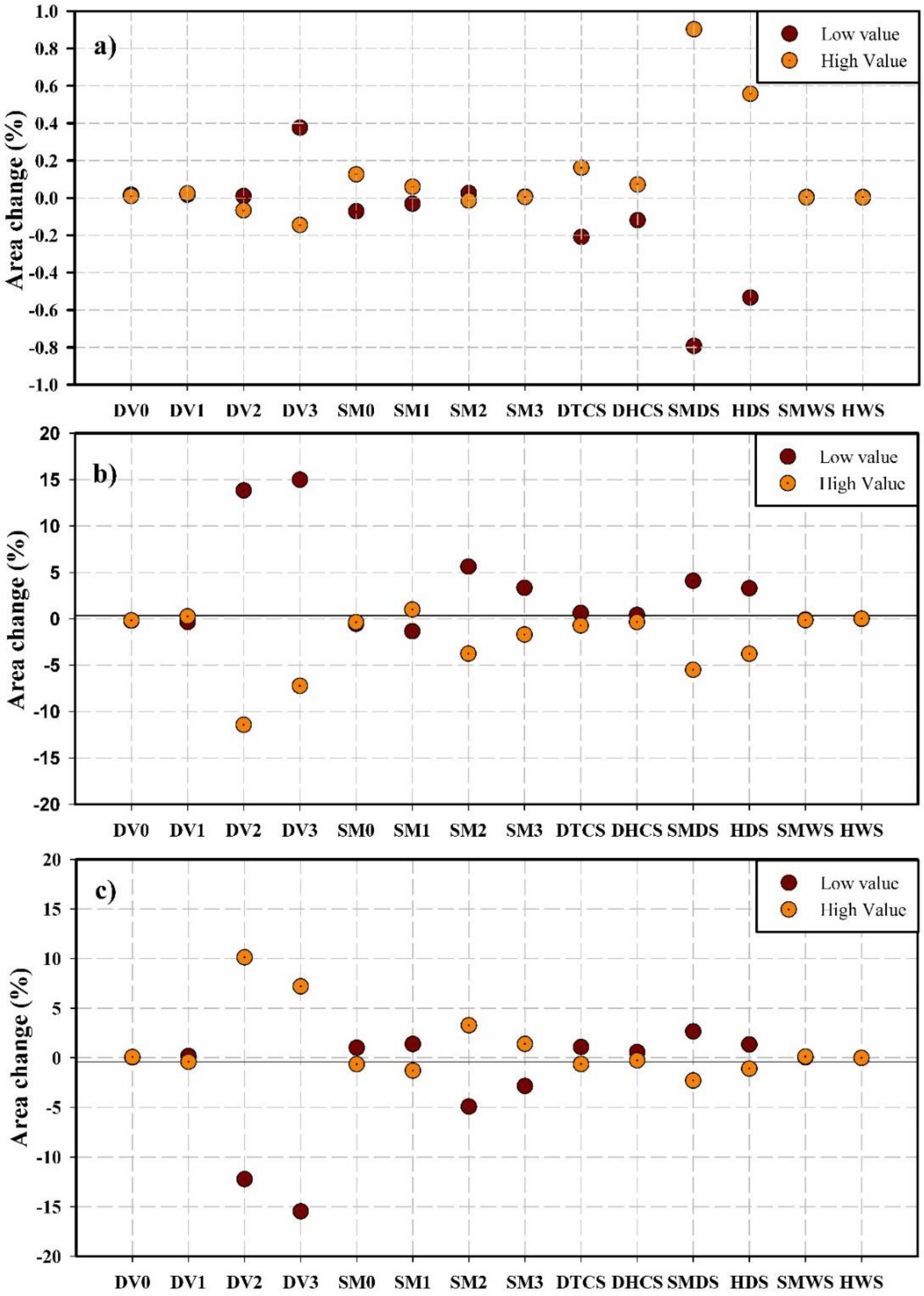


Fig. 6 Area changes in unsuitable areas (a), suitable areas (b), and optimal areas (c) for the potential distribution of *Anastrepha suspensa*.

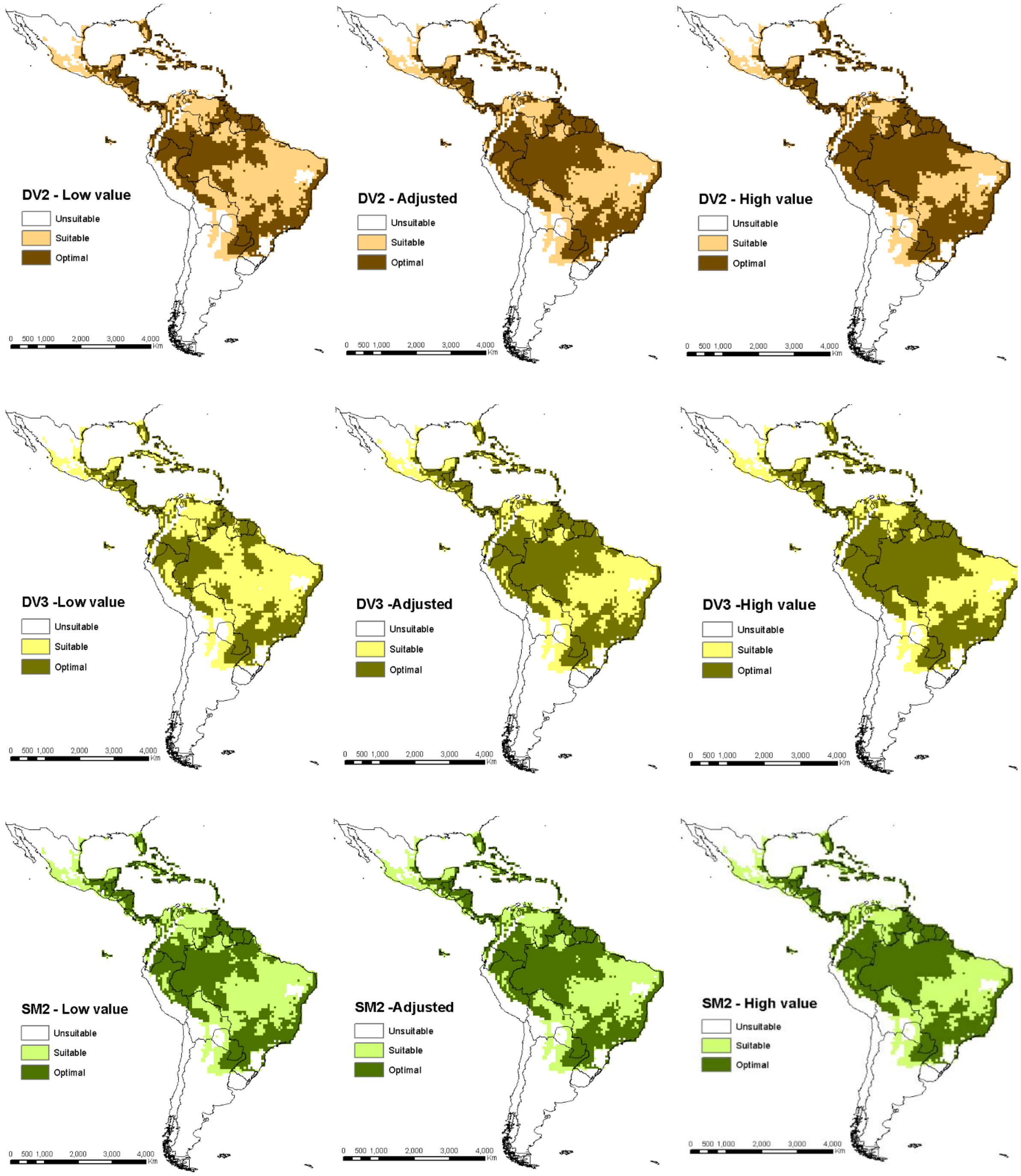


Fig. 7 Unsuitable, suitable, and optimal areas for *A. suspensa* with more sensitive parameters using lower and higher values than the best fit.

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Climate suitability modeling for *Anastrepha suspensa* (Diptera: Tephritidae): Current and future invasion risk analysis

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ABSTRACT

The Caribbean fruit fly, *Anastrepha suspensa* (Lower, 1862) (Diptera: Tephritidae), is a pest of significant economic importance in Central America, the Caribbean, and Florida (USA). This study was carried out to examine the influence of climate change on the space-time distribution of *A. suspensa* on temporal and spatial scales. The CLIMEX software was used to model the current distribution and for climate change. The future distribution was performed using two global climate models (GCMs), CSIRO-Mk3.0 (CS) and MIROC-H (MR), under the emission scenarios (SRES) A2 and A1B for the years 2050, 2080, and 2100. Given the results, it is expected that by the end of the century, the potential for global distribution of *A. suspensa* will decrease in all scenarios studied. However, areas with high climatic suitability in South America, the Caribbean, Central America, Africa, and Oceania could be observed until the end of the century, even with the temperature and precipitation forecasts of the scenarios. Tropical areas are favorable for the establishment of pests. Projections of suitable areas absent of *A.suspensa* can provide helpful information for preventive strategies of phytosanitary management to avoid the economic impact if the species is introduced.

Keywords: Climex, Climate changes, climatic scenarios, fruit fly, ecological niche model

INTRODUCTION

The *Anastrepha suspensa* (Lower, 1862) (Diptera: Tephritidae), known as the Caribbean fruit fly, is a pest of many fruits of the temperate and tropical zones, being more frequent in Myrtaceae, especially *Psidium guajava* (guava), and also in *Annona* sp., *Terminalia catappa*, and eventually *Citrus* spp. (EPPO 2018). subject to regional restrictions and considered a quarantine pest absent in South America, Asia, Australia, and Africa (CABI 2020).

The first infestation outside the place of origin, the Caribbean islands, occurred in 1931 in the state of Florida (USA), where it remained until 1936 and then became extinct (Swanson and Baranowski 1972). In 1965, a new infestation was discovered in Miami's Dade County when 14,000 adults were captured (Nigg et al. 1994). The migration to Florida may have occurred with up to three separate and isolated introductions, and recent genetic analyses have shown that there is constant gene flow from the Caribbean to Florida, likely due to the movement of infested fruit through human traffic (Kendra et al. 2007; Boykin et al. 2010). The current geographic distribution of *A. suspensa* includes the entire Caribbean region, Central America, and southern and central Florida (Adaime et al. 2018).

Several species of *Anastrepha* are considered important global pests, with a strong economic impact on food commodities, such as mango, citrus, guava, papaya, and melon (Barr et al. 2017). The pest increases management costs for suppressing or eradicating its populations, in addition to the consequent loss of sales to the international market due to sanitary blockades. The losses are due to the oviposition of adult females and the feeding of the larvae, which accelerate the maturation and senescence of the fruit (Adaime et al. 2018).

The spatial distribution of many small invertebrate species is often restricted by climatic conditions (Overgaard et al. 2014). Climate is an important variable for the spatial distribution of organisms, especially insects (ectodermal) (Deutsch et al. 2008; Shabani et al. 2016; Biber-Freudenberger et al. 2016). With climate change, these species can change their geographic distribution by being introduced and adapting to new areas.

According to Intergovernmental Panel on Climate Change (IPCC) reports, climate risks for the next two decades include global warming of up to 1.5 degrees Celsius and warming scenarios of more than 1.5 degrees Celsius for several decades (IPCC 2022).

Species distribution models can be used to project the potential geographic distributions of species. Among the most used models, we can mention ANUCLIM / BIOCLIM, CLIMATE, CLIMEX, DOMAIN, GARP, HABITAT, and MaxEnt (Phillips et al. 2006; Shabani et al. 2012, 2015; Ramirez-Cabral et al. 2016). As a semi-mechanistic modeling package, CLIMEX is especially suited to estimating the potential distributions of ectodermal species such as insects. (Kriticos et al. 2015).

Modeling ecological studies can be a useful tool to increase knowledge of seasonal patterns of insects and crops in the field and seasonal patterns of a favorable climate for species (Allstadt et al. 2015; da Silva et al. 2017). Works such as Shabani et al. (2017) and Byeon et al. (2018) used CLIMEX in comparison with other modeling software and concluded that their results can provide a more accurate approximation of the fundamental niche of a species.

In this study, we used CLIMEX to project the global distribution potential of *A. suspensa* under two different climate scenarios: at present and for the years 2050, 2080, and 2100.

MATERIAL AND METHODS

Climex Model

To estimate the global distribution potential of *A. suspensa*, we used CLIMEX 4.0.2 (Hearne Scientific Software, Melbourne, Australia). The ecoclimatic index (E), describes the general equation of climatic conditions for the installation and long-term presence of an insect population in a given location (Kriticos et al. 2015). The EI values ranged from 0 to 100. An EI value close to 0 indicates that the location does not meet the species' requirements for survival and persistence, and an EI value close to 100 indicates high climatic suitability similar to the place of origin of the species (Kriticos et al. 2015). EI is defined as follows: EI = 0 (unsuitable); $0 < EI < 30$ (suitable); and $EI \geq 30$ (optimal).

The annual growth rate was used to calculate the EI in CLIMEX (GI_A), annual stress index (SI), and limiting factors (eg. effective accumulated temperature). The GI_A describes the suitability of air temperature, soil moisture, or optimal growth days for the potential distribution of a species. The SI index describes the critical conditions of temperature and humidity that can delimit the distribution of the species.

The climatological requirements of a given species make it possible to assess the suitability of an area for population growth and determine the stress induced by inappropriate or adverse climatic conditions.

Climate data and climate change scenarios

We use the most recent historical climate data from Climond 10's spatial resolution from 1961–1990 (30 years centered on 1975), available for download from climond.org. This dataset is of high quality and provides a good resolution space. CLIMEX requires the following climate data: daily average, maximum and minimum air temperatures, monthly average precipitation, and daily average relative humidity at 09:00 and 15:00 h.

The potential distribution of *A. suspensa* was based on two Global Climate Models (GCM), CSIRO-Mk3.0 (CS) and MIROC-H (MR), using the scenarios A2 and A1B from the Special Report on Emissions Scenarios (SRES). They were obtained from the CliMond database. The GCMs were selected because they have a high-resolution horizontal grid on regional scales with variables of air temperature, relative humidity, sea level, pressure, and precipitation, increasing the accuracy of the observed climate (Kriticos et al. 2012; Taylor and Kumar 2012).

The CS model predicts a 2.11 °C increase in temperature and a 14% decrease in mean annual precipitation until 2100, whereas the MR model predicts a 4.31 °C increase in temperature and a 1% decrease in precipitation (Suppiah 2007; Chiew et al. 2009).

It was chosen to use a more optimistic scenario (A1B) and a more pessimistic one (A2) The A1B scenario presents low to medium global warming, predicting that there will be a balance between the use of fossil and non-fossil energy sources in the future, and the A2 scenario presents premises of coherence confirmed with the incorporation of economic, demographic, and technological variables related to greenhouse gases (GHG), derived from representative data from independent and self-sufficient countries in the world (Suppiah 2007; Chiew et al. 2009), exhibiting an increasing GHG trend until 2100.

The years with future projections of 2050, 2080, and 2100 were selected because they provide an overview of three time periods: one near (28 years), one in the medium term (58 years), and one in the more distant future (78 years).

Distribution Data Collection

Current distribution data for *A. suspensa* was obtained from databases such as the Global Biodiversity Information Facility (GBIF 2021) and the Center for Agriculture and Bioscience International (CABI 2020) and by reviewing the literature in articles, newsletters, books, and in published scientific citation indexing services (Swanson and Baranowski 1972; Greany et al. 1977; Burk and Webb 1984; Sharp 1986; Nigg et al. 1994; Sivinski et al. 1996; Kendra et al. 2006; Schetelig and Handler 2012). we were obtaining 35 occurrence records.

CLIMEX parameter settings

Parameter values were adjusted according to biological information reported for *A. suspensa*. The SI was used to determine the geographic limits of the species' potential distribution, and the GIA and the limiting factors were adjusted according to existing geographic distribution data.

Based on work with immature stages of *A. suspensa* by Prescott and Baranowski (1971), the ideal range for the development of the species, that is, the lower temperature limit (DV0) and the upper-temperature limit (DV3), were set at 15° C and 34° C respectively. Values below DV0 or above DV3 compromise the ability of the species to survive and develop generationally. The lowest ideal temperature (DV1) was set at 18°C (Adaime et al. 2018; CABI 2020) and the upper optimum temperature (DV2) at 28°C (Lawrence 1979). The ideal range for the development and persistence of *A. suspensa* is between DV1 and DV2.

The heat stress temperature threshold (TTHS) in CLIMEX cannot be lower than DV3 (Sharp and Chew 1987), so the TTHS was set to 40.56°C and the cold stress temperature threshold (TTCS) to 11°C (Prescott and Baranowski 1971). Completing a suspended generation of *A. suspensa* requires 152.6 °C days, this value being defined as the degree-days parameter (PDD) (Prescott and Baranowski 1971).

No studies were found on ideal humidity rates for *A. suspensa*. However, the global distributions recorded for *A. suspensa* (Fig.1) indicate a higher frequency of the species located in regions of high relative humidity with monthly rainfall above 60 mm (CABI 2020). Guava (the main host of *A. suspensa*) is cultivated in many countries with tropical and subtropical climates (Salazar et al. 2006), This implies that *A. suspensa* needs high humidity values in its habitats.

Thus, the humidity and wet stress parameters were defined using the standard data for humid tropical climates defined in the CLIMEX manual (Kriticos et al. 2015). Based on the standard values, the final moisture parameters were set as: lowest soil moisture limit (SM0) = 0.35, lowest optimum soil moisture (SM1) = 0.7, upper optimum soil moisture (SM2) = 1.5, upper soil moisture limit (SM3) = 2.5, Wet Stress Limit (SMWS) = 2.5, Wet Stress Rate (HWS) = 0.002 week^{-1}.

The Dry Stress Threshold (SMDS), Dry Stress Rate (HDS), and Cold Stress Temperature Rate (THCS) were adjusted by 0.25, -0.01 week^{-1}, and 0 week^{-1}, respectively, based on the same CLIMEX model for tropical humid climate (Table 1).

Model Validation

For a reliable prediction, the CLIMEX parameters should be based on the target species' currently known distribution and climate preferences (Kriticos et al. 2015). The distribution of *A. suspensa* is in Central America and the Caribbean, so adjustments were made until the values of the range of the favorable region agreed with those of the region of occurrence.

RESULTS

Potential global distribution of *A. suspensa* in the current climate

A. suspensa is widely present in Central America (Mexico), the Caribbean (Cuba, Dominican Republic, and Puerto Rico), and North America (restricted, present in Florida), as recorded in Fig1. The potential distribution in the current CLIMEX model climate for A. suspensa is shown in Fig2. The modeling for the species shows a high correspondence between the current distribution of the pest and the EI (Fig3).

In the comparison between the actual and the modeled distribution (Fig3), all occurrence points are in areas with adequate coverage, being 83% in optimal areas, determining the accuracy of the model adjustment to the actual occurrence records. Other regions, such as locations in South America, parts of Africa (western, central, and eastern), and Oceania, also showed a potential risk of *A. suspensa* invasion.

Based on the results generated by CLIMEX (Fig2), the distribution of suspended A in the northern hemisphere was bounded by EI equal to 0. In the United States (except Florida and South Texas), Canada, Greenland, Russia, and European countries, the accumulated annual temperature could not support the complete development of a generation.

Potential distribution of *A. suspensa* in the future climate

The potential future distribution for A. suspensa under the CSIRO-Mk3.0 (Fig4, Fig5, and Fig8) and MIROC-H (Fig6, Fig7, and Fig8) GCMs under SRESs A1B and A2 for 2050, 2080, and 2100 projects gradual loss of suitable and optimal areas for survival of the species. In the CS model, the suitability of the A2 scenario would be further reduced. (Fig5).

GCM CSIRO-Mk3.0

Although the model predicts a reduction in the global climate suitability areas, the southern regions of Brazil and Paraguay; northern Uruguay, western Argentina, Madagascar, and the state of Florida (USA); the border between the Dominican Republic of Congo, Rwanda, and Burundi; and southern Louisiana and Texas (USA) will remain with the optimal climate suitability for *A. suspensa* until 2100 under scenarios A1B and A2 (Fig4 and Fig5).

The A1B scenario indicates an increase of 4.943 million ha^{-1} in suitable areas for *A. suspensa* by 2100 (Fig8), in addition to a reduction in optimal areas of 6.78, 4.19, and 3.16 million ha^{-1} in 2050, 2080, and 2100, respectively, with the interval between 2050 and 2080 being the most drastic in optimal area reductions. Unsuitable areas will increase from 136.76 to 146.46 million ha^{-1} from 2050 to 2100, respectively.

For the A2 scenario on a global scale, between 2050 and 2100, suitable areas (0>EI>30) will decrease from 23.32 to 14.98 million ha^{-1} (Fig 8), while optimal areas (30<EI<100) will reduce from 7.47 to 2.35 million ha^{-1}. However, unfavorable areas (EI = 0) will have an increase of 15.42 million ha^{-1} from the current period to 2100.

In regions of Oceania, the change is similar in 2050 and 2080 under both SRESs (A1B and A2) with a gradual reduction of suitable areas in eastern India. However, by 2100 in Oceania, more suitable areas are projected relative to other locations in both models, with the A2 scenario being more drastic in reducing suitable and optimal areas.

In Central America, parts of South America, Africa, and Oceania, the climatic suitability for *A. suspensa* will decrease in each period in A1B and A2 (Fig8), but the reduction in suitability in the A2 scenario is more drastic in 2100. *Anastrepha suspensa* is currently distributed in this region, and according to projections with A1B and A2 for 2100, this area will remain suitable in some locations in Cuba, and Puerto Rico. The Dominican Republic, Florida (USA), and Mexico.

In South America, the climatic suitability for *A. suspensa* will be largely affected by the changes. Brazil shows a reduction in suitable and optimal areas by 2100 under both SRESs, and regions near the equator also exhibit lower invasion probability. Areas with high suitability in Argentina, Bolivia, Colombia, and Venezuela could disappear by the end of the century. The reduction in climatic suitability for *A. suspensa* is similar in both SRESs, with the largest reduction in suitable and ideal areas predicted for the A2 scenario.

The climatic suitability for *A. suspensa* in Africa will be reduce by 2100. Most ideal regions will gradually become suitable. In addition, some of the suitable regions in West and Central Africa will gradually change to unsuitable. The A1B scenario shows a greater presence of suitable areas in this territory.

In northern hemisphere regions, climatic conditions will remain unsuitable for *A. suspensa*'s survival until 2100.

GCM MIROC-H

The A1B scenario projects an increase in suitable areas of 8.43 million ha^{-1} from the current period to 2050, optimal areas will be reduced by 9.25 million ha^{-1} in 2050. The A2 scenario shows an increase for the same period of 7.95 million ha^{-1} in suitable areas. In the projections, Bolivia, Colombia, Côte d'Ivoire, Cuba, Brazil (Northern Region), and Peru will show changes from optimal to suitable climate areas in the projections. At the global level, the optimal area reduction could be 9.25 to 8.60 million ha^{-1} in 2050 for the A1B, and A2 scenarios, respectively.

For 2080, scenarios A1B and A2 show a reduction in areas classified as optimal. In the A1B scenario, the 8.54 million ha^{-1} in 2050 will gradually shrink to 5.62 million ha^{-1} in 2080. In A2, a reduction of 4.22 million ha^{-1} could occur in the period from 2050 to 2080 (Table 3). The largest reduction of optimal areas in this period is predicted for the territory of Central Africa (Fig6 and Fig7).

The suitable areas will also decrease in countries like Brazil, Cuba, the USA (Florida), India, Nigeria, and Venezuela. The A2 scenario projected the greatest reduction in suitable areas, from 22.90 (2050) to 22.59 million ha^{-1} (2080) (Fig8), while the A1B scenario shows the possibility of an increase in suitable areas from 2050 to 2080, which could reach 0.17 million ha^{-1}.

By 2100, the climate suitability projections for *A. suspensa* under the two SRES indicate little change in suitability in areas in southern Brazil and regions of Argentina, Paraguay, and Uruguay, remaining classified as optimal until 2100. Currently, suitable regions in Brazil, Colombia, Cuba, Venezuela, the Democratic Republic of Congo, India, and Peru are losing climate suitability. The reduction in these optimal areas will be from 17.79 million ha^{-1} (current period) to 4.25 and 3.24 million ha^{-1} in the A1B and A2 scenarios, respectively, by 2100. The region with the smallest changes in the climatic suitability of *A. suspensa* caused by climate change under the A1b and A2 scenarios was projected to be Oceania.

It was shown in both GCMs (CS and MR) under SRESs A1B and A2 that the density of *A. suspensa* reduces under future climate projections, suggesting that climate change will harm the distribution of this species based on differences in area size (Fig8).

DISCUSSION

Ecological studies through modeling can be a useful tool to increase the knowledge of seasonal patterns of insects and crop plants and favorable weather patterns for species (Allstadt et al. 2015; da Silva et al. 2017). Our model indicates that the geographic distribution potential of *A. suspensa* will be reduced in suitable and optimal areas under all climate change scenarios, but with expansion in certain territories (Fig8). From the results, we can make inferences regarding the predicted climate change, such as reducing potential areas for *A. suspensa*.

The expected rise in temperature over the next few decades will increase the chances of insect migration. The northward expansion has already been reported for several invasive insect species under climate change (Musolin 2007, Varner e Dearing 2014). Climate change causes an even greater risk of pest invasion because it can alter the intervals at which pests migrate through changes in air temperature, relative humidity, and soil moisture (Aljaryian et al. 2016). When a pest expands into a region with no usual hosts, it may exploit other host species to survive in the new habitat, becoming established (Ge et al. 2019).

According to the current climate projection, the tropical and subtropical climates of the world are the most favorable for the survival of *A. suspensa*. Like other species of the genus *Anastrepha*, this pest derives from tropical forest habitats (Adaime et al. 2018). South America, Africa (Central, Western, and Eastern), and Oceania are currently free of pests but have suitable and optimal areas for establishing *A. suspensa* populations in the future.

Topography, human activities, host availability, and natural enemies can affect the geographic distribution of pests. The presence of hosts is one of the most important factors because they provide food, shelter and function as breeding sites for insects. *A. suspensa* infests a wide variety of hosts and is of quarantine importance in citrus, a multi-billion dollar industry in Florida and Brazil (Boykin et al. 2006). Brazil also stands out as a major producer and exporter of several other fruit species, including guava (Vitti et al. 2020). The northeast, southeast, and south of the country have climatic suitability for *A. suspensa* by the model until 2100. Therefore, the invasion of *A. suspensa* in Brazil could cause economic severe effects in territories still free of the species.

Our results may help in recommendations for the control and prevention of the introduction of *A. suspensa* in areas that produce the pest's host fruits in South America, Africa, and Oceania. The quarantine recommendations should focus on the ideal and appropriate regions identified in this study~~,~~ to avoid the spatial spread of the insect, facilitated by the host range and the marketing of plant products between pest-free and pest-present countries. Long-term fixed monitoring in nearby regions that have climatic suitability should be carried out, and thus large outbreaks of *A. suspensa* can be prevented.

Indications of the geographical distribution based on the model for *A. suspensa* do not allow conclusions about the establishment of this insect in the sites, because CLIMEX uses algorithms to calculate the suitability of an area based on experimental climatic parameters for the species (Kriticos et al. 2017), excluding other factors such as food availability, geographical barriers, and predators (Shabani et al. 2012; Silva et al. 2017).

Conclusion

The potential geographic distribution of *A. suspensa*, an agricultural pest from Central America and the state of Florida (USA), was predicted under climate change scenarios. The simulations performed in CLIMEX identified areas with high potential for establishing the pest in regions close to its current distribution. By 2100, a decrease in the availability of areas with climatic suitability for the pest was predicted in the models tested, but areas in South America, Africa, and Oceania will continue with optimal suitability until the end of the century. Quarantine, prevention, and control measures must be applied in nearby regions to prevent the spread.

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Author contribution

Conceptualization: Geovani da Silva Santana; Methodology and validation: Geovani da Silva Santana and Ricardo Siqueira da Silva; Formal analysis: Geovani da Silva Santana and Ricardo Siqueira da Silva; Investigation: Geovani da Silva Santana; Resources: Geovani da Silva Santana; Writing—original draft preparation: Geovani da Silva Santana; Writing—review and Editing: Beatriz Ronchi-Teles, Cero Manoel dos Santos, Marcus Alverenga Soares, Philipe Guilherme Corcino Souza, Fausto Henrique Vieira Araújo, Caio Victor Soares de Aguiar and Geovani da Silva Santana. All authors read and approved the final manuscript.

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Statements and Declarations

The authors of the manuscript have no conflict of interest

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Table 1. CLIMEX parameter used for modeling the *Anastrepha suspensa*.

Parameter	Index	Values	Reference
Lower temperature limit	DV0	15 °C	(Prescott and Baranowski 1971)
Lowest ideal temperature	DV1	18 °C	(Adaime et al. 2018), CABI (2020)
Upper optimum temperature	DV2	28 °C	(Lawrence 1979)
Upper-temperature limit	DV3	34 °C	(Prescott and Baranowski 1971)
Lowest soil moisture limit	SM0	0.35 *	(Kriticos et al. 2015)
Lowest optimum soil moisture	SM1	0.7 *	(Kriticos et al. 2015)
Upper optimum soil moisture	SM2	1.5 *	(Kriticos et al. 2015)
Upper soil moisture limit	SM3	2.5 *	(Kriticos et al. 2015)
Cold stress temperature threshold	TTCS	11 °C	(Prescott and Baranowski 1971)
Cold Stress Temperature Rate	THCS	0 week^{-1}	(Kriticos et al. 2015)
Cold-day stress degree threshold	DTCS	15 °C day	(Kriticos et al. 2015)
Cold-day stress degree rate	DHCS	-0.001 week^{-1}	(Kriticos et al. 2015)
Heat stress temperature threshold	TTHS	40.56 °C	(Kriticos et al. 2015)
Heat stress temperature rate	THHS	0.0002 week^{-1}	(Sharp and Chew 1987)
Dry Stress Threshold	SMDS	0.25 *	(Kriticos et al. 2015)
Dry Stress Rate	HDS	-0.01 week^{-1}	(Kriticos et al. 2015)
Wet Stress Limit	SMWS	2.5 *	(Kriticos et al. 2015)
Wet Stress Rate	HWS	0.002 week^{-1}	(Kriticos et al. 2015)
Degree-days	PPD	152.6 °C days	(Prescott and Baranowski 1971)

* Values without units are estimated soil moisture indices where it ranges from dry = 0 and field capacity = 1.

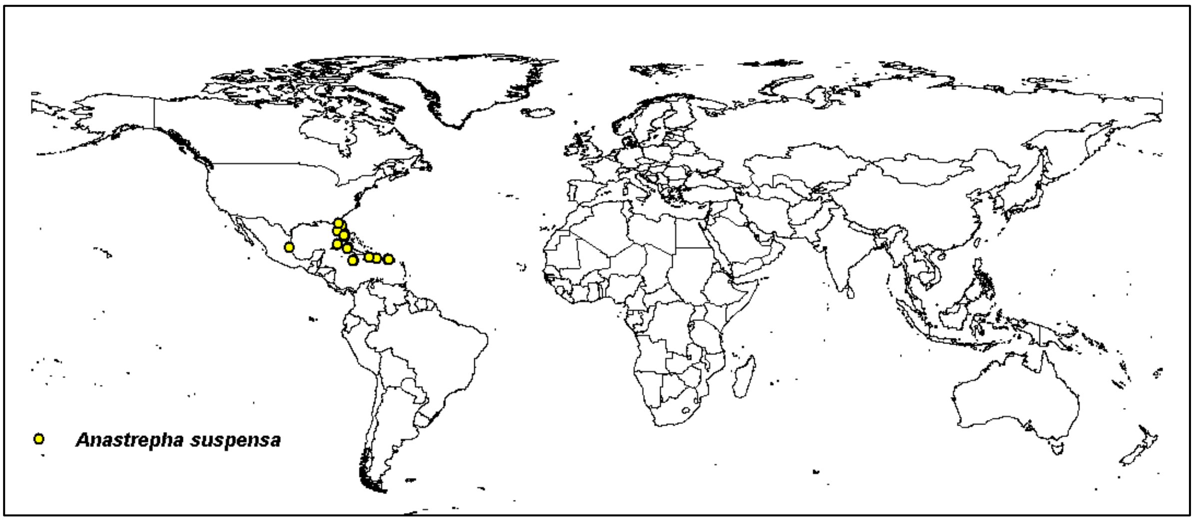

Fig. 1 Known global distribution of *Anastrepha suspensa*.

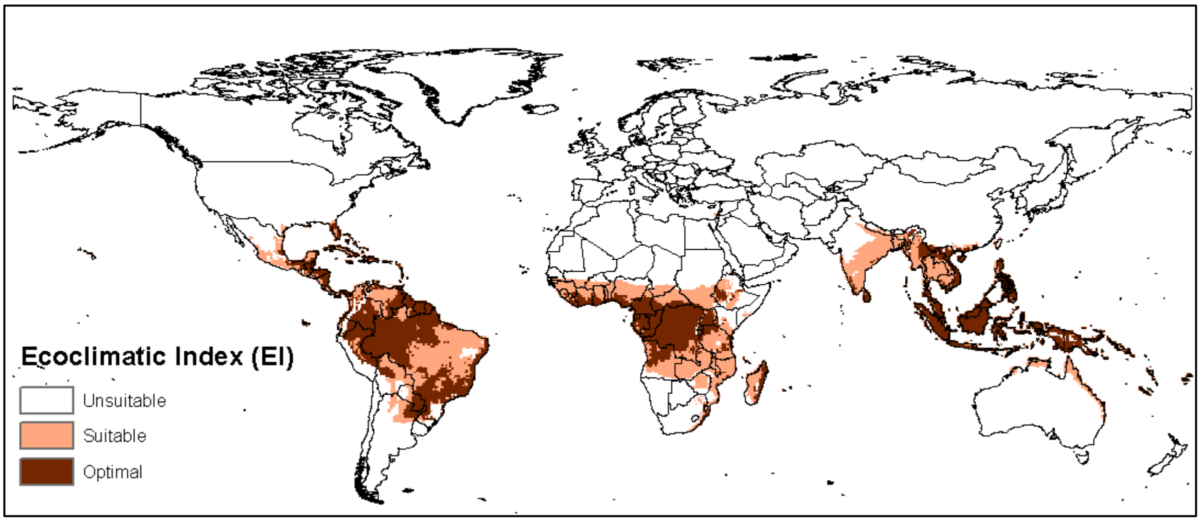

Fig. 2 Predicted potential global distribution of *Anastrepha suspensa* in the present time by CLIMEX. unsuitable(EI=0), suitable(0<EI<30) e optimal(EI>30)

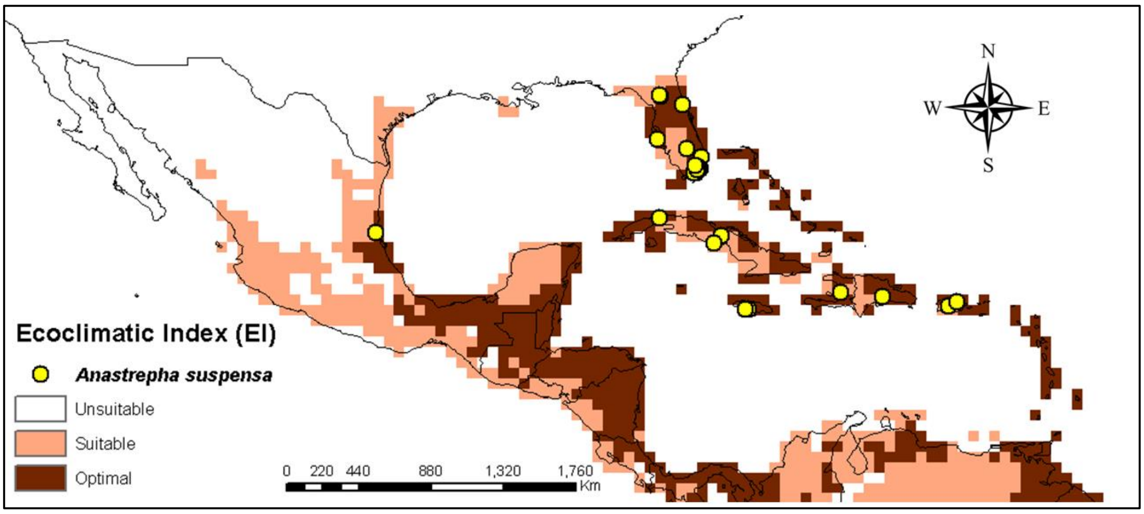

Fig. 3 Potential distribution of *Anastrepha suspensa* for validation with the actual distribution based on the EI index

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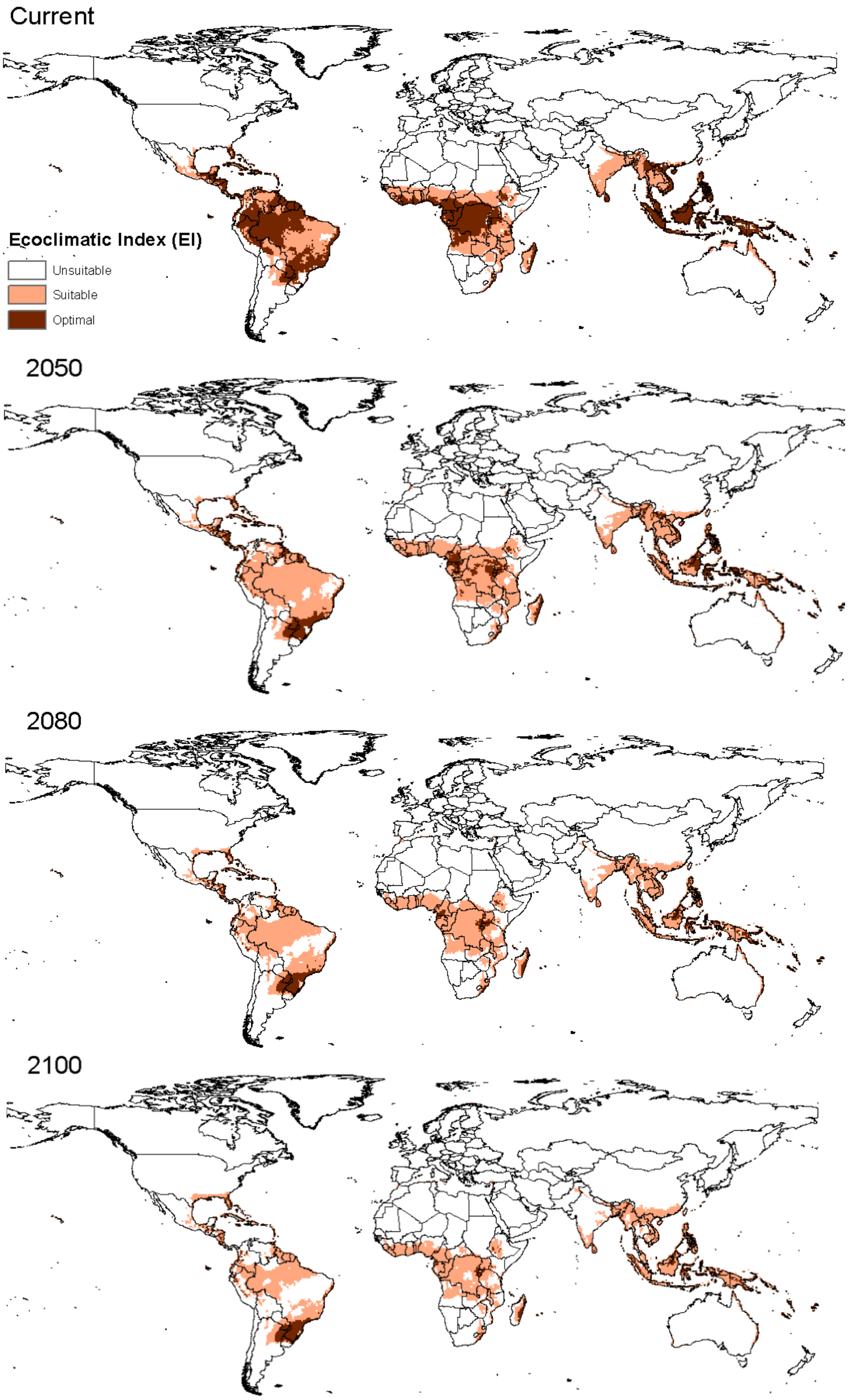

Fig. 4 Ecoclimatic index (EI) at present and future time for *Anastrepha suspensa* for the CSIRO-Mk3.0 GCM under the SRES A1B scenario for the years 2050, 2080, and 2100 on a global scale

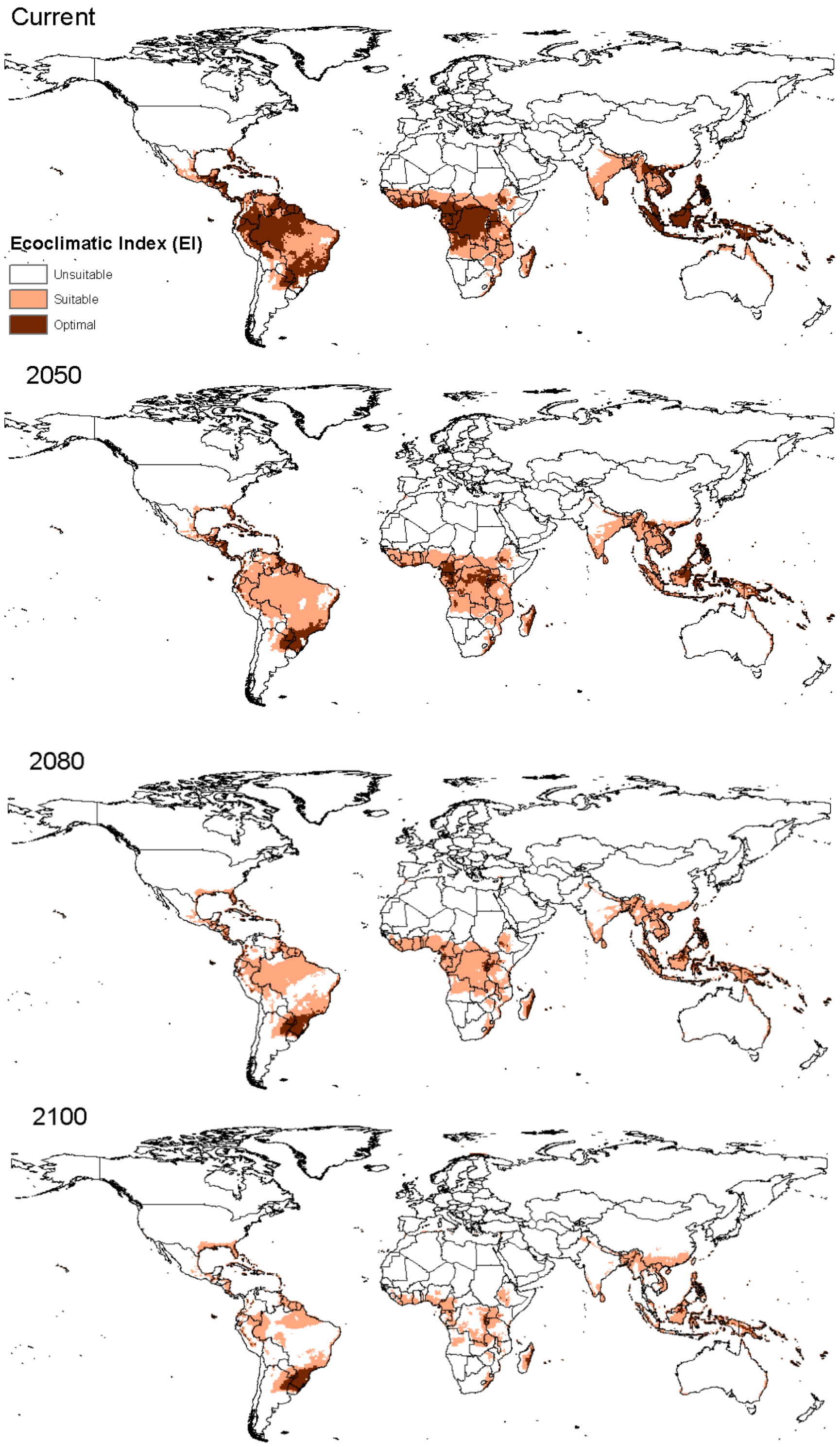

Fig. 5 Ecoclimatic index (EI) at present and future time for *Anastrepha suspensa* for the CSIRO-MK3.0 GCM under the SRES A2 scenario for the years 2030, 2080, and 2100 on a global scale.

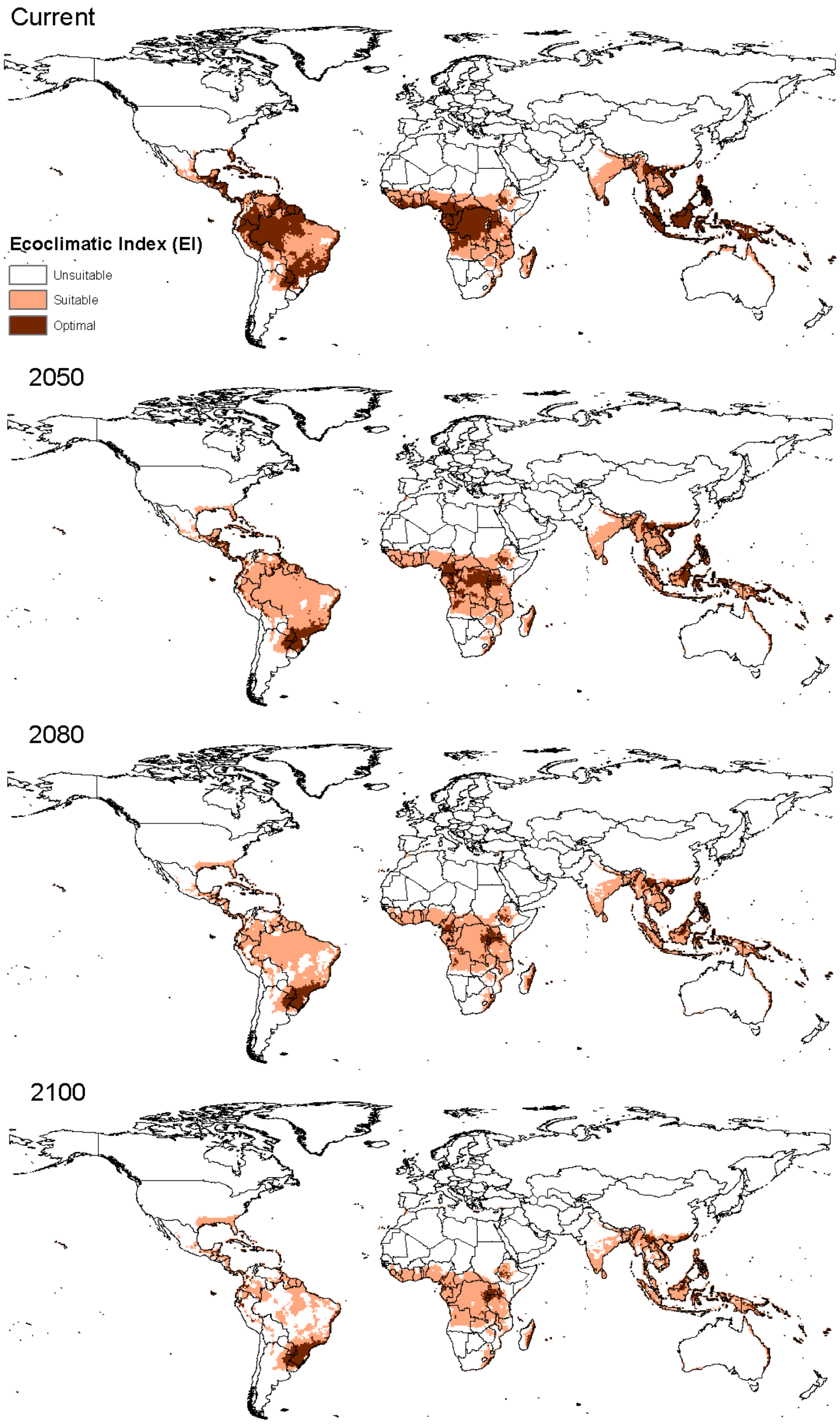

Fig. 6 Ecoclimatic index (EI) at present and future time for *Anastrepha suspensa* for GCM MIROC-H under SRES A1B scenario for the years 2030, 2080 and 2100 at global scale.

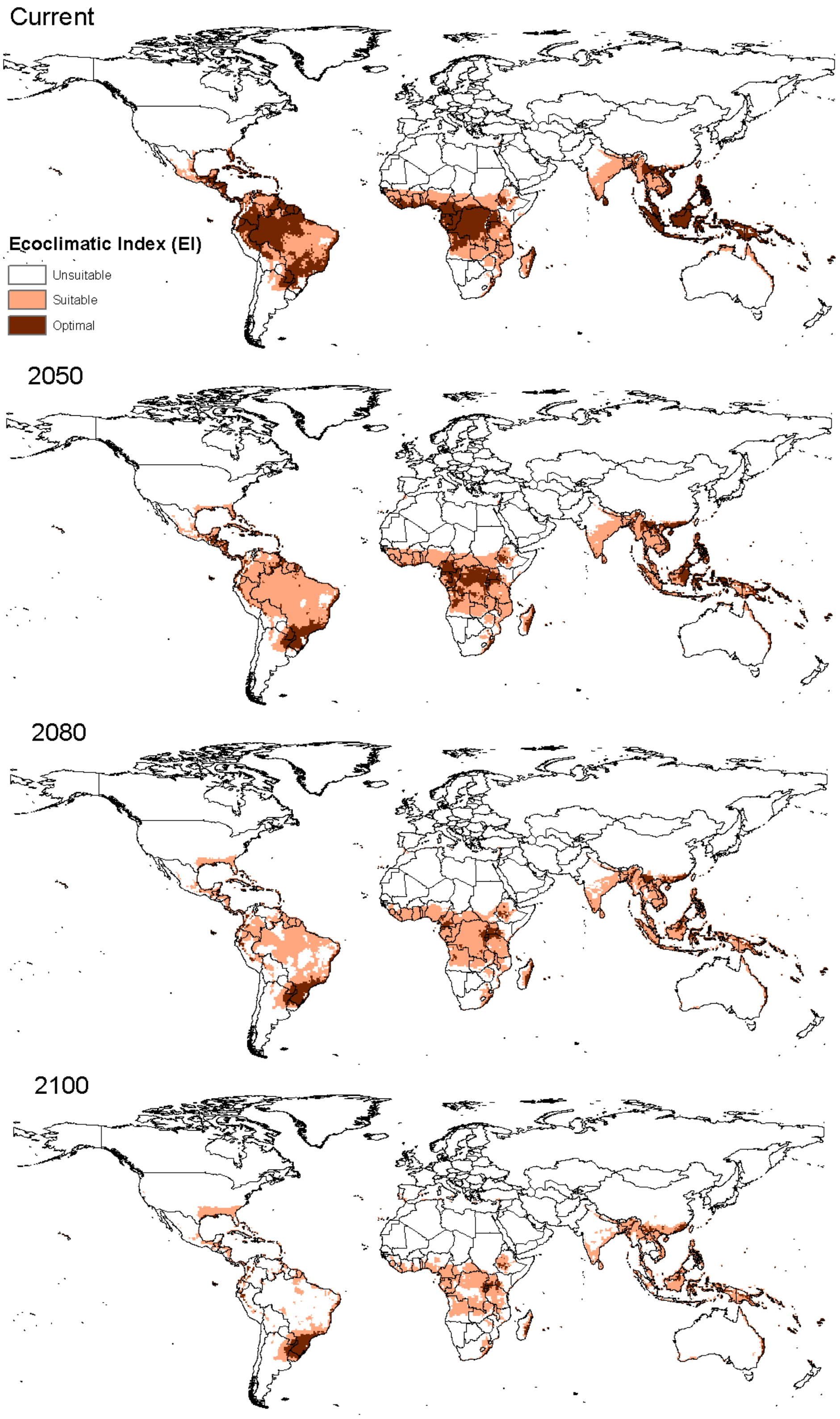

Fig. 7 Ecoclimatic index (EI) at present and future time for *Anastrepha suspensa* for GCM MIROC-H under the SRES A2 scenario for the years 2030, 2080, and 2100 on a global scale.

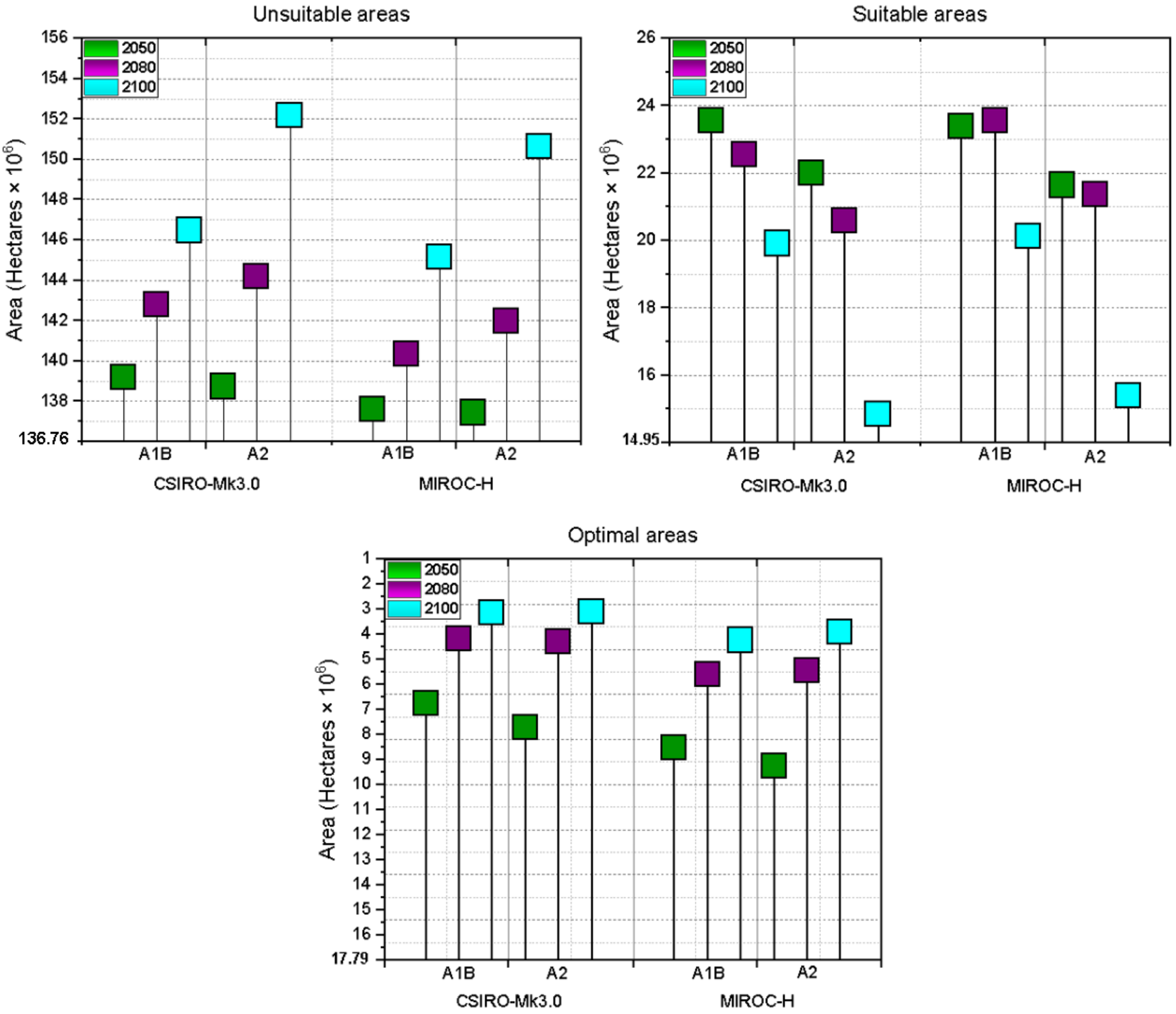

Fig. 8 Area (ha) with Ecoclimatic Index (EI) for *Anastrepha suspensa* in future time using CLIMEX running SRES A1B and A2 for 2050, 2080 and 2100 under CSIRO-Mk3.0 and MIROC-H at global scale.

Santana, G.S; Ronchi-Teles, B; dos Santos, C.M; da Silva, R.S. 2022. Risk analysis for *Anastrepha suspensa* (Diptera: Tephritidae) and potential areas for its biological control with *Diachasmimorpha longicaudata* (Hymenoptera: Braconidae) in the Americas. *Manuscrito submetido a revista Biological Control*.

Risk analysis for *Anastrepha suspensa* (Diptera: Tephritidae) and potential areas for its biological control with *Diachasmimorpha longicaudata* (Hymenoptera: Braconidae) in the Americas

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ABSTRACT

The Caribbean fruit fly *Anastrepha suspensa* (Diptera: Tephritidae) is a polyphagous pest causing economic losses in Central America, the Caribbean and South Florida. The parasitoid wasp *Diachasmimorpha longicaudata* (Hymenoptera: Braconidae) is the main parasitoid of *A. suspensa* in biological control programs. In this study, by modeling with CLIMEX software, climatically suitable areas were projected according to historical climate data. Areas with overlapping optimal climatic suitability for the joint establishment of the pest and parasitoid were mapped, indicating large areas with host presence in North, Central, and South America, with cold stress being the main climatic factor limiting distribution for both species. Tropical regions have the most potential for invasion, with optimal suitability in many areas. Through the projected distributions, this study can target quarantine strategies in areas most susceptible to invasion and establishment of the pest in each country. In addition, the use of classical biological control with the parasitoid in areas with climatic suitability is also recommended.

Keywords: caribbean fruit fly; Braconidae; CLIMEX modeling; biological control; niche overlap; climate suitability

1 Introduction

Many species of fruit flies (Diptera: Tephritidae) are invasive pests of horticultural crops worldwide because of their climatic adaptability, host range, and high reproduction (Sarwar, 2015). *Anastrepha suspensa* (Lower, 1862), better known as the Caribbean fruit fly, is a polyphagous species that attack about 100 temperate, subtropical, and tropical climate plants (EPPO, 2018; Swanson and Baranowski, 1972). with a preference for guava (*Psidium guajava*), jambo (*Syzygium jambos*), peach (*Prunus persica*), surinam cherry (*Eugenia uniflora*), and mature *Citrus* spp. (CABI, 2020; Weems et al., 2017).

The current occurrence of *A. suspensa* includes the entire Caribbean region, the coast of Mexico, and southern and central Florida (CABI, 2020). The first infestation is believed to have occurred in Key West, Florida (USA) in 1931 from collected adults, allowing the identification of guava as the main host. In 1936, the population became extinct through control programs promoted by the State Plant Board of Florida and the United States Department of Agriculture (Swanson and Baranowski, 1972; Weems et al., 2017). In 1965, 14,000 adults of *A. suspensa* were captured in Dade County (Miami), representing a new infestation after 30 years of eradication (Nigg et al., 1994).

Because they lay their eggs inside the fruit, most fruit flies are pests that cause failure and damage the quality of the fruit they infest (Suckling et al., 2016; Villalobos et al., 2017). The larvae consume the fruit flesh, leading to early ripening, fruit drop, and rotting (Adaime et al., 2018). An attacked fruit may have oviposition perforations, but it can be difficult to identify these or any other indicators of damage in the early stages of an infestation (CABI, 2020). Because of their direct impact and quarantine requirements set by importing countries, the presence of certain pest species restricts access to international markets (Lanzavecchia et al., 2014).

More than one strategy is needed for fruit fly management. Each method has its own requirements and may or may not be suitable for all cases (Suckling et al., 2016) . Within fruit fly management programs, biological control with parasitoids has been the most researched control strategy (Dias et al., 2018). The parasitoid *Diachasmimorpha longicaudata* (Ashmead, 1905) (Hymenoptera: Braconidae) is ideal for biological control programs due to its ability to be mass-reared on artificial diet and its high reproductive rate with rapid doubling (Ndlela et al., 2021) . Oviposition of *D. longicaudata* occurs on fruit fly larvae in infested fruit. The parasitoid larvae feed internally and emerge from fly pupae in the soil (Simmonds et al., 2016; Thompson, 2017)

Because of the *A. suspensa* infestation in 1965 in Florida, a biological control program was established by importing 11 species of parasitoids. In the following years, the release of the parasitoids *D. longicaudata* and *Doryctobracon areolatus* (Szépligeti, 1911) decreased *A. suspensa* populations in Florida by 40% (Baranowski et al., 1993; Ovruski et al., 2000). *D. longicaudata* has become established in areas determined in biological control programs in the Caribbean, Pacific Islands, South Florida, and Central and South American countries (Schliserman et al., 2016; Weems et al., 2017).

Predictive technologies, such as species distribution models (SDMs), allow for risk assessment and possible changes in species distribution and are an important component in pest control (Journé et al., 2020; Kolar and Lodge, 2001) SDMs include ANUCLIM/BIOCLIM, CLIMATE, CLIMEX, DOMAIN, GARP, HABITAT, and MaxEnt (Phillips et al., 2006; Ramirez-Cabral et al., 2016; Shabani et al., 2015, 2012).

CLIMEX is often used to estimate the impact of climate change on species, as it correlates climate and biological parameters to project niches on a temporal and spatial scale (Finch et al., 2021; Macfadyen and Kriticos, 2012). This way, the potential distribution can be examined in advance, and guidance can be provided to implement control measures for the target species (Byeon et al., 2018).

The objective of this study was to estimate the distribution potential of *A. suspensa* and the parasitoid *D. longicaudata* for the identification of ecologically suitable overlapping sites for the recommendation of classical biological control in case of invasion.

2 Material and methods

2.1 Occurrence data

The occurrence points of *A. suspensa*, *D. longicaudata*, and the main host crops of the pest *P. guajava*, *S. jambos*, *P. persica*, *E. uniflora* and *Citrus* spp. were obtained from the databases of the Global Biodiversity Information Facility (GBIF) (www.gbif.org) and the Center for

Agriculture and Bioscience International (www.cabi.org) and complemented with field work published in scientific articles.

Queries were made for synonyms of *A. suspensa* as *Anastrepha longimacula* (Greene, 1934), *Anastrepha unipuncta* (Seín, 1933), and *Trypeta suspensa* (Loew, 1862). Synonyms for *D. longicaudata* include *Biosteres compensans* (Silvestri, 1916), *Biosteres longicaudatus* (Ashmead, 1905), *Diachasmimorpha chocki* (Fullaway, 1953), *Diachasmimorpha formosana* (Fullaway, 1926), *Diachasmimorpha novocaledonica* (Fullaway, 1953), *Diachasmimorpha taiensis* (Fullaway, 1953) and *Opius longicaudatus* (Ashmead, 1905).

The accuracy of the points of occurrence obtained for *A. suspensa* and *D. longicaudata* was verified to affirm their veracity with the locality related through Google Maps (www.google.com/maps).

2.2 Meteorological data

Historical data from 1901 - 2017 with a spatial resolution of 10 km were used as they have good spatial resolution and high quality. These data have five climate variables: average monthly maximum temperature, average monthly minimum temperature, average monthly precipitation, and relative humidity at 9 am and 3 pm (Kriticos et al., 2012).

2.3 CLIMEX

CLIMEX is a simulation model that dynamically represents the structure of complex systems, such as the seasonal phenology of a species and its behavior over time through climate information (Huang et al., 2019; Kriticos et al., 2015) CLIMEX version 4.0 (Hearne software, Melbourne, Australia) was used for the analyses. We used the Compare Locations function to predict the potential distribution of areas with climatic suitability for *A. suspensa* and *D. longicaudata*.

CLIMEX simulates species distribution using the growth index (GI) and the stress index (SI) (Kriticos et al., 2015). . The Annual Population Growth Index (GIA) describes the potential for population growth during favorable climatic conditions as measured by the temperature (TI) and humidity (MI) indices (da Silva et al., 2018; Kriticos et al., 2015; Kumar et al., 2014) . The SI index addresses the species' ability to survive as measured by the quantity of cold stress (CS), heat stress (HS), wet stress (WS), and dry stress (DS) (Byeon et al., 2018).

The final result, which is the suitability for the presence of the target species in a given location, is represented by the ecoclimatic index (EI), which incorporates the GI and SI plus the degree days per generation (PDD). Ranging on a scale from 0 to 100, EI near 0 indicates climatic unsuitability for species survival in a given region, while EI>30 represents high climatic suitability for the long-term survival of a species (Kriticos et al., 2015). Values near 100 indicate optimal suitability for species introduction and establishment. For the present work, the range of EI was defined as EI = 0 (unsuitable), 0 < EI < 30 (suitable), and IE ≥ 30 (ideal).

2.4 CLIMEX parameter adjustment

The parameters were set based on the pest and parasitoid's current known distribution and thermal requirements, as found in the literature. We found 35 occurrences of *A. suspensa* and 51 for *D. longicaudata*, of which 33 were from sites where the parasitoid was released, but there was no establishment confirmation, and 18 with confirmation.

The parameters for lowest soil moisture threshold (SM0), lower optimum soil moisture (SM1), upper optimum soil moisture (SM2), and upper soil moisture threshold (SM3) were adjusted for humid tropical climate (Kriticos et al., 2015) based on the preferences of average temperature greater than 18°C and 1500 mm annual precipitation for *A. suspensa* (Adaime et al., 2018; CABI, 2020) and *D. longicaudata* for their successful introductions over the last century in tropical and subtropical climate against fruit flies belonging to the genus *Anastrepha* (Montoya et al., 2000; Ovruski et al., 2000) (Table 1).

The lower temperature limit (DV0), lower optimum temperature (DV1), upper optimal temperature (DV2), and upper temperature limit (DV3) were defined based on scientific experimental work (Table 1). For *A. suspensa*, the temperature limits for development were set at 15°C (DV0) and 34°C (DV3) (Prescott and Baranowski, 1971); the optimal range for development was set between 18°C (DV1) (Adaime et al., 2017; CABI, 2020) and 28°C (DV2) (Lawrence, 1979). The heat stress temperature limit (TTHS) and cold stress temperature limit (TTCS) were set at 40.56 °C and 11 °C, respectively (Prescott and Baranowski, 1971). Values above TTHS and below TTCS disrupt development. The number of degree days required to complete a generation was determined to be 152.6°C (Prescott and Baranowski, 1971).

The parameters for *D. longicaudata* were determined by Ndlela et al. (2021) , who determined temperature thresholds for the parasitoid, porting DV0 = 10 °C, DV1 = 15 °C, DV2 = 25 °C, DV3 = 33.7°C, TTHS = 35°C, and PDD = 333.33. The TTCS value was set at 7.33°C (Meirelles et al., 2015).

For the other stress indices, the model was fitted for *A. suspensa* and *D. longicaudata* based on the recommendations in Kriticos et al. (2015) for tropical humid climates (Table 1).

3 Results

3.1 Distribution potential of *A. suspensa* and *D. longicaudata*

The distribution potential for *A. suspensa* (Fig. 1) and *D. longicaudata* (Fig. 2) shows climatic suitability in the Caribbean, Central, North, and South America with suitable and ideal areas. *A. suspensa* presents areas with ideal climatic suitability distributed in Argentina, Brazil, Bolivia, Colombia, Costa Rica, Cuba, Florida (USA), Guatemala, Guyana, French Guyana, Honduras, Nicaragua, Panama, Paraguay, Peru, Dominican Republic, Suriname, and Venezuela. These regions may be suitable for the pest to establish a population and spread rapidly. Climate-suitable areas in Central America present a serious threat of invasion due to their proximity to areas where the pest occurs.

The areas with ideal climatic suitability for *D. longicaudata* (Fig. 2) are smaller than *A. suspensa*. The highest concentration of regions with ideal suitability is found in Guatemala, Nicaragua, Dominican Republic, French Guiana, Venezuela, Colombia, Brazil, Paraguay, and Argentina.

The current distribution of *A. suspensa* and *D. longicaudata* was validated based on areas where there is establishment of the species in Central America (Fig. 1A and Fig. 2A) and South America (Fig. 2B). The modeling showed high consistency with the geographic distribution; all occurrence points were located within the projected distribution.

3.2 Distribution limiting climatic variables for *A. suspensa* and *D. longicaudata*

The factors limiting the distribution of *A. suspensa* (Fig 3A and B) and *D. longicaudata* (Figs. 4A and B) in many regions of North and South America are associated with cold, heat, and drought stress. Cold stress is the main limiting factor for both species, especially in North

America and countries such as Chile, Argentina, and coastal Peru. Drought stress is more present in the United States, Mexico, Chile, Peru, and Argentina for *A. suspensa* and *D. longicaudata*. Heat stress was identified for *D. longicaudata* (Fig. 4A) in the southwestern United States and northern Mexico.

3.3 Development and propagation potential of *A. suspensa* and *D. longicaudata*

The GIA map for *A. suspensa* (Fig. 5A) and *D. longicaudata* (Fig. 6A) shows regions favorable for potential development throughout the year, in addition to regions with potential in the Caribbean, Central and South America. The midwestern and northeastern regions of the United States show migratory potential in favorable periods for both species.

Under ideal conditions, *A. suspensa* can reach 36.29 generations throughout the year (Fig. 5B). The most prone regions are found in northern Brazil, Colombia, Guatemala, Nicaragua, and Venezuela, as well as the entire Caribbean region and Florida. Other areas of South America have the potential for up to 27 generations.

D. longicaudata (Fig. 6B) exhibits potential for up to 21 generations in the Caribbean, Central America, and the tropical Amazon region of South America. These regions are more prone to long-term establishment, with the potential for multiple annual generations.

3.4 Areas with Classic Biological Control Potential

According to the projection of ideal overlapping areas between the two species (Fig. 7A), *A. suspensa* and *D. longicaudata* can coexist in regions of the Caribbean, North America, Central and South America.

In North America, the model indicates that in Florida, the northeastern region and coastline with the Atlantic Ocean have the greatest potential for areas of overlap in the United States. In Mexico, Tamaulipas, Vera Cruz, Puebla, and Chiapas are ideal areas for the joint establishment of *A. suspensa* and *D. longicaudata*. These regions have all major hosts (Fig. 7A-F).

All major hosts (Fig. 7A-F) have an occurrence in Central America. The model indicates overlapping areas with ideal climatic suitability are present in almost all of its territory, except for El Salvador, which did not show optimal suitability overlap.

In the Caribbean, all regions have areas of overlap. Jamaica and the Bahamas have the occurrence of *P. guajava* (Fig. 7B), *S. jambos* (Fig. 7C), and *Citrus* spp. (Fig. 7F) and suitability throughout their territory. Cuba and the Dominican Republic have small areas of overlap and occurrence of all major hosts, with *P. persica* occurring to a lesser extent.

A. suspensa does not occur in South America but has potential distribution and the presence of significant hosts for almost all countries in suitable and ideal areas. In Brazil, the areas of overlap between *A. suspensa* and *D. longicaudata* were located in the north in the states of Acre, Amazonas, Amapá, Pará, and Rondônia, having the presence of *Citrus* spp. (Fig. 7F), *E. uniflora* (Fig. 7E), and *P. guajava* (Fig. 7B). In the central-western and southern regions, in the states of Minas Gerais, Paraná, Santa Catarina, São Paulo, and Rio Grande do Sul, the greatest number of *Citrus* spp., *E. uniflora*, *P. persica* (Fig. 7D), *P. guajava*, and *S. jambos* (Fig. 7C) are concentrated in overlapping areas. Small areas of ideal suitability for both species are also present in the coastal region with the presence of the main hosts.

In Paraguay, the eastern region presents ideal establishment potential for *A. suspensa* and *D. longicaudata*. Also, it has occurrences of the main hosts (Fig. 7A-F), emphasizing *Citrus* spp., *E. uniflora*, and *P. guajava* due to the highest number of occurrences.

Argentinian mesopotamia has the establishment of *D. longicaudata* (Fig. 2B) and areas with potential overlap with *A. suspensa*. The most abundant hosts are *P. guajava* and *E. uniflora*, but all major hosts occur (Fig. 7A-F).

The Amazonian regions of Ecuador, Colombia, and Peru exhibit ideal climatic suitability and coincide with occurrences of *P. guajava*, *Citrus* spp., and *S. jambos*. Other countries like Guyana, French Guiana, Suriname, and Venezuela have regions overlapping *A. suspensa* and *D. longicaudauta* mainly in border areas with the presence of the main hosts, except *P. persica*, with occurrence only in French Guiana.

4 Discussion

The potential distribution of *A. suspensa* and *D. longicaudata* was estimated using CLIMEX and we identified the overlap of climatically ideal areas, the stress factors that limit the distribution of the species, plus the development and number of annual generations. The results were consistent through cross-validation between current occurrence and predicted distribution. In this context, our study indicates the success of a biological control program with *D. longicaudata* in the case of a possible invasion of *A. suspensa*.

In North and South America locations, *A. suspensa* and *D. longicaudata* lack conditions for establishment because they are species adapted to tropical and subtropical climates (Ovruski et al., 2000; Weems et al., 2017). *A. suspensa* is restricted to Central America and the Caribbean, but there is a risk of migration and establishment in South America due to the proximity of sites with climatically suitable occurrences and areas. At the same time, North America is limited by areas affected by drought and cold stresses (Fig. 3A-B), but it may have migratory potential during periods of the year favorable for development (Fig. 5A-B).

Fluctuations in temperature, rainfall, and constant winds are factors that hinder the establishment of *D. longicautada* (Messing et al., 1997; Sánchez et al., 2016) For example, dry and cold stresses may have restricted the establishment of *D. longicaudata* in Argentina after releases in Entre Rios, Jujuy, Province of Córdoba, Turica (SCHLISERMAN et al., 2003), San Juan and San Miguel de Tucuman (Sánchez et al., 2016) , regions that are outside the predicted potential distribution (Fig. 2B) and with drought and cold stress rates (Fig. 4). However, in Missiones and Salta, *D. longicaudata* became established after deliberate introductions (Oroño and Ovruski, 2007; Schliserman et al., 2003), areas with climatic suitability predicted by CLIMEX (Fig. 2B).

The modeling indicates that the likelihood of *A. suspensa* expanding its distribution is high due to the abundance of climatically suitable areas and host plants available throughout the projection. *A. suspensa* has been observed attacking *E. uniflora*, *P. guajava*, *P. persica*, *S. jambos*, and *Citrus* spp. in Florida (Burk, 1983; Greany et al., 1977; Sivinski et al., 1996; Weems et al., 2017). The Americas account for about 45% of the world's guava production (Maiorano, 2022), with most of it being produced in Central and South America (CABI, 2019). *A. suspensa* has been causing problems on *P. guajava* for several decades in South Florida (Heve et al., 2017; Weems et al., 2017).

In South America, there are currently no reports of the presence of *A. suspensa*, but significant damage could be caused if the pest were introduced. According to the modeling, these areas have ideal potential that could present risks to agricultural production in case of invasion. For example, the municipality of Casa Branca in southeastern Brazil is the largest orange producer in the world (IBGE, 2022).

In the absence of natural enemies, invasive pest insects arrive in new environments and rapidly increase in numbers in newly invaded areas . The use of insecticides against *A. suspensa* adults in infested orchards will not control larvae in fruits or on the ground (Heve et al., 2018), and sterile insect techniques and destruction of *A. suspensa* infested fruits are not observed in large commercial orchards because of high labor costs (Heve et al., 2018; Qin et al., 2015).

The population of *A. suspensa* can be reduced through chemical control using attractive baits (Adaime et al., 2018) and biological control with parasitoid wasps. Because *D. longicaudata* has been established in countries in the Caribbean, Central, and South America, introducing it to countries with similar climatic suitability may be an effective control method if *A. suspensa* is introduced.

Studies show that *D. longicaudata* attacks *A. suspensa* larvae on all its main fruit hosts (Sivinski et al., 1998, 1996) and has chances to establish itself without compromising pre-existing trophic relationships (Alvarenga et al., 2005). It can be recommended to use it together with other parasitoid species, such as *Doryctobracon crawfordi* (Viereck,1911) and *D. areolatus*, since, at the competition level, the two controls together become more effective than separately (Miranda et al., 2015; Sivinski et al., 1998).

CLIMEX is used as a species distribution model. However, the model has limitations that must be taken into consideration. The modeling was performed without the use of non-climate variables such as disease presence, biotic interactions, and host availability. Therefore, it should be considered that the species' metabolism may change with climate changes (Ge et al., 2019).

Climatically ideal areas should have intensified quarantine policies in product and host surveillance and monitoring with traps to prevent the occurrence of *A. suspensa*. However, this study may provide guidelines for the prevention of *A. suspensa* in areas with climatic suitability and hosts, as this method has been used to predict the possibility of using biological control measures on pest species (Dhileepan et al., 2006). and, as an alternative, the use of *D. longicaudata* as a control in overlapping areas.

5 Conclusions

The American continent has areas suitable for *A. suspensa* and *D. longicaudata*. The potential for establishment of *A. suspensa* in areas where the species is absent in countries that produce the main hosts, such as Guatemala, Nicaragua, Costa Rica, Panama, Colombia, Venezuela, Guyana, French Guiana, Suriname, Brazil, Peru, Bolivia, Paraguay, and Argentina, is at risk of pest invasion. *D. longicaudata* showed climatic suitability and areas with optimal overlap with the pest in large areas of North, South, and Central America.

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Ethical guidelines

Ethics approval was not required for this research.

Data availability statement

The data presented in this article is available on reasonable request from the corresponding author.

CRediT authorship contribution statement

Geovani Santana: Conceptualization, Investigation, Data curation, Methodology and validation, Formal analysis, Writing—original draft. **Beatriz Ronchi-Teles:** Resources**,** Writing-review & Editing. **Cícero dos Santos:** Writing-review & Editing. **Philipe Souza:** Writing-review & Editing. **Priscila Farnezi:** Writing-review & Editing. **Ricardo Siqueira:** Methodology and validation, Formal analysis, Supervision, Writing-review & Editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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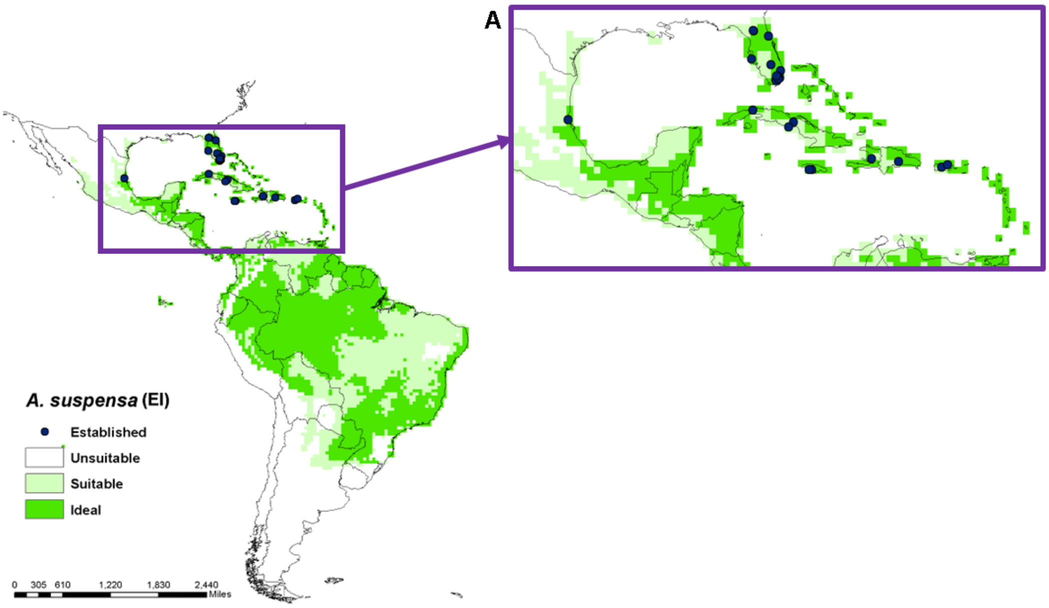

Fig. 1 Potential distribution of *Anastrepha suspensa* predicted by CLIMEX for the Americas and validation with current occurrence points (A).

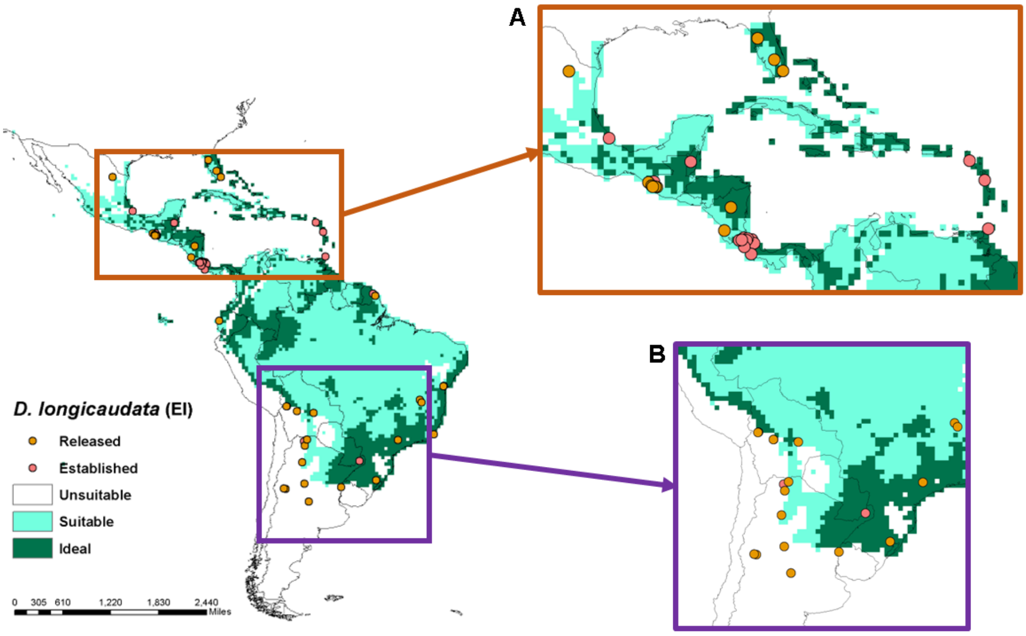

Fig. 2 Potential distribution of *Diachasmimorpha longicaudata* predicted by CLIMEX for the Americas and validation with establishment points in the Caribbean, Central and South America (A and B).

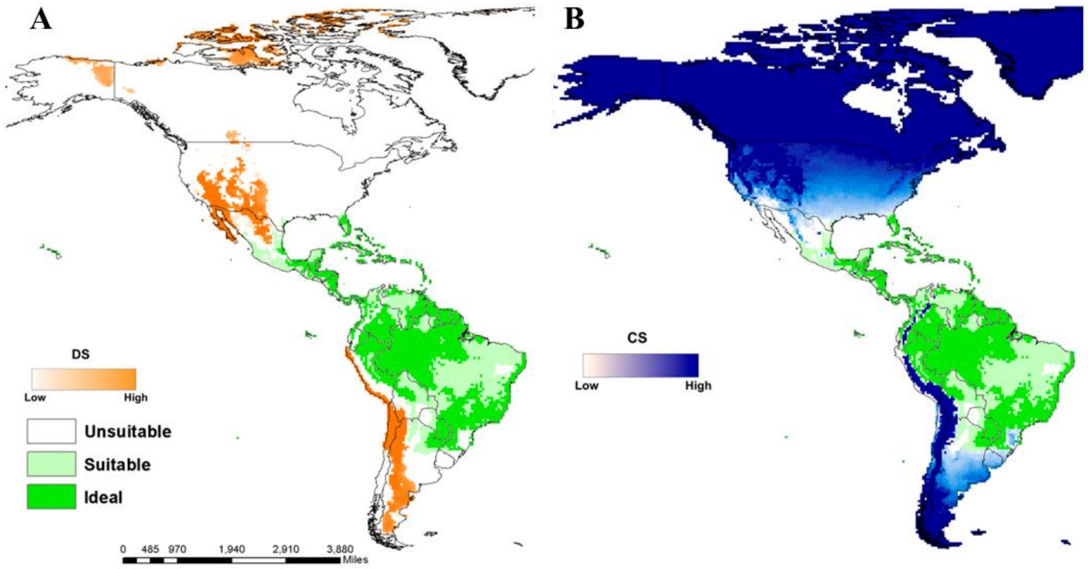

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Fig. 3 The main stresses (A and B) for *Anastrepha suspensa* projected by CLIMEX on the American continent.

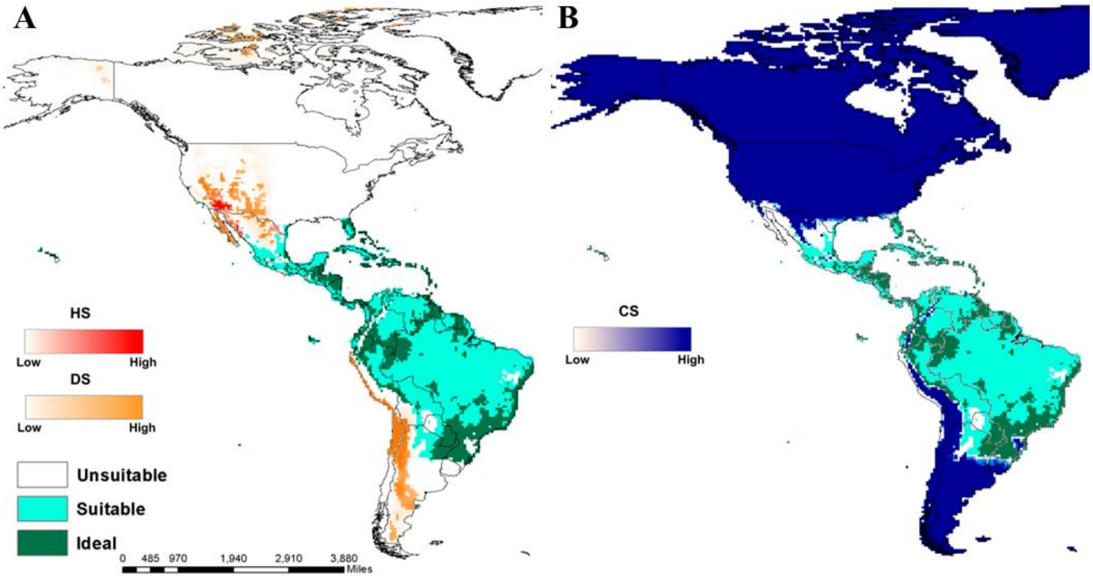

Fig. 4 The main stresses (A and B) for *Diachasmimorpha longicaudata* projected by CLIMEX on the American continent.

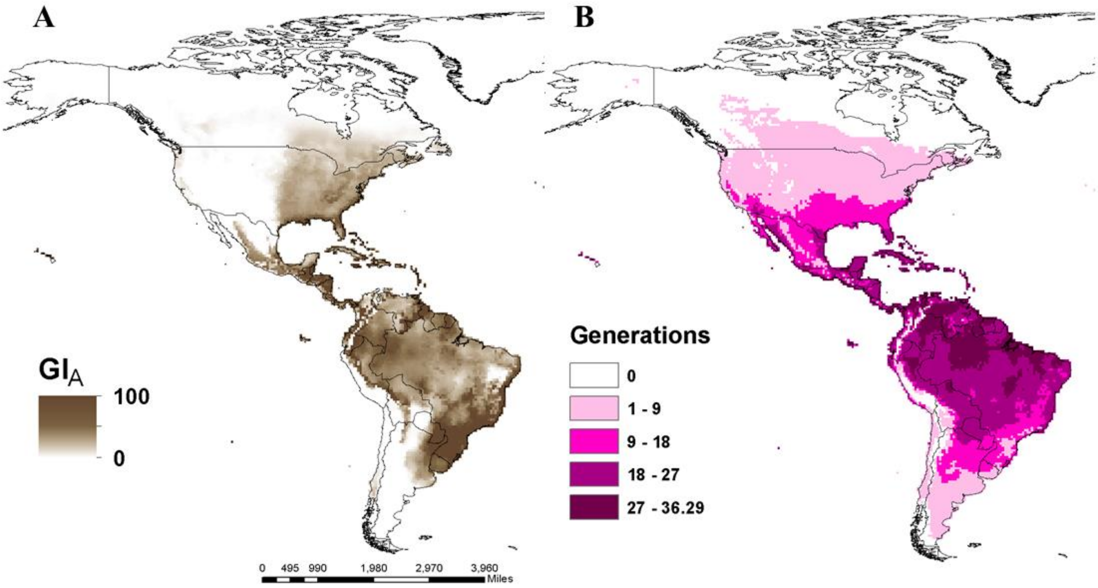

Fig. 5 Annual growth index (A) and annual number of generations (b) for *Anastrepha suspensa* by CLIMEX on the American continent.

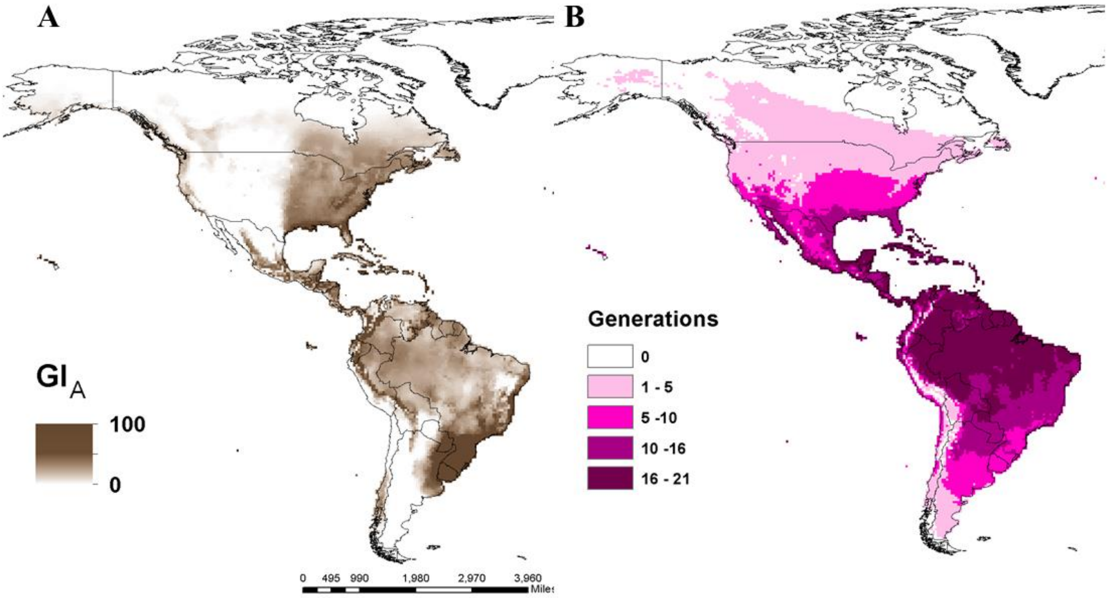

Fig. 6 Annual growth index (A) and annual number of generations (b) for *Diachasmimorpha longicaudata* by CLIMEX on the American continent.

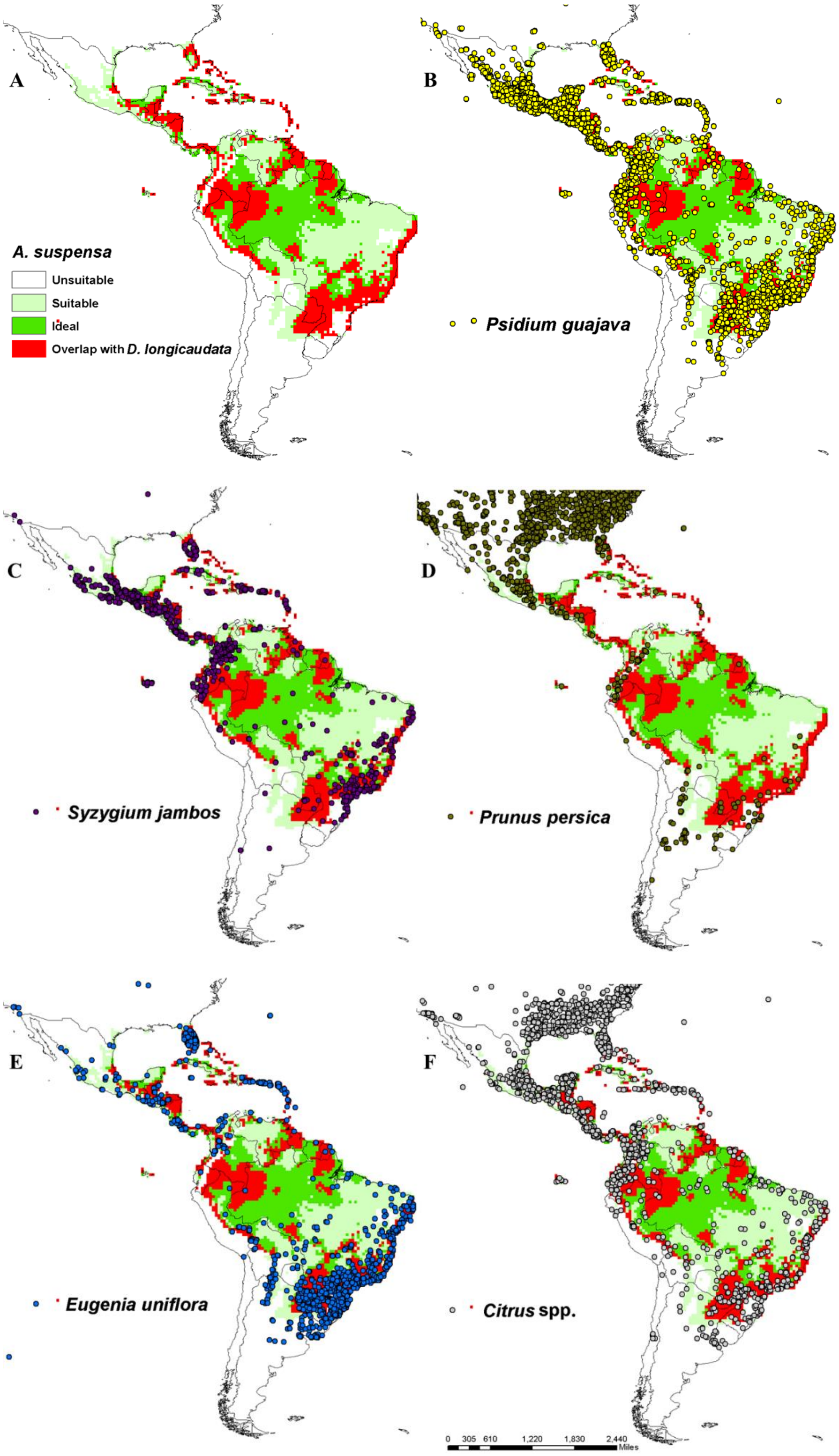

Fig. 7 Overlapping optimal areas of the potential distribution models of *Anastrepha suspensa* and *Diachasmimorpha longicaudata* (A) in crops of *Psidium guajava* (B), *Syzygium jambos* (C), *Prunus persica* (D), *Eugenia uniflora* (E) and *Citrus* spp. (F) for the Caribbean, North America, Central and South America.

Table 1. CLIMEX parameter values used for modeling *A. suspensa* and *D. longicaudata*

Index	**Parameters**	**Value**	
		A. suspensa	***D. longicaudata***
Moisture	**SM0** = lower soil moisture threshold	0.35*	0.35*
	SM1 = lower optimum soil moisture	0.7*	0.7*
	SM2 = upper optimum soil moisture	1.5*	1.5*
	SM3 = upper soil moisture threshold	2.5*	2.5*
Temperature	**DV0** = lower temperature limit	15°C	10°C
	DV1 = lower optimum temperature	18°C	15°C
	DV2 = upper optimum temperature	28°C	25°C
	DV3 = upper temperature limit	34°C	33.7°C
Cold stress	**TTCS** = cold stress temperature limit	11°C	7.33°C
	DTCS = degree-day threshold	15°C days	25°C days
	DHCS = stress accumulation rate	-0.001 week^{-1}	-0.02 week^{-1}
Heat stress	**TTHS** = heat stress temperature limit	40.56°C	35°C
	THHS = stress accumulation rate	0.0002 week^{-1}	0.0002 week^{-1}
	HDS = stress accumulation rate	-0.01 week^{-1}	-0.005 week^{-1}
	SMDS = soil moisture threshold	0.25*	0.2*
Wet stress	**SMWS** = soil moisture threshold	2.5*	2.5*
	HWS = stress accumulation rate	0.002 week^{-1}	0.002 week^{-1}
Degree days	**PDD** = degree days per generation	152.6°C days	333.33°C days

* Estimated soil moisture indices, ranging from 0 (dry) to 1, are given without units (field capacity).

SÍNTESE

A confiabilidade do modelo para estimar o potencial de distribuição de *A. suspensa* e *D. longicaudata*, assim como as análises espaço-temporais, foram validadas de conforme as ocorrências atuais. Portanto, a utilização desses modelos pode ser utilizada para prever as áreas que possuem adequação climática para a praga e o parasitoide. Porem vale ressalta que o modelo utiliza apenas variáveis climáticas, não considerando variáveis biológicas.

Os resultados mostram as áreas suscetíveis a invasão da praga, podendo apresentar impactos econômicos negativos em áreas que possuem seus principais hospedeiros. Entretanto, a utilização do parasitoide deve ser possível devido o potencial de distribuição ser semelhante ao da praga e áreas de sobreposição com condições climáticas ideais foram detectadas em áreas de cultivo dos principais hospedeiros. Ambas espécies são restringidas por estresses de calor, frio e seca, mas podem migrar para outras regiões ao decorrer do ano. No futuro, os modelos e cenários propostos mostram redução em áreas adequadamente climáticas para *A. suspensa* no mundo, devido o aumento gradual da seca por conta da diminuição das chuvas e aumento da temperatura propostos pelos modelos climáticos globais.

Através dos modelos de dinâmica espaço-temporal desenvolvidos, será possível a avaliação e elaboração de estratégias em áreas com condições climáticas ideais que possuem potencial de risco de invasão da *A. suspensa*. E por ser uma praga quarentenária ausente, o seu controle por método químico como inseticidas não poderia ocorrer em alguns lugares por falta de regulamentação do produto para a praga, sendo assim a utilização de controle biológico através do parasitoide *D. longicaudata* em áreas de sobreposição climática poderia ser eficiente, já que seu controle se dá por larvas de *A. suspensa* no fruto. Por tanto, diminuindo a quantidade de adultos da praga nas gerações seguintes.

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