PAULO ANTÔNIO SANTANA JÚNIOR

WORLDWIDE SPATIAL DISTRIBUTION OF *Tuta absoluta* (LEPIDOPTERA: GELECHIIDAE) AND ITS NATURAL ENEMIES UNDER CURRENT AND FUTURE CLIMATIC CHANGE CONDITIONS THROUGH MODELLING

Tese apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Fitotecnia, para obtenção do título de *Doctor Scientiae*

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APROVADA: 18 de janeiro de 2019.

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Marcelo Coutinho Picanço
(Orientador)

Aos meus pais e irmãs,

Pelo todo amor e carinho,

Dedico.

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SUMÁRIO

RESUMO

SANTANA JÚNIOR, Paulo Antônio, D.Sc., Universidade Federal de Viçosa, janeiro de 2019. **Distribuição espacial mundial de *Tuta absoluta* (Lepidoptera: Gelechiidae) e seus inimigos naturais sob condições climáticas atuais e futuras através da modelagem.** Orientador: Marcelo Coutinho Picanço.

Em apenas 10 anos o inseto *Tuta absoluta* se tornou mundialmente uma das pragas mais importantes. Desde sua introdução na Espanha em 2006, essa praga infestou aproximadamente 60% das áreas cultivadas com tomate em todo mundo. Neste trabalho, modelos de nicho ecológicos foram criados para identificar as áreas em risco de invasão de *T. absoluta* e os efeitos das mudanças climáticas previstas para essa praga e quatro de seus inimigos naturais (*Neochrysocharis formosa, Stenomesius japonicus, Pseudapanteles dignus* e *Macrolophus pygmaeus*). As áreas em risco de invasão de *T. absoluta* foram determinadas utilizando os softwares CLIMEX e MaxEnt. Devido suas adequabilidades climáticas, países produtores de tomate como China, México, Holanda e EUA devem ser preocupar com uma possível invasão de *T. absoluta* no futuro. O aumento em adequabilidade climática em campo nesses países não será acompanhada pelo aumento em adequabilidade climáticas para alguns dos inimigos naturais. Portanto, este estudo possibilitará agências de manejo de pragas melhorarem os seus programas de controle biológico e barreiras quarentenárias contra *T. absoluta*.

ABSTRACT

SANTANA JÚNIOR, Paulo Antônio, D.Sc., Universidade Federal de Viçosa, January, 2019. **Worldwide spatial distribution of *Tuta absoluta* (Lepidoptera: Gelechiidae) and its natural enemies under current and future climatic change conditions through modelling.** Adviser: Marcelo Coutinho Picanço.

In only 10 years the insect *Tuta absoluta* has become one of the most important threat for agriculture worldwide. Since its introduction in Spain in 2006, this pest has infected 60% of the tomato crops in many regions of the world. In this study, ecological niche models were built investigate the areas under risk of invasion of *T. absoluta* and the effect of climate change on it and four of its natural enemies (*Neochrysocharis formosa, Stenomesius japonicus, Pseudapanteles dignus*, and *Macrolophus pygmaeus*). We modelled the areas under risk and the effect of climate change on the pest and its natural enemies using CLIMEX and MaxEnt. Important tomato producers such as China, Mexico, the Netherlands, and the USA should be concerned about the risk of an eventual invasion of *T. absoluta* due to their climatic suitability for this pest. The increasing suitability for *T. absoluta* in open field in these countries will not be accompanied by an increase for some of the natural enemies. Therefore, this variation in suitability will have important consequences on biological control in these areas. Thus, this study allows pest management agencies to improve their biological control programs and quarantine measures against the tomato pinworm.

INTRODUÇÃO GERAL

O último século foi marcado por enorme crescimento tecnológico e isso possibilitou a grande expansão do processo de globalização. Este por sua vez, permitiu uma melhoria na qualidade de vida da população mundial em diversos setores como, saúde, educação e transporte. O aumento do transporte de pessoas é um bom exemplo deste crescimento. Em 1950, o número anual de pessoas que chegavam à Europa era de 25 milhões de pessoas (UNWTO 2017). Já em 2016, este número saltou para 750 milhões de pessoas, significando um aumento de 2800% no número de pessoas visitando este continente (UNWTO 2017). Embora todo este crescimento tenha resultado em incontáveis benefícios, ele também trouxe consequências negativas como, por exemplo, o aumento de problemas associados às pragas invasoras (Cook et al. 2011; Essl et al. 2011; Paini et al. 2016).

O inseto *Tuta absoluta* (Meyrick, 1917) (Lepidoptera: Gelechiidae) é um excelente exemplo deste problema. Este inseto é comumente conhecido no Brasil por Traça do tomateiro é considerado praga chave dessa cultura por mais de 50 anos na América do Sul. *T. absoluta* foi detectada pela primeira vez no Brasil em 1979 e desde seu primeiro relato, vem causando grandes prejuízos aos produtores de tomate do país (Bacci 2006; Guedes and Picanço 2012). Em 2006, essa praga foi detectada pela primeira vez no continente europeu, mais especificamente na Espanha, e desde então ela teve uma rápida expansão do seu habitat chegando a infestar aproximadamente 60% das áreas cultivadas com tomate em todo o mundo (Campos et al. 2017; Desneux et al. 2011; Desneux et al. 2010; Urbaneja et al. 2007). Atualmente, a *T. absoluta* encontra-se dispersa em mais de 60 países distribuídos pela América, Europa e Ásia sendo, portanto, considerada uma praga invasiva de importância mundial (Biondi et al. 2018).

Devido à sua chegada ao continente europeu, muitas pesquisas foram realizadas com o objetivo de conter sua expansão e permitir o manejo adequado desta praga em todo mundo. Para tal propósito, o primeiro e mais importante passo é conhecer as áreas climaticamente adequadas à Traça do tomateiro.

Essa informação é determinada principalmente através de modelos de nicho ecológico (Kumar et al. 2014; Shabani & Kumar 2013; Soberón 2005), os quais podem ser divididos em dois grupos: (i) modelos de correlação e (ii) modelos mecanicistas (Dormann et al. 2012; Kumar et al. 2014). Os modelos de correlação (ex. Generalized Linear Model, MaxEnt, Random Forest, Boosted Regression Tree, Bioclim), utilizam a correlação de dados de ocorrência das espécies e variáveis climáticas para fazerem projeções das possíveis áreas adequadas à uma determinada espécie (Kumar et al. 2014). Já os modelos mecanicistas (ex. CLIMEX ou Nichemapper), utilizam informações sobre parâmetros biológicos das espécies juntamente com variáveis climáticas para fazer suas projeções (Kumar et al. 2014).

Neste sentido, três trabalhos de modelagem (Desneux et al. 2010; Tonnang et al. 2015; Xian et al. 2017) utilizando o software CLIMEX foram publicados para estudar a distribuição espacial da Traça do tomateiro, porém, eles utilizam parâmetros do ciclo de vida deste inseto publicados na década de 80. Recentemente novos valores desses parâmetros foram publicados na literatura e, portanto, projeções mais precisas da distribuição espacial dessa praga podem ser feitas. Além disso, o conhecimento das áreas climaticamente adequadas à *T. absoluta* de fato é muito valioso, contudo, este conhecimento pode ser elevado a um novo patamar. Ainda não há nenhum trabalho sobre as áreas climaticamente adequadas e o efeito das mudanças climáticas previstas sobre os inimigos naturais da *T. absoluta*. Esta informação é extremamente valiosa para os programas de manejo e controle biológico dessa praga, uma vez que permite entender como a distribuição espacial, tanto a praga quanto seus inimigos naturais poderão ser alteradas frente às mudanças climáticas previstas.

A atividade humana tem sido repetidamente reportada com uma das principais causas no aquecimento global (Allen et al. 2018). Segundo o relatório do Painel Intergovernamental sobre Mudanças Climáticas (IPCC), desde a metade do século 20 até 2012 a temperature superficial do planeta já havia aumentado aproximadamente 0,85 °C (Allen et al. 2018). Este aumento de temperatura tem reultado em profundas alterações em sistemas humanos e naturais, levando em aumentos nos períodos de secas, inundações, aumento do nível dos oceanos, perda de biodiversidade e principalmente, alterando o habitat de muitas espécies (Allen et al. 2018). Muitos ecossistemas estão em risco devido a estas alterações no clima, sobretudo os sistemas agrícolas, uma vez que pode levar ao aumento de incidência de pragas e doenças devido a alterações na distribuição desses organismos. Portanto, estudar os efeitos das mudanças climáticas globais sobre as pragas e seus inimigos naturais é fundamental para o manejo integrado e pragas.

Assim, este trabalho tem os seguintes objetivos: (i) propor um novo modelo de distribuição espacial de *T. absoluta* utilizando novos parâmetros biológicos recentemente publicados; (ii) avaliar o efeito das mudanças climáticas globais previstas para 2050 e 2100 sobre à *T. absoluta* utilizando o software CLIMEX; (iii) propor modelos de distribuição espacial para a *T. absoluta* e quatro importantes inimigos naturais (3 parasitoides e 1 predador) desse inseto utilizando o software MaxEnt e (iv) avaliar o efeito das mudanças climáticas globais previstas para 2050 e 2070 sobres esses insetos utilizando o MaxEnt.

Dessa forma, este trabalho possibilitará atualizar as informações sobre as áreas em risco de invasões de *T. absoluta* nas condições de clima atual e futura e prover informações sobre o papel do controle biológico nessas áreas.

LITERATURA CITADA

Bacci L (2006) Factors determining the attack of *Tuta absoluta* on tomato. Doctoral dissertation, Universidade Federal de Viçosa

Biondi A, Guedes RNC, Wan F-H, Desneux N (2018) Ecology, Worldwide Spread, and Management of the Invasive South American Tomato Pinworm, *Tuta absoluta*: Past, Present, and Future Annual Review of Entomology 63:null doi:10.1146/annurev-ento-031616-034933

Campos MR, Biondi A, Adiga A, Guedes RNC, Desneux N (2017) From the Western Palaearctic region to beyond: *Tuta absoluta* 10 years after invading Europe Journal of Pest Science 90:787-796 doi:10.1007/s10340-017-0867-7

Cook DC, Fraser RW, Paini DR, Warden AC, Lonsdale WM, De Barro PJ (2011) Biosecurity and yield improvement technologies are strategic complements in the fight against food insecurity PLoS ONE 6:e26084 doi:10.1371/journal.pone.0026084

Desneux N, Luna MG, Guillemaud T, Urbaneja A (2011) The invasive South American tomato pinworm, *Tuta absoluta*, continues to spread in Afro-Eurasia and beyond: the new threat to tomato world production Journal of Pest Science 84:403-408 doi:10.1007/s10340-011-0398-6

Desneux N et al. (2010) Biological invasion of European tomato crops by *Tuta absoluta*: ecology, geographic expansion and prospects for biological control Journal of Pest Science 83:197-215 doi:10.1007/s10340-010-0321-6

Dormann CF et al. (2012) Correlation and process in species distribution models: bridging a dichotomy Journal of Biogeography 39:2119-2131 doi:10.1111/j.1365-2699.2011.02659.x

Essl F et al. (2011) Socioeconomic legacy yields an invasion debt Proceedings of the National Academy of Sciences 108:203-207 doi:10.1073/pnas.1011728108

Guedes RNC, Picanço MC (2012) The tomato borer *Tuta absoluta* in South America: pest status, management and insecticide resistance EPPO Bulletin 42:211-216 doi:10.1111/epp.2557

Kumar S, Neven LG, Yee WL (2014) Evaluating correlative and mechanistic niche models for assessing the risk of pest establishment Ecosphere 5:1-23 doi:10.1890/ES14-00050.1

M. R. Allen, O. P. Dube, W. Solecki, F. Aragón–Durand, W. Cramer, S. Humphreys, M. Kainuma, J. Kala, N. Mahowald, Y. Mulugetta, R. Perez, M. Wairiu, K. Zickfeld (2018) Framing and Context. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C.

Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)]. In Press.

Paini DR, Sheppard AW, Cook DC, De Barro PJ, Worner SP, Thomas MB (2016) Global threat to agriculture from invasive species Proceedings of the National Academy of Sciences 113:7575-7579 doi:10.1073/pnas.1602205113

Shabani F, Kumar L (2013) Risk levels of invasive *Fusarium oxysporum* f. sp. in areas suitable for date palm (*Phoenix dactylifera*) cultivation under various climate change projections PLoS ONE 8:e83404 doi:10.1371/journal.pone.0083404

Soberón J (2005) Interpretation of models of fundamental ecological niches and species' distributional areas. Biodiversity Informatics 2:1-10

Tonnang HEZ, Mohamed SF, Khamis F, Ekesi S (2015) Identification and risk assessment for worldwide invasion and spread of *Tuta absoluta* with a focus on Sub-Saharan Africa: Implications for phytosanitary measures and management PLoS ONE 10:e0135283 doi:10.1371/journal.pone.0135283

UNWTO UNWTO (2017) International tourist arrivals. Our World In Data. https://ourworldindata.org/grapher/international-tourist-arrivals-by-world-region. Accessed April 28th 2018

Urbaneja A, Vercher R, Navarro V, F GM, J.L. P (2007) La polilla del tomate, *Tuta absoluta* Phytoma Espana 194:16-23

Xian X, Han P, Wang S, Zhang G, Liu W, Desneux N, Wan F (2017) The potential invasion risk and preventive measures against the tomato leafminer *Tuta absoluta* in China Entomol Gen 36:319-333 doi:10.1127/entomologia/2017/0504

Chapter 1: Global geographic distribution of *Tuta absoluta* as affected by climate change

ABSTRACT

Over the last 10 years the insect *Tuta absoluta* has become one of the most important threats to agriculture worldwide. Since its introduction in Spain in 2006, this pest has infested 60% of the tomato crops in many regions of the world. Here we present the geographic distribution of *T. absoluta* at a global scale. Through the combination of spatial distribution models and the current distribution of the pest, this research makes projections of the threatened regions for this insect at the present and future times. We modelled the pest's potential distribution based on its new thermal requirement and the stress factors which limit this pest in Brazil. The model presented here showed large suitable areas for the tomato pinworm in the North and Central Americas, Africa, Europe, Asia and Oceania for the current and future times. Important tomato producers such as China, Mexico and the USA should be concerned about the risk of an eventual invasion of *T. absoluta* due to their climatic suitability for this pest. The climate changes predicted will affect *T. absoluta* negatively around the equator and positively near the poles. Regions with high latitude, for example the USA and Northern Europe, will become more suitable for the tomato pinworm due to the increase in temperature due to climate change. This study provides a comprehensive and current CLIMEX modelling effort for *T. absoluta*, allowing pest management agencies to increase their vigilance and improve quarantine measures.

Keywords: CLIMEX, ecosystem modelling, tomato pinworm, integrated pest management, ecological niche model, invasive alien species.

INTRODUCTION

One of the reasons for the decrease in yield in agriculture throughout the last century is associated with invasive pests reaching new areas (Campos et al. 2017; Cook et al. 2011; Kolar and Lodge 2001). Their access to potential sites can be related to the advent of globalization, especially the increasing interchange of people and products around the world (Cook et al. 2011; Essl et al. 2011; Paini et al. 2016). A recent and significant example of this problem is the spread of the invasive pest *Tuta absoluta* to the mainland Europe. *Tuta absoluta*, also known as the South American Tomato Pinworm, has been reported as a tomato pest in South America for more than 50 years (Desneux et al. 2011; Desneux et al. 2010; Guedes and Picanço 2012), and it can cause damages up to 80 - 100 % depending on the infestation level (Desneux et al. 2011). Until 2006 this pest was only found is South America. In 2006, the tomato pinworm was reported for the first time in Spain, causing damages to several tomato crops (Biondi et al. 2018; Desneux et al. 2011; Desneux et al. 2010; Martins et al. 2016; Silva et al. 2011). From a single invasive population from the central region of Chile (Biondi et al. 2018; Guillemaud et al. 2015) this pest has spread to several countries in Europe, Africa, Middle East, and Asia, causing large losses both in open field and greenhouse tomato crops (Biondi et al. 2018; Desneux et al. 2011; Desneux et al. 2010; Guimapi et al. 2016). A recent study showed that *T. absoluta* has infested 60% of the tomato crops in the world in the last 10 years, meaning an increase of its range radius by 800 km per year (Campos et al. 2017; Sankarganesh et al. 2017). Due to its high ability to cause damages in crops and infect new areas, this insect is in the spotlight as a pest worldwide.

Efforts to suppress the spread of *T. absoluta* damages are needed, and the first step for this effort is to gather information about the new potential areas where the pest can disperse. This information is very important since it allows governmental pest management agencies to implement sanitary barriers to prevent the entry of the tomato pinworm in their countries.

The potential distribution of a species has been assessed mainly through ecological niche models (Kumar et al. 2014; Shabani and Kumar 2013; Soberón 2005), which can be divided into two broad groups: correlative models and mechanistic models (Dormann et al. 2012; Kumar et al. 2014). Correlative models (e.g. Generalized Linear Model, MaxEnt, Random Forest, Boosted Regression Tree, Bioclim) correlate environmental variables and occurrence data to make projections of the potentially suitable areas for the species (Kumar et al. 2014). On the other hand, mechanistic models use the combination of environmental variables with information about the species environmental tolerances to make its projections (Kumar et al. 2014). CLIMEX is an example of a semi-mechanistic modelling software package which uses species parameters and climate variables to provide projections of the suitable areas for a species (Kriticos et al. 2015; Sutherst et al. 2007).

Regarding *T. absoluta,* there are three different CLIMEX models available in the literature (Desneux et al. 2010; Tonnang et al. 2015; Xian et al. 2017). In these studies, to adjust the models' parameters for the tomato pinworm, the authors used thermal requirement data that were published in the 1990's (Barrientos et al. 1998; Betancourt et al. 1996; Marcano 1995; Miranda et al. 1998). Initially, these thermal requirement thresholds were calculated based only on regression curves between the development time and temperature. However, a recently published study showed a different approach to calculating an insect's thermal requirement, and interestingly, the insect used in this study was *T. absoluta*. In this study, the authors used a life table study to investigate the overall effect of temperature on the tomato pinworm (Martins et al. 2016). By doing so, they were able to investigate the overall effect of temperature on the pest's life-cycle parameters, such as the net reproductive rate and intrinsic rate of population growth.

Consequently, they found different values of the thermal requirement for this pest, which might lead to a different projection of the spatial distribution of the tomato pinworm. Besides, key information that was not considered in previous modelling studies for *T. absoluta* was the stress factors which might limit the pest's range. This knowledge might be important in the areas where the species does not occur. However, to use this sort of information a great deal of field collected data is needed, which is difficult to obtain at broad scales.

The tomato pinworm has been reported as a pest in Brazil – the major tomato producer in South America – since 1979 (Guedes and Picanço 2012), and it has spread to the main tomato producing areas in this country. Coincidently, the tomato pinworm occupies areas which present high temperature and a well-characterized dry season (Bacci 2006; Gontijo et al. 2013), excluding areas such as the upper north regions (Gontijo et al. 2013) which are areas with intense and well-distributed precipitation throughout the year. Thus, the information about the areas where the pest does not occur might be useful in the modelling process, giving background information about the stress factors which could inhibit the pest's development. Although CLIMEX does not use absence data to build its model (Kriticos et al. 2015; Sutherst and Maywald 1985), these types of information could be used to point out the possibility of climate factors affecting the pest negatively.

Given this background, in this study, we aim to provide a comprehensive and current CLIMEX modelling effort for *T. absoluta*. To reach this aim, we introduce a new model for *T. absoluta* using CLIMEX, since the previous models for this pest used outdated thermal requirement values. Thus, we followed three steps: (i) used the new thermal requirement thresholds published by Martins et al. (2016), (ii) validated our model based not only on the occurrence data in South America but also on the areas known as *T. absoluta* absence in Brazil, and (iii) assessed the *T. absoluta* worldwide spatial distribution under the climate changes predicted for 2050 and 2100. Thus, in this article, we were able to update the information about the potential distribution of *T. absoluta*, and provide an insight into the risk of new introductions in the present and future time.

MATERIALS AND METHODS

Tuta absoluta Distribution

The occurrences of *T. absoluta* were cataloged and confirmed using the software PQR - EPPO Plant Quarantine Data Retrieval system (version 5.3.5, 2015) and through the search for scientific information on Web of Science, Science Direct, Google, PubMed, and MEDLINE. The keywords used during the search were *Tuta absoluta, Scrobipalpula absoluta*, tomato leafminer, tomato pinworm, South American tomato pinworm, tomato (*Solanum lycopersicum*), potato (*Solanum tuberosum*), first record, greenhouse, and open field. The occurrence data were classified among eight characteristics: continent, country, city/region, latitude, longitude, pest status (e.g. restricted, established, eradicated or transient), cultivation system (e.g. greenhouse or open field), year of first record and references (Table S1). By agricultural extension works in open field tomato cultivation, the absence data of *T. absoluta* were gathered through tomato farmer's interviews and field inspection performed during field expeditions executed by the Integrated Pest Management Laboratory of the Universidade Federal de Viçosa – UFV. Therefore, to build the model the occurrence data related to open-field reports, and *T. absoluta* absence in Brazil were used (Fig. 1, 2).

In order to identify a pattern in the dispersal of *T. absoluta,* the open-field occurrence records were classified into 19 groups based on the first occurrence. The oldest records received green colors and the most recent red to show the pattern clearly (Fig. 1).

CLIMEX Model

As described above, the spatial distribution of a species might be assessed through two broad groups of ecological niche models: correlative and mechanistic models (Kumar et al. 2014; Shabani and Kumar 2013; Soberón 2005). Correlative models correlate environmental variables and occurrence data to make projections of the potentially suitable areas for the species (Kumar et al. 2014). These models require little information about the links ruling the species environmental tolerances and, therefore, is advantageous in situations in which there is no information about the organisms responses to climatic factors (Kearney and Porter 2009).

On the other hand, in some situations the factors limiting the species distribution is important since the species niche is a response to the interactions among its physiological response and the climatic factors (Kearney and Porter 2009). Therefore, one of the fundamental factors which might limit a species distribution is its physiological tolerance to the environment (Kearney and Porter 2009). In this context, mechanistic models use the combination of environmental variables with information about the species environmental tolerances to make its projections (Kumar et al. 2014). This type of model is advantageous when the information about the species environmental tolerances is available. Another important aspect that might be assessed through mechanistic models is the stress factor which might limit the species distribution. Thus, based on the fact that *T. absoluta* thermal requirements are available and updated, and the need to incorporate the stress parameters in our model, in this study the semi-mechanistic modelling software package CLIMEX was chosen to build the model for the tomato pinworm.

CLIMEX is a bioclimatic niche model that uses species parameters and climate variables to provide projections of the suitable areas for a species (Kriticos et al. 2015; Sutherst et al. 2007). It has been applied for estimating the potential distribution of a wide range of species (Shabani and Kumar 2013). Climex is based on the assumption that if you know where a certain species occurs, its tolerable climatic conditions can be predicted (Sutherst et al. 2007). Therefore, it maximizes the species favorable growth season and minimizes the unfavorable growth season (Silva et al. 2016; Sutherst and Maywald 1985; Sutherst et al. 2007). This software makes projections using the combination of specific climatic parameters derived from biological information (e.g. thermal and moisture requirement) and known species distributions (Kriticos et al. 2015; Kumar et al. 2014; Sutherst and Maywald 1985). Through the Ecoclimatic index (EI), the software makes projections of the species climatic suitability based on growth and stress indices. The EI is scaled from 0 to 100, where 0 means unsuitable areas for the species development, and 100 highly suitable areas (Sutherst et al. 2007).

Climatic Data, Model, and Scenarios

For parameter calibration, we used data from 148 open-field occurrences and published biological data for *T. absoluta* (Martins et al. 2016). To build the model, data from Brazil were omitted and it was only used for validation. We used the CliMond 10′ gridded climate data for modelling in CLIMEX since it provides a good spatial resolution (Kriticos et al. 2012). The CliMond 10′ consists of long-term values of monthly average minimum and maximum temperature ($T_{\min}$ and $T_{\max}$), precipitation (P_{total}) and relative humidity at 09:00 h (RH09:00) and 15:00 h (RH15:00) (Kriticos et al. 2012). The A2 SRES scenario and the global climate model (GCM) CSIRO-Mk3.0 (CS) of the Centre for Climate Research, Australia were used to perform the modelling procedure for *T. absoluta* in the climate changes predicted for 2050 and 2100.

Recently, the Intergovernmental Panel on Climate Change - IPCC published the Fifth Assessment Report (AR5) describing four updated greenhouse gas trajectories (the representative concentration pathways - RCPs) designed to replace the SRES scenarios. According to van Vuuren and Carter (2014) the key factor which differentiates RCPs from the SRES is its CO_2 concentration (van Vuuren and Carter 2014). The A2 SRES assumes an increase of CO_2 concentrations by the end of the century to 846 ppm. Its best RCP equivalent is the RCP 8.5, which assumes a concentration by the same time of 936 ppm. Another difference between these two equivalent scenarios is related to the temperature increase. The predicted temperature increases for the period from 2090–2099 for the A2 SRES is approximately 6 °C, while for the RCP 8.5 is 7 °C. Therefore, due to its best equivalence to the recently available RCP 8.5, in this study, the A2 SRES scenario was used to model the impact of the climate changes for *T. absoluta*. Besides, the A2 SRES incorporates representative data of technological, demographic and economic variables relating to greenhouse gas (GHG) from countries independent and self-reliant, which gives it proven consistency in its assumptions (Silva et al. 2017). The CliMond database currently does not have data for RCP scenarios.

Fitting CLIMEX Parameters

In an attempt to build a more reliable model, we adjusted the parameters in CLIMEX accordingly to *T. absoluta* distribution data in open field. Afterward, the growth and stress parameters were adjusted. These parameters were adjusted based on the thermal requirements data recently published for *T. absoulta* (Martins et al. 2016). CLIMEX stress parameter values were adjusted based on the best agreement between the observed and potential distribution of the species, and aiming to exclude the areas where the pest is known to be absent in Brazil, where good and detailed field data had been collected over a long period of time.

Growth Parameters

Temperature index: In the study published by Martins et al. (2016) the author indicated that the lower and upper-temperature threshold for *T. absoluta* was 7 and 34.6 °C, respectively. It is also mentioned that the tomato pinworm decreases its development at a temperature below 14 °C and has optimum development at 30 °C. These thermal requirements are different from those used in previous modelling studies for *T. absoluta* (Desneux et al. 2010; Tonnang et al. 2015; Xian et al. 2017). Therefore, we set the low threshold (DV0) to 7, lower optimum temperature (DV1) to 14, upper optimum temperature (DV2) to 30, and upper threshold temperature (DV3) to 34.6 °C. The tomato pinworm requires 460 degree days to complete its development (Barrientos Z et al. 1998); for this reason we set the degree days per generation (PDD) to 460 °C days (Table 1).

Moisture index: For the moisture index we set the lower soil moisture threshold (SM0) to 0.1 (denoting permanent wilting point), lower optimum soil moisture (SM1) to 0.4, upper optimum soil moisture (SM2) to 1.6, and upper soil moisture threshold (SM3) to 2.0 to suit the regions where *T. absoluta* records are found (Gontijo et al. 2013).

Stress Index

Cold stress: The temperature threshold for cold stress (TTCS) was set to 7 °C based on Martins et al. (2016), who found that *T. absoluta* survival was highly affected when exposed to temperatures lower than 7 °C. The cold stress accumulation (THCS) was set to -0.00025 week^{-1} to fit the pest distribution in the areas of occurrences.

Heat stress: Temperature affects insects in many parameters of their life cycle. It can affect their reproduction, survival, behavior, and mortality. Martins et al. (2016) demonstrated that the heat stress affects *T. absoluta* by decreasing its survival and reproduction, and increasing its mortality. Therefore, we set the temperature threshold for heat stress (TTHS) to 34.6 °C and the heat stress accumulation rate (THHS) to 0.0001 week^{-1}.

Dry stress: This parameter was adjusted in final model calibration step considering areas where *T. absoluta* is known to be present. *Tuta absoluta* is well known to be distributed in most central regions in Brazil with low relative humidity. Therefore, the dry stress threshold moisture level (SMDS) was set to 0.1, and dry stress accumulation (HDS) at a rate of -0.01 week^{-1}. These values account for the Brazilian Savannah region where the tomato pinworm is well established and a very important pest (Gontijo et al. 2013).

Wet Stress: Wet stress can affect insect in several ways, especially increasing mortality due to high precipitation (Bacci 2006; Pereira et al. 2007). Therefore, the wet stress parameter (SMWS) was set to 2.0 and the stress accumulation rate (HWS) at 0.015 week^{-1}. The parameter values showed adequate match with the pest known distributions, for example, the Brazilian Atlantic forest area (Gontijo et al. 2013).

Hot-Wet Stress: This parameter was adjusted in the final model calibration step considering areas where *T. absoluta* is known to be absent. In Brazil, *T. absoluta* has its development limited in areas with intense and well-distributed precipitation during the year. Thus, we added the hot-wet interaction stress parameter in this study to narrow down the areas where *T. absoluta* is known to be absent, for example, the north-western Brazil. Based on this information, the hot-wet temperature threshold (TTHW) was set to 30 °C, the hot-wet moisture threshold (MTHW) to 0.6 SMC, and the hot-wet stress rate (PHW) to 0.003 week^{-1}.

Model calibration and validation

In the calibration step, the initial model was based on areas where *T. absoluta* is known to be absent in north-western Brazil and present in most central regions in Brazil. After minor adjustments to CLIMEX parameters (Dry stress and Hot-Wet Stress), most of these areas were modelled as having unsuitable conditions in north-western Brazil and high suitability conditions in southeast Brazil for *T. absoluta*. Thereafter the model was validated by comparing output to known distributions of *T. absoluta* in Brazil. Besides this, we performed a visual verification of the areas where *T.*

absoluta is known to be distributed around the world. We calculated the percentage of the occurrence points of tomato pinworm that fall within the model prediction suitable conditions for tomato pinworm. These observations were used to evaluate our model's reliability. Through the Ecoclimatic Index (EI) the suitable areas for the tomato pinworm were classified as unsuitable (EI < 0), marginally suitable (0 < EI < 30) and highly suitable (EI > 30) (Kumar et al. 2014).

RESULTS

Tuta absoluta records

Tuta absoluta is reported in 177 localities throughout the Americas, Africa, Europe and Asia. Among these, 148 occurrences correspond to open-field reports (Fig. 1).

In the American continent, the occurrences were distributed through thirteen countries, which were Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Ecuador, Panama, Paraguay, Peru, Uruguay, and Venezuela. In Europe, the pest was reported in open field in Albania, Bosnia-Herzegovina, Bulgaria, Cyprus, Czech Republic, France, Greece, Hungary, Italy, Malta, Montenegro, Portugal, Serbia, Spain, the Netherlands and Turkey. In Asia, India, Iran, Iraq, Israel, Jordan, Qatar, Saudi Arabia, Syria, and Yemen. In Africa, the insect was reported in Algeria, Egypt, Ethiopia, Kenya, Libya, Morocco, Niger, Nigeria, Senegal, Sudan, Tanzania, and Tunisia (Fig. 1).

Based on the current distribution of the tomato pinworm and the years in which it was reported for the first time in each country, it is possible to identify a pattern in this pest's dispersal (Fig. 1). After its introduction in Spain in 2006, this pest moved in three different directions. First, the tomato pinworm moved eastward infecting many countries in the Mediterranean region until it reached the Middle-East. Afterwards, the tomato pinworm moved southwards, colonizing the countries of the Sub-Saharan Africa and, later on, kept moving towards India and Bangladesh (Fig. 1). Due to the introduction of the tomato pinworm in Panama and Cayman Islands in 2011 and Costa Rica in 2014, it is possible to identify another direction in which the pest has moved from South America upward to Central America (Fig.1).

Potential distribution

The potential distribution of *T. absoluta* in the current time matches well with its known distributions. Our model showed 90% of agreement with the current distribution of the tomato pinworm in the validation area (Fig. 2). Considering the whole world, from 148 occurrences, 135 fell within the areas considered suitable by our model, meaning an agreement of 91%. The new parameter values used in our model resulted in a different projection for *T. absoluta* compared with the models previously published (Desneux et al. 2010; Tonnang et al. 2015). It is important to point out the models exclusion of some areas in the Brazilian North region – areas without records of the pest – due to the incorporation of the heat-wet stress parameter in our model (Fig. 2, 4a).

This model showed large suitable areas for the tomato pinworm in the North and Central Americas, Africa, Europe, Asia and Oceania for the current time (Fig. 3a). In the American continent, the new projected areas correspond to Honduras, Nicaragua, Guatemala, Belize, Mexico, Caribbean area, and the USA. In Africa, the new suitable areas correspond to Angola, Benin, Cameroon, Central African Rep., Congo, Côte D'Lvoire, Dem. Rep. of Congo, Eq. Guinea, Gabon, Ghana, Guinea, Guinea-Bissau, Liberia, Madagascar, Malawi, Mali, Mozambique, São Tomé and Prince, Sierra Leone, Somalia and Togo (Fig. 3a). In Asia, the suitable areas were Bhutan, Cambodia, China, India, Indonesia, Lao PDD, Malaysia, Myanmar, Nepal, Philippines, Sri Lanka, Thailand, Timor-Leste, and Vietnam. In Oceania, Australia, Fiji, New Caledonia, Papua New Guinea, Solomon Island, Vanuatu, and New Zealand were the suitable areas (Fig. 3a).

In general, the climate changes projected for 2050 and 2100 leads to a reduction in the high suitable areas for the tomato pinworm (Fig. 3b,c). Compared with the current time, our projection shows a decrease of 44 and 54% in these areas by 2050 and 2100, respectively (Fig. 3bc). Therefore, large areas in South America, Sub-Saharan Africa, and some areas in Asia may become unsuitable for the tomato pinworm in the future

(Fig. 3). Besides, the climate changes predicted might increase the effect of the hot-wet stress in those areas (Fig. 4). On the other hand, in the South-East and Mid-West of the USA and others countries in the north and east of Europe, such as United Kingdom, Denmark, Russia and Turkey, may become more suitable for the pest due to the climate changes (Fig. 3bc). In these areas, a potential reduction in the cold stress is predicted. Moderately suitable areas might increase 15% by 2100 compared to the present time. Likewise, the unsuitable areas for the tomato pinworm might increase 9 and 8 % by 2050 and 2100, respectively. Therefore, our projection showed an expansion of the high and moderate suitable areas for the tomato pinworm toward the poles, and a decrease in suitable areas near the equator.

DISCUSSION

The new parameters values used in the modelling process had a large influence in our model, especially those related to the temperature, cold and hot-wet stresses. The differences in the temperature parameters are due to the methods used to calculate such parameters. Most of the studies to calculate the thermal thresholds for insects use the relations between the development rate and temperature through regression curves. As ectothermic organisms, insects tend to decrease its development time as the temperature increases to an optimal (Damos and Savopoulou-Soultani 2012; Martins et al. 2016). However, reduction in the development time does not mean an improved performance for the insect. In fact, strong reductions in the insect development time might lead to negative effects in its reproduction and survival (Damos and Savopoulou-Soultani 2012). Therefore, the calculation of thermal requirement based on this method does not consider the effect of temperature in these life-cycle parameters.

On the other hand, by calculating the insect's thermal requirement based on life table study parameters (e.g. net reproductive rate and intrinsic rate of population growth), the effect of temperature on reproduction and survival is considered. This, allows the researchers to understand the role of temperature in the insect's life cycle, especially in its development, reproduction and mortality/survival. Therefore, when it comes to temperature, this method enables us to understand the overall effect of this climatic factor on the insect, and consequently a more precise projection of its distribution. Therefore, the high percentages of agreement with the validation area (90%) and the whole world (91%) have shown our model's reliability. Hence, the model proposed in this study proved to be appropriated to assess the potential risk of new introductions for *T. absoluta*.

Our model shows better predictions than models already published for *T. absoluta* due to our models match with the spatial context of the field sample considering known and absent distribution of *T. absoluta* in Brazil and valuable information from biological bioassays (Martins et al. 2016). The absence data, when used, generally produces better models (Brotons et al. 2004). This fact may be observed in the predictions of published models. They predicted all areas in Brazil to be suitable for *T. absoluta* (Tonnang et al. 2015). However, this fact is not observed in Brazil. It is essential to know that species distribution models are influenced in some way by the quality, integrity, and potential biases of the data (Stohlgren, 2007). The models published have merit; however the lack of access of important data (e.g. biological life table parameters, absence data) could compromise predictions and create wrong interpretation of risk levels of invasion in some regions.

The tomato pinworm is known to be highly affected by precipitation, especially increasing its mortality during the rainy season (Bacci 2006) (Unpublished data from the IPM Lab – UFV). The Brazilian North region is an area with high temperature, and intense and well-distributed precipitation during almost the whole year. Besides, regarding the occurrences of the tomato pinworm, there are no records of this insect in this region (Fig. 2). Therefore, by adding the hot-wet stress in our model it was possible to exclude those areas with high temperature and intense precipitation – known to be *T. absoluta* absent (i.e. Brazilian North region) (Fig. 4a).

The most important contribution of this study is a comprehensive and current CLIMEX modelling effort for *T. absoluta*. From the current distribution of *T. absoluta* it is possible to notice this pest's ability to disperse to new areas (Fig. 1). According to Guillemaud et al. (2015) the tomato pinworm reached Spain through a single invasive population from the central region of Chile. After invading the Baltic region, the pest moved towards the Middle East, mainly through the Mediterranean. Afterwards, the tomato pinworm dispersed in two different directions, southward to the Sub-Saharan Africa, and eastward to India and Bangladesh (Fig. 1). Based on our model, *T. absoluta* has taken advantage of the high (EI > 30) suitability of these areas in the dispersal process (Fig. 1, 3). From Europe to Asia there are several countries important as tomato producers, for example, Turkey, Iran, India, and China; four out of six of the world's largest producers (Fig. 3). The latter is the largest tomato producer in the world with a production of approximately 50 million tonnes (FAO 2017a) and most important, free from *T. absoluta*. Therefore, efforts to prevent the introduction of the tomato pinworm in China should be intensified, especially during the favorable growth season where the pest development is maximized. The model presented here also highlights the risk of invasion in others countries such as Australia and New Zealand, both with large areas suitable for the pest and tomato production.

Another important area under risk of *T. absoluta*'s invasion is North America (Fig. 3). Recently, the tomato pinworm was reported in three countries in Central America, Panama, Cayman Island and Costa Rica. Based on our projection, there are large areas in North America that are highly suitable (EI > 30) for this pest, but still not infested. In this region lies the USA and Mexico, the third and the tenth major tomato producers in the world, and both countries are free from the tomato pinworm. Therefore, these two countries should be concerned and aware of the risk of an eventual invasion of *T. absoluta*.

The predicted climate changes will affect *T. absoluta* negatively in some regions. In general, the total area suitable for this pest will decrease by 2050 and 2100, especially in areas around the equator. South America, Sub-Saharan Africa and some areas in Asia will become unsuitable for the tomato pinworm. On the other hand, the USA and most northern countries in Europe will become more suitable. The global climate model (GCM) CSIRO-Mk3.0 (CS) data under A2 SRES scenario used in this study predicts a temperature increase of 2.11 °C and a decrease of 14% in the precipitation by 2100 (Silva et al. 2017). According to Martins et al. (2016), *T. absoluta* showed a substantial reduction in its survival when the temperatures were around 33 °C. Therefore, in areas around the equator, where the annual average temperature goes around 30 °C, the increase of 2.11 °C might increase the insect mortality due to the hot-wet stress (Fig. 4). On the other hand, in regions with high latitude, for example the USA and Northern Europe, areas will become more suitable for the tomato pinworm due to the same increase in temperature, and therefore, a reduction in the cold stress in these areas (Fig. 4b,c).

In this sense, areas that are currently unsuitable for *T. absoluta* will potentially become suitable for this pest due to the climate change affects (Fig. 4). Thus, countries such as United Kingdom and Netherland, which have intercepted infected tomatoes with *T. absoluta* in the past, might need to increase their efforts to prevent the entry of the pest in their greenhouses, especially during the favorable growth season, due to more suitable climatic conditions for the pest development in the future (Fig. 3, 4).

Limitation of modelling approach and transferability

Any species distribution is limited basically due to three components: (i) the ability to reach a potential site, (ii) to develop in a specific environmental condition, and (iii) the ability to compete with others occupying the same habitat (Begon et al. 2005). In this study, we took into account only climatic factors, in other words, *T. absoluta*'s ability to develop within its environmental tolerances. Therefore, it is important to point out that there are other components that might limit the tomato pinworm distribution, such as geographic barriers, natural enemies and so forth. Besides, in studies of spatial distributions, there are some uncertainties. They might be related to the broad-scale outdated climate data currently available, associated with the model parameterization, and the magnitude that the climate changes projected will occur (Barry and Elith 2006; Silva et al. 2017; Taylor and Kumar 2012).

Likewise, the evolution and acclimation process which insects are likely to pass through was not considered in this modelling either (Hance et al. 2007; Thomson et al. 2010). The projection of the climate change effects on insects normally assumes that its thermal requirements are static and cannot evolve (Thomson et al. 2010). However, these physiological requirements are plastic and they might respond differently during the evolutionary course (Thomson et al. 2010).

Another important aspect that is recurrently considered in modelling studies is its transferability. Transferability is the concept of models' cross-applicability in space and time, and it is especially important in studies for predictions of risk of pest invasion and climate change effects. It is mainly affected by the prediction variables used in the study (e.g. indirect and direct predictor variables) (Randin et al. 2006). Elevation illustrates very well the negative effect of indirect predictor in transferability when incorporated in the model. Depending on the latitude, the same area in the same altitude might express differences in temperatures (Jarnevich et al. 2015). Thus, by using such predictors, the model may lose its cross-applicability and, therefore, might be inappropriate to assess risk of pest invasion. On the other hand, direct predictors are more physiologically meaningful to the organism, consequentially, they have more influence in the organism's distribution.

In this context, regarding to transferability, this study has two advantages: (i) the use of only direct predictors such as temperature and humidity and (ii) the use of thermal requirements specifically calculated for the pest studied. For these reasons, once again, the model presented here proved to be appropriate to highlight the areas under potential risk of invasion of *T. absoluta*.

CONCLUSION

The model presented in the study made it possible to update the information about the potential distribution of *T. absoluta* in the future. Our model showed to be very consistent with the current distribution of the tomato pinworm and enabled us to identify areas under major risk of invasion of the tomato pinworm. Due to its importance as tomato producers, countries such as China, Mexico, and the USA should be concerned about the risk of *T. absoluta* invasion because of the increasing climatic suitability for this insect at the current and future time. The climate changes predicted will affect *T. absoluta* negatively around the equator, decreasing the suitable areas for the tomato pinworm development, especially in South America, Africa and areas in Asia. By 2100, the risk of *T. absoluta* invasion in the USA and Northern Europe will increase due to the increase of climatic suitability in these areas. The outputs generated as part of this research could be used by relevant countries for increased vigilance and improved quarantine measures.

Table 1. CLIMEX parameter values used for *Tuta absoluta* modelling.

Index	**Parameter**	**Previous values**			**New values**	**Unit**
		Desneux et al. (2010)	Tonnang et al. (2015)	Xian et al. (2017)		
Temperature	DV0 = lower threshold	8	8	8	7	°C
	DV1 = lower optimum temperature	20	20	20	14	°C
	DV2 = upper optimum temperature	25	30	25	30	°C
	DV3 = upper threshold	35	42	35	34.6	°C
Moisture	SM0 = lower soil moisture threshold	0.1	0.1	0.01	0.1	[a]
	SM1 = lower optimum soil moisture	0.4	0.4	0.1	0.4	[a]
	SM2 = upper optimum soil moisture	0.7	1.5	0.6	1.6	[a]
	SM3 = upper soil moisture threshold	2	4	1.8	2	[a]
Cold stress	TTCS = temperature threshold	3	3	4	7	°C
	THCS = stress accumulation rate	-0.001	-0.001	0	-0.00025	week^{-1}
	DTCS = degree day threshold	15	15	-	-	°C days
	DHCS = stress accumulation rate	-0.001	-0.0001	-	-	week^{-1}
Heat stress	TTHS = temperature threshold	35	-	41	34.6	°C
	THHS = stress accumulation rate	0.0015	-	0.0015	0.0001	week^{-1}
Dry stress	SMDS = soil moisture threshold	0.1	0.1	0.001	0. 1	
	HDS = stress accumulation rate	-0.01	-0.01	-0.02	-0.01	week^{-1}
Wet Stress	SMWS = soil moisture threshold	2	2	2	2	[a]
	HWS = stress accumulation rate	0.002	0.002	0.002	0.015	week^{-1}
Hot-Wet Stress	TTHW = hot-wet temperature threshold	-	-	-	30	°C
	MTHW = hot-wet moisture threshold	-	-	-	0.6	SMC
	PHW = hot-wet stress rate	-	-	-	0.003	week^{-1}
Degree Days	PDD= degree days per generation	460	460	460	460	°C days

[a] Values without units are dimensionless indices of soil moisture (0 = over dry, 1 = field capacity).

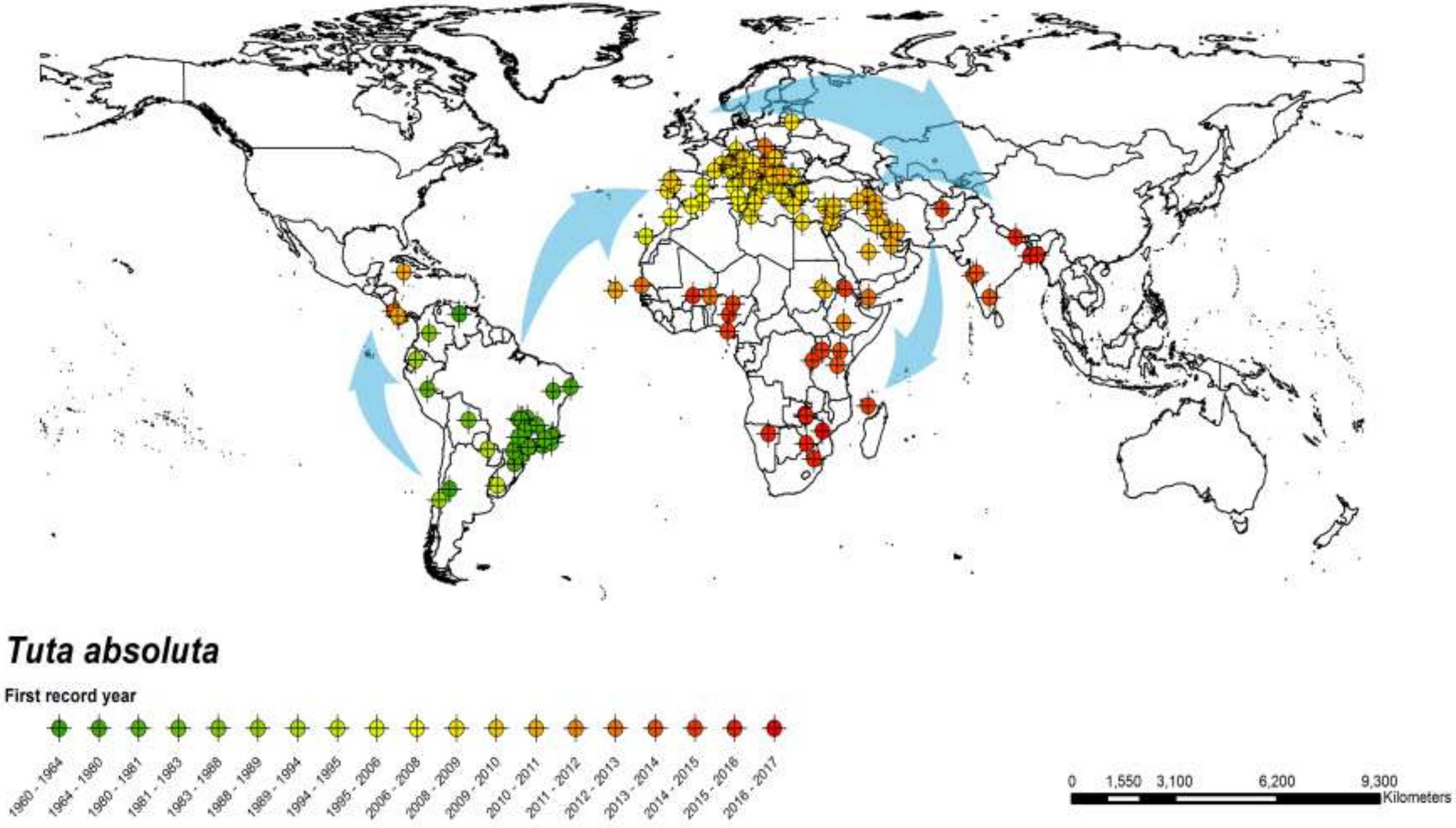

Figure 1. Current global distribution of *Tuta absoluta* in open field tomato crops and pattern of movement from South America to Europe and elsewhere. The occurrence records were divided into groups based on first recorded occurrence.

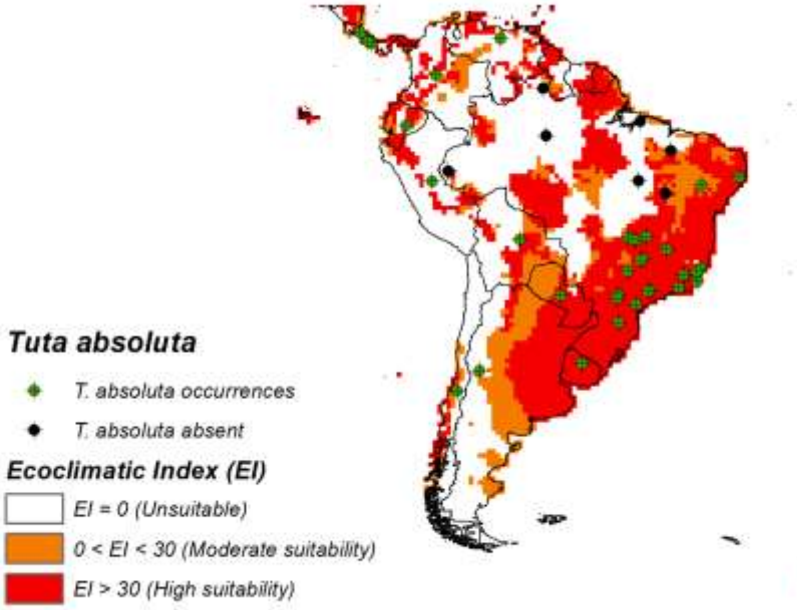

Figure 2. Current and potential distribution of *Tuta absoluta* in validation region based on EI index. The areas in White (EI=0), orange (0<EI<30), and red (EI>30) indicate unsuitable, moderate suitability and high suitability, respectively.

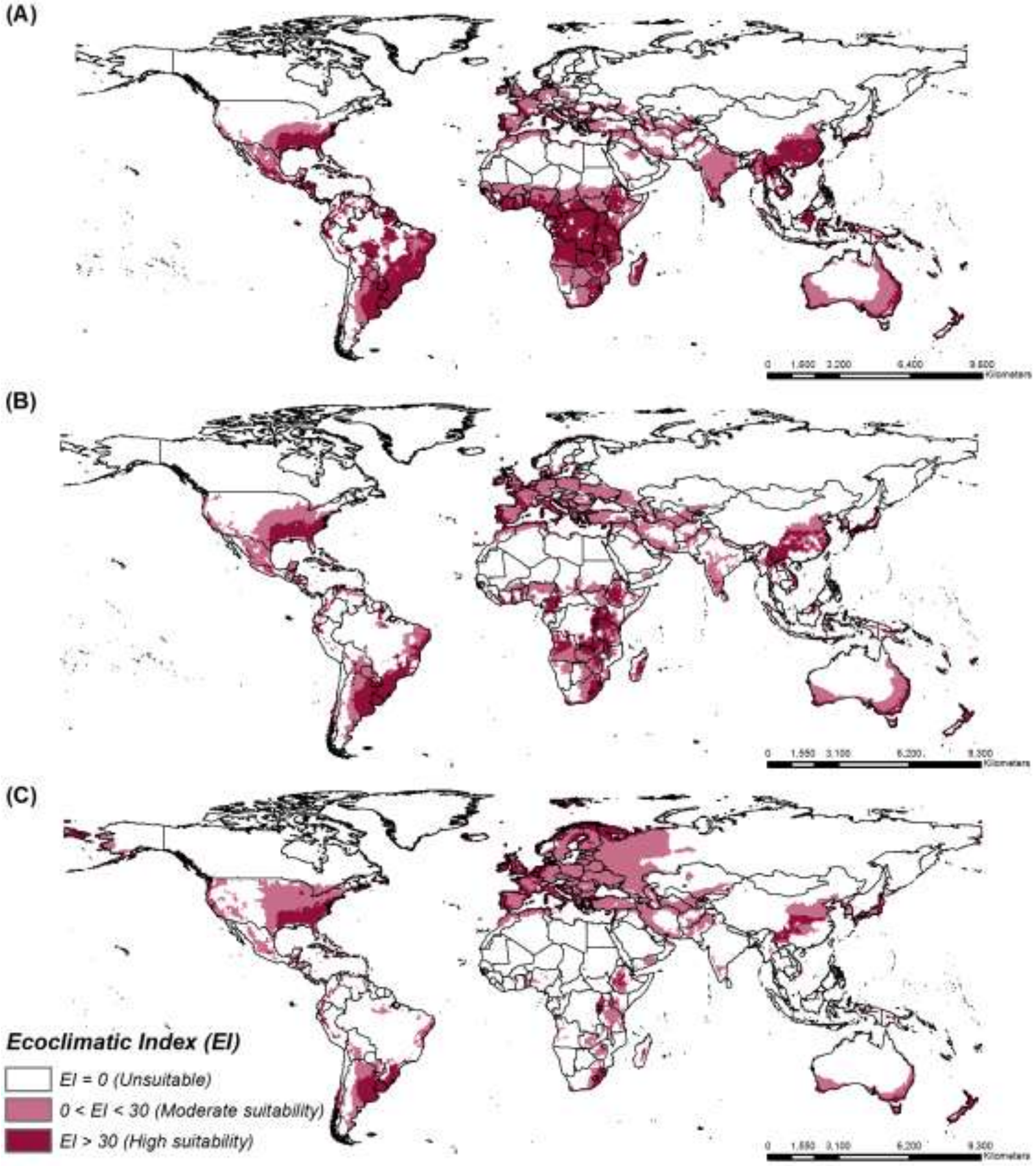

Figure 3. The Ecoclimatic Index (EI) for *Tuta absoluta* modeled using CLIMEX in the (a) present time and CSIRO-Mk3.0 GCM running the SRES A2 scenario for (b) 2050 and (c) 2100. The projections show a decrease in suitability around the equator and an increase in suitability in northern Europe and Americas in 2050 and 2100.

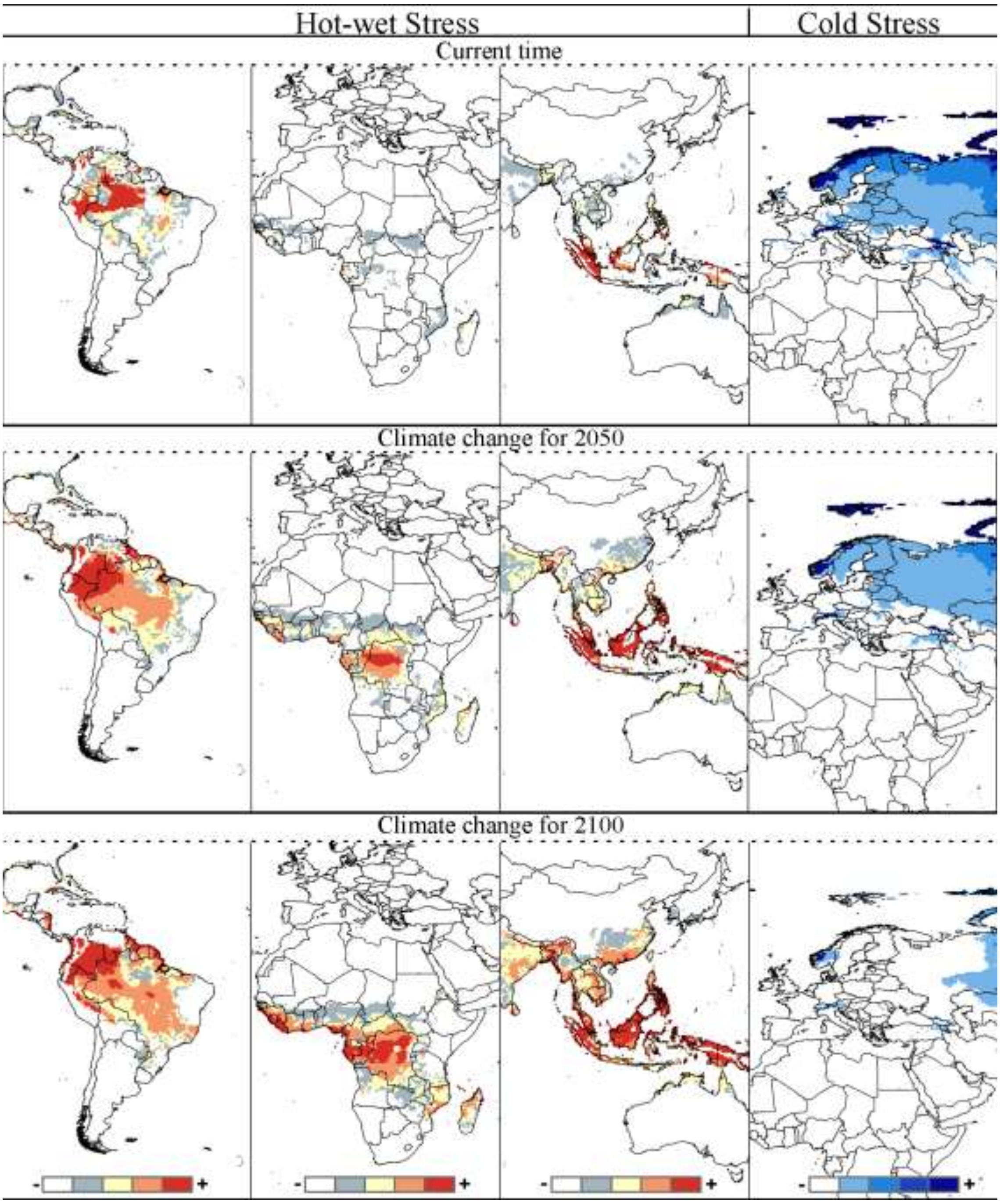

Figure 4. Projections of Hot-Wet Stress in South America, Africa, and Asia, and cold stress in Europe in the current scenario, climate change for 2050, and 2100. Heat stress is seen increasing around the equator and cold stress decreasing in northern Europe.

REFERENCES

Bacci L (2006) Factors determining the attack of *Tuta absoluta* on tomato. Doctoral dissertation, Universidade Federal de Viçosa

Barrientos RZ, Apablaza JH, Norero AS, Estay P (1998) Temperatura base y constante térmica de desarrollo de la polilla del tomate, *Tuta absoluta* (Lepidoptera: Gelechiidae) Ciencia e Investigación Agraria 25:133-137 doi:http://dx.doi.org/10.7764/rcia.v25i3.659.

Barrientos Z R, Apablaza H J, Norero S A, Estay P P (1998) Threshold temperature and thermal constant for the development of the South american tomato moth, *Tuta absoluta* (Lepidoptera: Gelechiidae) [1998] Ciencia e investigación agraria 25

Barry S, Elith J (2006) Error and uncertainty in habitat models J Appl Ecol 43:413-423 doi:10.1111/j.1365-2664.2006.01136.x

Begon M, Townsend CR, Harper JL (2005) ECOLOGY: From individuals to ecosystems. 4th ed edn. BLACKWELL PUBLISHING, Malden, MA

Betancourt CM, I.B. S, Rodríguez JJ (1996) Influencia de la temperatura sobre la reproduccion y el desarrollo de *Scrobipalpuloides absoluta* (Meyrick) (Lepidoptera: Gelechiidae) Rev Bras Biol 56:661–670

Biondi A, Guedes RNC, Wan F-H, Desneux N (2018) Ecology, Worldwide Spread, and Management of the Invasive South American Tomato Pinworm, *Tuta absoluta*: Past, Present, and Future Annu Rev Entomol 63:null doi:10.1146/annurev-ento-031616-034933

Brotons L, Thuiller W, Araújo MB, Hirzel AH (2004) Presence-absence versus presence-only modelling methods for predicting bird habitat suitability Ecography 27:437-448 doi:doi:10.1111/j.0906-7590.2004.03764.x

Campos MR, Biondi A, Adiga A, Guedes RNC, Desneux N (2017) From the Western Palaearctic region to beyond: *Tuta absoluta* 10 years after invading Europe J Pest Sci 90:787-796 doi:10.1007/s10340-017-0867-7

Cook DC, Fraser RW, Paini DR, Warden AC, Lonsdale WM, De Barro PJ (2011) Biosecurity and yield improvement technologies are strategic complements in the fight against food insecurity PLoS ONE 6:e26084 doi:10.1371/journal.pone.0026084

Damos P, Savopoulou-Soultani M (2012) Temperature-driven models for insect development and vital thermal requirements Psyche 2012:13 doi:10.1155/2012/123405

Desneux N, Luna MG, Guillemaud T, Urbaneja A (2011) The invasive South American tomato pinworm, *Tuta absoluta*, continues to spread in Afro-Eurasia and beyond: the new threat to tomato world production J Pest Sci 84:403-408 doi:10.1007/s10340-011-0398-6

Desneux N et al. (2010) Biological invasion of European tomato crops by *Tuta absoluta*: ecology, geographic expansion and prospects for biological control J Pest Sci 83:197-215 doi:10.1007/s10340-010-0321-6

Dormann CF et al. (2012) Correlation and process in species distribution models: bridging a dichotomy J Biogeogr 39:2119-2131 doi:10.1111/j.1365-2699.2011.02659.x

Essl F et al. (2011) Socioeconomic legacy yields an invasion debt Proceedings of the National Academy of Sciences 108:203-207 doi:10.1073/pnas.1011728108

FAO (2017) FAO Statistical Yearbook. Food and Agriculture Organization of the United Nations. http://www.fao.org/faostat/en/#data/QC/visualize. Accessed 08 of August 2017

Gontijo PC, Picanço MC, Pereira EJG, Martins JC, Chediak M, Guedes RNC (2013) Spatial and temporal variation in the control failure likelihood of the tomato leaf miner, *Tuta absoluta* Ann Appl Biol 162:50-59 doi:10.1111/aab.12000

Guedes RNC, Picanço MC (2012) The tomato borer *Tuta absoluta* in South America: pest status, management and insecticide resistance EPPO Bulletin 42:211-216 doi:10.1111/epp.2557

Guillemaud T et al. (2015) The tomato borer, *Tuta absoluta*, invading the Mediterranean Basin, originates from a single introduction from Central Chile Scientific Reports 5:8371 doi:10.1038/srep08371

https://www.nature.com/articles/srep08371#supplementary-information

Guimapi RYA, Mohamed SA, Okeyo GO, Ndjomatchoua FT, Ekesi S, Tonnang HEZ (2016) Modeling the risk of invasion and spread of Tuta absoluta in Africa Ecol Complex 28:77-93 doi:https://doi.org/10.1016/j.ecocom.2016.08.001

Hance T, Baaren Jv, Vernon P, Boivin G (2007) Impact of Extreme Temperatures on Parasitoids in a Climate Change Perspective Annu Rev Entomol 52:107-126 doi:10.1146/annurev.ento.52.110405.091333

Jarnevich CS, Stohlgren TJ, Kumar S, Morisette JT, Holcombe TR (2015) Caveats for correlative species distribution modeling Ecological Informatics 29:6-15 doi:https://doi.org/10.1016/j.ecoinf.2015.06.007

Kearney M, Porter W (2009) Mechanistic niche modelling: combining physiological and spatial data to predict species' ranges Ecol Lett 12:334-350 doi:10.1111/j.1461-0248.2008.01277.x

Kolar CS, Lodge DM (2001) Progress in invasion biology: predicting invaders Trends Ecol Evol 16:199-204 doi:http://dx.doi.org/10.1016/S0169-5347(01)02101-2

Kriticos DJ, Maywald G, Yonow T, Zurcher E, Herrmann N, Sutherst R (2015) CLIMEX Version 4: exploring the effects of climate on plants, animals and diseases CSIRO , Canberra:184

Kriticos DJ, Webber BL, Leriche A, Ota N, Macadam I, Bathols J, Scott JK (2012) CliMond: global high-resolution historical and future scenario climate surfaces for bioclimatic modelling Methods in Ecology and Evolution 3:53-64 doi:10.1111/j.2041-210X.2011.00134.x

Kumar S, Neven LG, Yee WL (2014) Evaluating correlative and mechanistic niche models for assessing the risk of pest establishment Ecosphere 5:1-23 doi:10.1890/ES14-00050.1

Marcano R (1995) Efecto de la temperatura sobre el desarrollo y la reproduccion de *Scrobipalpula absoluta* (Meyrick) (Lepidoptera: Gelechiidae) Bol Entomol Venez 10:69-75

Martins JC, Picanco MC, Bacci L, Guedes RNC, Santana PA, Jr., Ferreira DO, Chediak M (2016) Life table determination of thermal requirements of the tomato borer *Tuta absoluta* J Pest Sci 89:897-908 doi:10.1007/s10340-016-0729-8

Miranda MMM, Picanço M, Zanuncio JC, Guedes RNC (1998) Ecological life table of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) Biocontrol Sci Technol 8:597-606 doi:10.1080/09583159830117

Paini DR, Sheppard AW, Cook DC, De Barro PJ, Worner SP, Thomas MB (2016) Global threat to agriculture from invasive species Proceedings of the National Academy of Sciences 113:7575-7579 doi:10.1073/pnas.1602205113

Pereira EJG, Picanço MC, Bacci L, Crespo ALB, Guedes RNC (2007) Seasonal mortality factors of the coffee leafminer, *Leucoptera coffeella* Bull Entomol Res 97:421-432 doi:10.1017/S0007485307005202

Randin CF, Dirnböck T, Dullinger S, Zimmermann NE, Zappa M, Guisan A (2006) Are niche-based species distribution models transferable in space? J Biogeogr 33:1689-1703 doi:doi:10.1111/j.1365-2699.2006.01466.x

Sankarganesh E, Firake DM, Sharma B, Verma VK, Behere GT (2017) Invasion of the South American Tomato Pinworm, *Tuta absoluta,* in northeastern India: a new challenge and biosecurity concerns Entomol Gen 36:335-345 doi:10.1127/entomologia/2017/0489

Shabani F, Kumar L (2013) Risk levels of invasive *Fusarium oxysporum* f. sp. in areas suitable for date palm (*Phoenix dactylifera*) cultivation under various climate change projections PLoS ONE 8:e83404 doi:10.1371/journal.pone.0083404

Silva GA, Picanço MC, Bacci L, Crespo ALB, Rosado JF, Guedes RNC (2011) Control failure likelihood and spatial dependence of insecticide resistance in the tomato pinworm, *Tuta absoluta* Pest Manage Sci 67:913-920 doi:10.1002/ps.2131

Silva RS, Kumar L, Shabani F, Picanço MC (2016) Assessing the impact of global warming on worldwide open field tomato cultivation through CSIRO-Mk3·0 global climate model The Journal of Agricultural Science 155:407-420 doi:10.1017/S0021859616000654

Silva RS, Kumar L, Shabani F, Picanço MC (2017) Potential risk levels of invasive *Neoleucinodes elegantalis* (small tomato borer) in areas optimal for open-field *Solanum lycopersicum* (tomato) cultivation in the present and under predicted climate change Pest Manage Sci 73:616-627 doi:10.1002/ps.4344

Soberón J (2005) Interpretation of models of fundamental ecological niches and species’ distributional areas. Biodiversity Informatics 2:1-10

Sutherst RW, Maywald GF (1985) A computerised system for matching climates in ecology Agric, Ecosyst Environ 13:281-299 doi:http://dx.doi.org/10.1016/0167-8809(85)90016-7

Sutherst RW, Maywald GF, Kriticos DJ (2007) CLIMEX Version 3: User’s Guide Melbourne: Hearne Scientific Software Pty Ltd

Taylor S, Kumar L (2012) Sensitivity analysis of CLIMEX parameters in modelling potential distribution of *Lantana camara* L PLoS ONE 7:e40969 doi:10.1371/journal.pone.0040969

Thomson LJ, Macfadyen S, Hoffmann AA (2010) Predicting the effects of climate change on natural enemies of agricultural pests Biol Control 52:296-306 doi:https://doi.org/10.1016/j.biocontrol.2009.01.022

Tonnang HEZ, Mohamed SF, Khamis F, Ekesi S (2015) Identification and risk assessment for worldwide invasion and spread of *Tuta absoluta* with a focus on

Sub-Saharan Africa: Implications for phytosanitary measures and management PLoS ONE 10:e0135283 doi:10.1371/journal.pone.0135283

van Vuuren DP, Carter TR (2014) Climate and socio-economic scenarios for climate change research and assessment: reconciling the new with the old Clim Change 122:415-429 doi:10.1007/s10584-013-0974-2

Xian X, Han P, Wang S, Zhang G, Liu W, Desneux N, Wan F (2017) The potential invasion risk and preventive measures against the tomato leafminer *Tuta absoluta* in China Entomol Gen 36:319-333 doi:10.1127/entomologia/2017/0504

Supplementary Material 1

Continent	Country	City/Region	Latitude	Longitude	Status	Cultivation system*	First record	Reference
Africa	Algeria	Mostaganem	36.001108	0.171081	Restricted	G/F	2008	(Boualem et al. 2012)
Africa	Botswana	Bobirwa	-21.947314	28.427295	Established	F	2016	(BOPA 2016)
Africa	Burkina Faso	Ouahigouya	13.588415	-2.410885	Established	F	2016	(Son et al. 2017)
Africa	Cape Verde	Santiago Island	14.91674	-23.546943	Established	F	2011	(MDR 2013)
Africa	Egypt	Marsa Matrouh district	31.348803	27.316578	Established	F	2009	(Moussa et al. 2013)
Africa	Eritrea	No Detail	15.275616	38.918617	Established	F	2015	(Tonnang et al. 2015)
Africa	Ethiopia	No Detail	7.123198	38.53438	Established	G/F	2012	(OIRED 2014)
Africa	Kenya	Isiolo	0.323142	37.579597	Established	G/F	2014	(Tonnang et al. 2015)
Africa	Libya	Tripoli	32.793836	13.255524	Reported	F	2009	(Russell-IPM 2009b)
Africa	Mayotte Island	No Detail	-12.831767	45.189847	Established	F	2015	(EPPO 2016)
Africa	Morocco	Nador	35.130256	-2.940007	Reported	F	2008	(Ouardi et al. 2012)
Africa	Morocco	Doukkala-Abda	32.54091	-8.749236	Reported	F	2008	(Ouardi et al. 2012)
Africa	Mozambique	Manica Province	-18.938623	32.852267	Established	F	2017	(FAO 2017b)
Africa	Namibia	Grootfontein	-19.574671	18.120624	Established	F	2016	(Hortidaily.com 2016)
Africa	Niger	Niamey	13.461806	2.145497	Restricted	F	2013	(Adamou et al. 2017)
Africa	Nigeria	Abuja	9.077036	7.383002	Reported	F	2015	(Russell-IPM 2015)
Africa	Nigeria	Port Harcourt	5.113461	6.966339	Reported	F	2015	(Russell-IPM 2015)
Africa	Nigeria	Kadawa	11.651055	8.442298	Reported	F	2015	(Russell-IPM 2015)
Africa	Rwanda	No Detail	-1.99247	30.043952	Established	F	2015	(FAO 2015)
Africa	Senegal	Niayes	16.025276	-16.475995	Established	F	2013	(Pfeiffer et al. 2013)
Africa	South Africa	Mpumalanga province	-25.608331	30.494477	Established	F	2016	(Visser et al. 2017)
Africa	Sudan	Khartoum	15.457954	32.578514	Established	G/F	2010	(Mohamed et al. 2012)
Africa	Sudan	Gezira	14.862267	33.365045	Established	G/F	2010	(Mohamed et al. 2012)
Africa	Tanzania	Ngarenanyuki	-3.141642	36.88714	Reported	F	2014	(Kariathi et al. 2016)
Africa	Tunisia	Akouda	35.884521	10.564716	Established	G/F	2008	(Abbes et al. 2012)
Africa	Tunisia	Kairouan	35.672353	10.125144	Established	G/F	2008	(Abbes et al. 2012)

Africa	Tunisia	Bizerte	37.279824	9.824324	Established	G/F	2008	(Abbes et al. 2012)
Africa	Uganda	Central Uganda	0.462261	32.713914	Established	F	2015	(Tumuhaise et al. 2016)
Africa	Zambia	Kafue	-15.524732	28.285985	Established	F	2016	(FAO 2016c)
Africa	Zambia	Chibombo	-14.947109	28.026013	Established	F	2016	(FAO 2016c)
Africa	Zambia	Lusaka West	-15.293455	28.364192	Established	F	2016	(FAO 2016c)
America	Argentina	Mendoza	-32.88627	-68.7343	Established	F	1964	(Bahamondes and Mallea 1969)
America	Bolivia	Los Valles region	-16.290154	-63.588653	Established	F	1983	(Moore 1983)
America	Brazil	Apiaí	-24.500418	-48.849221	Established	F	1979	(Gontijo et al. 2013)
America	Brazil	Araguari	-18.736884	-47.96103	Established	F	1979	(Gontijo et al. 2013)
America	Brazil	Brasília	-15.893205	-47.548611	Established	F	1979	(Gontijo et al. 2013)
America	Brazil	Buritizeiro	-17.51816	-44.944898	Established	F	1979	(Gontijo et al. 2013)
America	Brazil	Caçador	-26.785598	-51.04855	Established	F	1979	(Gontijo et al. 2013)
America	Brazil	Coimbra	-20.84322	-42.793801	Established	F	1979	(Gontijo et al. 2013)
America	Brazil	Goianápolis	-16.33427	-48.877758	Established	F	1979	(Gontijo et al. 2013)
America	Brazil	Goiás	-16.003734	-49.932884	Established	F	1979	(Gontijo et al. 2013)
America	Brazil	Londrina	-23.333917	-51.094976	Established	F	1979	(Gontijo et al. 2013)
America	Brazil	Marilândia do Sul	-23.789674	-51.307491	Established	F	1979	(Gontijo et al. 2013)
America	Brazil	Ouro Verde de Goiás	-16.26239	-49.219963	Established	F	1979	(Gontijo et al. 2013)
America	Brazil	Paty do Alferes	-22.411125	-43.431317	Established	F	1979	(Gontijo et al. 2013)
America	Brazil	Paulínia	-22.742477	-47.109185	Established	F	1979	(Gontijo et al. 2013)
America	Brazil	Santa Teresa	-19.936828	-40.598447	Established	F	1979	(Gontijo et al. 2013)
America	Brazil	São João da Barra	-21.636845	-41.048443	Established	F	1979	(Gontijo et al. 2013)
America	Brazil	Sumaré	-22.831676	-47.299374	Established	F	1979	(Gontijo et al. 2013)
America	Brazil	Uberlândia	-18.884244	-48.347803	Established	F	1979	(Gontijo et al. 2013)
America	Brazil	Venda Nova do Imigrante	-20.317366	-41.124843	Established	F	1979	(Gontijo et al. 2013)
America	Brazil	Viçosa	-20.768015	-42.869794	Established	F	1979	(Gontijo et al. 2013)
America	Brazil	Votuporanga	-20.361158	-49.928986	Established	F	1979	(Gontijo et al. 2013)
America	Brazil	Petrolina	-9.342407	-40.543664	Established	F	1979	(Gontijo et al. 2013)

America	Brazil	Camocim de São Félix	-8.345833	-35.759604	Established	F	1979	(Gontijo et al. 2013)
America	Cayman Island	No detail	19.324937	-81.191388	Established	F	2011	(USDA 2011)
America	Chile	Maule	-35.480911	-71.503646	Established	F	1970	(Vargas 1970)
America	Colombia	Widespread	4.590603	-74.271125	Established	F	1989	(Garcia 1989)
America	Costa Rica	Widespread	9.859778	-83.884164	Established	F	2014	(FAO 2014)
America	Ecuador	Widespread	-1.831239	-77.962445	Established	F	1989	(Schotman 1989)
America	Panama	Chiriqui	8.586946	-82.384479	Established	F	2011	(Roda et al. 2015)
America	Panama	Río Sereno	8.830535	-82.860761	Established	F	2011	(Roda et al. 2015)
America	Paraguay	Widespread	-23.334251	-58.431586	Established	F	1994	(JICA 1994)
America	Peru	Widespread	-8.928226	-74.706033	Established	F	1975	(Razuri and Vargas 1975)
America	Uruguay	Widespread	-31.976613	-55.697	Established	F	1995	(Bentancourt and Scatoni 1995)
America	Venezuela	Widespread	9.214475	-66.040884	Established	F	1964	(Povolný 1984)
Asia	Afghanistan	Chagcharan	34.52376	65.310373	Established	F	2015	(Hossain et al. 2016)
Asia	Bangladesh	Jessore	23.14429	89.21201	Established	F	2016	(Hossain et al. 2016)
Asia	Bangladesh	Comilla	23.442542	91.197407	Established	F	2016	(Hossain et al. 2016)
Asia	India	Pune	18.543357	73.846529	Established	G/F	2014	(Kalleshwaraswamy et al. 2015)
Asia	India	Ahmednagar	19.092404	74.727779	Established	G/F	2014	(Kalleshwaraswamy et al. 2015)
Asia	India	Kolar	13.137747	78.146667	Established	G/F	2014	(Kalleshwaraswamy et al. 2015)
Asia	Iran	Azarbijan	37.501905	45.033012	Established	G/F	2011	(Baniameri and Cheraghian 2012)
Asia	Iran	Kurdistan	35.928326	47.121305	Established	G/F	2011	(Baniameri and Cheraghian 2012)
Asia	Iran	Darreh Shahr	33.143412	47.383226	Established	G/F	2011	(Baniameri and Cheraghian 2012)
Asia	Iran	Malekshahi	33.397896	46.581891	Established	G/F	2011	(Baniameri and Cheraghian 2012)
Asia	Iran	Khuseztan	31.512219	48.728284	Established	G/F	2011	(Baniameri and Cheraghian 2012)
Asia	Iran	Busher	28.957705	51.057914	Established	G/F	2011	(Baniameri and Cheraghian 2012)

Asia	Iran	Kermanshah	34.323607	47.110293	Established	G/F	2011	(Baniameri and Cheraghian 2012)
Asia	Iran	Fars	28.98875	53.138937	Established	G/F	2011	(Baniameri and Cheraghian 2012)
Asia	Iraq	Basrah	30.49116	47.776809	Established	F	2010	(USAID 2012)
Asia	Iraq	Nineveh	36.299204	42.297306	Established	F	2010	(USAID 2012)
Asia	Israel	Havat MaShash	31.074052	34.860463	Established	F	2010	(Seplyarsky et al. 2010)
Asia	Jordan	Southern Jordan Valley	32.455067	35.54759	Established	G/F	2009	(Al-Jboory et al. 2012)
Asia	Kuwait	Wafraf	28.622081	48.110276	Established	G	2010	(Russell-IPM 2011)
Asia	Kyrgyzstan	Bishkek	42.942416	74.547678	Established	G	2016	(Esenali Uulu et al. 2017)
Asia	Lebanon	Jbei	34.128737	35.662369	Established	F	2011	(FAO 2016b)
Asia	Nepal	Kathmandu	27.655585	85.409944	Established	F	2016	(Bajracharya et al. 2016)
Asia	Qatar	Al-Khor	25.66017	51.51671	Restricted	G/F	2011	(Al-turaihi 2014)
Asia	Saudi Arabia	Al Quwaiiyah	24.150018	45.285784	Established	F	2010	(Russell-IPM 2010b)
Asia	Syria	Baniyas	35.160417	35.942724	Restricted	F	2010	(Russell-IPM 2010a)
Asia	Turkmenistan	Latvia	38.090268	58.282514	Established	G	2015	(Bratu et al. 2015)
Asia	United Arab Emirates	Abu Dhabi	23.43911	53.850994	Restricted	G	2012	(EPPO 2012)
Asia	Yemen	Coast area	13.156721	45.302085	Established	F	2013	(EPPO 2013b)
Europe	Albania	Counties of Durrës	41.511384	19.625226	Restricted	G/F	2009	(Russell-IPM 2009a)
Europe	Austria	Burgenland	47.131063	16.258744	Established	G	2010	(Gabl and Hausdorf 2010)
Europe	Belgium	Flanders	51.002363	3.690114	Established	G	2009	(PURE-IPM 2017)
Europe	Bosnie-Herzégovine	Laktaši	44.904005	17.309419	Restricted	G/F	2012	(Đurić et al. 2012)
Europe	Bosnie-Herzégovine	Ljubinje	42.955944	18.078751	Restricted	G/F	2012	(Đurić et al. 2012)
Europe	Bosnie-Herzégovine	Trebinje	42.701874	18.341813	Restricted	G/F	2012	(Đurić et al. 2012)
Europe	Bosnie-	Bijeljina	44.753851	19.245182	Restricted	G/F	2012	(Đurić et al. 2012)

	Herzégovine							
Europe	Bosnie-Herzégovine	Banja Luka	44.779011	17.175318	Restricted	G/F	2012	(Đurić et al. 2012)
Europe	Bulgaria	Rakovski	42.255912	24.950736	Established	G/F	2009	(Karadjova et al. 2013)
Europe	Bulgaria	Yunatsite	42.24408	24.26269	Established	G/F	2009	(Karadjova et al. 2013)
Europe	Croatia	Split-Dalmatia	43.506071	16.81897	Established	G	2010	(Mladen Šimala et al. 2011)
Europe	Cyprus	Geri	35.127642	33.43022	Established	G/F	2009	(NEPPO 2011)
Europe	Czech Republic	Prostějov	49.486414	17.086172	Reported	F	2013	(FAO 2016a)
Europe	France	Corse	42.053265	8.993548	Established	F	2009	(Trottin-Caudal et al. 2012)
Europe	France	Rhone-Alpes	45.193537	5.42955	Established	F	2009	(Trottin-Caudal et al. 2012)
Europe	France	Languedoc-Roussillon	43.578781	3.25981	Established	F	2009	(Trottin-Caudal et al. 2012)
Europe	Georgia	Tbilisi	41.705091	44.865688	Established	G	2011	(EPPO 2011)
Europe	Germany	Baden-Württemberg	48.665453	9.349663	Transient/under eradication	F	2009	(EPPO 2013a)
Europe	Greece	Crete	35.298198	24.820401	Established	G/F	2009	(Roditakis et al. 2010)
Europe	Greece	Peloponnesus	37.499724	22.375024	Established	G/F	2009	(Roditakis et al. 2010)
Europe	Greece	Western Greece	38.349379	21.521738	Established	G/F	2009	(Roditakis et al. 2010)
Europe	Guernsey	No Detail	49.469164	-2.603443	Reported/Restricted	G/P	2010	(EPPO 2010a)
Europe	Hungary	Szentkirály	46.90964	19.924573	Established	F	2010	(János and Imre 2014)
Europe	Hungary	Kiskunfélegyháza	46.689568	19.866425	Established	F	2010	(János and Imre 2014)
Europe	Italy	Brescia	45.565885	10.175329	Established	F	2009	(Speranza and Sannino 2012)
Europe	Italy	Modena	44.666899	10.953965	Established	F	2010	(Speranza and Sannino 2012)
Europe	Italy	Bologna	44.510527	11.266707	Established	F	2010	(Speranza and Sannino 2012)
Europe	Italy	Parma	44.802667	10.377267	Established	F	2010	(Speranza and Sannino 2012)
Europe	Italy	Piacenza	45.028435	9.674375	Established	F	2010	(Speranza and Sannino 2012)
Europe	Italy	Reggio Emilia	44.597408	11.219976	Established	F	2010	(Speranza and Sannino 2012)

Europe	Italy	Turin	45.124109	7.607659	Established	F	2009	(Speranza and Sannino 2012)
Europe	Italy	Cuneo	44.372416	7.557533	Established	F	2009	(Speranza and Sannino 2012)
Europe	Italy	Alessandria	44.916815	8.640232	Established	F	2009	(Speranza and Sannino 2012)
Europe	Italy	Asti	44.898848	8.176828	Established	F	2009	(Speranza and Sannino 2012)
Europe	Italy	Cremona	45.123494	10.02449	Established	F	2009	(Speranza and Sannino 2012)
Europe	Italy	Verona	45.416253	11.01368	Established	F	2009	(Speranza and Sannino 2012)
Europe	Italy	Venezia	45.444674	12.38234	Established	G	2009	(Speranza and Sannino 2012)
Europe	Italy	Rovigo	45.095458	11.799678	Established	F	2009	(Speranza and Sannino 2012)
Europe	Italy	Grosseto	42.772056	11.133477	Established	F	2009	(Speranza and Sannino 2012)
Europe	Italy	Umbria	42.940941	12.625307	Established	F	2010	(Speranza and Sannino 2012)
Europe	Italy	Lecce	40.345074	18.225617	Established	F	2009	(Speranza and Sannino 2012)
Europe	Italy	Trento	46.078923	11.147304	Established	G/F	2010	(Speranza and Sannino 2012)
Europe	Italy	Bolzano	46.49978	11.373935	Established	G/F	2010	(Speranza and Sannino 2012)
Europe	Italy	Genova	44.453586	9.090893	Established	G/F	2008	(Speranza and Sannino 2012)
Europe	Italy	Imperia	43.902574	8.052439	Established	G/F	2009	(Speranza and Sannino 2012)
Europe	Italy	Savona	44.340607	8.428889	Established	G/F	2009	(Speranza and Sannino 2012)
Europe	Italy	Lazio	41.735661	13.034733	Established	G/F	2010	(Speranza and Sannino 2012)
Europe	Italy	Abruzzo	42.235223	13.737715	Established	G/F	2009	(Speranza and Sannino 2012)
Europe	Italy	Naples	40.942716	14.140682	Established	G/F	2008	(Speranza and Sannino 2012)
Europe	Italy	Cosenza	39.29716	16.224605	Established	G/F	2008	(Speranza and Sannino 2012)
Europe	Italy	Ragusa	36.938428	14.72794	Established	G/F	2009	(Speranza and Sannino 2012)
Europe	Italy	Oristano	39.900175	8.573575	Established	G/F	2008	(Speranza and Sannino 2012)

Europe	Kosovo	Mamusha	42.320534	20.728415	Established	G	2010	(EPPO 2010b)
Europe	Lithuania	Pagiriai	55.357309	24.40943	Restricted	G	2009	(Ostrauskas and Ivinskis 2010)
Europe	Lithuania	Vidmantai	55.897649	21.140203	Restricted	G	2009	(Ostrauskas and Ivinskis 2010)
Europe	Lithuania	Naujosios Kietaviškės	54.755987	24.585823	Restricted	G	2009	(Ostrauskas and Ivinskis 2010)
Europe	Malta	Ħad-Dingli	35.862253	14.38764	Established	G/F	2009	(Dandria and Catania 2009)
Europe	Montenegro	Ulcinj	41.9310884	19.238701	Established	G/F	2010	(Hrnčić and Radonjić 2012)
Europe	Montenegro	Podgorica	42.406125	19.278319	Established	G/F	2010	(Hrnčić and Radonjić 2012)
Europe	Netherlands	No Detail	52.132633	5.291266	under eradication	G	2009	(NPPO 2009)
Europe	Portugal	Mafra	38.950801	-9.342572	Established	F	2009	(Figueiredo et al. 2010)
Europe	Portugal	Alentejo	40.312837	-7.800862	Established	F	2010	(Figueiredo et al. 2010)
Europe	Portugal	Vila do Conde	41.35553	-8.713878	Established	F	2010	(Figueiredo et al. 2010)
Europe	Romania	Bihor county	47.032646	22.156768	Established	G	2009	(Baeţan et al. 2013)
Europe	Romania	Maramures county	47.67376	23.745629	Established	G	2010	(Baeţan et al. 2013)
Europe	Romania	Arad county	46.256935	21.600818	Established	G	2011	(Baeţan et al. 2013)
Europe	Russia	Krasnodar	45.636001	39.68838	Established	G	2010	(EPPO 2010c)
Europe	Serbia	Pčinjski	42.600096	22.028051	Established	G/F	2011	(Toševski et al. 2011)
Europe	Serbia	Leskovac	43.015468	21.918314	Established	G	2011	(Toševski et al. 2011)
Europe	Slovenia	Slovene Istria	45.495819	13.823713	Established	F	2009	(Žežlina et al. 2011)
Europe	Spain	Castello´n de la Plana	39.973402	-0.025929	Established	G/F	2006	(Urbaneja et al. 2007)
Europe	Spain	Canary islands	27.88009	-15.447964	Established	F	2006	(Urbaneja et al. 2007)
Europe	Switzerland	Geneva	46.156668	6.128174	Reported	G	2009	(EPPO 2009)
Europe	Turkey	Izmir	38.382551	27.210839	Established	F	2009	(Kılıç 2010)
Europe	Ukraine	Odessa	46.451888	30.672764	Transient/under eradication	G	2014	(EPPO 2014)
Europe	United Kingdom	Cambridgeshire	52.205271	0.206946	Transient/under eradication	G/P	2009	(NEPPO 2014)
Europe	United Kingdom	Essex	51.72455	0.511062	Transient/under eradication	G/P	2009	(NEPPO 2014)

Europe	United Kingdom	Isle of Wight	50.635952	-1.310581	Transient/under eradication	G/P	2009	(NEPPO 2014)
Europe	United Kingdom	Lancashire	53.742831	-2.790615	Transient/under eradication	G/P	2009	(NEPPO 2014)
Europe	United Kingdom	Suffolk	52.036468	1.399996	Transient/under eradication	G/P	2009	(NEPPO 2014)
Europe	United Kingdom	Worcestershire	52.25013	-2.261989	Transient/under eradication	G/P	2009	(NEPPO 2014)
Europe	United Kingdom	East Yorkshire	53.829132	-0.227233	Transient/under eradication	G/P	2009	(NEPPO 2014)

* Cultivation system under (G) greenhouses or (F) open-field tomato crops, and (P) detections in packing house facilities

REFERENCES

Abbes K, Harbi A, Chermiti B (2012) The tomato leafminer Tuta absoluta (Meyrick) in Tunisia: current status and management strategies EPPO Bulletin 42:226-233 doi:10.1111/epp.2559

Adamou H et al. (2017) Geographical distribution of the tomato borer, Tuta absoluta Meyrick (Lepidoptera. Gelichiidae) in Niger Scholars Academic Journal of Biosciences 5:108-113 doi:10.21276/sajb.2017.5.2.4

Al-Jboory IJ, Katbeh-Bader A, Shakir A-Z (2012) First Observation and Identification of Some Natural Enemies Collected from Heavily Infested Tomato by *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in Jordan Middle-East Journal of Scientific Research 11:787-790

Al-turaihi EH (2014) The Impact Of Newly Introduced Insect Tomato Borer (*Tuta Absoluta*) On Environment And Agriculture In Qatar EEPP0072 Energy & Environment doi:10.5339/qfarc.2014.EEPP0072

Baeţan R, Oltean I, Vărădie P, Florian T (2013) Researches concerning the spreading of *Tuta absoluta* Species into greenhouses from west of Romania Bulletin UASMV serie Agriculture 70:110-112 doi:10.15835/buasvmcn-agr:9775

Bahamondes LA, Mallea AL (1969) Biologia en Mendoza de Scrobipalpula absoluta (Meyrick) Polvony (Lepidoptera: Gelechiidae), espécie nueva para la Republica Argentina Revista de la Facultad de Ciencias Agrarias 15:96-104

Bajracharya ASR, Mainali RP, Bhat B, Bista S, Shashank PR, Meshram NM (2016) The first record of South American tomato leaf miner, *Tuta absoluta* (Meyrick 1917) (Lepidoptera: Gelechiidae) in Nepal Journal of Entomology and Zoology Studies 4:1359-1363

Baniameri V, Cheraghian A (2012) The first report and control strategies of Tuta absoluta in Iran EPPO Bulletin 42:322-324 doi:10.1111/epp.2577

Bentancourt CM, Scatoni IB (1995) Description of the development stages of the "tomato borer", Scrobipalpuloides absoluta (Meyrick) (Lep., Gelechiidae) Boletin de Investigacion - Facultad de Agronomia, Universidad de la Republica 45:1-14

BOPA BPA- (2016) Ministry warns of tomato leaf miner. http://www.dailynews.gov.bw/news-details.php?nid=32839. Accessed August, 15th 2017

Boualem M, Allaoui H, Hamadi R, Medjahed M (2012) Biologie et complexe des ennemis naturels de Tuta absoluta à Mostaganem (Algérie) EPPO Bulletin 42:268-274 doi:10.1111/epp.2570

Bratu E, Petcuci AM, Sovarel G (2015) Efficacy of the Product Spinosad an Insecticide Used in the Control of Tomato Leafminer (*Tuta absoluta* - Meyrick, 1917)

Bulletin of University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca Horticulture 72:209-210 doi:10.15835/buasvmcn-hort:10876

Dandria D, Catania A (2009) *Tuta absoluta* (Povolny, 1994), an important agricultural pest in Malta (Lepidoptera: Gelechiidae) Bulletin of the entomological Society of Malta 2:57-60

Đurić Z, Hrnčić S, Vujanović M, Đurić B, Mitrić S (2012) Tuta absoluta (Meyrick) (Lepidoptera, Gelechiidae) in the Republic of Srpska (Bosnia and Herzegovina) EPPO Bulletin 42:337-340 doi:10.1111/epp.2581

EPPO EPPO- (2009) First report of Tuta absoluta in Switzerland. https://gd.eppo.int/reporting/article-397. Accessed August 15th 2017

EPPO EPPO- (2010a) First report of Tuta absoluta in Guernsey. https://gd.eppo.int/taxon/GNORAB/distribution/GG. Accessed August, 15th 2017

EPPO EPPO- (2010b) First report of Tuta absoluta in Kosovo http://archives.eppo.int/EPPOReporting/2010/Rse-1006.pdf. Accessed August, 15th 2017

EPPO EPPO- (2010c) First report of Tuta absoluta in Russia. https://gd.eppo.int/taxon/GNORAB/distribution/RU. Accessed August, 15th 2017

EPPO EPPO- (2011) First report of Tuta absoluta in Georgia. https://gd.eppo.int/taxon/GNORAB/distribution/GE. Accessed August, 15th 2017

EPPO EPPO- (2012) First report of Tuta absoluta in the United Arab Emirates. https://gd.eppo.int/reporting/article-2540. Accessed August, 15th 2017

EPPO EPPO- (2013a) First report of Tuta absoluta in Germany. https://gd.eppo.int/taxon/GNORAB/distribution/DE. Accessed August 15th 2017

EPPO EPPO- (2013b) First report of *Tuta absoluta* in Yemen. https://gd.eppo.int/taxon/GNORAB/distribution/YE. Accessed August, 15th 2017

EPPO EPPO- (2014) First report of Tuta absoluta in Ukraine. https://gd.eppo.int/taxon/GNORAB/distribution/UA. Accessed August, 15th 2017

EPPO EPPO- (2016) First report of Tuta absoluta in Mayotte. https://gd.eppo.int/reporting/article-5538. Accessed August, 15th 2017

Esenali Uulu T, Ulusoy MR, Çalışkan AF (2017) First record of tomato leafminer Tuta absoluta Meyrick (Lepidoptera: Gelechiidae) in Kyrgyzstan EPPO Bulletin 47:285-287 doi:10.1111/epp.12390

FAO FaAOotUN- (2014) *Tuta absoluta*. https://www.ippc.int/en/countries/costa-rica/pestreports/2014/05/tuta-absoluta-1/. Accessed August, 15th 2017

FAO FaAOotUN- (2015) Quarterly Early Warning Bulletin for Food and Agriculture. http://www.fao.org/3/a-i4783e.pdf. Accessed August, 15th 2017

FAO FaAOotUN- (2016a) First report of Tuta absoluta in the Czech Republic (2013). https://www.ippc.int/en/countries/czech-republic/pestreports/2016/12/first-report-of-tuta-absoluta-in-the-czech-republic/. Accessed August, 15th 2017

FAO FaAOotUN- (2016b) Introducing IPM to Lebanese farmers: reducing the risk of "Tomato Borer" invasive plant pest. http://www.fao.org/lebanon/programmes-and-projects/success-stories/ipm/en/. Accessed August 15th 2007

FAO FaAOotUN- (2016c) REPORTING PEST PRESENCE: PRELIMINARY SURVEILLANCE REPORTS ON TUTA ABSOLUTA IN ZAMBIA. https://www.ippc.int/en/countries/zambia/pestreports/2016/09/reporting-pest-presence-preliminary-surveillance-reports-on-tuta-absoluta-in-zambia/. Accessed August, 15th 2017

FAO FaAOotUN- (2017) Occurrence of tomato leaf miner (Tuta absoluta) in Mozambique https://www.ippc.int/en/countries/mozambique/pestreports/2017/01/occurrence-of-tomato-leaf-miner-tuta-absoluta-in-mozambique/. Accessed August, 15th 2017

Figueiredo E, Payer R, Mexía A, Rodrigues S (2010) Situación actual de Tuta absoluta en Portugal Phytoma España 217:118-119

Gabl I, Hausdorf H (2010) First report of Tuta absoluta (Meyrick, 1917) in Austria and first monitoring results. Journal für Kulturpflanzen 65:1-8

Garcia RF (1989) Plagas del tomate y su manejo. ICA, Palmira, Colombia

Gontijo PC, Picanço MC, Pereira EJG, Martins JC, Chediak M, Guedes RNC (2013) Spatial and temporal variation in the control failure likelihood of the tomato leaf miner, *Tuta absoluta* Annals of Applied Biology 162:50-59 doi:10.1111/aab.12000

Hortidaily.com (2016) *Tuta absolut*a now also in Namibia. http://www.hortidaily.com/article/30198/Tuta-absoluta-now-also-in-Namibia. Accessed August, 15th 2017

Hossain MS, Mian MY, Muniappan R (2016) First Record of *Tuta absoluta* (Lepidoptera: Gelechiidae) from Bangladesh J Agric Urban Entomol 32:101-105

Hrnčić S, Radonjić S (2012) Tomato leafminer – Tuta absoluta Meyrick (Lepidoptera, Gelechiidae) – current status in Montenegro EPPO Bulletin 42:341-343 doi:10.1111/epp.2582

János Á, Imre F (2014) Recent data on the distribution and biology of *Tuta absoluta* (Meyrick, 1917) in Hungary (Lepidoptera: Gelechiidae) e-Acta Naturalia Pannonica 7:5-14

JICA IANAdCIdJ- (1994) Control integrado de la palomilla del tomate Scrobipalpula absoluta (Meyrick, 1917). Caacupé, Paraguay

Kalleshwaraswamy CM, Murthy MS, Viraktamath CA, Kumar NKK (2015) Occurrence of Tuta absoluta (Lepidoptera: Gelechiidae) in the Malnad and Hyderabad-Karnataka Regions of Karnataka, India Florida Entomologist 98:970-971 doi:10.1653/024.098.0326

Karadjova O, Z. Ilieva Z, Krumov V, Petrova E, Ventsislavov V (2013) *Tuta absoluta* (meyrick) (Lepidoptera: Gelechiidae): Potential for entry , establishment and spread in bulgaria Bulgarian Journal of Agricultural Science 19:563-571

Kariathi V, Kassim N, Kimanya M, Yildiz F (2016) Pesticide exposure from fresh tomatoes and its relationship with pesticide application practices in Meru district Cogent Food & Agriculture 2:1196808 doi:10.1080/23311932.2016.1196808

Kılıç T (2010) First record of Tuta absoluta in Turkey Phytoparasitica 38:243-244 doi:10.1007/s12600-010-0095-7

MDR MdDR- (2013) Detection of *Tuta absoluta* (Meyrick, 1917) in Cape Verde. http://www.mdr.gov.cv/index.php/2012-03-12-18-11-28/relatorios/download/18-relatorios/369-detection-of-tuta-absoluta-meyrick-1917-in-cape-verde. Accessed August, 15th 2017

Mladen Šimala M, Masten Milek T, Seljak G (2011) The results of the monitoring of south american tomato moth *Tuta absoluta* Povolny, 1994 (lepidoptera: Gelechiidae) in 2010 in Croatia Plant Protection Society of Slovenia

Mohamed ESI, Mohamed ME, Gamiel SA (2012) First record of the tomato leafminer, Tuta absoluta (Meyrick) (Lepidoptera: Gelechiidae) in Sudan EPPO Bulletin 42:325-327 doi:10.1111/epp.2578

Moore JE (1983) Control of tomato leafminer (Scrobipalpula absoluta) in Bolivia. Tropical Pest Management 29:231-238

Moussa S, Sharma A, Baiomy F, El-Adl FE (2013) The Status of Tomato Leafminer; *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in Egypt and Potential Effective Pesticides Academic Journal of Entomology 6:110-115 doi:10.5829/idosi.aje.2013.6.3.75130

NEPPO LOplpdvaP-O- (2011) The current status of the tomato borer *Tuta absoluta* in Greece and Cyprus. http://www.neppo.org/wp-content/uploads/2014/05/roditakis-Tuta-greece-cyprus-AGADIR1.pdf. Accessed August, 15th 2017

NEPPO LOplpdvaP-O- (2014) The current incidence of tomato borer, *Tuta absoluta*, in the uk. http://www.neppo.org/wp-content/uploads/2014/05/KevinGormanAgadir1.pdf. Accessed August, 15th 2017

NPPO NPPOotN- (2009) Tuta absoluta Povolny (Gelechiidae) – tomato leaf miner - in tomato packaging facility in The Netherlands. https://english.nvwa.nl/documents/chek/chek/chek/documents/pest-report-tuta-absoluta-in-the-netherlands-at-tomato-packaging-facility. Accessed August, 15th 2017

OIRED OoIREaD- (2014) *Tuta absoluta*: the tomato leafminer. http://www.oired.vt.edu/ipmil/wp-content/uploads/2014/06/13-Muniappan-Tuta-absoluta-15May2014.pdf. Accessed August, 15th 2017

Ostrauskas H, Ivinskis P (2010) Records of the Tomato Pinworm (Tuta absoluta (Meyrick, 1917)) – Lepidoptera: Gelechiidae – in Lithuania Acta Zoologica Lituanica 20:151-155 doi:10.2478/v10043-010-0016-5

Ouardi K, Chouibani M, Rahel MA, El Akel M (2012) Stratégie Nationale de lutte contre la mineuse de la tomate Tuta absoluta Meyrick EPPO Bulletin 42:281-290 doi:10.1111/epp.2568

Pfeiffer DG, Muniappan R, Sall D, Diatta P, Diongue A, Dieng EO (2013) First Record of Tuta absoluta (Lepidoptera: Gelechiidae) in Senegal Florida Entomologist 96:661-662 doi:10.1653/024.096.0241

Povolný D (1984) Four new Neotropical Gnorimoschemini from Venezuela (Lepidoptera, Gelechiidae) Deutsche Entomologische Zeitschrift 31:299-311

PURE-IPM (2017) Integrated management of the invasive tomato leafminer Tuta absoluta in Flanders (Belgium). http://www.pure-ipm.eu/sites/default/files/content/files/van%20Damme%20Veerle_0.pdf. Accessed August, 15th 2017

Razuri V, Vargas E (1975) Biology and behaviour of *Scrobipalpula absoluta* Meyrick (Lepidoptera: Gelechiidae) on tomatoes Revista Peruana de Entomologia 18:84-89

Roda AL, Brambila J, Barria J, Euceda X, Korytkowski C (2015) Efficiency of Trapping Systems for Detecting Tuta absoluta (Lepidoptera: Gelechiidae) Journal of Economic Entomology 108:2648-2654 doi:10.1093/jee/tov248

Roditakis E, Papachristos D, Roditakis NE (2010) Current status of the tomato leafminer Tuta absoluta in Greece EPPO Bulletin 40:163-166 doi:10.1111/j.1365-2338.2009.02367.x

Russell-IPM TaIN (2009a) Tuta absoluta in Albania. http://www.tutaabsoluta.com/news/55/tuta-absoluta-in-albania. Accessed August, 15th 2017

Russell-IPM *Ta*IN (2009b) *Tuta absolut*a in Libya. http://www.tutaabsoluta.com/news?news=17&lang=en. Accessed August, 15th 2017

Russell-IPM TaIN (2010a) Initial reports of Tuta absoluta in Syria. http://www.tutaabsoluta.com/news?news=143. Accessed August, 15th 2017

Russell-IPM TaIN (2010b) *Tuta absoluta* reaches Saudi Arabia. http://www.tutaabsoluta.com/news/227/ptuta-absoluta-reaches-saudi-arabiap. Accessed August, 15th 2017

Russell-IPM TaIN (2011) Tuta absoluta in KUWAIT. http://www.tutaabsoluta.com/reports/163/tuta-absoluta-in-kuwait. Accessed August, 15th 2017

Russell-IPM TaIN (2015) Nigerian Press Conference on Tuta absoluta http://www.russellipm.com/uncategorized/nigerian-press-conference-on-tuta-absoluta/. Accessed August, 15th 2017

Schotman CYL (1989) Plant pests of quarantine importance to the Caribbean RLAC-PROVEG:21-80

Seplyarsky V, Weiss M, Haberman A (2010) Tuta absoluta Povolny (Lepidoptera: Gelechiidae), a new invasive species in Israel Phytoparasitica 38:445-446 doi:10.1007/s12600-010-0115-7

Son D et al. (2017) First Record of Tuta absoluta (Meyrick, 1917) (Lepidoptera: Gelechiidae) in Burkina Faso African Entomology 25:259-263 doi:10.4001/003.025.0259

Speranza S, Sannino L (2012) The current status of Tuta absoluta in Italy EPPO Bulletin 42:328-332 doi:10.1111/epp.2579

Tonnang HEZ, Mohamed SF, Khamis F, Ekesi S (2015) Identification and risk assessment for worldwide invasion and spread of *Tuta absoluta* with a focus on Sub-Saharan Africa: Implications for phytosanitary measures and management PLoS ONE 10:e0135283 doi:10.1371/journal.pone.0135283

Toševski I, Jović J, Mitrović M, Cvrković T (2011) *Tuta absoluta* (Meyrick, 1917) (Lepidoptera, Gelechiidae): a new pest of tomato in Serbia Pestic Phytomed 26:197–204 doi:10.2298/PIF1103197T

Trottin-Caudal Y, Baffert V, Leyre JM, Hulas N (2012) Experimental studies on Tuta absoluta (Meyrick) in protected tomato crops in France: biological control and integrated crop protection EPPO Bulletin 42:234-240 doi:10.1111/epp.2560

Tumuhaise V, Khamis FM, Agona A, Sseruwu G, Mohamed SA (2016) First record of Tuta absoluta (Lepidoptera: Gelechiidae) in Uganda International Journal of Tropical Insect Science 36:135-139 doi:10.1017/S1742758416000035

Urbaneja A, Vercher R, Navarro V, F GM, J.L. P (2007) La polilla del tomate, Tuta absoluta Phytoma Espana 194:16-23

USAID UIAP- (2012) Iraqi Farmers Collaborate in Control of *Tuta absoluta*. http://www.inma-iraq.com/newsroom/iraqi-farmers-collaborate-control-tuta-absoluta. Accessed August, 15th 2017

USDA USDoA- (2011) New Pest Response Guidelines Tomato Leafminer (*Tuta absoluta*). https://www.aphis.usda.gov/import_export/plants/manuals/emergency/downloads/Tuta-absoluta.pdf. Accessed August, 15th 2017

Vargas HC (1970) Observaciones sobre la biologfa y enemigos naturales de la polilla del tomate, Gnorimoschema absoluta (Meyrick) (Lepidoptera: Gelechiidae) Idesia (Chile)

Visser D, Uys VM, Nieuwenhuis RJ, Pieterse W (2017) First records of the tomato leaf miner *Tuta absoluta* (Meyrick, 1917) (Lepidoptera: Gelechiidae) in South Africa BioInvasions Records 6:1-5

Žežlina I, Benko Beloglavec A, Pajk O (2011) Tomato leaf miner (*Tuta absoluta* Povolny) - results of its special surveillance in slovenia in year 2010 Plant Protection Society of Slovenia

Chapter 2: Worldwide spatial distribution of natural enemies under climatic change conditions: An investigation using parasitoids and a predator of the tomato leaf miner, *Tuta absoluta* (Lepidoptera: Gelechiidae) through modelling

ABSTRACT

Many studies have been conducted to figure out the countries under risk of *T. absoluta* invasion. However, none has investigated the suitable areas and the impact of climate change on its natural enemies. Here for the first time, a model was applied at a global scale to investigate the effect of climate change on four natural enemies (*Neochrysocharis formosa, Stenomesius japonicus, Pseudapanteles dignus*, and *Macrolophus pygmaeus*) of the invasive pest *T. absoluta*. The key aim was to understand whether increases in the tomato pest would be accompanied by increases in its natural enemies and identify regions where there is a mismatch in the pest and its parasitoids and predator. We modelled the effect of climate change on the pest and its natural enemies using the Global Climate Model (GCM) HadGEM2_ES under the RCP4.5 scenario in MaxEnt. Climate change will lead to an increase in the suitable areas for *T. absoluta,* especially in the North hemisphere. Countries such as China, the Netherlands, the United Kingdom, Germany, the USA, and Mexico will be under risk of *T. absoluta*. The increasing suitability for *T. absoluta* in open field in these countries will not be accompanied by an increase in some of the natural enemies. Therefore, this variation in suitability will have important consequences on biological control in these areas. Thus, this study allows pest management agencies to improve their biological control programs and quarantine measures against the tomato pinworm.

Keywords: MaxEnt, ecosystem modelling, tomato pinworm, biological control, ecological niche model, invasive alien species.

INTRODUCTION

When it comes to non-native insects spreading to new areas, the fundamental question raised is: Why do non-native insects become invasive pests? Several studies have addressed this subject (Fridley and Sax 2014; Heimpel et al. 2013; Lowry et al. 2013), and the role of natural enemies has been reported as a key factor controlling non-native species in an invaded area (Duan et al. 2015).

In a study published in 2015, a group of researchers in the USA investigated the population dynamics of an invasive forest pest and its natural enemies – native and exotic agents – and the implications in the biological control through a life table study (Duan et al. 2015). The authors found that, initially, the native natural enemy was the one which most contributed to the total mortality of this pest. Over the years, mortality caused by the pest co-evolved natural enemy introduced in a classical biological control program, increased and contributed significantly to reduce its growth. Therefore, this study highlighted the importance of both native and exotic natural enemies (i.e. conservational and classical biological control) to suppress the damages caused by this insect (Duan et al. 2015). Thus, the biological control has a fundamental role inhibiting the spread of invasive pests.

Biological control is defined as *"The use of living organisms to suppress the population density or impact of a specific pest organism, making it less abundant or less damaging than it would otherwise be"* (Eilenberg et al. 2001). It can be divided into classical, inoculation, inundation, and conservational biological control. Classical biological control is the use of an exotic natural enemy to control the pest in the invaded area (Eilenberg et al. 2001), usually a co-evolved pest natural enemy is used. In the inoculation biological control, the aim is to release a number of natural enemies expecting that they will multiply and control the pest but in a short period of time (Eilenberg et al. 2001). In the inundative strategy, the control is not permanent as well, however, is made exclusively by the number of natural enemies released (i.e. without the expectation of the natural enemy reproduction) (Eilenberg et al. 2001). The conservational biological control, in turn, is the one made by native natural enemies present in the area, and it is accomplished by enhancing the environment and protecting natural enemies, intending to increase its development and improve the control made by these organisms.

Recently, one invasive pest which has gained a lot of attention is the South American tomato pinworm, *Tuta absoluta*. This insect has been reported as a pest in South America since the 1970's; and in 2006 it was reported for the first time in Europe (Desneux et al. 2011; Desneux et al. 2010; Gontijo et al. 2013; Guedes and Picanço 2012). Since then, the tomato pinworm has rapidly spread to several countries in Europe, Africa, and Asia, and infected approximately 60% of the tomato crops worldwide (Campos et al. 2017). Many studies have been conducted trying to figure out the countries under risk of *T. absoluta* invasion and the effect of the climate changes on this pest (Biondi et al. 2018; Campos et al. 2017; Desneux et al. 2010; Santana et al. 2018; Tonnang et al. 2015). However, based on our review, no study has been undertaken to investigate the suitable areas for its natural enemies and the impact of climate change predicted on these biological control agents.

The potentially suitable areas and the effect of climate change on species are assessed mainly through ecological niche and bioclimatic models (Kumar et al. 2015; Shabani and Kumar 2013; Soberón 2005). One tool frequently used in prediction and assessment of climate change impact on different species is the correlative maximum entropy-based model or MaxEnt (Kumar et al. 2014; Kumar et al. 2015; Kumar and Stohlgren 2009). It correlates species occurrence and background data points from spatial environmental variables representing different environmental gradients to make projections of the suitable areas for the species (Phillips et al. 2006). Therefore, MaxEnt does not need species physiological information to make its projections, which is an advantage of this software. Besides, MaxEnt has also been widely recognized to perform robust projections even with small sample sizes (Kumar and Stohlgren 2009; Townsend Peterson et al. 2007).

Tuta absoluta has many species of natural enemies reported, coming from more the 160 taxa (Biondi et al. 2018). They are divided into parasitoids, predators, and entomopathogens (Biondi et al. 2018). In this study, we selected three parasitoids (*Neochrysocharis formosa, Stenomesius japonicus,* and *Pseudapanteles dignus*) and one Hemipteran predator (*Macrolophus pygmaeus*) of *T. absoluta* to investigate the effect of climate change on these natural enemies. They were chosen based on their high potential to control *T. absoluta* (Biondi et al. 2018), and their distribution in many parts of the world.

In this sense, this study aims to investigate the suitable areas for four natural enemies (3 parasitoids and 1 predator) of *T. absoluta* at a global scale, and the effect of climate change predicted for 2050 and 2070 on these natural enemies. This study will provide a comprehensive understanding of the effect of climate change on the natural enemies of the tomato pinworm and will allow Integrated Pest Management agencies to define strategies to control *T. absoluta* in the invaded areas using natural enemies, such as parasitoids and predators. This study will also identify those areas at greatest risk from *T. absoluta* due to them having less favorable conditions for the natural enemies, enabling *T. absoluta* to thrive in these regions, or spread uninhibited.

MATERIALS AND METHODS

Natural enemy species

Neochrysocharis formosa

Neochrysocharis formosa (Westwood) (Hymenoptera: Eulophidae) is an endoparasitoid distributed in all continents, except Australia, therefore, it is recorded in both native and invaded areas of *T. absoluta* (Biondi et al. 2018; Luna et al. 2011). *N. formosa* is well known as a parasitoid of leaf-mining and gall-forming insects of different orders such as Lepidoptera, Coleoptera, Diptera, and Hymenoptera (Luna et al. 2011; Wang et al. 2014). It has been reported as a 1st instar larvae parasitoid of *T. absoluta* in the Mediterranean basin, South America, and Africa (Dehliz and Guénaoui 2015; Urbaneja et al. 2012), and at a temperature of 25 ºC, its development extends from 14 to 16 day (Urbaneja et al. 2012).

Stenomesius japonicus

Stenomesius sp. nr. *japonicus* (Ashmead) (Hymenoptera: Eulophidae) is an ectoparasitoid distributed in open fields in many regions in Asia and with a few reports in Algeria, Australia, Egypt, France, and Spain (Chailleux et al. 2014; Gadallah et al. 2015). It is a 2nd – 3rd instar *T. absoluta* larvae ectoparasitoid and has been reported as the natural enemy of other Lepidopteran species, especially of Gelechiidae, Gracillariidae and Lyonetiidae families (Urbaneja et al. 2012). From our knowledge, this species lacks a comprehensive study of its thermal requirements.

Pseudapanteles dignus

Pseudapanteles dignus (Muesebeck, 1938) (Hymenoptera: Braconidae) is a koinobiont endoparasitoid distributed in the American continent (Luna et al. 2015). In its native range, this parasitoid is able to reduce *T.absoluta* population in the open field from between 33 to 64% (Luna et al. 2015). *P. dignus* parasitizes all larval stages of the tomato pinworm (Luna et al. 2015). Based on these reasons, this endoparasitoid has an important potential to be used in the biological control of *T. absoluta*. Therefore, identifying the suitable areas and effects of climate changes on this insect are essential.

Macrolophus pygmaeus

From all species of natural enemies in this study, *Macrolophus pygmaeus* (Rambur) (Heteroptera: Miridae) is the one most studied. This Hemipteran predator is a polyphagous predator and has been reared and commercialized for biological control of many tomato pests, especially whitefly eggs, aphids, mites, thrips, and moth eggs (Backer et al. 2014b). It is distributed in the Palearctic region and was detected attacking *T. absoluta* right after the pest invasion (Urbaneja et al. 2012). Under laboratory conditions, *M. pygmaeus* was able to consume more than 100 eggs of *T. absoluta* per day (Urbaneja et al. 2012). It was also able to reduce the tomato pinworm population significantly in an experiment in a semi-field (Urbaneja et al. 2012). As most of the greenhouses in the Mediterranean basin are roll-up sides for ventilation, it is common for the exchange of insects from outside to occur (Backer et al. 2014b). Therefore, this predator has an important role in conservational biological control in this region.

As can be seen, each natural enemy has its importance as a biological control agent of *T. absoluta* in different regions of the world and undertakes their role as natural enemies in different lifecycle stages of the pest. Therefore, for these reasons, they were chosen as models to study the effect of climate change on the biological control of *T. absoluta*.

Species Occurrence Data

In order to be able to compare the suitable areas for *T. absoluta* and its natural enemies, and the effect of climate change on the biological control of this pest, we developed five (pest and four natural enemies) spatial distribution models.

For this purpose, the occurrences in open field of *T. absoluta* and its natural enemies, *N. formosa, S. japonicus, M. pygmaeus,* and *P. dignus* were cataloged and confirmed through the search for scientific information on Web of Science, Science Direct, Google, PubMed, and MEDLINE. The occurrence data were classified among four characteristics: species, country, latitude, longitude, and references (Table S1).

A total of 147 unique records were confirmed for the presence of *Tuta absoluta* in the American, European, African and Asian continents (Fig. 1a). For *N. formosa* 60 sites were confirmed distributed through all continents, except Oceania (Fig 2a). For *S. japonicus,* 36 sites were confirmed and were distributed over Asia and Europe (Fig. 3a). *M. pygmaeus* were confirmed in 26 sites, mainly in the Mediterranean basin (Fig. 4a). *P. dingus,* in turn, was confirmed in 18 sites distributed only in the American continent (Fig. 5a). There are no reported occurrences outside this continent for *P. dingus* (Fig. 5a).

In order to achieve the data spatial independence, the records of *T. absoluta* were reduced from 147 to 144 after applying the spatial filtering tool using spThin package available in R software (version 3.2.2) (Aiello-Lammens et al. 2015; R Development Team 2015). The occurrence data were kept at least 10 km apart from each other (Boria et al. 2014; Veloz 2009). According to Boria et al. (2014), this method performs a better spatial autocorrelation reduction than other methods available and allows to keep most of the records possible. Regarding each natural enemy, since their occurrence records were more than 10 km apart, no reduction was necessary. Therefore, to build the models, the insects' occurrence data – filtered data for *T. absoluta* – related to open-field were used.

Environmental Data

In this study nineteen variables were considered, among them, eleven are derived from monthly temperature and eight from monthly precipitation (Table 1). The variables layer were obtained from Worldclim dataset (http://www.worldclim.org) (Hijmans et al. 2005) at 5 min resolution (~10 km), which is sufficient to support climatic variables at global scale (Daly 2006). The Worldclim variables were derived from monthly temperature and precipitation, seasonal variation, and climatic extreme indices covering a period of time from 1950 to 2001 (Hijmans et al. 2005).

To avoid multicollinearity, the environmental variables were examined for cross-correlation (Dormann et al. 2013). This procedure was undertaken using the SDMtoolbox and only one variable derived from each set of the highly correlated predictors (Pearson correlation coefficient, $r = |0.75|$) was included in the model (Kumar et al. 2014). Thus, in this study, only six environmental variables were selected and considered biologically relevant to be included in the models (Tables 1, 3, 5, 7, 9).

Model Development and Validation

In this study, the correlative maximum entropy-based model or MaxEnt (version 3.3.3k) (Phillips et al. 2006) was chosen to assess the impact of climate change on the invasive pest and its natural enemies. This correlative model correlates background data points from spatial environmental variables representing different environmental gradients and species occurrence data to make projections of the potentially suitable areas for the species (Phillips et al. 2006). It classifies the areas from 0 to 1, where 0 means unsuitable areas for the species development, and 1 highly suitable areas. MaxEnt is also recognized to perform projections well even with small samples sizes

(Kumar and Stohlgren 2009; Townsend Peterson et al. 2007), which is an important characteristic for this study since field occurrence data for natural enemies are very sparse in the literature. Considering that this study has been carried out on a global scale, to build the model a total of 50,000 background points were randomly selected from the areas where each insect currently occurs (Brown 2014; Jarnevich et al. 2015). Additionally, a sampling bias surface – using a kernel density estimate – was developed using the SDMToolbox, since the data collected was from external sources and we could not control the sampling process (Brown 2014).

Aiming to select the best model for each insect, different settings were adjusted in MaxEnt, seeing that the default setting (i.e. Autofeature) sometimes does not develop the most appropriated model (Jarnevich et al. 2015; Kumar et al. 2014; Merow et al. 2013). Consequently, different combinations of regularization multiplier (RM) and feature types were set to generate different models. The RM allows MaxEnt to select the features which contributes the most to the model, resulting in a reduction in the model overfitting (Merow et al. 2013). It is recommended to explore a range of RM coefficient values and choose the one which maximizes a measure of fit on a cross-validation data set (Merow et al. 2013). For studies on a global scale it is also recommended to use RM values ≥ 1, which avoids the model' overfitting and results in simpler models (Merow et al. 2013).Thus, the RM values used in this study were 1.0, 1.5, and 2.0. In this sense, different sets of MaxEnt features (e.g. linear [L], quadratic [Q], product [P], threshold [T], and hinge [H]) and RM combinations were executed to obtain the best model for each insect (Tables 2, 4, 6, 8, 10). To prevent extrapolations outside the species environmental range, the 'fade-by-clamping' option was selected in the software as well (Owens et al. 2013). Species 'Response Curves' were also generated, employing the 'Jacknife' feature, the percent contribution, and permutation importance in MaxEnt (Phillips et al. 2006).

Through the ‘Response Curves’ it is possible to assess the relationships between the predicted probabilities for the species and each environmental predictor (Kumar et al. 2014; Phillips et al. 2006). Therefore, all curves were evaluated and were kept for further evaluations only for the models which presented biologically coherent curves (Fig. S1, S2, S3, S4, S5, S6). The ‘Jacknife’ feature evaluates the relative influence of different environmental predictors on the insects’ distribution (Fig. S7). The percent contribution estimates the contribution of each variable to the model, and the permutation importance indicates how much the model depends on a specific variable (Phillips et al. 2006).

In order to select the best model for each species, we ran a 10-fold cross-validation in MaxEnt to calculate the AUC_{cv} (area under the receiver operating characteristic [ROC] curve) (Peterson et al. 2008) and the test sensitivity at 0 and 10% training Omission Rates (OR) (Kumar et al. 2015; Liu et al. 2013). The AUC_{cv} is a measurement of the model’s ability to discriminate presence from background. It can be classified into five categories: (i) $AUC_{cv} < 0.5$ model predictions are worse than random; (ii) $AUC_{cv} = 0.5$ predictions are not better than random; (iii) $0.5 < AUC_{cv} < 0.7$ indicate models poor performance; (iv) $0.7 \leq AUC_{cv} < 0.9$ reasonable or moderate performance; and (v) $AUC_{cv} \geq 0.9$ indicates high performance (Galdino et al. 2016). The OR, in turn, means that zero and ten percent, respectively, of training presence locations for the model fall outside the predicted suitable area. Therefore, for test sensitivity at 0 and 10% training OR threshold is expected to have values of 0 and 0.10, respectively. Values higher than the expected indicates models poor performance (Boria et al. 2014).

Afterwards, the best models were ranked based on 10% training OR, 0% training OR, and AUC_{cv}, respectively (Liu et al. 2013; Merow et al. 2013). When it comes to invasive species (i.e. *T. absoluta*) it is recommended to prioritize OR since it gives more emphasis to sensitivity in the model, while AUC_{cv} gives the same weight to sensitivity and specificity (Fielding and Bell 2002; Zweig and Campbell 1993). The MaxEnt' projected areas for each species were classified in four categories: unsuitable; low suitability; moderate suitability; and highly suitable. The classification was made based on the Prevalence Threshold Approach (Liu et al. 2013). This threshold approach was selected based on its simplicity and efficiency to define habitats and non-habitats (Liu et al. 2013).

Future Projections and Model Combinations

The future projections for 2050 and 2070 for both the invasive pest and its natural enemies were performed using the Global Climate Model (GCM) HadGEM2_ES under the Special Report on Emissions Scenarios (SRES) scenario RCP4.5. This model has been widely used to assess the spatial distribution of many species under climate change, ecosystems, and other long timescale components of the Earth system. It has also been used to perform the centennial CMIP5 experiments, which includes the simulations of the RCPs currently available (Dike et al. 2015). HadGEM2_ES was initially introduced by the Hadley Centre Global Environmental Model and it was one of the models used on the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) and the associated cycle of the fifth phase of the CMIP5 (http://www.ipcc.ch/report/ar5/wg1/) (Taylor et al. 2012). The model takes into account forcing which include greenhouse gases emissions, aerosols, solar irradiance, ozone, and others (Andrews et al. 2012).

The Anthropogenic Greenhouse Gases (GHG) emissions are widely known to increase the global mean surface temperature, and it has been related to being driven by population size, economic activity, lifestyle, energy use, land use patterns, and so forth (IPCC 2014). Based on these factors, the Representative Concentration Pathways (RCPs) are used for making projections of the effects of climate change (IPCC 2014).

They are divided into four categories: RCP2.6 which predicts a severe mitigation scenario; the RCPs 4.5 and 6.0 which predict an intermediate scenario, and the RCP8.5 which predicts a very high CHG emission. In this study, we selected the RCP4.5 scenario to project the effect of climate change on *T*. *absoluta* and its natural enemies due to its more reasonable scenario of climate change. RCP4.5 projects an increase in the global surface temperature from 1.1 to 2.6 ºC by the end of the 21st century (IPCC 2014). It also projects changes in precipitation. Most areas infected by *T*. *absoluta* such as South America, Mediterranean basin, and Africa are expected to have increased temperature and decreased precipitation (IPCC 2014).

RESULTS

Pest: *Tuta absoluta*

Based on the current distribution of *T. absoluta,* this insect occurs in areas with mean annual temperature and precipitation varying from 6.0 to 29.5 ºC, and 39 to 3808 mm, respectively (Table 1). The variables that most contributed for the tomato pinworm projections (i.e. percent contribution) were Bio 7 - Temperature Annual Range (46.5%), Bio 1 - Annual Mean Temperature (39.5%), and Bio 2 - Mean Diurnal Range (6.2%) (Table 1). The variables which most influenced the model individually (i.e. permutation importance) were Annual Mean Temperature (62%), followed by Mean Diurnal Range (16%), and Temperature Annual Range (8.4%) (Table 1).

All 10 models tested to project the potential distribution of *T. absoluta* performed well (Table 2). They had low values of test omission rates at 0 and 10%, and good AUC_{cv} values. The OR at 0 and 10% varied from 0.0071 to 0.0133, and 0.12 to 0.21, respectively. The AUC_{cv} values, in turn, varied from 0.84 to 0.88 (Table 2). Thus, the best model for the tomato pinworm included six environmental variables, linear [L], quadratic [Q], and product [P] features, RM = 1.0, and had the lowest test OR, at 10 and 0%, respectively (Table 2).

The MaxEnt projections for the current time matched well with the current distribution of *T. absoluta* (Fig. 1a, b). Most of the moderate and highly suitable areas for this pest correspond to the areas infected with this insect (e.g. South America, Mediterranean basin and Africa). Overall, the climate changes projected for 2050 and 2070 will lead to a decrease in the suitable areas for the tomato pinworm in the Southern hemisphere and an increase in the Northern hemisphere (Fig 1c, d). South America, Sub Saharan Africa, some areas in Asia and Australia will decrease in the suitability for this pest due to climate change. On the other hand, the Mediterranean basin, North of Europe, North America, and some areas in China will become more suitable (Fig. 1c, d). Countries free from *T. absoluta* such as the USA, Mexico, the Netherlands, Germany, the United Kingdom, and China will become more suitable for the pest in the future (Fig. 1c, d).

Natural enemy: *Neochrysocharis formosa*

The current field distribution of the parasitoid *N. formosa* suggests that this insect occurs in areas with mean annual temperature and precipitation from 4.3 to 29.4 ºC and 65 to 2985 mm, respectively (Table 3). The variables that most contributed for this parasitoid projections were Bio 1 - Annual Mean Temperature (53%), Bio 7 - Temperature Annual Range (26.6%), and Bio 2 - Mean Diurnal Range (12.5%) (Table 3). Annual Mean Temperature was also the variable which most influenced the model individually (62%), followed by Mean Diurnal Range (26.8%), and Temperature Annual Range (7%) (Table 3).

A total of 13 models were tested to project the potential distribution of *N. formosa* and all performed well (Table 4). They also had low values of test omission rates at 0 and 10%, and good AUC_{cv} values. The OR at 0 and 10% varied from 0.02 to 0.0767 and 0.12 to 0.25, respectively (Table 4). The AUC_{cv} values, in turn, varied from 0.86 to 0.88 (Table 4). Thus, the best model for *N. formosa* included six environmental variables, linear [L], and quadratic [Q] features, RM = 1.0, and had the lowest test OR, at 10 and 0%, respectively (Table 4).

The MaxEnt projections for the current time also paired well with the current distribution of *N. formosa* (Fig. 2a, b). Most of the projected suitable areas for this parasitoid correspond to the areas occupied by this insect (e.g. Europe and Asia). When it comes to climate change, it will lead to a decrease in the suitable areas for *N. formosa* in South America, Sub Saharan Africa, some areas in the Middle East, China and

Australia. On the other hand, the Mediterranean basin and North of Europe will become more suitable for this parasitoid (Fig. 2c, d).

Through the combination of *T. absoluta* and *N. formosa* projections for 2070 it is possible to highlight some areas under high risk of the pest infestation, especially in Europe, (Fig. 6a). Countries such as the United Kingdom, the Netherlands, France, Germany, and Italy will have large areas highly suitable for *T. absoluta,* but with low and moderate suitability for *N. formosa* (Fig. 6a). Spain, Portugal, Morocco, and some countries in South America, all infected by the tomato pinworm, also possess small areas under high risk (Fig. 6a). Therefore, based on the projection, in these areas *N. formosa* will not find the best conditions to execute full control in open-field.

Natural enemy: *Stenomesius japonicus*

The current field distribution of another important parasitoid *S. japonicus* suggests that this insect occurs in areas with mean annual temperature and precipitation from 5.2 to 28.6 ºC, and 9.0 to 2497 mm, respectively (Table 5). The variables that most contributed to this parasitoid projections were Bio 1 - Annual Mean Temperature (54.8%), Bio 2 - Mean Diurnal Range (27.8%), and Bio 7 - Temperature Annual Range (11.7%) (Table 5). Annual Mean Temperature was also the variable which most influenced the model individually (61%), followed by Mean Diurnal Range (23.7%), and Temperature Annual Range (11.4%) (Table 5).

Twelve models were tested to project the potential distribution of *S. japonicus* and all performed properly (Table 6). They also had low values of test omission rates at 0 and 10%, and good AUC_{cv} values. The OR at 0 and 10% varied from 0.02 5to 0.058 and 0.14 to 0.26, respectively (Table 6). The AUC_{cv} values, in turn, varied from 0.86 to 0.88 (Table 6). Thus, the best model for *S. japonicus* included six environmental variables, linear [L], and quadratic [Q] features, RM = 1.0, and had the lowest test OR, at 10 and 0%, respectively (Table 6).

MaxEnt projections for the current time also paired well with the current distribution of *S. japonicus* (Fig. 3a, b).The projected suitable areas for this parasitoid correspond to areas in Asia, Europe, some areas in Africa, Americas, and Australia (Fig. 3a, b). Regarding climate change, a different pattern was observed for this insect. Overall, the climate changes for 2050 and 2070 will lead to an increase of the suitable areas for this insect in all continents (Fig. 3c, d).

When it comes to the combination of *T. absoluta* and *S. japonicus* projections for 2070 it is also possible to highlight areas under high risk of the pest infestation (Fig. 6b). Countries such as the United Kingdom and the Netherlands will have large areas highly suitable for *T. absoluta,* but with low and moderate suitability for *S. japonicus* (Fig. 6b). Some areas in Chile, Peru, Ecuador, Colombia, France, Germany, Portugal, Spain, Italy, Morocco, Egypt, China, and New Zealand also possess some areas under high risk (Fig. 6b). Thus, based on the projection, in these areas *S. japonicus* will not be fully effective as a control method in open-field.

Natural enemy: *Macrolophus pygmaeus*

The current field distribution of the predator *M. pygmaeus* suggests that this insect occurs in areas with mean annual temperature and precipitation from 9.6 to 19.6 ºC, and 301 to 2560 mm, respectively (Table 7). The variables that most contributed to this predator projections were Bio 1 - Annual Mean Temperature (47.8%), Bio 7 - Temperature Annual Range (25.8%), and Bio 2 - Mean Diurnal Range (11.7%) (Table 7). Annual Mean Temperature was also the variable which most influenced the model individually (70.2%), followed by Mean Diurnal Range (19.7%), and Precipitation Seasonality (4.8%) (Table 7).

A total of 10 models were tested to project the potential distribution of *M. pygmaeus* and all performed very well (Table 8). They had low values of test omission rates at 0 and 10%, and very good AUC_{cv} values. The OR at 0 and 10% varied from 0.03 to 0.3 and 0.15 to 0.38, respectively (Table 4). The AUC_{cv} values, in turn, varied from 0.94 to 0.97 (Table 8). Thus, the best model for *M. pygmaeus* included six environmental variables, linear [L], and quadratic [Q] features, RM = 1.5, and had the lowest test OR, at 10 and 0%, respectively (Table 8).

The MaxEnt projections for the current time also matched well with the current distribution of *M. pygmaeus* (Fig. 4a, b). The projected suitable areas for this predator correspond to areas in Europe, China, small areas in South and North America, and Australia and New Zealand. When it comes to climate change, it will lead to a decrease in the suitable areas for *M. pygmaeus* in South and North America, Africa, China and Australia. On the other hand, the Mediterranean basin and North of Europe will become more suitable for this predator (Fig. 4c, d).

The combination of *T. absoluta* and *M. pygmaeus* projections for 2070 showed areas under high risk of the pest infestation mainly in Portugal, few areas in Chile, Peru, Ecuador, China, Morocco, Egypt, Greece, and New Zealand (Fig. 6c). Thus, based on the projections, in these areas, *M. pygmaeus* will not find the best condition for its full development in open-field.

Natural enemy: *Pseudapanteles dignus*

The current field distribution of the parasitoid *P. dignus* is restricted to the American continent. This natural enemy occurs in areas with mean annual temperature and precipitation from 14.1 to 26.5 ºC, and 173 to 4794 mm, respectively (Table 9). The variables that most contributed for this predator projections were Bio 1 - Annual Mean Temperature (67.6%), Bio 7 - Temperature Annual Range (16.8%), and Bio 14 –

Precipitation of the driest month (12.6%) (Table 9). Temperature Annual Range was also the variable which most influenced the model individually (45.9%), followed by Annual Mean Temperature (36%), and Precipitation of the Driest Month (12.1%) (Table 9).

A total of 13 models were tested to project the potential distribution of *P. dignus* and all performed properly (Table 10). They also had low values of test omission rates at 0 and 10%, and good AUC_{cv} values. The OR at 0 and 10% varied from 0.05 to 0.15 and 0.10 to 0.45, respectively (Table 10). The AUC_{cv} values, in turn, varied from 0.74 to 0.86 (Table 10). Thus, the best model for *P. dignus* included six environmental variables, linear [L], product [P], threshold [T], and hinge [H] features, RM = 1.0, and had the lowest test OR, at 10 and 0%, respectively (Table 10).

The MaxEnt projections for the current time also matched well with the current distribution of *P. dignus* (Fig. 5a, b). The projected suitable areas for this parasitoid correspond to areas in South, Central and small parts of North America, Sub Saharan Africa, Mediterranean basin, Asia, and Oceania. Regarding the climate change, it will lead to a small decrease in the suitable areas for *P. dignus* in South America, Africa, and Australia. On the other hand, the USA, the Mediterranean basin and North of Europe will become more suitable for this parasitoid (Fig. 5c, d).

Regarding the parasitoid *P. dignus,* the combination with *T. absoluta* projections for 2070 showed large areas under high risk of the pest infestation, especially in Europe, (Fig. 6d). Once again, countries such as the United Kingdom, the Netherlands, France, Germany, and Italy, will have large areas highly suitable for *T. absoluta,* but with low and moderate suitability for *P. dignus* (Fig. 6d). Algeria, Morocco, Egypt, China, New Zealand, Chile, Peru, and Colombia also possess few areas under high risk for *T. absoluta* with low and moderate suitability for *P. dignus* (Fig. 6d). Therefore, this parasitoid will have some restriction in some areas in this countries.

DISCUSSION

For the first time, a spatial distribution model was used to assess the impact of climate change on four important natural enemies (3 parasitoids and 1 predator) of the invasive pest *T. absoluta*. According to the validation statistic, all projections undertaken in this study performed properly ($AUC_{cv} \geq 0.85$), which highlight the model's reliability.

Overall, the mean annual temperature was the environmental variable that most contributed to all five species projections. This variable has been reported as one that most contributes to species distributions, especially at global scale studies (Galdino et al. 2016; Kumar et al. 2015; West et al. 2015). On average, the models projected suitable areas for the insects in localities with a mean annual temperature around 18 ºC. Especially for *T. absoluta,* this temperature differs from those reported as optimal for this pest, i.e., 30 ºC (Martins et al. 2016). This difference might be related with two aspects: (i) the model uses a series of 50 years of climatic data, and (ii) insect's thermal requirement essays usually are made using different constant temperatures under controlled laboratory conditions, therefore, the effect of fluctuations in temperature are not detected. Another important variable was the mean diurnal range in temperature (except *P. dinus*). Several studies have addressed the effect of variations in temperature on ectothermic organisms (BALE 1999; Liu et al. 1995; Vangansbeke et al. 2015); they state that variations in diurnal temperature might be beneficial to arthropods (increasing body size and oviposition, prey consumption, etc.), especially in lower temperature ranges (Vangansbeke et al. 2015).

Regarding climate change, in general, it is seen an increasing suitability for all insects studied near the poles and a decrease around the equator, the only exception was *S. japonicus,* which is predicted to increase its range in both hemispheres. MaxEnt projected suitable areas for *T. absoluta* in countries where the tomato cultivation is important and the pest has not reached yet, for example, China, the USA, Mexico, the Netherlands, the United Kingdom, and Germany (FAO 2017a). Therefore, the knowledge about the suitability of these areas for *T. absoluta'*s natural enemies is essential for the establishment of a solid biological control program for this invasive pest. The only natural enemy that will be able to cover most of the countries under high risk of *T. absoluta* invasion – except some areas in China – will be the predator *M. pygmaeus*. Therefore, in countries where this predator occurs naturally, practices to preserve and improve its development in open-field should be considered (e.g. pesticide selectivity, environment manipulation, etc.). Besides, this predator might be a good agent for a classical biological control program in countries where the pest might invade, for example, the USA and Mexico.

The ectoparasitoid *S. japonicus* is reported to be found naturally in areas affected by *T. absoluta* in Europe and some areas in Asia (Biondi et al. 2018). Our projections indicate that climate change will increase the suitable areas for this ectoparasitoid in all areas currently affected by the tomato pinworm. This information is extremely valuable, making *S. japonicus* an important candidate to be used in the biological control of *T. absoluta,* especially in case of invasion in China where conditions are highly suitable for both species, pest, and natural enemy. Besides, some areas in Mexico and large areas in the USA were projected as highly suitable for this ectoparasitoid. Therefore, in a scenario of an eventual invasion of *T. absoluta* in these countries, *S. japonicus* could also be a candidate to be imported. In the other hand, countries such as the Netherland, United Kingdom, and Germany, all with records of interception of *T. abslouta* in the past (EPPO 2013a; NEPPO 2014; NPPO 2009), will either have low or moderate suitability for *S. japonicus*. Therefore, the use of this natural enemy in the biological control of *T. absoluta* will be restricted to inoculative and inundative releases, which aim a temporary establishment (Eilenberg et al. 2001).

The same situation described applies to *N. formosa*. This parasitoid is reported in both native and invaded regions affected by the tomato pinworm (Biondi et al. 2018), and based on our projections, climate change will lead to an increase in the suitable areas for this natural enemy, especially in Europe, keeping this parasitoid as important biological control agent of *T. absoluta* for most countries in this continent in the future. Similar to *S. japonicus*, in some areas in Portugal, the Netherlands, United Kingdom, and Germany, *N. formosa* will be restricted to be used only in temporary releases.

The endoparasitoid *P. dignus* has been reported as responsible for up to 40% of natural control of *T. absoluta* in South America (Luna et al. 2015; Nieves et al. 2015b). For this reason, in this study, we investigated the worldwide suitability for this natural enemy because of its potential use as a control agent of *T. absoluta* and its restricted distribution in the American continent. As can be seen, the currently suitable areas for *P. dignus* correspond mostly to the areas where *T. absoluta* has been reported. However, climate change will lead to a decrease of the suitable areas for this natural enemy. The only exception is a small increase in the Mediterranean basin and a shift westward in China. Therefore, based on our projections, this parasitoid will still be an important biological control agent in its native range, however, its use in other regions (e.g. some areas in Europe) will be only feasible for inundation and inoculation biological control in greenhouses.

Limitation of modelling approach and transferability

It is important to point out that the low suitability of some areas for all natural enemies studied does not make the biological control of *T. absoluta* unfeasible. It has to be clear that this study considers only climatic variables; therefore, in a controlled environment such as greenhouses, the use of these natural enemies will still be an important tool for pest management. Besides, climate change can affect natural enemies in a number of ways, for example, changing the synchrony between prey-predator, habitat distribution, affecting thermal/humidity responses, host quality, and crop management (Thomson et al. 2010). In this study, we focused only on the effect of climate change affecting the habitats suitability. Additionally, there are some uncertainties related to spatial distribution studies, and they might be associated mainly with future levels of greenhouse gas emissions, the magnitude by which the climate change projections will occur, models parameterization, and the currently available broad-scale climate data (Barry and Elith 2006; Taylor and Kumar 2012). Another important aspect is that insects are likely to evolve and adapt under climate changes (Hance et al. 2007; Thomson et al. 2010). However, these physiological requirements are plastic and through the acclimation and diapause/quiescence they might respond differently during the evolutionary course (Thomson et al. 2010).

Transferability is the concept of models' cross-applicability in space and time, and it receives special attention in correlative models. It is mainly affected by the prediction variables used in the study (e.g. direct and indirect predictor variables) (Randin et al. 2006). Direct predictors are more physiologically meaningful to the organism consequentially; they have more influence its distribution. Thus, in order to build a more transferable model as possible, in this study only direct predictors were used.

This study provides useful information of the spatial distribution of four natural enemies of *T. absoluta*. This knowledge is an essential part of the implementation of a complete biological control program for this invasive pest. Our models proved to be reliable with the current distribution of each insect studied. Thus, it enabled us to identify the suitable areas for the natural enemies of the tomato pinworm and make projections of the effect of climate change on these insects. Climate change will lead to an increase in the suitable areas for *T. absoluta,* especially in the North hemisphere. In this sense, countries such as China, the Netherlands, the United Kingdom, Germany, the

USA, and Mexico will be under risk of an invasion of *T. absoluta*. The increasing suitability for *T. absoluta* in open field in these countries will not be accompanied by some of the natural enemies. In the Netherlands, the United Kingdom, and Germany, the parasitoids (i.e. *N. formosa*, *S. japonicus*, and *P. dignus*) will be important biological control agents mainly for inoculation and inundation biological control. On the other hand, for *M. pygmaeus,* due to the high suitability for this predator in these countries, strategies to preserve and improve its development in open field should be considered. In case of eventual invasion of the tomato pinworm in the USA and Mexico, all natural enemies will be good candidates to be used for the biological control. In China, the predator *M. pygmaeus* and the parasitoid *P. dignus* will have restrictions in some areas. Therefore, the results generated in this research will be useful for the countries under risk of an invasion of *T. absoluta* and will allow them to increase vigilance and quarantine measures.

Table 1: Environmental variables considered in *T. absoluta* niche models, and average percent contribution of environmental variables in the *T. absoluta* distribution model; values were averaged across 10 replicate runs. General statistics were calculated using all occurrences (n = 150). (Min=minimum, Max=maximum, and SD = standard deviation).

Variable	Percent contribution	Permutation importance	Min.	Max.	Mean	SD
Temperature annual range (bio7; °C)	**46.5**	**8.4**	**10.6**	**44.6**	**24.1**	**7.1**
Annual mean temperature (bio1; °C)	**39.5**	**62**	**6.0**	**29.5**	**18.1**	**5.3**
Mean diurnal range in temperature (bio2; °C)	**6.2**	**16**	**5.4**	**17.1**	**10.8**	**2.5**
Precipitation of driest month (bio14; mm)	**4.4**	**6.2**	**0**	**257**	**21.9**	**29.7**
Precipitation seasonality (CV) (bio15)	**2.1**	**4.7**	**10**	**159**	**63.6**	**33.7**
Mean annual precipitation (bio12; mm)	**1.4**	**2.6**	**39**	**3808**	**905.7**	**607.6**
Isothermality (bio3)	-	-	26.0	87.0	47.8	16.6
Temperature seasonality (SD x 100) (bio4)	-	-	238.0	9247.0	4555.4	2516.4
Maximum temperature of warmest month (bio5; °C)	-	-	19.8	46.0	30.5	4.5
Minimum temperature of coldest month (bio6; °C)	-	-	-16.3	21.6	6.4	7.0
Mean temperature of wettest quarter (bio8; °C)	-	-	-5.6	31.2	17.3	6.7
Mean temperature of driest quarter (bio9; °C)	-	-	-1.0	37.7	19.2	7.7
Mean temperature of warmest quarter (bio10; °C)	-	-	14.4	35.7	23.8	3.9
Mean temperature of coldest quarter (bio11; °C)	-	-	-6.8	26.1	12.2	7.8
Precipitation of wettest month (bio13; mm)	-	-	10.0	732.	153.2	105.0
Precipitation of wettest quarter (bio16; mm)	-	-	17.0	1704.0	402.4	271.7
Precipitation of driest quarter (bio17; mm)	-	-	0.0	860.0	81.9	100.5
Precipitation of warmest quarter (bio18; mm)	-	-	0.0	1193.0	221.7	224.7
Precipitation of coldest quarter (bio19; mm)	-	-	0.0	1138.0	189.7	187.8

Bold font indicates variables in the final model. Source of data: WorldClim (http://www.worldclim.org/bioclim) (Hijmans et al. 2005).

Table 2: Summary of performance statistics of *T. absoluta* MaxEnt models. The best model is highlighted in bold.

Model Rank	**Variables**	**MaxEnt settings**		**OR**		**Test AUC$_{cv}$ (±SD)**
		Features	**RM**	**10%**	**0%**	
1	**bio1,bio2,bio7, bio12, bio14, bio15**	**LQP**	**1.0**	**0.12**	**0.0071**	**0.87 ± 0.03**
2	Same as above	LP	1.0	0.13	0.0071	0.84 ± 0.04
3	Same as above	LPH	1.0	0.15	0.0067	0.88 ± 0.029
4	Same as above	LH	1.0	0.15	0.0071	0.88 ± 0.032
5	Same as above	LQH	1.0	0.15	0.0071	0.88 ± 0.022
6	Same as above	LQT	1.0	0.18	0.0071	0.88 ± 0.022
7	Same as above	LTH	1.0	0.18	0.0071	0.88 ± 0.026
8	Same as above	LPT	1.0	0.19	0.0067	0.88 ± 0.029
9	Same as above	LQPTH	1.0	0.19	0.0067	0.88 ± 0.038
10	Same as above	LT	1.0	0.21	0.0133	0.88 ± 0.049

Note: Variables' full names (see Table 1). L, Q, P, T, and H are linear, quadratic, product, threshold and hinge features, respectively. RM is regularization multiplier, and SD is the standard deviation. OR is test omission rate. Test AUC$_{cv}$ is MaxEnt 10-fold cross-validation Area Under the ROC curve.

Table 3: Environmental variables considered in *Neochrysocharis formosa* niche models, and average percent contribution of environmental variables in the *N. formosa* distribution model; values were averaged across 10 replicate runs. General statistics were calculated using all occurrences (n = 61). (Min=minimum, Max=maximum, and SD = standard deviation).

Variable	Percent contribution	Permutation importance	Min.	Max.	Mean	SD
Annual mean temperature (bio1; °C)	**53**	**59.1**	**4.3**	**29.4**	**18.6**	**5.4**
Temperature annual range (bio7; °C)	**26.6**	**7**	**10.7**	**45.9**	**24.9**	**7.0**
Mean diurnal range in temperature (bio2; °C)	**12.5**	**26.8**	**6.4**	**17.1**	**10.5**	**2.3**
Precipitation of driest month (bio14; mm)	**6.6**	**5**	**0.0**	**150.0**	**17.9**	**25.1**
Precipitation seasonality (CV) (bio15)	**1**	**1.5**	**17.0**	**149.0**	**69.1**	**30.7**
Mean annual precipitation (bio12; mm)	**0.3**	**0.6**	**65.0**	**2985.0**	**1013.4**	**820.9**
Isothermality (bio3)	-	-	20.0	89.0	44.4	14.6
Temperature seasonality (SD x 100) (bio4)	-	-	309.0	12440.0	5010.9	2540.6
Maximum temperature of warmest month (bio5; °C)	-	-	22.8	43.4	31.3	4.1
Minimum temperature of coldest month (bio6; °C)	-	-	-16.6	21.2	6.5	7.6
Mean temperature of wettest quarter (bio8; °C)	-	-	5.6	32.7	17.4	7.7
Mean temperature of driest quarter (bio9; °C)	-	-	-9.9	33.5	20.4	8.2
Mean temperature of warmest quarter (bio10; °C)	-	-	17.3	33.5	24.8	3.8
Mean temperature of coldest quarter (bio11; °C)	-	-	-11.1	26.3	12.1	7.9
Precipitation of wettest month (bio13; mm)	-	-	15.0	728.0	191.8	178.8
Precipitation of wettest quarter (bio16; mm)	-	-	27.0	1831.0	500.6	468.7
Precipitation of driest quarter (bio17; mm)	-	-	0.0	514.0	71.9	88.0
Precipitation of warmest quarter (bio18; mm)	-	-	0.0	926.0	226.5	262.2
Precipitation of coldest quarter (bio19; mm)	-	-	0.0	852.0	211.3	196.4

Bold font indicates variables in the final model. Source of data: WorldClim (http://www.worldclim.org/bioclim) (Hijmans et al. 2005).

Table 4: Summary of performance statistics of *Neochrysocharis formosa* MaxEnt models. The best model is highlighted in bold.

Model Rank	Variables	MaxEnt settings		OR		Test AUC$_{cv}$ (±SD)
		Features	RM	10%	0%	
1	**bio1,bio2,bio7, bio12, bio14, bio15**	**LQ**	**1.0**	**0.12**	**0.0200**	**0.88 ± 0.06**
2	Same as above	LH	1.5	0.12	0.0367	0.88 ± 0.08
3	Same as above	LQH	1.0	0.13	0.0367	0.88 ± 0.05
4	Same as above	LQP	1.0	0.13	0.0367	0.86 ± 0.05
5	Same as above	LQPH	1.0	0.13	0.0367	0.88 ± 0.05
6	Same as above	LH	1.5	0.14	0.0333	0.88 ± 0.08
7	Same as above	LQ	1.5	0.14	0.0333	0.87 ± 0.08
8	Same as above	LPH	1.0	0.15	0.0400	0.88 ± 0.07
9	Same as above	LTH	1.0	0.17	0.0567	0.87 ± 0.08
10	Same as above	LPT	1.0	0.17	0.0767	0.86 ± 0.07
11	Same as above	LQPT	1.0	0.18	0.0700	0.86 ± 0.06
12	Same as above	LQT	1.0	0.20	0.0367	0.87 ± 0.05
13	Same as above	LQPTH	1.0	0.25	0.0400	0.87 ± 0.06

Note: Variables' full names (see Table 1). L, Q, P, T, and H are linear, quadratic, product, threshold and hinge features, respectively. RM is regularization multiplier, and SD is the standard deviation. OR is test omission rate. Test AUC$_{cv}$ is MaxEnt 10-fold cross-validation Area Under the ROC curve.

Table 5: Environmental variables considered in *Stenomesius japonicus* niche models, and average percent contribution of environmental variables in the *S. japonicus* distribution model; values were averaged across 10 replicate runs. General statistics were calculated using all occurrences (n = 37). (Min=minimum, Max=maximum, and SD = standard deviation).

Variable	Percent contribution	Permutation importance	Min.	Max.	Mean	SD
Annual mean temperature (bio1; °C)	**54.8**	**61**	**5.2**	**28.6**	**19.6**	**6.1**
Mean diurnal range in temperature (bio2; °C)	**27.8**	**23.7**	**7.6**	**17.0**	**10.1**	**2.2**
Temperature annual range (bio7; °C)	**11.7**	**11.4**	**11.4**	**43.2**	**26.8**	**8.1**
Precipitation of driest month (bio14; mm)	**3.7**	**2.5**	**0.0**	**70.0**	**24.8**	**21.3**
Mean annual precipitation (bio12; mm)	**1.6**	**1.1**	**9.0**	**2497.0**	**1184.3**	**639.1**
Precipitation seasonality (CV) (bio15)	**0.3**	**0.2**	**13.0**	**140.0**	**69.4**	**30.5**
Isothermality (bio3)	-	-	413.0	11342.0	5659.0	2923.4
Temperature seasonality (SD x 100) (bio4)	-	-	24.2	41.7	33.0	4.4
Maximum temperature of warmest month (bio5; °C)	-	-	-15.5	22.2	6.2	9.7
Minimum temperature of coldest month (bio6; °C)	-	-	11.4	43.2	26.8	8.1
Mean temperature of wettest quarter (bio8; °C)	-	-	9.0	29.6	22.6	5.5
Mean temperature of driest quarter (bio9; °C)	-	-	-8.6	31.9	16.0	10.9
Mean temperature of warmest quarter (bio10; °C)	-	-	17.9	33.4	26.6	3.7
Mean temperature of coldest quarter (bio11; °C)	-	-	-8.6	26.0	12.1	9.6
Precipitation of wettest month (bio13; mm)	-	-	3.0	580.0	224.9	123.6
Precipitation of wettest quarter (bio16; mm)	-	-	5.0	1349.0	578.8	319.1
Precipitation of driest quarter (bio17; mm)	-	-	0.0	259.0	90.1	73.1
Precipitation of warmest quarter (bio18; mm)	-	-	0.0	1073.0	408.6	290.0
Precipitation of coldest quarter (bio19; mm)	-	-	5.0	1349.0	154.5	218.8

Bold font indicates variables in the final model. Source of data: WorldClim (http://www.worldclim.org/bioclim) (Hijmans et al. 2005).

Table 6: Summary of performance statistics of *Stenomesius japonicus* MaxEnt models. The best model is highlighted in bold.

Model Rank	**Variables**	**MaxEnt settings**		**OR**		**Test AUC$_{cv}$ (±SD)**
		Features	**RM**	**10%**	**0%**	
1	**bio1,bio2,bio7, bio12, bio14, bio15**	**LQ**	**1.0**	**0.14**	**0.0333**	**0.88 ± 0.064**
2	Same as above	LPH	1.0	0.16	0.0250	0.88 ± 0.072
3	Same as above	LQH	2.0	0.19	0.0250	0.86 ± 0.071
4	Same as above	LQT	1.0	0.19	0.0333	0.86 ± 0.093
5	Same as above	LH	1.0	0.19	0.0583	0.87 ± 0.074
6	Same as above	LQH	1.0	0.20	0.0250	0.86 ± 0.081
7	Same as above	LH	2.0	0.23	0.0250	0.85 ± 0.070
8	Same as above	LQPT	1.0	0.23	0.0333	0.88 ± 0.049
9	Same as above	LQPH	1.0	0.23	0.0333	0.86 ± 0.112
10	Same as above	LQPTH	1.0	0.24	0.0250	0.86 ± 0.122
11	Same as above	LPT	1.0	0.26	0.0250	0.88 ± 0.085
12	Same as above	LTH	1.0	0.26	0.0583	0.85 ± 0.093

Note: Variables' full names (see Table 1). L, Q, P, T, and H are linear, quadratic, product, threshold and hinge features, respectively. RM is regularization multiplier, and SD is the standard deviation. OR is test omission rate. Test AUC$_{cv}$ is MaxEnt 10-fold cross-validation Area Under the ROC curve.

Table 7: Environmental variables considered in *Macrolophus pygmaeus* niche models, and average percent contribution of environmental variables in the *M. pygmaeus* distribution model; values were averaged across 10 replicate runs. General statistics were calculated using all occurrences (n = 26). (Min=minimum, Max=maximum, and SD = standard deviation).

Variable	Percent contribution	Permutation importance	Min.	Max.	Mean	SD
Annual mean temperature (bio1; °C)	**47.8**	**70.2**	**9.6**	**19.6**	**15.0**	**2.2**
Temperature annual range (bio7; °C)	**25.8**	**1.1**	**9.5**	**33.5**	**25.4**	**5.5**
Mean diurnal range in temperature (bio2; °C)	**11.7**	**19.7**	**7.0**	**12.0**	**9.3**	**1.7**
Mean annual precipitation (bio12; mm)	**8.9**	**2.2**	**301.0**	**2560.0**	**725.2**	**442.2**
Precipitation seasonality (CV) (bio15)	**4.2**	**4.8**	**14.0**	**85.0**	**43.1**	**17.6**
Precipitation of driest month (bio14; mm)	**1.5**	**2**	**0.0**	**128.0**	**22.6**	**26.5**
Isothermality (bio3)	-	-	30.0	84.0	37.6	10.7
Temperature seasonality (SD x 100) (bio4)	-	-	443.0	7332.0	5624.4	1499.7
Maximum temperature of warmest month (bio5; °C)	-	-	20.9	33.8	29.1	3.1
Minimum temperature of coldest month (bio6; °C)	-	-	-2.0	13.4	3.6	4.0
Mean temperature of wettest quarter (bio8; °C)	-	-	5.9	18.2	12.3	3.8
Mean temperature of driest quarter (bio9; °C)	-	-	2.6	26.0	20.0	6.4
Mean temperature of warmest quarter (bio10; °C)	-	-	15.9	26.0	22.4	2.3
Mean temperature of coldest quarter (bio11; °C)	-	-	2.6	17.4	8.1	3.6
Precipitation of wettest month (bio13; mm)	-	-	46.0	315.0	101.5	53.7
Precipitation of wettest quarter (bio16; mm)	-	-	115.0	896.0	270.1	154.1
Precipitation of driest quarter (bio17; mm)	-	-	3.0	425.0	91.1	85.3
Precipitation of warmest quarter (bio18; mm)	-	-	7.0	639.0	112.9	127.4
Precipitation of coldest quarter (bio19; mm)	-	-	86.0	578.0	215.5	114.6

Bold font indicates variables in the final model. Source of data: WorldClim (http://www.worldclim.org/bioclim) (Hijmans et al. 2005)

Table 8: Summary of performance statistics of *Macrolophus pygmaeus* MaxEnt models. The best model is highlighted in bold.

Model Rank	Variables	MaxEnt settings		OR		Test AUC_{cv} (±SD)
		Features	RM	10%	0%	
1	**bio1,bio2,bio7, bio12, bio14, bio15**	**LQ**	**1.5**	**0.15**	**0.1000**	**0.96 ± 0.062**
2	Same as above	LP	1.0	0.17	0.0333	0.94 ± 0.064
3	Same as above	LQ	1.0	0.17	0.0667	0.96 ± 0.058
4	Same as above	LQP	1.0	0.18	0.0833	0.94 ± 0.097
5	Same as above	LT	1.0	0.30	0.2500	0.97 ± 0.017
6	Same as above	LH	1.0	0.32	0.2667	0.97 ± 0.044
7	Same as above	LPT	1.0	0.33	0.1333	0.97 ± 0.036
8	Same as above	LQH	1.5	0.33	0.2833	0.95 ± 0.103
9	Same as above	LQPTH	1.0	0.37	0.2333	0.96 ± 0.073
10	Same as above	LQH	1.0	0.38	0.3000	0.95 ± 0.092

Note: Variables' full names (see Table 1). L, Q, P, T, and H are linear, quadratic, product, threshold and hinge features, respectively. RM is regularization multiplier, and SD is the standard deviation. OR is test omission rate. Test AUC_{cv} is MaxEnt 10-fold cross-validation Area Under the ROC curve.

Table 9: Environmental variables considered in *Pseudapanteles dignus* niche models, and average percent contribution of environmental variables in the *P. dignus* distribution model; values were averaged across 10 replicate runs. General statistics were calculated using all occurrences (n = 19). (Min=minimum, Max=maximum, and SD = standard deviation).

Variable	Percent contribution	Permutation importance	Min.	Max.	Mean	SD
Annual mean temperature (bio1; °C)	**67.6**	**36**	**14.1**	**26.5**	**20.2**	**3.8**
Temperature annual range (bio7; °C)	**16.8**	**45.9**	**10.2**	**31.5**	**21.6**	**6.3**
Precipitation of driest month (bio14; mm)	**12.6**	**12.1**	**0.0**	**254.0**	**34.2**	**59.0**
Mean annual precipitation (bio12; mm)	**2.9**	**5.4**	**173.0**	**4794.0**	**1085.5**	**1031.8**
Mean diurnal range in temperature (bio2; °C)	**0**	**0.5**	**5.5**	**16.7**	**11.8**	**3.0**
Precipitation seasonality (CV) (bio15)	**0**	**0**	**13.0**	**104.0**	**60.9**	**28.8**
Isothermality (bio3)	-	-	35.0	74.0	55.9	10.5
Temperature seasonality (SD x 100) (bio4)	-	-	773.0	5941.0	3382.8	1594.7
Maximum temperature of warmest month (bio5; °C)	-	-	25.8	35.0	31.1	2.4
Minimum temperature of coldest month (bio6; °C)	-	-	-0.7	21.3	9.5	6.5
Mean temperature of wettest quarter (bio8; °C)	-	-	11.9	27.2	22.0	5.1
Mean temperature of driest quarter (bio9; °C)	-	-	9.3	26.1	18.4	5.2
Mean temperature of warmest quarter (bio10; °C)	-	-	20.5	27.8	24.5	2.5
Mean temperature of coldest quarter (bio11; °C)	-	-	6.7	25.1	15.9	5.6
Precipitation of wettest month (bio13; mm)	-	-	24.0	569.0	166.9	130.8
Precipitation of wettest quarter (bio16; mm)	-	-	51.0	1504.0	445.7	342.6
Precipitation of driest quarter (bio17; mm)	-	-	6.0	1005.0	126.0	228.6
Precipitation of warmest quarter (bio18; mm)	-	-	11.0	1022.0	323.0	265.0
Precipitation of coldest quarter (bio19; mm)	-	-	9.0	1278.0	194.2	286.3

Bold font indicates variables in the final model. Source of data: WorldClim (http://www.worldclim.org/bioclim) (Hijmans et al. 2005).

Table 10: Summary of performance statistics of *Pseudapanteles dignus* MaxEnt models. The best model is highlighted in bold.

Model Rank	Variables	MaxEnt settings		OR		Test AUC$_{cv}$ (±SD)
		Features	RM	10%	0%	
1	**bio1,bio2,bio7, bio12, bio14, bio15**	**LPTH**	**1.0**	**0.10**	**0.1000**	**0.85 ± 0.097**
2	Same as above	LH	2.0	0.10	0.1000	0.85 ± 0.079
3	Same as above	LH	1.5	0.15	0.0500	0.86 ± 0.070
4	Same as above	LQ	1.0	0.15	0.1000	0.76 ± 0.123
5	Same as above	LQTH	1.0	0.20	0.1500	0.82 ± 0.136
6	Same as above	LH	1.0	0.25	0.0500	0.84 ± 0.069
7	Same as above	LTH	1.0	0.25	0.1000	0.86 ± 0.104
8	Same as above	LPH	1.0	0.25	0.1500	0.83 ± 0.110
9	Same as above	LQP	1.0	0.25	0.1500	0.74 ± 0.110
10	Same as above	LQPH	1.0	0.30	0.1000	0.81 ± 0.115
11	Same as above	LT	1.0	0.30	0.1000	0.80 ± 0.113
12	Same as above	LQH	1.0	0.35	0.1500	0.78 ± 0.203
13	Same as above	LPT	1.0	0.45	0.1000	0.76 ± 0.112

Note: Variables' full names (see Table 1). L, Q, P, T, and H are linear, quadratic, product, threshold and hinge features, respectively. RM is regularization multiplier, and SD is the standard deviation. OR is test omission rate. Test AUC$_{cv}$ is MaxEnt 10-fold cross-validation Area Under the ROC curve.

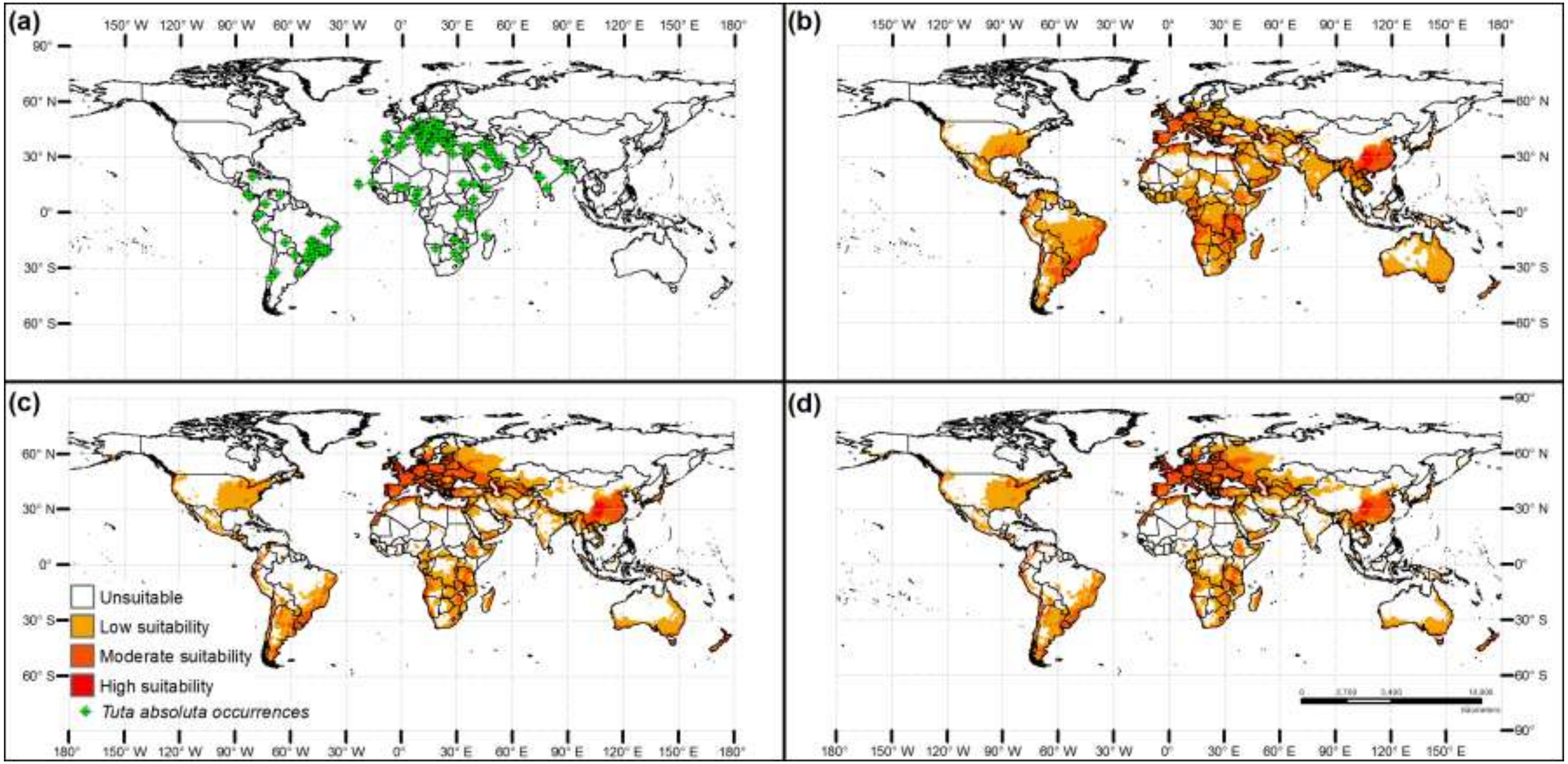

Figure 1: Current global distribution of *Tuta absoluta* in open field tomato crops (a), the potential distribution at the current time (b), and future projections for 2050 (c) and 2070 (d) using the MaxEnt model running the RCP 4.5 scenario.

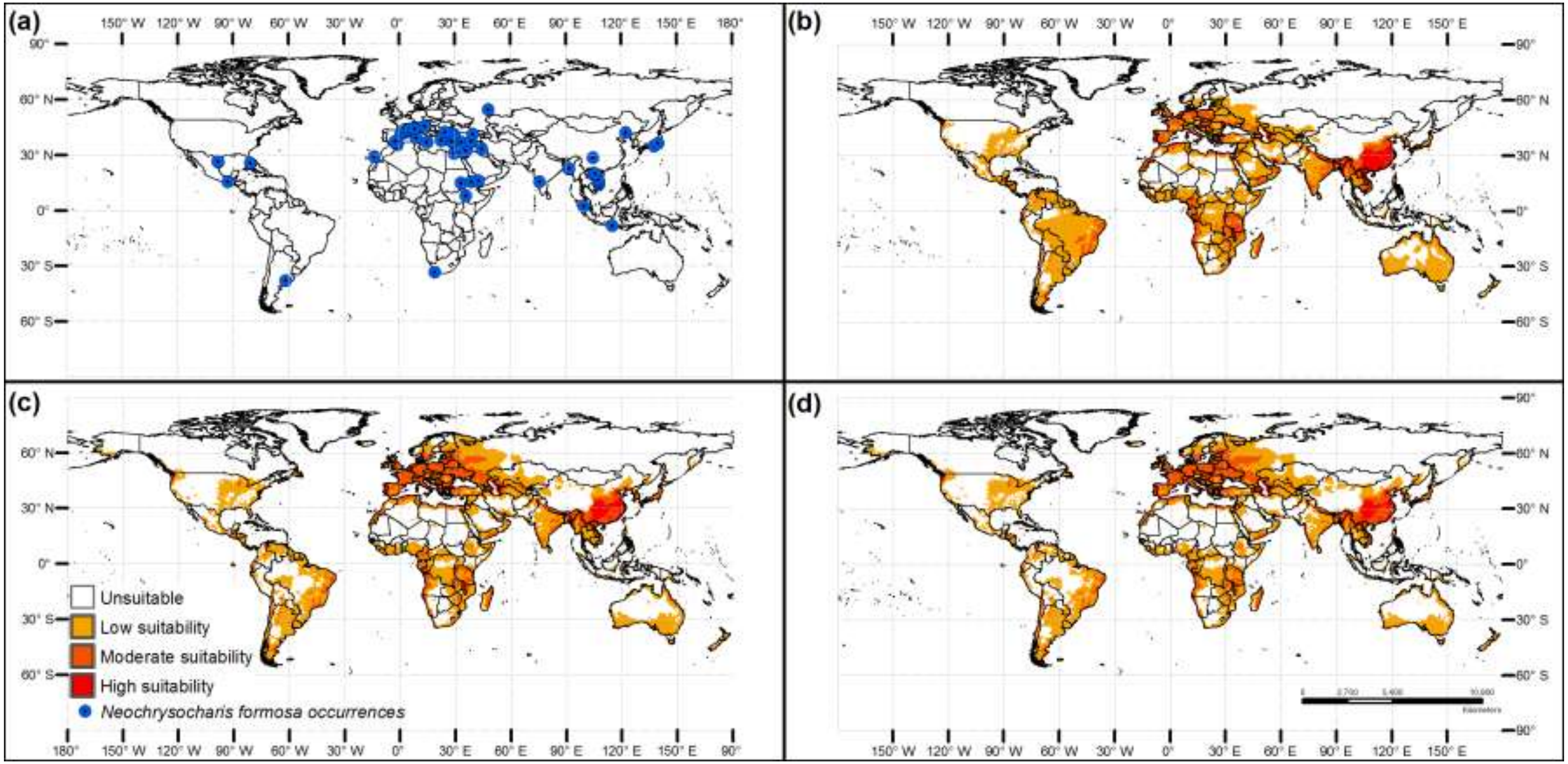

Figure 2: Current global distribution of *Neochrysocharis formosa* in open field (a), the potential distribution at the current time (b), and future projections for 2050 (c) and 2070 (d) using the MaxEnt model running the RCP 4.5 scenario.

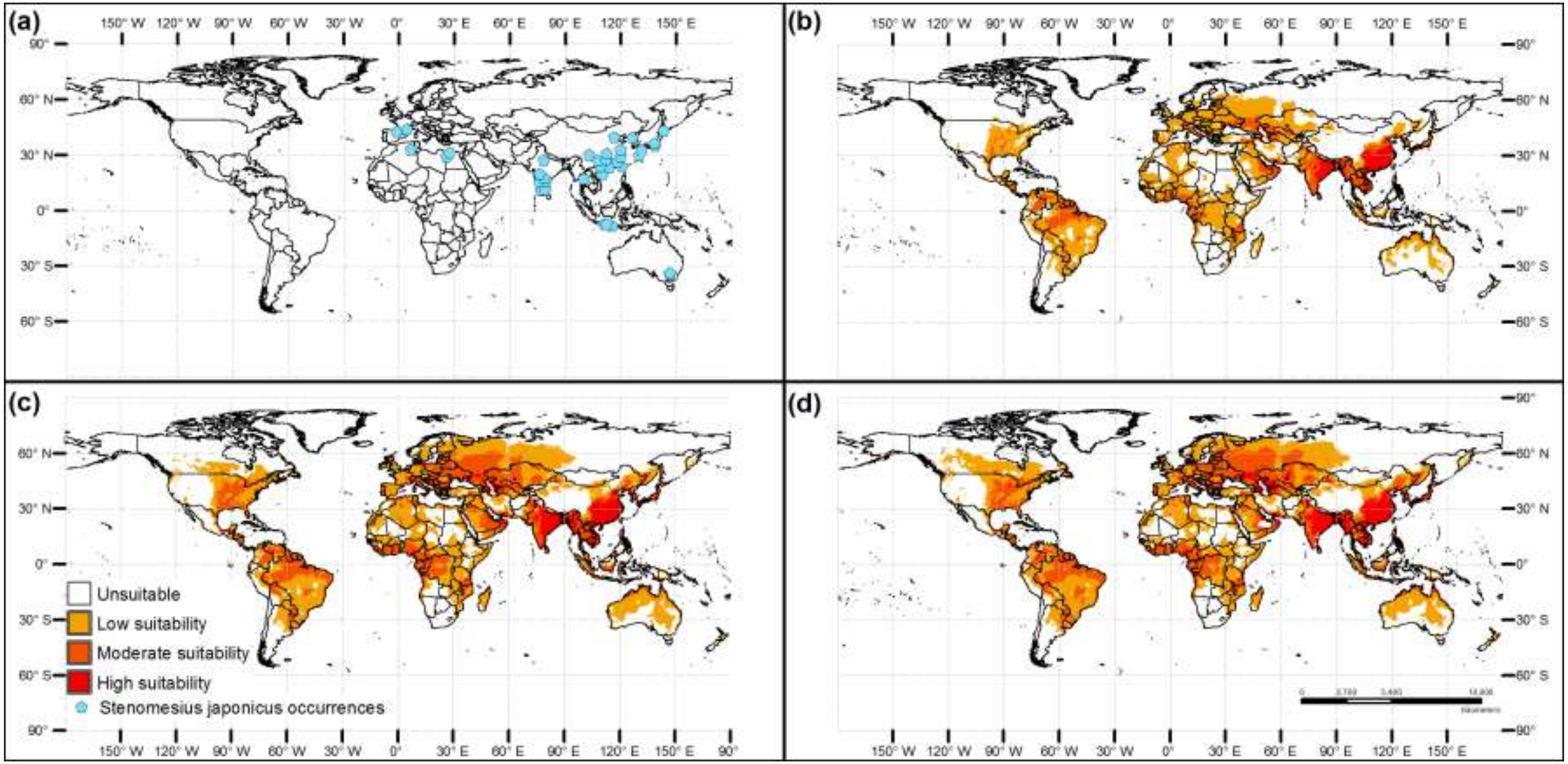

Figure 3: Current global distribution of *Stenomesius japonicus* in open field (a), the potential distribution at the current time (b), and future projections for 2050 (c) and 2070 (d) using the MaxEnt model running the RCP 4.5 scenario.

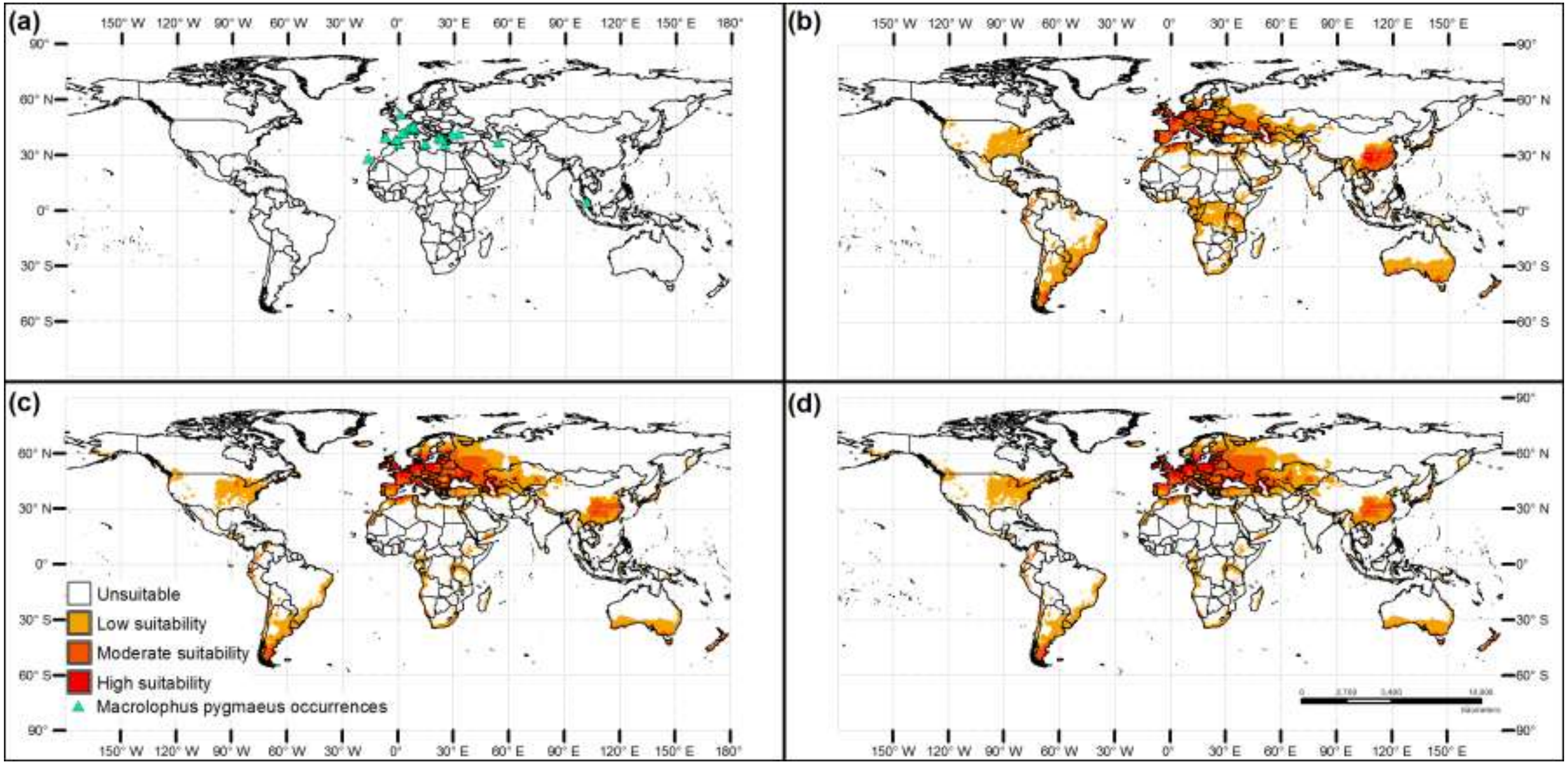

Figure 4: Current global distribution of *Macrolophus pygmaeus* in open field (a), the potential distribution at the current time (b), and future projections for 2050 (c) and 2070 (d) using the MaxEnt model running the RCP 4.5 scenario.

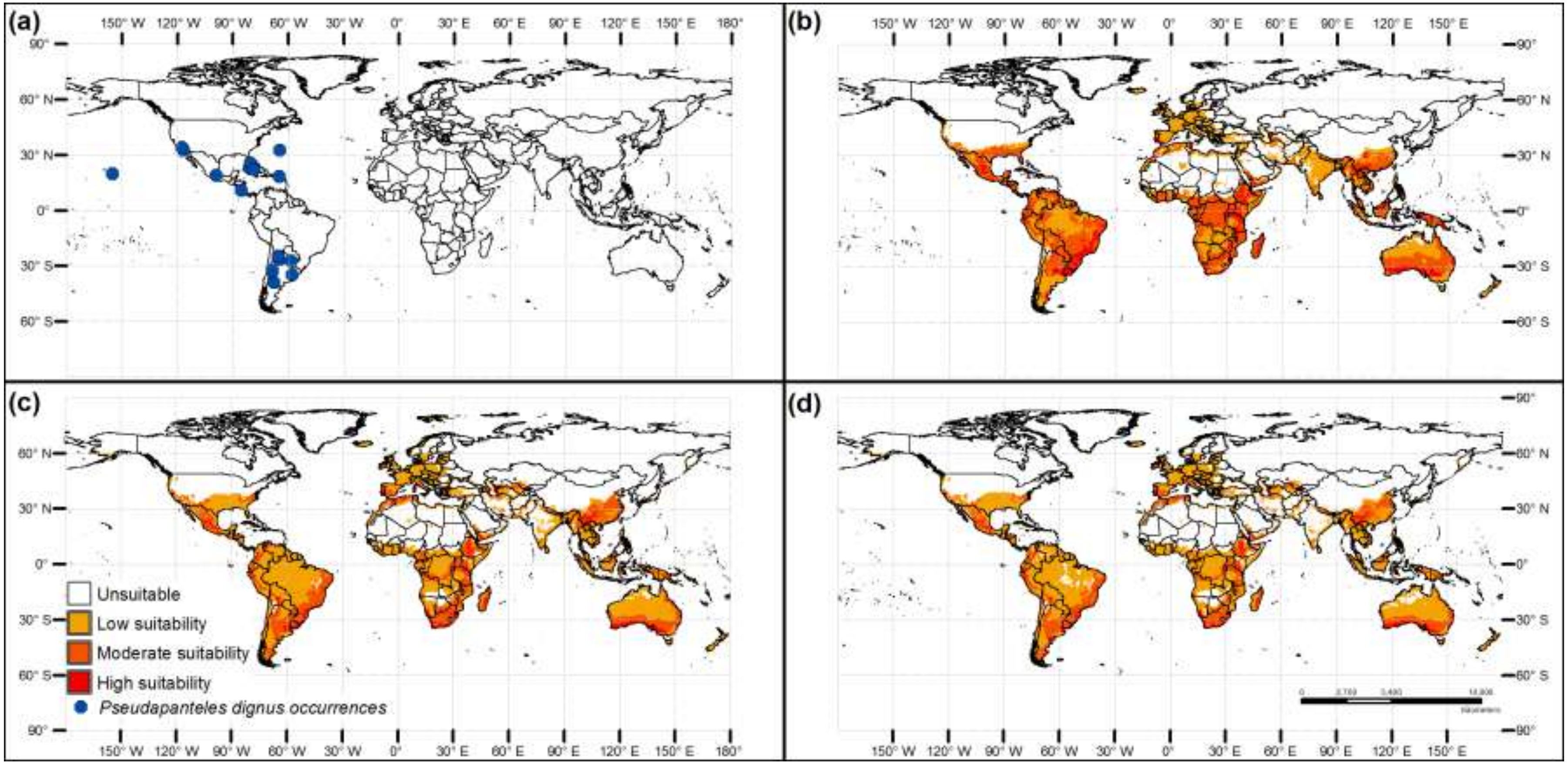

Figure 5: Current global distribution of *Pseudapanteles dignus* in open field (a), the potential distribution at the current time (b), and future projections for 2050 (c) and 2070 (d) using the MaxEnt model running the RCP 4.5 scenario.

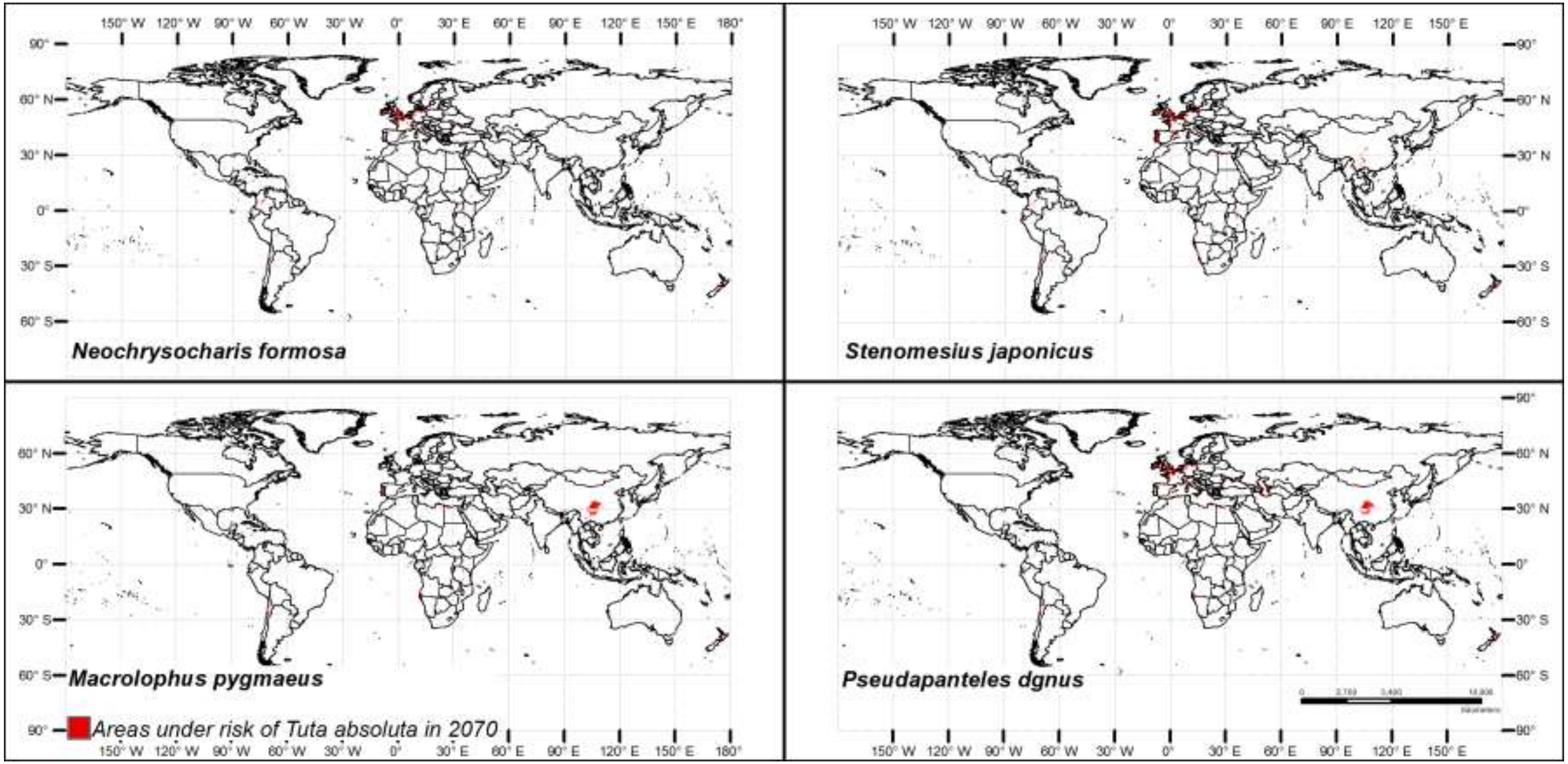

Figure 6: Agreement in the MaxEnt projection of optimal areas for *Tuta absoluta* and low and moderate for its natural enemies under HadGEM2_ES (GCM) running the RCP 4.5 for 2070. The areas marked in red are where *T. absoluta* projections are for highest suitability while that for the natural enemies is only low or moderate, making these areas at higher risk of invasion by *T. absoluta*.

REFERENCES

Aiello-Lammens ME, Boria RA, Radosavljevic A, Vilela B, Anderson RP (2015) spThin: an R package for spatial thinning of species occurrence records for use in ecological niche models Ecography 38:541-545 doi:10.1111/ecog.01132

Andrews T, Gregory JM, Webb MJ, Taylor KE (2012) Forcing, feedbacks and climate sensitivity in CMIP5 coupled atmosphere-ocean climate models Geophysical Research Letters 39:n/a-n/a doi:10.1029/2012GL051607

Bacci L (2006) Factors determining the attack of *Tuta absoluta* on tomato. Doctoral dissertation, Universidade Federal de Viçosa

Backer LD, Megido RC, Haubruge É, Verheggen FJ (2014) *Macrolophus pygmaeus* (Rambur) as an efficient predator of the tomato leafminer *Tuta absoluta* (Meyrick) in Europe. A review Biotechnol Agron Soc Environ 18:536-543

BALE B (1999) Comparison of development and growth of nettle-feeding larvae of Nymphalidae (Lepidoptera) under constant and alternating temperature regimes EJE 96:143-148

Barrientos RZ, Apablaza JH, Norero AS, Estay P (1998) Temperatura base y constante térmica de desarrollo de la polilla del tomate, *Tuta absoluta* (Lepidoptera: Gelechiidae) Ciencia e Investigación Agraria 25:133-137 doi:http://dx.doi.org/10.7764/rcia.v25i3.659.

Barrientos Z R, Apablaza H J, Norero S A, Estay P P (1998) Threshold temperature and thermal constant for the development of the South american tomato moth, *Tuta absoluta* (Lepidoptera: Gelechiidae) [1998] Ciencia e investigación agraria 25

Barry S, Elith J (2006) Error and uncertainty in habitat models Journal of Applied Ecology 43:413-423 doi:10.1111/j.1365-2664.2006.01136.x

Begon M, Townsend CR, Harper JL (2005) ECOLOGY: From individuals to ecosystems. 4th ed edn. BLACKWELL PUBLISHING, Malden, MA

Betancourt CM, I.B. S, Rodríguez JJ (1996) Influencia de la temperatura sobre la reproduccion y el desarrollo de *Scrobipalpuloides absoluta* (Meyrick) (Lepidoptera: Gelechiidae) Revista Brasileira de Biologia 56:661–670

Biondi A, Guedes RNC, Wan F-H, Desneux N (2018) Ecology, Worldwide Spread, and Management of the Invasive South American Tomato Pinworm, *Tuta absoluta*: Past, Present, and Future Annual Review of Entomology 63:null doi:10.1146/annurev-ento-031616-034933

Boria RA, Olson LE, Goodman SM, Anderson RP (2014) Spatial filtering to reduce sampling bias can improve the performance of ecological niche models Ecological Modelling 275:73-77 doi:https://doi.org/10.1016/j.ecolmodel.2013.12.012

Brown JL (2014) SDMtoolbox: a python-based GIS toolkit for landscape genetic, biogeographic and species distribution model analyses Methods in Ecology and Evolution 5:694-700 doi:10.1111/2041-210X.12200

Campos MR, Biondi A, Adiga A, Guedes RNC, Desneux N (2017) From the Western Palaearctic region to beyond: *Tuta absoluta* 10 years after invading Europe Journal of Pest Science 90:787-796 doi:10.1007/s10340-017-0867-7

Chailleux A, Desneux N, Arnó J, Gabarra R (2014) Biology of two key Palaearctic larval ectoparasitoids when parasitizing the invasive pest *Tuta absoluta* Journal of Pest Science 87:441-448 doi:10.1007/s10340-014-0557-7

Cook DC, Fraser RW, Paini DR, Warden AC, Lonsdale WM, De Barro PJ (2011) Biosecurity and yield improvement technologies are strategic complements in the fight against food insecurity PLoS ONE 6:e26084 doi:10.1371/journal.pone.0026084

Da Silva RS, Kumar L, Shabani F, Picanço MC (2017) Potential risk levels of invasive *Neoleucinodes elegantalis* (small tomato borer) in areas optimal for open-field *Solanum lycopersicum* (tomato) cultivation in the present and under predicted climate change Pest Management Science 73:616-627 doi:10.1002/ps.4344

Daly C (2006) Guidelines for assessing the suitability of spatial climate data sets International Journal of Climatology 26:707-721 doi:10.1002/joc.1322

Damos P, Savopoulou-Soultani M (2012) Temperature-driven models for insect development and vital thermal requirements Psyche 2012:13 doi:10.1155/2012/123405

Dehliz A, Guénaoui Y (2015) Natural Enemies of *Tuta absoluta* (Lepidoptera: Gelechiidae) in Oued Righ Region, An Arid Area of Algeria Academic Journal of Entomology 8:72-79 doi:10.5829/idosi.aje.2015.8.2.9491

Desneux N, Luna MG, Guillemaud T, Urbaneja A (2011) The invasive South American tomato pinworm, *Tuta absoluta*, continues to spread in Afro-Eurasia and beyond: the new threat to tomato world production Journal of Pest Science 84:403-408 doi:10.1007/s10340-011-0398-6

Desneux N et al. (2010) Biological invasion of European tomato crops by *Tuta absoluta*: ecology, geographic expansion and prospects for biological control Journal of Pest Science 83:197-215 doi:10.1007/s10340-010-0321-6

Dike VN, Shimizu MH, Diallo M, Lin Z, Nwofor OK, Chineke TC (2015) Modelling present and future African climate using CMIP5 scenarios in HadGEM2-ES International Journal of Climatology 35:1784-1799 doi:10.1002/joc.4084

Dormann CF et al. (2013) Collinearity: a review of methods to deal with it and a simulation study evaluating their performance Ecography 36:27-46 doi:10.1111/j.1600-0587.2012.07348.x

Dormann CF et al. (2012) Correlation and process in species distribution models: bridging a dichotomy Journal of Biogeography 39:2119-2131 doi:10.1111/j.1365-2699.2011.02659.x

Duan JJ, Bauer LS, Abell KJ, Ulyshen MD, Van Driesche RG (2015) Population dynamics of an invasive forest insect and associated natural enemies in the aftermath of invasion: implications for biological control Journal of Applied Ecology 52:1246-1254 doi:10.1111/1365-2664.12485

Eilenberg J, Hajek A, Lomer C (2001) Suggestions for unifying the terminology in biological control BioControl 46:387-400 doi:10.1023/a:1014193329979

EPPO (2013) First report of *Tuta absoluta* in Germany. European Plant Protection Organization. https://gd.eppo.int/taxon/GNORAB/distribution/DE. Accessed August 15th 2017

Essl F et al. (2011) Socioeconomic legacy yields an invasion debt Proceedings of the National Academy of Sciences 108:203-207 doi:10.1073/pnas.1011728108

FAO (2017) FAO Statistical Yearbook. Food and Agriculture Organization of the United Nations. http://www.fao.org/faostat/en/#data/QC/visualize. Accessed 08 of August 2017

Fielding AH, Bell JF (2002) A review of methods for the assessment of prediction errors in conservation presence/absence models Environmental Conservation 24:38-49 doi:undefined

Fridley JD, Sax DF (2014) The imbalance of nature: revisiting a Darwinian framework for invasion biology Global Ecology and Biogeography 23:1157-1166 doi:10.1111/geb.12221

Gadallah NS, Yefremova ZA, Yegorenkova EN, Soliman AM, El-Ghiet UMA, Edmardash YA, Edmardash YA (2015) A review of the family Eulophidae (Hymenoptera: Chalcidoidea) of Egypt, with thirty three new records Zootaxa 4058:15 doi:10.11646/zootaxa.4058.1.3

Galdino TVdS, Kumar S, Oliveira LSS, Alfenas AC, Neven LG, Al-Sadi AM, Picanço MC (2016) Mapping Global Potential Risk of Mango Sudden Decline Disease Caused by *Ceratocystis fimbriata* PLOS ONE 11:e0159450 doi:10.1371/journal.pone.0159450

Gontijo PC, Picanço MC, Pereira EJG, Martins JC, Chediak M, Guedes RNC (2013) Spatial and temporal variation in the control failure likelihood of the tomato leaf miner, *Tuta absoluta* Annals of Applied Biology 162:50-59 doi:10.1111/aab.12000

Guedes RNC, Picanço MC (2012) The tomato borer *Tuta absoluta* in South America: pest status, management and insecticide resistance EPPO Bulletin 42:211-216 doi:10.1111/epp.2557

Guillemaud T et al. (2015) The tomato borer, *Tuta absoluta*, invading the Mediterranean Basin, originates from a single introduction from Central Chile Scientific Reports 5:8371 doi:10.1038/srep08371

https://www.nature.com/articles/srep08371#supplementary-information

Hance T, Baaren Jv, Vernon P, Boivin G (2007) Impact of Extreme Temperatures on Parasitoids in a Climate Change Perspective Annual Review of Entomology 52:107-126 doi:10.1146/annurev.ento.52.110405.091333

Heimpel GE, Yang Y, Hill JD, Ragsdale DW (2013) Environmental Consequences of Invasive Species: Greenhouse Gas Emissions of Insecticide Use and the Role of Biological Control in Reducing Emissions PLOS ONE 8:e72293 doi:10.1371/journal.pone.0072293

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas International Journal of Climatology 25:1965-1978 doi:10.1002/joc.1276

IPCC (2014) Climate Change 2014: Synthesis Report. IPCC, Geneva, Switzerland

Jarnevich CS, Stohlgren TJ, Kumar S, Morisette JT, Holcombe TR (2015) Caveats for correlative species distribution modeling Ecological Informatics 29:6-15 doi:https://doi.org/10.1016/j.ecoinf.2015.06.007

Kearney M, Porter W (2009) Mechanistic niche modelling: combining physiological and spatial data to predict species' ranges Ecology Letters 12:334-350 doi:10.1111/j.1461-0248.2008.01277.x

Kolar CS, Lodge DM (2001) Progress in invasion biology: predicting invaders Trends in Ecology & Evolution 16:199-204 doi:http://dx.doi.org/10.1016/S0169-5347(01)02101-2

Kriticos DJ, Maywald G, Yonow T, Zurcher E, Herrmann N, Sutherst R (2015) CLIMEX Version 4: exploring the effects of climate on plants, animals and diseases CSIRO , Canberra:184

Kriticos DJ, Webber BL, Leriche A, Ota N, Macadam I, Bathols J, Scott JK (2012) CliMond: global high-resolution historical and future scenario climate surfaces for bioclimatic modelling Methods in Ecology and Evolution 3:53-64 doi:10.1111/j.2041-210X.2011.00134.x

Kumar S, Neven LG, Yee WL (2014) Evaluating correlative and mechanistic niche models for assessing the risk of pest establishment Ecosphere 5:1-23 doi:10.1890/ES14-00050.1

Kumar S, Neven LG, Zhu H, Zhang R (2015) Assessing the Global Risk of Establishment of *Cydia pomonella* (Lepidoptera: Tortricidae) using CLIMEX and MaxEnt Niche Models Journal of Economic Entomology 108:1708-1719 doi:10.1093/jee/tov166

Kumar S, Stohlgren TJ (2009) Maxent modeling for predicting suitable habitat for threatened and endangered tree *Canacomyrica monticola* in New Caledonia Journal of Ecology and The Natural Environment 1:094-098

Liu C, White M, Newell G (2013) Selecting thresholds for the prediction of species occurrence with presence-only data Journal of Biogeography 40:778-789 doi:10.1111/jbi.12058

Liu S-S, Zhang G-M, Zhu J (1995) Influence of Temperature Variations on Rate of Development in Insects: Analysis of Case Studies from Entomological Literature Annals of the Entomological Society of America 88:107-119 doi:10.1093/aesa/88.2.107

Lowry E et al. (2013) Biological invasions: a field synopsis, systematic review, and database of the literature Ecology and Evolution 3:182-196 doi:10.1002/ece3.431

Luna M, Wada V, La Salle J, Sánchez N (2011) *Neochrysocharis formosa* (Westwood) (Hymenoptera: Eulophidae), a newly recorded parasitoid of the tomato moth, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae), in Argentina Neotropical Entomology 40:412-414

Luna MG et al. (2015) Potential of Biological Control Agents Against *Tuta absoluta* (Lepidoptera: Gelechiidae): Current Knowledge in Argentina Florida Entomologist 98:489-494 doi:10.1653/024.098.0215

Marcano R (1995) Efecto de la temperatura sobre el desarrollo y la reproduccion de *Scrobipalpula absoluta* (Meyrick) (Lepidoptera: Gelechiidae) Boletín de Entomología Venezolana 10:69-75

Martins JC, Picanco MC, Bacci L, Guedes RNC, Santana PA, Jr., Ferreira DO, Chediak M (2016) Life table determination of thermal requirements of the tomato borer *Tuta absoluta* Journal of Pest Science 89:897-908 doi:10.1007/s10340-016-0729-8

Merow C, Smith MJ, Silander JA (2013) A practical guide to MaxEnt for modeling species' distributions: what it does, and why inputs and settings matter Ecography 36:1058-1069 doi:10.1111/j.1600-0587.2013.07872.x

Miranda MMM, Picanço M, Zanuncio JC, Guedes RNC (1998) Ecological life table of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) Biocontrol Science and Technology 8:597-606 doi:10.1080/09583159830117

NEPPO (2014) The current incidence of tomato borer, *Tuta absoluta*, in the uk. http://www.neppo.org/wp-content/uploads/2014/05/KevinGormanAgadir1.pdf. Accessed August, 15th 2017

Nieves EL, Pereyra PC, Luna MG, Medone P, Sánchez NE (2015) Laboratory Population Parameters and Field Impact of the Larval Endoparasitoid *Pseudapanteles dignus* (Hymenoptera: Braconidae) on its Host *Tuta absoluta* (Lepidoptera: Gelechiidae) in Tomato Crops in Argentina Journal of Economic Entomology 108:1553-1559 doi:doi.org/10.1093/jee/tov115

NPPO (2009) *Tuta absoluta* Povolny (Gelechiidae) – tomato leaf miner - in tomato packaging facility in The Netherlands. National Plant Protection Organization of the Netherlands. https://english.nvwa.nl/documents/chek/chek/chek/documents/pest-report-tuta-absoluta-in-the-netherlands-at-tomato-packaging-facility. Accessed August, 15th 2017

Owens HL et al. (2013) Constraints on interpretation of ecological niche models by limited environmental ranges on calibration areas Ecological Modelling 263:10-18 doi:https://doi.org/10.1016/j.ecolmodel.2013.04.011

Paini DR, Sheppard AW, Cook DC, De Barro PJ, Worner SP, Thomas MB (2016) Global threat to agriculture from invasive species Proceedings of the National Academy of Sciences 113:7575-7579 doi:10.1073/pnas.1602205113

Pereira EJG, Picanço MC, Bacci L, Crespo ALB, Guedes RNC (2007) Seasonal mortality factors of the coffee leafminer, *Leucoptera coffeella* Bulletin of Entomological Research 97:421-432 doi:10.1017/S0007485307005202

Peterson AT, Papeş M, Soberón J (2008) Rethinking receiver operating characteristic analysis applications in ecological niche modeling Ecological Modelling 213:63-72 doi:https://doi.org/10.1016/j.ecolmodel.2007.11.008

Phillips SJ, Anderson RP, Schapire RE (2006) Maximum entropy modeling of species geographic distributions Ecological Modelling 190:231-259 doi:https://doi.org/10.1016/j.ecolmodel.2005.03.026

R Development Team (2015) R: A Language and Environment for Statistical Computing, 3.2.2 edn. The R Foundation for Statistical Computing, Vienna, Austria. doi:http://www.R-project.org/

Santana PA, Jr., Kumar L, Silva RSD, Picanço MC (2018) Routes of dispersion of *Tuta absoluta* in the world from the past until present and future projection based on climate change Journal of Pest Science doi:(In progress)

Shabani F, Kumar L (2013) Risk levels of invasive *Fusarium oxysporum* f. sp. in areas suitable for date palm (*Phoenix dactylifera*) cultivation under various climate change projections PLoS ONE 8:e83404 doi:10.1371/journal.pone.0083404

Silva GA, Picanço MC, Bacci L, Crespo ALB, Rosado JF, Guedes RNC (2011) Control failure likelihood and spatial dependence of insecticide resistance in the tomato pinworm, *Tuta absoluta* Pest Management Science 67:913-920 doi:10.1002/ps.2131

Silva RS, Kumar L, Shabani F, Picanço MC (2016) Assessing the impact of global warming on worldwide open field tomato cultivation through CSIRO-Mk3·0 global climate model The Journal of Agricultural Science 155:407-420 doi:10.1017/S0021859616000654

Soberón J (2005) Interpretation of models of fundamental ecological niches and species' distributional areas. Biodiversity Informatics 2:1-10

Sutherst RW, Maywald GF (1985) A computerised system for matching climates in ecology Agriculture, Ecosystems & Environment 13:281-299 doi:http://dx.doi.org/10.1016/0167-8809(85)90016-7

Sutherst RW, Maywald GF, Kriticos DJ (2007) CLIMEX Version 3: User's Guide Melbourne: Hearne Scientific Software Pty Ltd

Taylor KE, Stouffer RJ, Meehl GA (2012) An Overview of CMIP5 and the Experiment Design Bulletin of the American Meteorological Society 93:485-498 doi:10.1175/bams-d-11-00094.1

Taylor S, Kumar L (2012) Sensitivity analysis of CLIMEX parameters in modelling potential distribution of *Lantana camara* L PLoS ONE 7:e40969 doi:10.1371/journal.pone.0040969

Thomson LJ, Macfadyen S, Hoffmann AA (2010) Predicting the effects of climate change on natural enemies of agricultural pests Biological Control 52:296-306 doi:https://doi.org/10.1016/j.biocontrol.2009.01.022

Tonnang HEZ, Mohamed SF, Khamis F, Ekesi S (2015) Identification and risk assessment for worldwide invasion and spread of *Tuta absoluta* with a focus on Sub-Saharan Africa: Implications for phytosanitary measures and management PLoS ONE 10:e0135283 doi:10.1371/journal.pone.0135283

Townsend Peterson A, Papeş M, Eaton M (2007) Transferability and model evaluation in ecological niche modeling: a comparison of GARP and Maxent Ecography 30:550-560 doi:10.1111/j.0906-7590.2007.05102.x

Urbaneja A, González-Cabrera J, Arnó J, Gabarra R (2012) Prospects for the biological control of *Tuta absoluta* in tomatoes of the Mediterranean basin Pest Management Science 68:1215-1222 doi:10.1002/ps.3344

van Vuuren DP, Carter TR (2014) Climate and socio-economic scenarios for climate change research and assessment: reconciling the new with the old Climatic Change 122:415-429 doi:10.1007/s10584-013-0974-2

Vangansbeke D, Nguyen DT, Audenaert J, Verhoeven R, Gobin B, Tirry L, De Clercq P (2015) Prey consumption by phytoseiid spider mite predators as affected by diurnal temperature variations BioControl 60:595-603 doi:10.1007/s10526-015-9677-0

Veloz SD (2009) Spatially autocorrelated sampling falsely inflates measures of accuracy for presence-only niche models Journal of Biogeography 36:2290-2299 doi:10.1111/j.1365-2699.2009.02174.x

Wang W, Lu S-L, Liu W-X, Cheng L-S, Zhang Y-B, Wan F-H (2014) Effects of Five Naturally Occurring Sugars on the Longevity, Oogenesis, and Nutrient Accumulation Pattern in Adult Females of the Synovigenic Parasitoid *Neochrysocharis formosa* (Hymenoptera: Eulophidae) Neotropical Entomology 43:564-573 doi:10.1007/s13744-014-0247-4

West AM, Kumar S, Wakie T, Brown CS, Stohlgren TJ, Laituri M, Bromberg J (2015) Using High-Resolution Future Climate Scenarios to Forecast Bromus tectorum Invasion in Rocky Mountain National Park PLOS ONE 10:e0117893 doi:10.1371/journal.pone.0117893

Zweig MH, Campbell G (1993) Receiver-operating characteristic (ROC) plots: a fundamental evaluation tool in clinical medicine Clinical Chemistry 39:561-577

Supplementary Material 2

Table S1: Worldwide occurrences of *Tuta absoluta* and its natural enemies, *Macrolophus pygmaeus*, *Neochrysocharis formosa*, *Pseudapanteles dignus*, and *Stenomesius japonicus* in open field.

Species	**Country**	**Latitude**	**Longitude**	**References**
Macrolophus pygmaeus	Algeria	35.98677	0.161996	(Boualem et al. 2012; Dehliz and Guénaoui 2015)
Macrolophus pygmaeus	France	43.80475	4.346267	(Biondi et al. 2013)
Macrolophus pygmaeus	France	43.90998	5.294053	(Biondi et al. 2013)
Macrolophus pygmaeus	Greece	39.696548	21.62943	(Lykouressis et al. 2008)
Macrolophus pygmaeus	Greece	39.342907	21.84687	(Lykouressis et al. 2008)
Macrolophus pygmaeus	Greece	38.407049	23.098712	(Lykouressis et al. 2008)
Macrolophus pygmaeus	Greece	35.410145	24.706931	(Lykouressis et al. 2008)
Macrolophus pygmaeus	Greece	38.452291	22.872037	(Lykouressis et al. 2008)
Macrolophus pygmaeus	Iran	36.730924	53.747832	(Backer et al. 2014a)
Macrolophus pygmaeus	Italy	44.047659	8.206135	(Ingegno et al. 2009)
Macrolophus pygmaeus	Italy	44.358027	8.52813	(Ingegno et al. 2009)
Macrolophus pygmaeus	Italy	45.041591	7.470738	(Ingegno et al. 2009)
Macrolophus pygmaeus	Italy	45.050766	7.522814	(Ingegno et al. 2009)
Macrolophus pygmaeus	Malaysia	4.481557	101.378374	(Sanchez et al. 2012)
Macrolophus pygmaeus	Malta	36.043803	14.255646	(Carapezza and Mifsud 2015)
Macrolophus pygmaeus	Portugal	39.416169	-7.460379	(Sanchez et al. 2012)
Macrolophus pygmaeus	Portugal	39.296257	-7.442161	(Sanchez et al. 2012)

Macrolophus pygmaeus	Spain	28.037995	-16.639907	(Gabarra et al. 2014; Jauset et al. 2015)
Macrolophus pygmaeus	Spain	41.562057	2.406487	(Gabarra et al. 2014; Jauset et al. 2015)
Macrolophus pygmaeus	Spain	38.060317	-1.935936	(Gabarra et al. 2014; Jauset et al. 2015)
Macrolophus pygmaeus	Spain	38.194871	-1.891041	(Gabarra et al. 2014; Jauset et al. 2015)
Macrolophus pygmaeus	Spain	38.185517	-1.722938	(Gabarra et al. 2014; Jauset et al. 2015)
Macrolophus pygmaeus	Spain	41.590188	1.515263	(Gabarra et al. 2014; Jauset et al. 2015)
Macrolophus pygmaeus	Turkey	41.42748	32.100225	(Sanchez et al. 2012)
Macrolophus pygmaeus	Turkey	41.059381	28.617147	(Sanchez et al. 2012)
Macrolophus pygmaeus	United Kingdom	51.912537	0.883238	(EPPO 2018)
Neochrysocharis formosa	Algeria	35.319845	-1.222995	(Dehliz and Guénaoui 2015)
Neochrysocharis formosa	Argentina	-38.064312	-61.661945	(Luna et al. 2011; Urbaneja et al. 2012)
Neochrysocharis formosa	Bangladesh	22.341119	91.809932	(Mazumdar and Bhuiya 2016)
Neochrysocharis formosa	Bangladesh	22.50875	91.80907	(Mazumdar and Bhuiya 2016)
Neochrysocharis formosa	Bulgaria	42.162457	24.691863	(Deleva et al. 2016)
Neochrysocharis formosa	Canary Islands	29.04872	-13.567908	(Báez and Askew 1999)
Neochrysocharis formosa	China	41.938899	122.530955	(Wang et al. 2014)
Neochrysocharis formosa	China	28.419297	104.717333	(Wang et al. 2014)
Neochrysocharis formosa	Egypt	30.835537	29.633832	(Doğanlar and Elsayed 2015)
Neochrysocharis formosa	Eritrea	15.331068	39.065769	(Silvestri 1914)
Neochrysocharis formosa	Eritrea	15.479301	38.918837	(Silvestri 1914)

Neochrysocharis formosa	Ethiopia	7.849092	36.079216	(Abate 1991)
Neochrysocharis formosa	France	43.57805	3.255002	(Biondi et al. 2013)
Neochrysocharis formosa	France	43.586521	5.312412	(Biondi et al. 2013)
Neochrysocharis formosa	France	43.954521	6.043616	(Biondi et al. 2013)
Neochrysocharis formosa	Greece	37.634887	22.743942	(Tsagkarakis et al. 2013a; Tsagkarakis et al. 2013b)
Neochrysocharis formosa	India	15.315749	75.713552	(Ballal et al. 2016)
Neochrysocharis formosa	Indonesia	-8.249697	115.134852	(Sunari et al. 2016)
Neochrysocharis formosa	Indonesia	2.12069	99.814262	(Sunari et al. 2016)
Neochrysocharis formosa	Iraq	33.223119	44.476353	(Rassoul and Saffar 2014)
Neochrysocharis formosa	Italy	36.685205	15.121643	(Ferracini et al. 2012)
Neochrysocharis formosa	Italy	36.730524	14.73555	(Ferracini et al. 2012)
Neochrysocharis formosa	Italy	39.017234	8.993015	(Ferracini et al. 2012)
Neochrysocharis formosa	Italy	43.860567	7.841733	(Ferracini et al. 2012)
Neochrysocharis formosa	Italy	44.092158	8.205235	(Ferracini et al. 2012)
Neochrysocharis formosa	Japan	34.820005	137.711187	(蔡 and 西東 2011)
Neochrysocharis formosa	Japan	36.086856	140.055188	(蔡 and 西東 2011)
Neochrysocharis formosa	Jordan	31.048427	35.486962	(Ghabeish and Allawi 2001)
Neochrysocharis formosa	Jordan	31.760162	35.818321	(Ghabeish and Allawi 2001)
Neochrysocharis formosa	Jordan	31.843536	35.90097	(Ghabeish and Allawi 2001)

Neochrysocharis formosa	Jordan	32.087158	35.847994	(Ghabeish and Allawi 2001)
Neochrysocharis formosa	Jordan	32.265663	35.893286	(Ghabeish and Allawi 2001)
Neochrysocharis formosa	Mexico	15.307458	-92.716533	(Insectoid 2018)
Neochrysocharis formosa	Russia	54.351594	48.224913	(Yefremova et al. 2013)
Neochrysocharis formosa	Slovenia	45.520684	13.764164	(Trdan et al. 2013)
Neochrysocharis formosa	South Africa	-33.650842	19.024822	(CABI 2017)
Neochrysocharis formosa	Spain	36.85746	-2.411659	(Gabarra et al. 2014; Urbaneja et al. 2012)
Neochrysocharis formosa	Spain	36.953329	-2.092608	(Gabarra et al. 2014; Urbaneja et al. 2012)
Neochrysocharis formosa	Spain	40.677874	0.58809	(Gabarra et al. 2014; Urbaneja et al. 2012)
Neochrysocharis formosa	Spain	42.042663	3.170776	(Gabarra et al. 2014; Urbaneja et al. 2012)
Neochrysocharis formosa	Sudan	14.872687	33.358042	(Ghoneim 2014; Insectoid 2018)
Neochrysocharis formosa	Turkey	36.634462	33.625243	(Cıkman et al. 2008)
Neochrysocharis formosa	Turkey	36.764693	28.791428	(Cıkman et al. 2008)
Neochrysocharis formosa	Turkey	36.964351	28.685036	(Cıkman et al. 2008)
Neochrysocharis formosa	Turkey	37.131816	38.91228	(Cıkman et al. 2008)
Neochrysocharis formosa	Turkey	37.144979	28.288233	(Cıkman et al. 2008)
Neochrysocharis formosa	Turkey	40.158803	26.436848	(Cıkman et al. 2008)
Neochrysocharis formosa	Turkey	40.854804	29.866792	(Cıkman et al. 2008)
Neochrysocharis formosa	Turkey	40.983645	39.708647	(Cıkman et al. 2008)
Neochrysocharis formosa	Turkey	41.735981	27.203491	(Cıkman et al. 2008)

Neochrysocharis formosa	USA	25.43135	-80.515081	(Hernández et al. 2011)
Neochrysocharis formosa	USA	26.173019	-97.94074	(Hernández et al. 2011)
Neochrysocharis formosa	USA	26.365168	-98.226061	(Hernández et al. 2011)
Neochrysocharis formosa	Vietnam	13.949184	107.986424	(Tran 2009)
Neochrysocharis formosa	Vietnam	14.655455	107.832478	(Tran 2009)
Neochrysocharis formosa	Vietnam	15.537805	108.019796	(Tran 2009)
Neochrysocharis formosa	Vietnam	16.455667	107.644203	(Tran 2009)
Neochrysocharis formosa	Vietnam	19.234405	104.924339	(Tran 2009)
Neochrysocharis formosa	Vietnam	19.813432	105.804932	(Tran 2009)
Neochrysocharis formosa	Yemen	16.018621	42.987405	(Yefremova 2007)
Pseudapanteles dignus	Argentina	-35.034629	-57.983574	(Luna et al. 2015; Nieves et al. 2015a)
Pseudapanteles dignus	Argentina	-38.952892	-67.962506	(Luna et al. 2015; Nieves et al. 2015a)
Pseudapanteles dignus	Argentina	-26.83405	-65.132134	(Luna et al. 2015; Nieves et al. 2015a)
Pseudapanteles dignus	Argentina	-27.563994	-58.772985	(Luna et al. 2015; Nieves et al. 2015a)
Pseudapanteles dignus	Argentina	-24.826511	-65.459915	(Luna et al. 2015; Nieves et al. 2015a)
Pseudapanteles dignus	Argentina	-32.881463	-68.717864	(Luna et al. 2015; Nieves et al. 2015a)
Pseudapanteles dignus	Argentina	-32.709708	-68.653205	(Luna et al. 2015; Nieves et al. 2015a)
Pseudapanteles dignus	Bermuda	32.309439	-64.751795	(Fernandez-Triana et al. 2014)
Pseudapanteles dignus	Costa Rica	10.601903	-85.451605	(Fernandez-Triana et al. 2014)
Pseudapanteles dignus	Cuba	22.801653	-81.224574	(Sierra-Peña et al. 2012)

Pseudapanteles dignus	Cuba	21.942844	-78.728821	(Sierra-Peña et al. 2012)
Pseudapanteles dignus	Mexico	18.880766	-99.037551	(Fernandez-Triana et al. 2014)
Pseudapanteles dignus	United States	19.611415	-155.082994	(Fernandez-Triana et al. 2014)
Pseudapanteles dignus	United States	33.736803	-117.736458	(Fernandez-Triana et al. 2014)
Pseudapanteles dignus	United States	32.564445	-116.904573	(Fernandez-Triana et al. 2014)
Pseudapanteles dignus	United States	33.507283	-117.690508	(Fernandez-Triana et al. 2014)
Pseudapanteles dignus	United States	25.511532	-80.528061	(Fernandez-Triana et al. 2014)
Pseudapanteles dignus	Virgin Islands	18.33744	-64.893788	(Fernandez-Triana et al. 2014)
Stenomesius japonicus	Algeria	33.122291	6.098289	(Dehliz and Guénaoui 2015)
Stenomesius japonicus	Australia	-34.573296	146.386508	(James and Stevens 1992)
Stenomesius japonicus	Australia	-33.855854	146.28797	(James and Stevens 1992)
Stenomesius japonicus	China	39.57739	116.387174	(Zhu and Huang 2002)
Stenomesius japonicus	China	33.136833	119.776101	(Zhu and Huang 2002)
Stenomesius japonicus	China	29.1391	119.787047	(Zhu and Huang 2002)
Stenomesius japonicus	China	26.482498	117.943766	(Zhu and Huang 2002)
Stenomesius japonicus	China	30.737118	112.236185	(Zhu and Huang 2002)
Stenomesius japonicus	China	27.625483	111.856811	(Zhu and Huang 2002)
Stenomesius japonicus	China	23.384065	113.761632	(Zhu and Huang 2002)
Stenomesius japonicus	China	23.720302	108.818462	(Zhu and Huang 2002)
Stenomesius japonicus	China	23.699495	120.502603	(Zhu and Huang 2002)

Stenomesius japonicus	China	19.569876	109.944043	(Zhu and Huang 2002)
Stenomesius japonicus	China	30.260865	102.808272	(Zhu and Huang 2002)
Stenomesius japonicus	China	26.839376	107.293425	(Zhu and Huang 2002)
Stenomesius japonicus	Egypt	31.348803	27.316578	(Gadallah et al. 2015)
Stenomesius japonicus	Egypt	29.206331	25.529299	(Gadallah et al. 2015)
Stenomesius japonicus	France	43.948168	4.141925	(Biondi et al. 2013)
Stenomesius japonicus	India	10.749866	76.619092	(Hayat et al. 2005; Lakshmi et al. 2016)
Stenomesius japonicus	India	17.296791	78.498622	(Hayat et al. 2005; Lakshmi et al. 2016)
Stenomesius japonicus	India	15.317898	75.713694	(Hayat et al. 2005; Lakshmi et al. 2016)
Stenomesius japonicus	India	15.912475	79.742282	(Hayat et al. 2005; Lakshmi et al. 2016)
Stenomesius japonicus	India	19.75239	75.714973	(Hayat et al. 2005; Lakshmi et al. 2016)
Stenomesius japonicus	India	11.127295	78.657704	(Hayat et al. 2005; Lakshmi et al. 2016)
Stenomesius japonicus	India	27.175676	78.081746	(Hayat et al. 2005; Lakshmi et al. 2016)
Stenomesius japonicus	Indonesia	-7.618545	110.741425	(Ubaidillah 2007)
Stenomesius japonicus	Indonesia	-7.610171	112.316577	(Ubaidillah 2007)
Stenomesius japonicus	Indonesia	-8.414331	115.200519	(Ubaidillah 2007)
Stenomesius japonicus	Japan	34.984163	138.440826	(Kamijo 1976)
Stenomesius japonicus	Japan	43.154537	142.929027	(Kamijo 1976)
Stenomesius japonicus	Japan	36.073212	138.017092	(Kamijo 1976)
Stenomesius japonicus	Japan	32.640592	130.952469	(Kamijo 1976)

Stenomesius japonicus	Japan	29.655281	129.720659	(Kamijo 1976)
Stenomesius japonicus	North Korea	39.364376	126.134248	(Kamijo 1979)
Stenomesius japonicus	Spain	42.587066	-1.327186	(Chailleux et al. 2014; Gabarra et al. 2014)
Stenomesius japonicus	Thailand	17.184174	99.876458	(Thailand 2017)
Tuta absoluta	Afghanistan	34.52376	65.310373	(Hossain et al. 2016)
Tuta absoluta	Albania	41.511384	19.625226	(Russell-IPM 2009a)
Tuta absoluta	Algeria	36.001108	0.171081	(Boualem et al. 2012)
Tuta absoluta	Argentina	-32.88627	-68.7343	(Bahamondes and Mallea 1969)
Tuta absoluta	Bangladesh	23.14429	89.21201	(Hossain et al. 2016)
Tuta absoluta	Bangladesh	23.442542	91.197407	(Hossain et al. 2016)
Tuta absoluta	Bolivia	-16.290154	-63.588653	(Moore 1983)
Tuta absoluta	Bosnia and Herzegovina	44.904005	17.309419	(Đurić et al. 2012)
Tuta absoluta	Bosnia and Herzegovina	42.955944	18.078751	(Đurić et al. 2012)
Tuta absoluta	Bosnia and Herzegovina	42.701874	18.341813	(Đurić et al. 2012)
Tuta absoluta	Bosnia and Herzegovina	44.753851	19.245182	(Đurić et al. 2012)
Tuta absoluta	Bosnia and Herzegovina	44.779011	17.175318	(Đurić et al. 2012)
Tuta absoluta	Botswana	-21.947314	28.427295	(BOPA 2016)
Tuta absoluta	Brazil	-24.500418	-48.849221	(Gontijo et al. 2013)
Tuta absoluta	Brazil	-18.736884	-47.96103	(Gontijo et al. 2013)
Tuta absoluta	Brazil	-15.893205	-47.548611	(Gontijo et al. 2013)

Tuta absoluta	Brazil	-17.51816	-44.944898	(Gontijo et al. 2013)
Tuta absoluta	Brazil	-26.785598	-51.04855	(Gontijo et al. 2013)
Tuta absoluta	Brazil	-20.84322	-42.793801	(Gontijo et al. 2013)
Tuta absoluta	Brazil	-16.33427	-48.877758	(Gontijo et al. 2013)
Tuta absoluta	Brazil	-16.003734	-49.932884	(Gontijo et al. 2013)
Tuta absoluta	Brazil	-23.333917	-51.094976	(Gontijo et al. 2013)
Tuta absoluta	Brazil	-23.789674	-51.307491	(Gontijo et al. 2013)
Tuta absoluta	Brazil	-16.26239	-49.219963	(Gontijo et al. 2013)
Tuta absoluta	Brazil	-22.411125	-43.431317	(Gontijo et al. 2013)
Tuta absoluta	Brazil	-22.742477	-47.109185	(Gontijo et al. 2013)
Tuta absoluta	Brazil	-19.936828	-40.598447	(Gontijo et al. 2013)
Tuta absoluta	Brazil	-21.636845	-41.048443	(Gontijo et al. 2013)
Tuta absoluta	Brazil	-22.831676	-47.299374	(Gontijo et al. 2013)
Tuta absoluta	Brazil	-18.884244	-48.347803	(Gontijo et al. 2013)
Tuta absoluta	Brazil	-20.317366	-41.124843	(Gontijo et al. 2013)
Tuta absoluta	Brazil	-20.768015	-42.869794	(Gontijo et al. 2013)
Tuta absoluta	Brazil	-20.361158	-49.928986	(Gontijo et al. 2013)
Tuta absoluta	Brazil	-9.342407	-40.543664	(Gontijo et al. 2013)
Tuta absoluta	Brazil	-8.345833	-35.759604	(Gontijo et al. 2013)
Tuta absoluta	Bulgaria	42.255912	24.950736	(Karadjova et al. 2013)

Tuta absoluta	Bulgaria	42.24408	24.26269	(Karadjova et al. 2013)
Tuta absoluta	Burkina Faso	13.588415	-2.410885	(Son et al. 2017)
Tuta absoluta	Cape Verde	14.91674	-23.546943	(MDR 2013)
Tuta absoluta	Cayman Island	19.312323	-81.21201	(USDA 2011)
Tuta absoluta	Chile	-35.480911	-71.503646	(Vargas 1970)
Tuta absoluta	Colombia	4.590603	-74.271125	(Garcia 1989)
Tuta absoluta	Costa Rica	9.859778	-83.884164	(FAO 2014)
Tuta absoluta	Cyprus	35.127642	33.43022	(Mladen Šimala et al. 2011)
Tuta absoluta	Czech Republic	49.486414	17.086172	(NEPPO 2011)
Tuta absoluta	Ecuador	-1.831239	-77.962445	(Schotman 1989)
Tuta absoluta	Egypt	31.307355	27.294672	(Moussa et al. 2013)
Tuta absoluta	Eritrea	15.275616	38.918617	(Tonnang et al. 2015)
Tuta absoluta	Ethiopia	7.123198	38.53438	(OIRED 2014)
Tuta absoluta	France	42.053265	8.993548	(Trottin-Caudal et al. 2012)
Tuta absoluta	France	45.193537	5.42955	(Trottin-Caudal et al. 2012)
Tuta absoluta	France	43.578781	3.25981	(Trottin-Caudal et al. 2012)
Tuta absoluta	Germany	48.665453	9.349663	(EPPO 2013a)
Tuta absoluta	Greece	35.298198	24.820401	(Roditakis et al. 2010)
Tuta absoluta	Greece	37.499724	22.375024	(Roditakis et al. 2010)
Tuta absoluta	Greece	38.349379	21.521738	(Roditakis et al. 2010)

Tuta absoluta	Hungary	46.90964	19.924573	(János and Imre 2014)
Tuta absoluta	Hungary	46.689568	19.866425	(János and Imre 2014)
Tuta absoluta	India	18.543357	73.846529	(Kalleshwaraswamy et al. 2015)
Tuta absoluta	India	19.092404	74.727779	(Kalleshwaraswamy et al. 2015)
Tuta absoluta	India	13.137747	78.146667	(Kalleshwaraswamy et al. 2015)
Tuta absoluta	Iran	37.501905	45.033012	(Baniameri and Cheraghian 2012)
Tuta absoluta	Iran	35.928326	47.121305	(Baniameri and Cheraghian 2012)
Tuta absoluta	Iran	33.143412	47.383226	(Baniameri and Cheraghian 2012)
Tuta absoluta	Iran	33.397896	46.581891	(Baniameri and Cheraghian 2012)
Tuta absoluta	Iran	31.512219	48.728284	(Baniameri and Cheraghian 2012)
Tuta absoluta	Iran	28.957705	51.057914	(Baniameri and Cheraghian 2012)
Tuta absoluta	Iran	34.323607	47.110293	(Baniameri and Cheraghian 2012)
Tuta absoluta	Iran	28.98875	53.138937	(Baniameri and Cheraghian 2012)
Tuta absoluta	Iraq	30.49116	47.776809	(USAID 2012)
Tuta absoluta	Iraq	36.299204	42.297306	(USAID 2012)
Tuta absoluta	Israel	31.074052	34.860463	(Seplyarsky et al. 2010)
Tuta absoluta	Italy	44.453586	9.090893	(Speranza and Sannino 2012)
Tuta absoluta	Italy	40.942716	14.140682	(Speranza and Sannino 2012)
Tuta absoluta	Italy	39.29716	16.224605	(Speranza and Sannino 2012)
Tuta absoluta	Italy	39.897096	8.579102	(Speranza and Sannino 2012)

Tuta absoluta	Italy	45.565885	10.175329	(Speranza and Sannino 2012)
Tuta absoluta	Italy	45.124109	7.607659	(Speranza and Sannino 2012)
Tuta absoluta	Italy	44.372416	7.557533	(Speranza and Sannino 2012)
Tuta absoluta	Italy	44.916815	8.640232	(Speranza and Sannino 2012)
Tuta absoluta	Italy	44.898848	8.176828	(Speranza and Sannino 2012)
Tuta absoluta	Italy	45.123494	10.02449	(Speranza and Sannino 2012)
Tuta absoluta	Italy	45.416253	11.01368	(Speranza and Sannino 2012)
Tuta absoluta	Italy	45.095458	11.799678	(Speranza and Sannino 2012)
Tuta absoluta	Italy	42.772056	11.133477	(Speranza and Sannino 2012)
Tuta absoluta	Italy	40.345074	18.225617	(Speranza and Sannino 2012)
Tuta absoluta	Italy	43.90624	8.054132	(Speranza and Sannino 2012)
Tuta absoluta	Italy	44.340607	8.428889	(Speranza and Sannino 2012)
Tuta absoluta	Italy	42.235223	13.737715	(Speranza and Sannino 2012)
Tuta absoluta	Italy	36.938428	14.72794	(Speranza and Sannino 2012)
Tuta absoluta	Italy	44.666899	10.953965	(Speranza and Sannino 2012)
Tuta absoluta	Italy	44.510527	11.266707	(Speranza and Sannino 2012)
Tuta absoluta	Italy	44.802667	10.377267	(Speranza and Sannino 2012)
Tuta absoluta	Italy	45.028435	9.674375	(Speranza and Sannino 2012)
Tuta absoluta	Italy	44.597408	11.219976	(Speranza and Sannino 2012)
Tuta absoluta	Italy	42.940941	12.625307	(Speranza and Sannino 2012)

Tuta absoluta	Italy	46.078923	11.147304	(Speranza and Sannino 2012)
Tuta absoluta	Italy	46.49978	11.373935	(Speranza and Sannino 2012)
Tuta absoluta	Italy	41.735661	13.034733	(Speranza and Sannino 2012)
Tuta absoluta	Jordan	32.455067	35.54759	(Al-Jboory et al. 2012)
Tuta absoluta	Kenya	0.323142	37.579597	(Tonnang et al. 2015)
Tuta absoluta	Lebanon	34.128991	35.665962	(FAO 2016b)
Tuta absoluta	Libya	32.793836	13.255524	(Russell-IPM 2009b)
Tuta absoluta	Malta	35.862253	14.38764	(Dandria and Catania 2009)
Tuta absoluta	Mayotte Island	-12.831767	45.189847	(EPPO 2016)
Tuta absoluta	Montenegro	41.9310884	19.238701	(Hrnčić and Radonjić 2012)
Tuta absoluta	Montenegro	42.406125	19.278319	(Hrnčić and Radonjić 2012)
Tuta absoluta	Morocco	35.130256	-2.940007	(Ouardi et al. 2012)
Tuta absoluta	Morocco	32.54091	-8.749236	(Ouardi et al. 2012)
Tuta absoluta	Mozambique	-18.938623	32.852267	(FAO 2017b)
Tuta absoluta	Namibia	-19.574671	18.120624	(Hortidaily.com 2016)
Tuta absoluta	Nepal	27.655585	85.409944	(Bajracharya et al. 2016)
Tuta absoluta	Niger	13.461806	2.145497	(Adamou et al. 2017)
Tuta absoluta	Nigeria	9.077036	7.383002	(Russell-IPM 2015)
Tuta absoluta	Nigeria	5.113461	6.966339	(Russell-IPM 2015)
Tuta absoluta	Nigeria	11.651055	8.442298	(Russell-IPM 2015)

Tuta absoluta	Panama	8.586946	-82.384479	(Roda et al. 2015)
Tuta absoluta	Panama	8.830535	-82.860761	(Roda et al. 2015)
Tuta absoluta	Paraguay	-23.334251	-58.431586	(JICA 1994)
Tuta absoluta	Peru	-8.928226	-74.706033	(Razuri and Vargas 1975)
Tuta absoluta	Portugal	38.950801	-9.342572	(Figueiredo et al. 2010)
Tuta absoluta	Portugal	40.312837	-7.800862	(Figueiredo et al. 2010)
Tuta absoluta	Portugal	41.35553	-8.713878	(Figueiredo et al. 2010)
Tuta absoluta	Qatar	25.66017	51.51671	(Al-turaihi 2014)
Tuta absoluta	Rwanda	-1.99247	30.043952	(FAO 2015)
Tuta absoluta	Saudi Arabia	24.150018	45.285784	(Russell-IPM 2010b)
Tuta absoluta	Senegal	16.025276	-16.475995	(Pfeiffer et al. 2013)
Tuta absoluta	Serbia	42.600096	22.028051	(Toševski et al. 2011)
Tuta absoluta	Slovenia	45.495819	13.823713	(Žežlina et al. 2011)
Tuta absoluta	South Africa	-25.608331	30.494477	(Visser et al. 2017)
Tuta absoluta	Spain	27.88009	-15.447964	(Urbaneja et al. 2007)
Tuta absoluta	Spain	39.973402	-0.025929	(Urbaneja et al. 2007)
Tuta absoluta	Sudan	15.457954	32.578514	(Mohamed et al. 2012)
Tuta absoluta	Sudan	14.862267	33.365045	(Mohamed et al. 2012)
Tuta absoluta	Syria	35.160417	35.942724	(Russell-IPM 2010a)
Tuta absoluta	Tanzania	-3.141642	36.88714	(Kariathi et al. 2016)

Tuta absoluta	Tunisia	35.884521	10.564716	(Abbes et al. 2012)
Tuta absoluta	Tunisia	35.672353	10.125144	(Abbes et al. 2012)
Tuta absoluta	Tunisia	37.279824	9.824324	(Abbes et al. 2012)
Tuta absoluta	Turkey	38.382551	27.210839	(Kılıç 2010)
Tuta absoluta	Uganda	0.462261	32.713914	(Tumuhaise et al. 2016)
Tuta absoluta	Uruguay	-31.976613	-55.697	(Bentancourt and Scatoni 1995)
Tuta absoluta	Venezuela	9.214475	-66.040884	(Povolný 1984)
Tuta absoluta	Yemen	13.156721	45.302085	(EPPO 2013b)
Tuta absoluta	Zambia	-15.524732	28.285985	(FAO 2016c)
Tuta absoluta	Zambia	-14.947109	28.026013	(FAO 2016c)
Tuta absoluta	Zambia	-15.293455	28.364192	(FAO 2016c)

RESPONSE CURVES

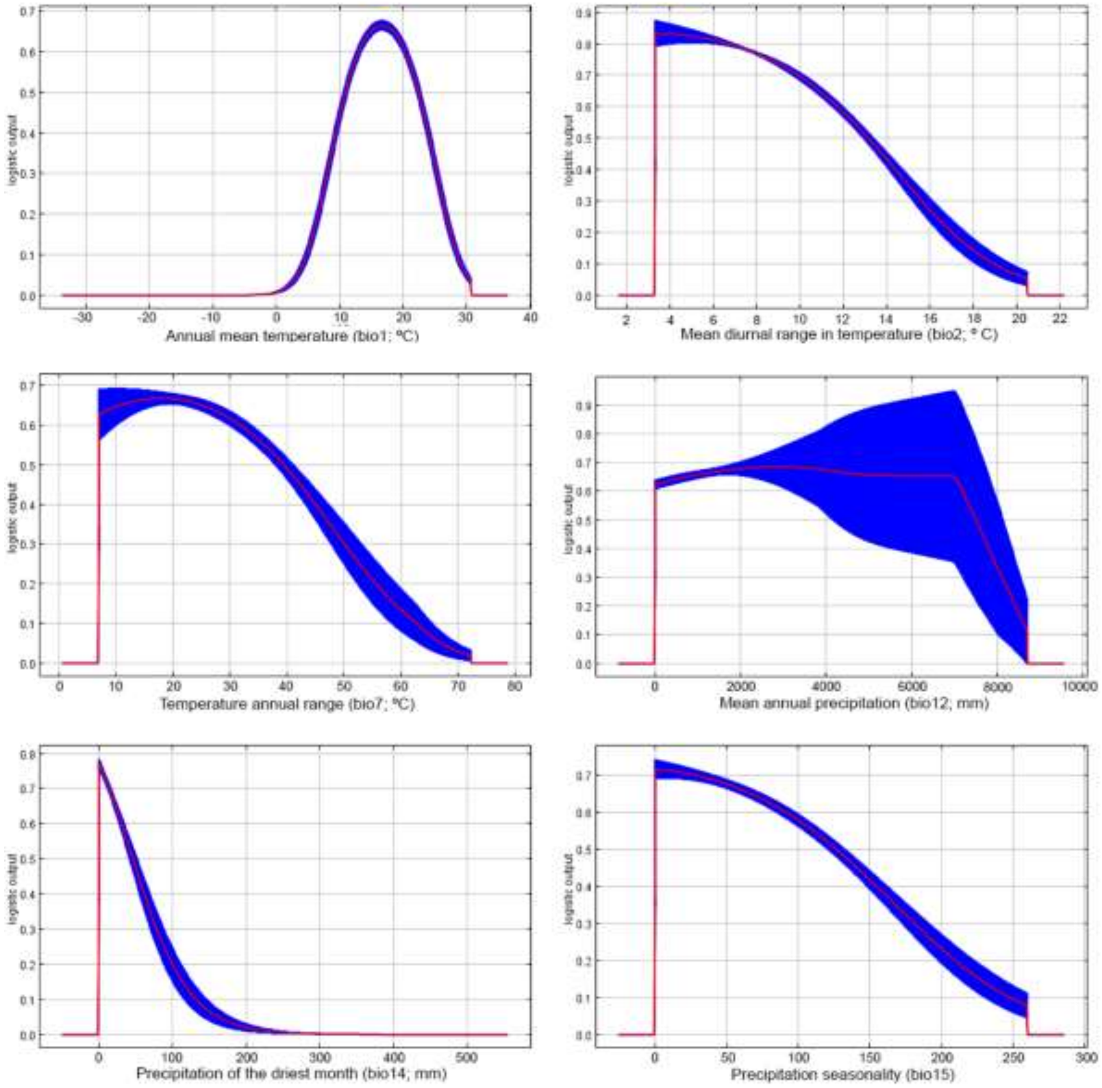

Figure S2. Response curves of the best predictors of *Tuta absoluta* in the best model.

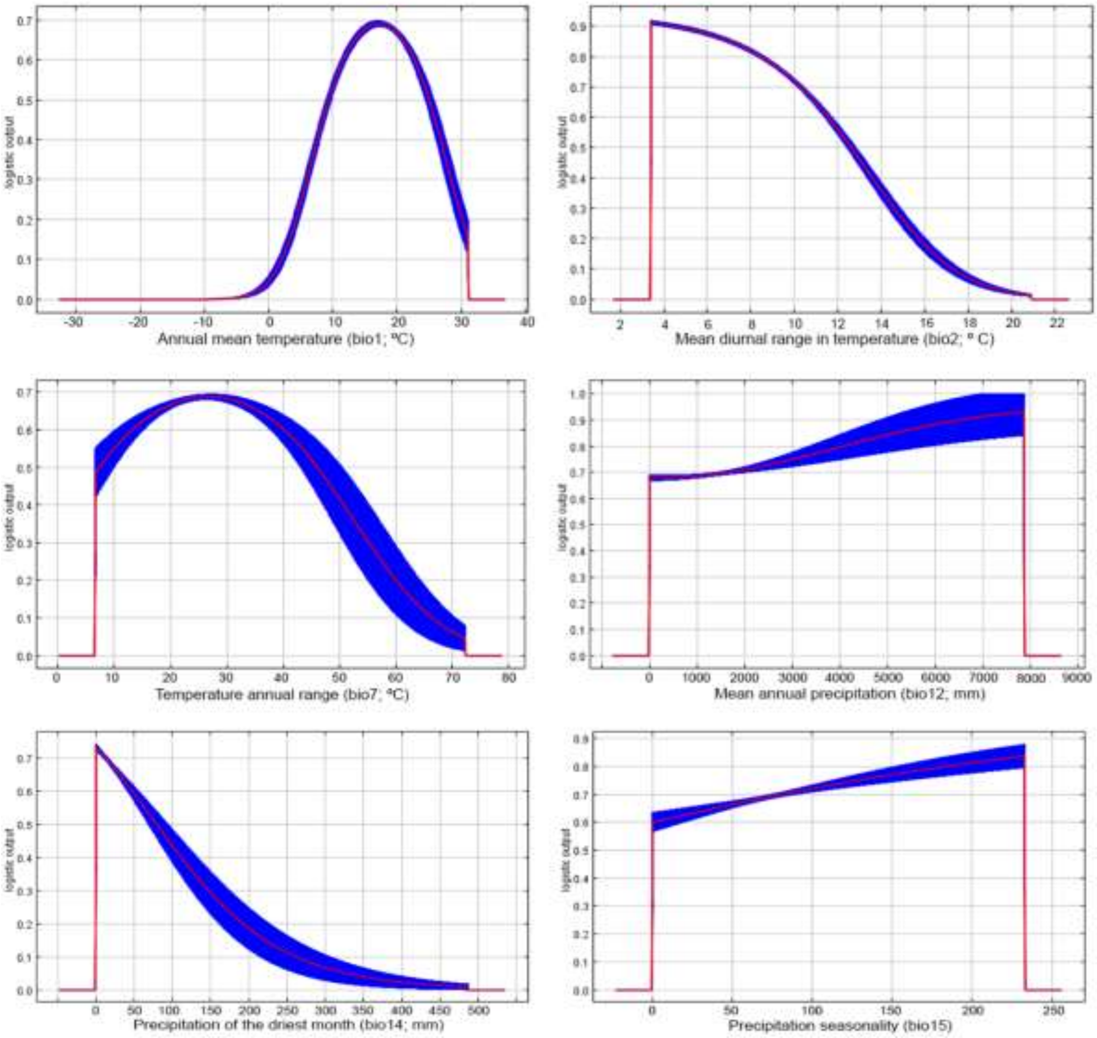

Figure S3. Response curves of the best predictors of *Neochrysocharis formosa* in the best model.

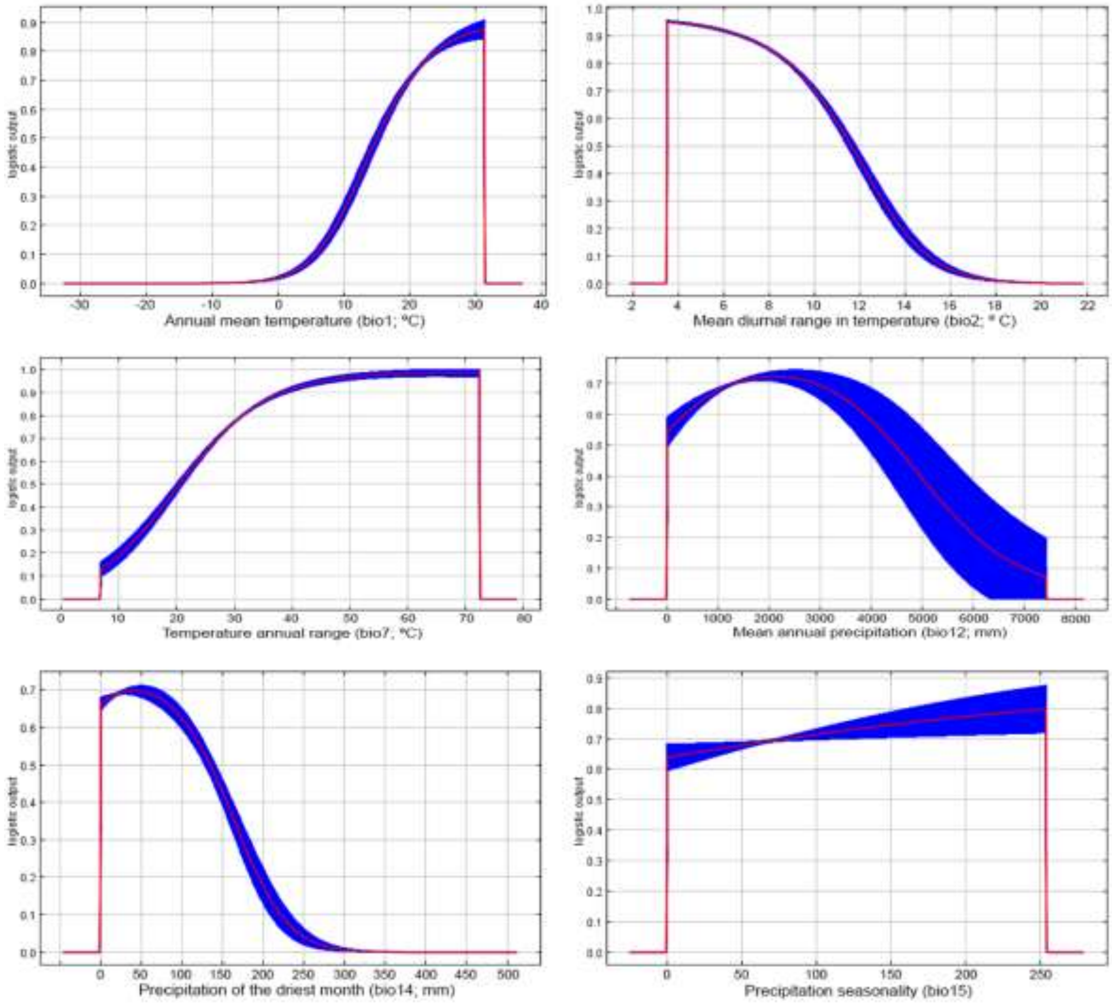

Figure S4. Response curves of the best predictors of *Stenomesius japonicus* in the best model.

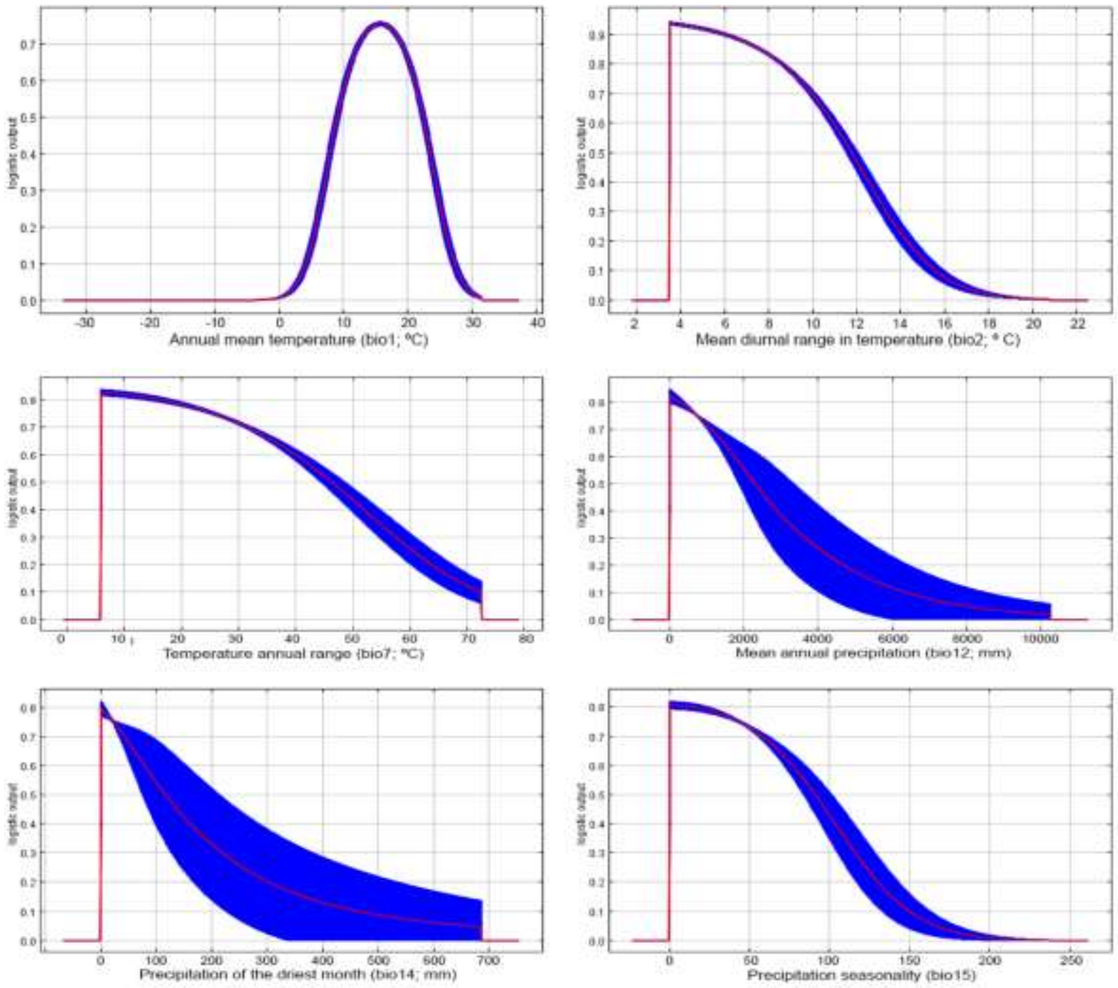

Figure S5. Response curves of the best predictors of *Macrolophus pygmaeus* in the best model.

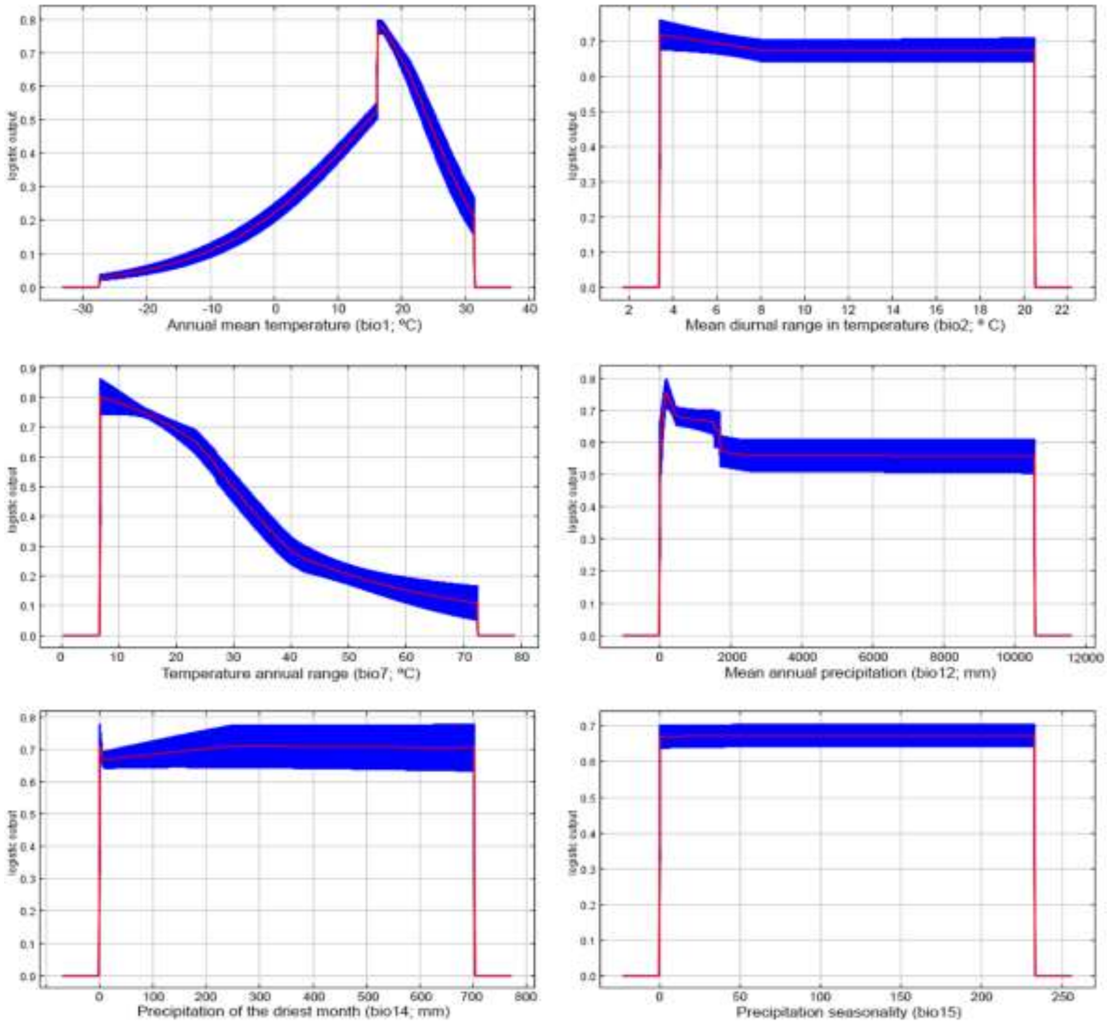

Figure S6. Response curves of the best predictors of *Pseudapanteles dignus* in the best model.

JACKKNIFE TEST

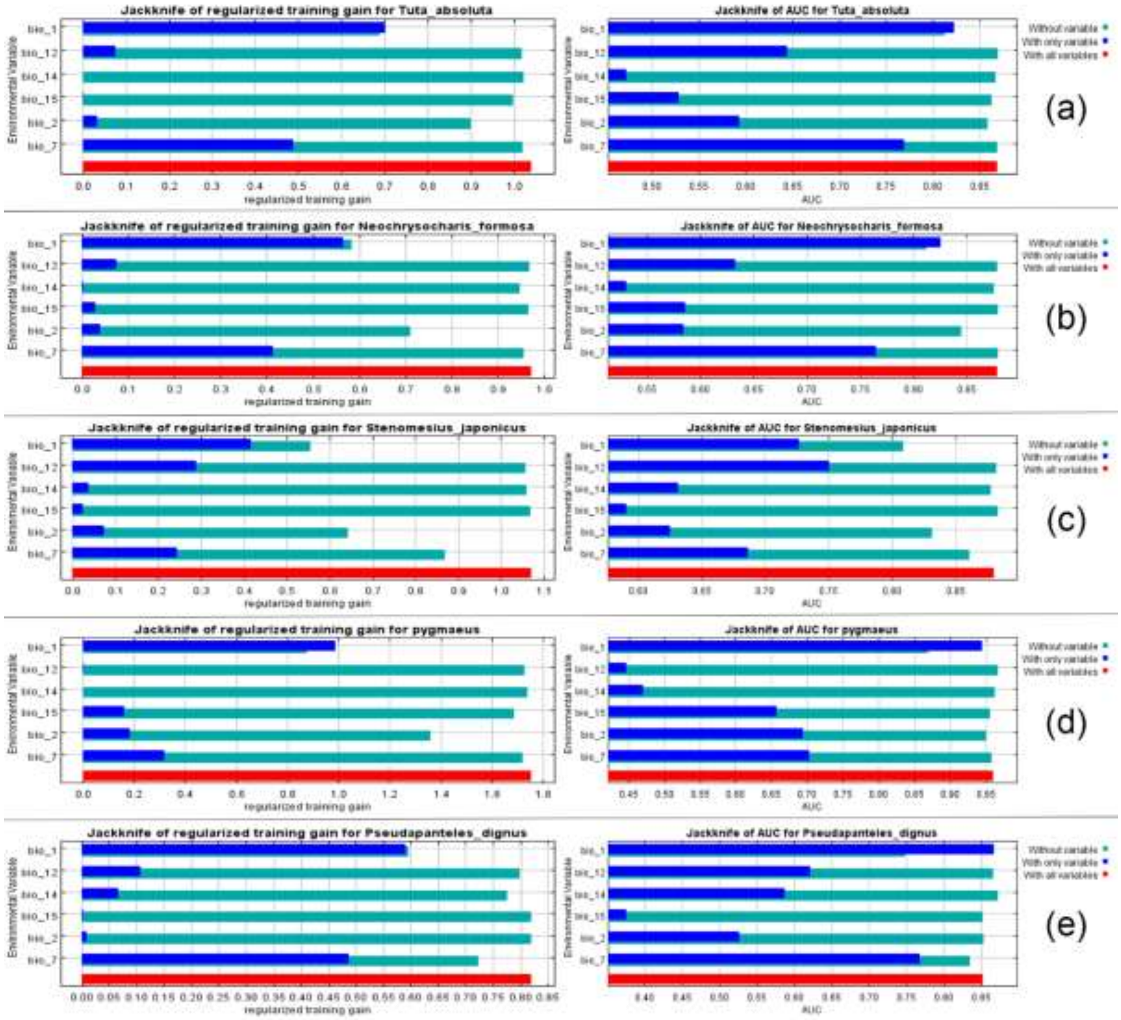

Figure S7. Relative importance of the environmental variables based on the Jackknife test. Regularized training gain and AUC in *Tuta absoluta* (a), *Neochrysocharis formosa* (b), *Stenomesius japonicus* (c), *Macrolophus pygmaeus* (d), and *Pseudapanteles dignus* (e) models.

REFERENCES

Abate T (1991) The bean fly, Ophiomyia phaseoli (Tryon) (Dipt., Agromyzidae), and its parasitoids in Ethiopia J Appl Entomol 111:278-285 doi:10.1111/j.1439-0418.1991.tb00324.x

Abbes K, Harbi A, Chermiti B (2012) The tomato leafminer Tuta absoluta (Meyrick) in Tunisia: current status and management strategies EPPO Bulletin 42:226-233 doi:10.1111/epp.2559

Adamou H et al. (2017) Geographical distribution of the tomato borer, Tuta absoluta Meyrick (Lepidoptera. Gelichiidae) in Niger Scholars Academic Journal of Biosciences 5:108-113 doi:10.21276/sajb.2017.5.2.4

Aiello-Lammens ME, Boria RA, Radosavljevic A, Vilela B, Anderson RP (2015) spThin: an R package for spatial thinning of species occurrence records for use in ecological niche models Ecography 38:541-545 doi:10.1111/ecog.01132

Al-Jboory IJ, Katbeh-Bader A, Shakir A-Z (2012) First Observation and Identification of Some Natural Enemies Collected from Heavily Infested Tomato by *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in Jordan Middle-East Journal of Scientific Research 11:787-790

Al-turaihi EH (2014) The Impact Of Newly Introduced Insect Tomato Borer (*Tuta Absoluta*) On Environment And Agriculture In Qatar EEPP0072 Energy & Environment doi:10.5339/qfarc.2014.EEPP0072

Andrews T, Gregory JM, Webb MJ, Taylor KE (2012) Forcing, feedbacks and climate sensitivity in CMIP5 coupled atmosphere-ocean climate models Geophys Res Lett 39:n/a-n/a doi:10.1029/2012GL051607

Bacci L (2006) Factors determining the attack of *Tuta absoluta* on tomato. Doctoral dissertation, Universidade Federal de Viçosa

Backer LD, Megido RC, Haubruge É, Verheggen FJ (2014a) *Macrolophus pygmaeus* (Rambur) as an efficient predator of the tomato leafminer Tuta absoluta (Meyrick) in Europe. A review BASE [En ligne 18:536-543

Backer LD, Megido RC, Haubruge É, Verheggen FJ (2014b) *Macrolophus pygmaeus* (Rambur) as an efficient predator of the tomato leafminer *Tuta absoluta* (Meyrick) in Europe. A review Biotechnol Agron Soc Environ 18:536-543

Baeţan R, Oltean I, Vărădie P, Florian T (2013) Researches concerning the spreading of *Tuta absoluta* Species into greenhouses from west of Romania Bulletin UASMV serie Agriculture 70:110-112 doi:10.15835/buasvmcn-agr:9775

Báez M, Askew RR (1999) New records of Chalcidoidea (Hymenoptera) from the Canary Islands Asociación española de Entomología 23:65-82

Bahamondes LA, Mallea AL (1969) Biologia en Mendoza de Scrobipalpula absoluta (Meyrick) Polvony (Lepidoptera: Gelechiidae), espécie nueva para la Republica Argentina Revista de la Facultad de Ciencias Agrarias 15:96-104

Bajracharya ASR, Mainali RP, Bhat B, Bista S, Shashank PR, Meshram NM (2016) The first record of South American tomato leaf miner, *Tuta absoluta* (Meyrick 1917) (Lepidoptera: Gelechiidae) in Nepal Journal of Entomology and Zoology Studies 4:1359-1363

BALE B (1999) Comparison of development and growth of nettle-feeding larvae of Nymphalidae (Lepidoptera) under constant and alternating temperature regimes EJE 96:143-148

Ballal CR, Gupta A, M. Mohan, Lalitha Y, Verghese A (2016) The new invasive pest *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in India and its natural enemies along with evaluation of Trichogrammatids for its biological control Curr Sci 110

Baniameri V, Cheraghian A (2012) The first report and control strategies of Tuta absoluta in Iran EPPO Bulletin 42:322-324 doi:10.1111/epp.2577

Barrientos RZ, Apablaza JH, Norero AS, Estay P (1998) Temperatura base y constante térmica de desarrollo de la polilla del tomate, *Tuta absoluta* (Lepidoptera: Gelechiidae) Ciencia e Investigación Agraria 25:133-137 doi:http://dx.doi.org/10.7764/rcia.v25i3.659.

Barrientos Z R, Apablaza H J, Norero S A, Estay P P (1998) Threshold temperature and thermal constant for the development of the South american tomato moth, *Tuta absoluta* (Lepidoptera: Gelechiidae) [1998] Ciencia e investigación agraria 25

Barry S, Elith J (2006) Error and uncertainty in habitat models J Appl Ecol 43:413-423 doi:10.1111/j.1365-2664.2006.01136.x

Begon M, Townsend CR, Harper JL (2005) ECOLOGY: From individuals to ecosystems. 4th ed edn. BLACKWELL PUBLISHING, Malden, MA

Bentancourt CM, Scatoni IB (1995) Description of the development stages of the "tomato borer", Scrobipalpuloides absoluta (Meyrick) (Lep., Gelechiidae) Boletin de Investigacion - Facultad de Agronomia, Universidad de la Republica 45:1-14

Betancourt CM, I.B. S, Rodríguez JJ (1996) Influencia de la temperatura sobre la reproduccion y el desarrollo de *Scrobipalpuloides absoluta* (Meyrick) (Lepidoptera: Gelechiidae) Rev Bras Biol 56:661–670

Biondi A, Chailleux A, Lambion J, Han P, Zappalà L, Desneux N (2013) Indigenous Natural Enemies Attacking *Tuta absoluta* (Lepidoptera: Gelechiidae) in Southern France Egyptian Journal of Biological Pest Control 23:117-121

Biondi A, Guedes RNC, Wan F-H, Desneux N (2018) Ecology, Worldwide Spread, and Management of the Invasive South American Tomato Pinworm, *Tuta absoluta*: Past, Present, and Future Annu Rev Entomol 63:null doi:10.1146/annurev-ento-031616-034933

BOPA BPA- (2016) Ministry warns of tomato leaf miner. http://www.dailynews.gov.bw/news-details.php?nid=32839. Accessed August, 15th 2017

Boria RA, Olson LE, Goodman SM, Anderson RP (2014) Spatial filtering to reduce sampling bias can improve the performance of ecological niche models Ecol Model 275:73-77 doi:https://doi.org/10.1016/j.ecolmodel.2013.12.012

Boualem M, Allaoui H, Hamadi R, Medjahed M (2012) Biologie et complexe des ennemis naturels de *Tuta absoluta* à Mostaganem (Algérie) EPPO Bulletin 42:268-274 doi:10.1111/epp.2570

Bratu E, Petcuci AM, Sovarel G (2015) Efficacy of the Product Spinosad an Insecticide Used in the Control of Tomato Leafminer (*Tuta absoluta* - Meyrick, 1917)

Bulletin of University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca Horticulture 72:209-210 doi:10.15835/buasvmcn-hort:10876

Brotons L, Thuiller W, Araújo MB, Hirzel AH (2004) Presence-absence versus presence-only modelling methods for predicting bird habitat suitability Ecography 27:437-448 doi:doi:10.1111/j.0906-7590.2004.03764.x

Brown JL (2014) SDMtoolbox: a python-based GIS toolkit for landscape genetic, biogeographic and species distribution model analyses Methods in Ecology and Evolution 5:694-700 doi:10.1111/2041-210X.12200

CABI (2017) Neochrysocharis formosa. https://www.cabi.org/isc/datasheet/13171. Accessed January, 24 2018

Campos MR, Biondi A, Adiga A, Guedes RNC, Desneux N (2017) From the Western Palaearctic region to beyond: *Tuta absoluta* 10 years after invading Europe J Pest Sci 90:787-796 doi:10.1007/s10340-017-0867-7

Carapezza A, Mifsud D (2015) New records of true bugs (Hemiptera, Heteroptera) from the Maltese Islands Bulletin of the Entomological Society of Malta 27:27–50

Chailleux A, Desneux N, Arnó J, Gabarra R (2014) Biology of two key Palaearctic larval ectoparasitoids when parasitizing the invasive pest Tuta absoluta J Pest Sci 87:441-448 doi:10.1007/s10340-014-0557-7

Cıkman E, Civelek HS, Weintraub PG (2008) The parasitoid complex ofLiriomyza cicerina on chickpea (Cicer arietinum) Phytoparasitica 36:211-216 doi:10.1007/bf02980765

Cook DC, Fraser RW, Paini DR, Warden AC, Lonsdale WM, De Barro PJ (2011) Biosecurity and yield improvement technologies are strategic complements in the fight against food insecurity PLoS ONE 6:e26084 doi:10.1371/journal.pone.0026084

Daly C (2006) Guidelines for assessing the suitability of spatial climate data sets International Journal of Climatology 26:707-721 doi:10.1002/joc.1322

Damos P, Savopoulou-Soultani M (2012) Temperature-driven models for insect development and vital thermal requirements Psyche 2012:13 doi:10.1155/2012/123405

Dandria D, Catania A (2009) *Tuta absoluta* (Povolny, 1994), an important agricultural pest in Malta (Lepidoptera: Gelechiidae) Bulletin of the entomological Society of Malta 2:57-60

Dehliz A, Guénaoui Y (2015) Natural Enemies of *Tuta absoluta* (Lepidoptera: Gelechiidae) in Oued Righ Region, An Arid Area of Algeria Academic Journal of Entomology 8:72-79 doi:10.5829/idosi.aje.2015.8.2.9491

Deleva E, Harizanova V, Draganova S (2016) Biotic mortality factors in field populations of Tuta absoluta Meyrick (Lepidoptera: Gelechiidae) in South Bulgaria Agrarni Nauki 8:61-67

Desneux N, Luna MG, Guillemaud T, Urbaneja A (2011) The invasive South American tomato pinworm, *Tuta absoluta*, continues to spread in Afro-Eurasia and beyond: the new threat to tomato world production J Pest Sci 84:403-408 doi:10.1007/s10340-011-0398-6

Desneux N et al. (2010) Biological invasion of European tomato crops by *Tuta absoluta*: ecology, geographic expansion and prospects for biological control J Pest Sci 83:197-215 doi:10.1007/s10340-010-0321-6

Dike VN, Shimizu MH, Diallo M, Lin Z, Nwofor OK, Chineke TC (2015) Modelling present and future African climate using CMIP5 scenarios in HadGEM2-ES International Journal of Climatology 35:1784-1799 doi:10.1002/joc.4084

Doğanlar M, Elsayed AK (2015) Parasitoids complex in summer populations of Asphondylia punica Marchal, 1897 (Diptera: Cecidomyiidae) on the Mediterranean Saltbush, Atriplex halimus L. (Chenopodiaceae) in Egypt, with descriptions of new species from Eupelmidae and Eulophidae (Hymenoptera: Chalcidoidea) Munis Entomology & Zoology 10:75-85

Dormann CF et al. (2013) Collinearity: a review of methods to deal with it and a simulation study evaluating their performance Ecography 36:27-46 doi:10.1111/j.1600-0587.2012.07348.x

Dormann CF et al. (2012) Correlation and process in species distribution models: bridging a dichotomy J Biogeogr 39:2119-2131 doi:10.1111/j.1365-2699.2011.02659.x

Duan JJ, Bauer LS, Abell KJ, Ulyshen MD, Van Driesche RG (2015) Population dynamics of an invasive forest insect and associated natural enemies in the aftermath of invasion: implications for biological control J Appl Ecol 52:1246-1254 doi:10.1111/1365-2664.12485

Đurić Z, Hrnčić S, Vujanović M, Đurić B, Mitrić S (2012) Tuta absoluta (Meyrick) (Lepidoptera, Gelechiidae) in the Republic of Srpska (Bosnia and Herzegovina) EPPO Bulletin 42:337-340 doi:10.1111/epp.2581

Eilenberg J, Hajek A, Lomer C (2001) Suggestions for unifying the terminology in biological control BioControl 46:387-400 doi:10.1023/a:1014193329979

EPPO (2013a) First report of *Tuta absoluta* in Germany. European Plant Protection Organization. https://gd.eppo.int/taxon/GNORAB/distribution/DE. Accessed August 15th 2017

EPPO EaMPPO (2018) Commercially used biological control agents. Accessed January, 24 2018

EPPO EPPO- (2009) First report of Tuta absoluta in Switzerland. https://gd.eppo.int/reporting/article-397. Accessed August 15th 2017

EPPO EPPO- (2010a) First report of Tuta absoluta in Guernsey. https://gd.eppo.int/taxon/GNORAB/distribution/GG. Accessed August, 15th 2017

EPPO EPPO- (2010b) First report of Tuta absoluta in Kosovo http://archives.eppo.int/EPPOReporting/2010/Rse-1006.pdf. Accessed August, 15th 2017

EPPO EPPO- (2010c) First report of Tuta absoluta in Russia. https://gd.eppo.int/taxon/GNORAB/distribution/RU. Accessed August, 15th 2017

EPPO EPPO- (2011) First report of Tuta absoluta in Georgia. https://gd.eppo.int/taxon/GNORAB/distribution/GE. Accessed August, 15th 2017

EPPO EPPO- (2012) First report of Tuta absoluta in the United Arab Emirates. https://gd.eppo.int/reporting/article-2540. Accessed August, 15th 2017

EPPO EPPO- (2013b) First report of *Tuta absoluta* in Yemen. https://gd.eppo.int/taxon/GNORAB/distribution/YE. Accessed August, 15th 2017

EPPO EPPO- (2014) First report of Tuta absoluta in Ukraine. https://gd.eppo.int/taxon/GNORAB/distribution/UA. Accessed August, 15th 2017

EPPO EPPO- (2016) First report of Tuta absoluta in Mayotte. https://gd.eppo.int/reporting/article-5538. Accessed August, 15th 2017

Esenali Uulu T, Ulusoy MR, Çalışkan AF (2017) First record of tomato leafminer Tuta absoluta Meyrick (Lepidoptera: Gelechiidae) in Kyrgyzstan EPPO Bulletin 47:285-287 doi:10.1111/epp.12390

Essl F et al. (2011) Socioeconomic legacy yields an invasion debt Proceedings of the National Academy of Sciences 108:203-207 doi:10.1073/pnas.1011728108

FAO (2017a) FAO Statistical Yearbook. Food and Agriculture Organization of the United Nations. http://www.fao.org/faostat/en/#data/QC/visualize. Accessed 08 of August 2017

FAO FaAOotUN- (2014) *Tuta absoluta*. https://www.ippc.int/en/countries/costa-rica/pestreports/2014/05/tuta-absoluta-1/. Accessed August, 15th 2017

FAO FaAOotUN- (2015) Quarterly Early Warning Bulletin for Food and Agriculture. http://www.fao.org/3/a-i4783e.pdf. Accessed August, 15th 2017

FAO FaAOotUN- (2016a) First report of Tuta absoluta in the Czech Republic (2013). https://www.ippc.int/en/countries/czech-republic/pestreports/2016/12/first-report-of-tuta-absoluta-in-the-czech-republic/. Accessed August, 15th 2017

FAO FaAOotUN- (2016b) Introducing IPM to Lebanese farmers: reducing the risk of "Tomato Borer" invasive plant pest. http://www.fao.org/lebanon/programmes-and-projects/success-stories/ipm/en/. Accessed August 15th 2007

FAO FaAOotUN- (2016c) REPORTING PEST PRESENCE: PRELIMINARY SURVEILLANCE REPORTS ON TUTA ABSOLUTA IN ZAMBIA. https://www.ippc.int/en/countries/zambia/pestreports/2016/09/reporting-pest-presence-preliminary-surveillance-reports-on-tuta-absoluta-in-zambia/. Accessed August, 15th 2017

FAO FaAOotUN- (2017b) Occurrence of tomato leaf miner (Tuta absoluta) in Mozambique https://www.ippc.int/en/countries/mozambique/pestreports/2017/01/occurrence-of-tomato-leaf-miner-tuta-absoluta-in-mozambique/. Accessed August, 15th 2017

Fernandez-Triana JL, Janzen D, Hallwachs W, Whitfield JB, Smith MA, Kula R (2014) Revision of the genus Pseudapanteles (Hymenoptera, Braconidae, Microgastrinae), with emphasis on the species in Area de Conservación Guanacaste, northwestern Costa Rica ZooKeys 446 doi:10.3897/zookeys.446.8195

Ferracini C, Ingegno BL, Navone P, Ferrari E, Mosti M, Tavella L, Alma A (2012) Adaptation of Indigenous Larval Parasitoids to Tuta absoluta (Lepidoptera: Gelechiidae) in Italy J Econ Entomol 105:1311-1319 doi:10.1603/EC11394

Fielding AH, Bell JF (2002) A review of methods for the assessment of prediction errors in conservation presence/absence models Environ Conserv 24:38-49 doi:undefined

Figueiredo E, Payer R, Mexía A, Rodrigues S (2010) Situación actual de Tuta absoluta en Portugal Phytoma España 217:118-119

Fridley JD, Sax DF (2014) The imbalance of nature: revisiting a Darwinian framework for invasion biology Global Ecol Biogeogr 23:1157-1166 doi:10.1111/geb.12221

Gabarra R et al. (2014) Native parasitoids associated with Tuta absoluta in the tomato production areas of the Spanish Mediterranean Coast BioControl 59:45-54 doi:10.1007/s10526-013-9545-8

Gabl I, Hausdorf H (2010) First report of Tuta absoluta (Meyrick, 1917) in Austria and first monitoring results. Journal für Kulturpflanzen 65:1-8

Gadallah NS, Yefremova ZA, Yegorenkova EN, Soliman AM, El-Ghiet UMA, Edmardash YA, Edmardash YA (2015) A review of the family Eulophidae (Hymenoptera: Chalcidoidea) of Egypt, with thirty three new records Zootaxa 4058:15 doi:10.11646/zootaxa.4058.1.3

Galdino TVdS, Kumar S, Oliveira LSS, Alfenas AC, Neven LG, Al-Sadi AM, Picanço MC (2016) Mapping Global Potential Risk of Mango Sudden Decline Disease Caused by *Ceratocystis fimbriata* PLOS ONE 11:e0159450 doi:10.1371/journal.pone.0159450

Garcia RF (1989) Plagas del tomate y su manejo. ICA, Palmira, Colombia

Ghabeish I, Allawi T (2001) Agromyzid Leafminers and Their Parasitoids in Jordan Dirasat, Agricultural Sciences 28:177-177

Ghoneim K (2014) PARASITIC INSECTS AND MITES AS POTENTIAL BIOCONTROL AGENTS FOR A DEVASTIVE PEST OF TOMATO, Tuta absoluta Meyrick (LEPIDOPTERA: GELECHIIDAE)IN THE WORLD: A REVIEW IJRRAS 19:36-68

Gontijo PC, Picanço MC, Pereira EJG, Martins JC, Chediak M, Guedes RNC (2013) Spatial and temporal variation in the control failure likelihood of the tomato leaf miner, *Tuta absoluta* Ann Appl Biol 162:50-59 doi:10.1111/aab.12000

Guedes RNC, Picanço MC (2012) The tomato borer *Tuta absoluta* in South America: pest status, management and insecticide resistance EPPO Bulletin 42:211-216 doi:10.1111/epp.2557

Guillemaud T et al. (2015) The tomato borer, *Tuta absoluta*, invading the Mediterranean Basin, originates from a single introduction from Central Chile Scientific Reports 5:8371 doi:10.1038/srep08371

https://www.nature.com/articles/srep08371#supplementary-information

Guimapi RYA, Mohamed SA, Okeyo GO, Ndjomatchoua FT, Ekesi S, Tonnang HEZ (2016) Modeling the risk of invasion and spread of Tuta absoluta in Africa Ecol Complex 28:77-93 doi:https://doi.org/10.1016/j.ecocom.2016.08.001

Hance T, Baaren Jv, Vernon P, Boivin G (2007) Impact of Extreme Temperatures on Parasitoids in a Climate Change Perspective Annu Rev Entomol 52:107-126 doi:10.1146/annurev.ento.52.110405.091333

Hayat M, Aftab H, Perveen S (2005) Taxonomic notes on Indian Eulophidae (Hymenoptera: Chalcidoidea) — 2. On the types of some Eulophinae, Entedoninae and Euderinae Orient Insects 39:1-14 doi:10.1080/00305316.2005.10417412

Heimpel GE, Yang Y, Hill JD, Ragsdale DW (2013) Environmental Consequences of Invasive Species: Greenhouse Gas Emissions of Insecticide Use and the Role of Biological Control in Reducing Emissions PLOS ONE 8:e72293 doi:10.1371/journal.pone.0072293

Hernández R, Guo K, Harris M, Liu T-X (2011) Effects of selected insecticides on adults of two parasitoid species of Liriomyza trifolii: Ganaspidium nigrimanus (Figitidae) and Neochrysocharis formosa (Eulophidae) Insect Sci 18:512-520 doi:10.1111/j.1744-7917.2010.01391.x

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas International Journal of Climatology 25:1965-1978 doi:10.1002/joc.1276

Hortidaily.com (2016) *Tuta absolut*a now also in Namibia. http://www.hortidaily.com/article/30198/Tuta-absoluta-now-also-in-Namibia. Accessed August, 15th 2017

Hossain MS, Mian MY, Muniappan R (2016) First Record of *Tuta absoluta* (Lepidoptera: Gelechiidae) from Bangladesh J Agric Urban Entomol 32:101-105

Hrnčić S, Radonjić S (2012) Tomato leafminer – Tuta absoluta Meyrick (Lepidoptera, Gelechiidae) – current status in Montenegro EPPO Bulletin 42:341-343 doi:10.1111/epp.2582

Ingegno BL, Pansa MG, Tavella L (2009) Tomato colonization by predatory bugs (Heteroptera: Miridae) in agroecosystems of NW Italy IOBC/WPRS Bulletin 49:287-291

Insectoid (2018) Neochrysocharis formosa. http://insectoid.info/insecta/hymenoptera/eulophidae/neochrysocharis_formosa/. Accessed January, 24 2018

IPCC (2014) Climate Change 2014: Synthesis Report. IPCC, Geneva, Switzerland

James DG, Stevens MM (1992) STENOMESIUS JAPONICUS (ASHMEAD) (HYMENOPTERA: EULOPHIDAE), A PARASITOID OF THE INTRODUCED BIOLOGICAL CONTROL AGENT DIALECTICA SCALARIELLA (ZELLER) (LEPIDOPTERA: GRACILLARIIDAE) Aust J Entomol 31:233-234 doi:10.1111/j.1440-6055.1992.tb00496.x

János Á, Imre F (2014) Recent data on the distribution and biology of *Tuta absoluta* (Meyrick, 1917) in Hungary (Lepidoptera: Gelechiidae) e-Acta Naturalia Pannonica 7:5-14

Jarnevich CS, Stohlgren TJ, Kumar S, Morisette JT, Holcombe TR (2015) Caveats for correlative species distribution modeling Ecological Informatics 29:6-15 doi:https://doi.org/10.1016/j.ecoinf.2015.06.007

Jauset AM, Edo-Tena E, Castañé C, Agustí N, Alomar O, Grozeva S (2015) Comparative cytogenetic study of three Macrolophus species (Heteroptera, Miridae) Comparative Cytogenetics 9:613-623 doi:10.3897/CompCytogen.v9i4.5530

JICA IANAdCIdJ- (1994) Control integrado de la palomilla del tomate Scrobipalpula absoluta (Meyrick, 1917). Caacupé, Paraguay

Kalleshwaraswamy CM, Murthy MS, Viraktamath CA, Kumar NKK (2015) Occurrence of Tuta absoluta (Lepidoptera: Gelechiidae) in the Malnad and Hyderabad-Karnataka Regions of Karnataka, India Fla Entomol 98:970-971 doi:10.1653/024.098.0326

Kamijo K (1976) Notes on ASHMEAD's and CRAWFORD's Types of Eulophidae (Hymenoptera, Chalcidoidea) from Japan 昆蟲 44:482-495

Kamijo KB (1979) Eulophidae (Hymenoptera) from Korea, with Description of Two New Species* Annalis Hsitorico-Naturales Musei Nationalis Hungarici 71

Karadjova O, Z. Ilieva Z, Krumov V, Petrova E, Ventsislavov V (2013) *Tuta absoluta* (meyrick) (Lepidoptera: Gelechiidae): Potential for entry , establishment and spread in bulgaria Bulgarian Journal of Agricultural Science 19:563-571

Kariathi V, Kassim N, Kimanya M, Yildiz F (2016) Pesticide exposure from fresh tomatoes and its relationship with pesticide application practices in Meru district Cogent Food & Agriculture 2:1196808 doi:10.1080/23311932.2016.1196808

Kearney M, Porter W (2009) Mechanistic niche modelling: combining physiological and spatial data to predict species' ranges Ecol Lett 12:334-350 doi:10.1111/j.1461-0248.2008.01277.x

Kılıç T (2010) First record of Tuta absoluta in Turkey Phytoparasitica 38:243-244 doi:10.1007/s12600-010-0095-7

Kolar CS, Lodge DM (2001) Progress in invasion biology: predicting invaders Trends Ecol Evol 16:199-204 doi:http://dx.doi.org/10.1016/S0169-5347(01)02101-2

Kriticos DJ, Maywald G, Yonow T, Zurcher E, Herrmann N, Sutherst R (2015) CLIMEX Version 4: exploring the effects of climate on plants, animals and diseases CSIRO , Canberra:184

Kriticos DJ, Webber BL, Leriche A, Ota N, Macadam I, Bathols J, Scott JK (2012) CliMond: global high-resolution historical and future scenario climate surfaces for bioclimatic modelling Methods in Ecology and Evolution 3:53-64 doi:10.1111/j.2041-210X.2011.00134.x

Kumar S, Neven LG, Yee WL (2014) Evaluating correlative and mechanistic niche models for assessing the risk of pest establishment Ecosphere 5:1-23 doi:10.1890/ES14-00050.1

Kumar S, Neven LG, Zhu H, Zhang R (2015) Assessing the Global Risk of Establishment of *Cydia pomonella* (Lepidoptera: Tortricidae) using CLIMEX and MaxEnt Niche Models J Econ Entomol 108:1708-1719 doi:10.1093/jee/tov166

Kumar S, Stohlgren TJ (2009) Maxent modeling for predicting suitable habitat for threatened and endangered tree *Canacomyrica monticola* in New Caledonia Journal of Ecology and The Natural Environment 1:094-098

Lakshmi DMP, Narendran T, Presty J, Baaby J (2016) Distribution and diversity of Chalcidoidea (Hymenoptera) associated with rice ecosystem in Palakkad district of Kerala state International Journal of Entomology Research 1:6-9

Liu C, White M, Newell G (2013) Selecting thresholds for the prediction of species occurrence with presence-only data J Biogeogr 40:778-789 doi:10.1111/jbi.12058

Liu S-S, Zhang G-M, Zhu J (1995) Influence of Temperature Variations on Rate of Development in Insects: Analysis of Case Studies from Entomological Literature Ann Entomol Soc Am 88:107-119 doi:10.1093/aesa/88.2.107

Lowry E et al. (2013) Biological invasions: a field synopsis, systematic review, and database of the literature Ecology and Evolution 3:182-196 doi:10.1002/ece3.431

Luna M, Wada V, La Salle J, Sánchez N (2011) *Neochrysocharis formosa* (Westwood) (Hymenoptera: Eulophidae), a newly recorded parasitoid of the tomato moth, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae), in Argentina Neotrop Entomol 40:412-414

Luna MG et al. (2015) Potential of Biological Control Agents Against Tuta absoluta (Lepidoptera: Gelechiidae): Current Knowledge in Argentina Fla Entomol 98:489-494 doi:10.1653/024.098.0215

Lykouressis D, Giatropoulos A, Perdikis D, Favas C (2008) Assessing the suitability of noncultivated plants and associated insect prey as food sources for the omnivorous predator Macrolophus pygmaeus (Hemiptera: Miridae) Biol Control 44:142-148 doi:https://doi.org/10.1016/j.biocontrol.2007.11.003

Marcano R (1995) Efecto de la temperatura sobre el desarrollo y la reproduccion de *Scrobipalpula absoluta* (Meyrick) (Lepidoptera: Gelechiidae) Bol Entomol Venez 10:69-75

Martins JC, Picanco MC, Bacci L, Guedes RNC, Santana PA, Jr., Ferreira DO, Chediak M (2016) Life table determination of thermal requirements of the tomato borer *Tuta absoluta* J Pest Sci 89:897-908 doi:10.1007/s10340-016-0729-8

Mazumdar S, Bhuiya BA (2016) Parasitoids (Hymenoptera) of leafminer flies (Diptera: Agromyzidae) from Bangladesh Journal of Threatened Taxa 8:8714–8718 doi:10.11609/jott.2741.8.4.8714-8718

MDR MdDR- (2013) Detection of *Tuta absoluta* (Meyrick, 1917) in Cape Verde. http://www.mdr.gov.cv/index.php/2012-03-12-18-11-28/relatorios/download/18-relatorios/369-detection-of-tuta-absoluta-meyrick-1917-in-cape-verde. Accessed August, 15th 2017

Merow C, Smith MJ, Silander JA (2013) A practical guide to MaxEnt for modeling species' distributions: what it does, and why inputs and settings matter Ecography 36:1058-1069 doi:10.1111/j.1600-0587.2013.07872.x

Miranda MMM, Picanço M, Zanuncio JC, Guedes RNC (1998) Ecological life table of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) Biocontrol Sci Technol 8:597-606 doi:10.1080/09583159830117

Mladen Šimala M, Masten Milek T, Seljak G (2011) The results of the monitoring of south american tomato moth *Tuta absoluta* Povolny, 1994 (lepidoptera: Gelechiidae) in 2010 in Croatia Plant Protection Society of Slovenia

Mohamed ESI, Mohamed ME, Gamiel SA (2012) First record of the tomato leafminer, Tuta absoluta (Meyrick) (Lepidoptera: Gelechiidae) in Sudan EPPO Bulletin 42:325-327 doi:10.1111/epp.2578

Moore JE (1983) Control of tomato leafminer (Scrobipalpula absoluta) in Bolivia. Tropical Pest Management 29:231-238

Moussa S, Sharma A, Baiomy F, El-Adl FE (2013) The Status of Tomato Leafminer; *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in Egypt and Potential Effective Pesticides Academic Journal of Entomology 6:110-115 doi:10.5829/idosi.aje.2013.6.3.75130

NEPPO (2014) The current incidence of tomato borer, *Tuta absoluta*, in the uk. http://www.neppo.org/wp-content/uploads/2014/05/KevinGormanAgadir1.pdf. Accessed August, 15th 2017

NEPPO LOplpdvaP-O- (2011) The current status of the tomato borer *Tuta absoluta* in Greece and Cyprus. http://www.neppo.org/wp-content/uploads/2014/05/roditakis-Tuta-greece-cyprus-AGADIR1.pdf. Accessed August, 15th 2017

Nieves EL, Pereyra PC, Luna MG, Medone P, Sánchez NE (2015a) Laboratory Population Parameters and Field Impact of the Larval Endoparasitoid Pseudapanteles dignus (Hymenoptera: Braconidae) on its Host Tuta absoluta (Lepidoptera: Gelechiidae) in Tomato Crops in Argentina J Econ Entomol 108:1553-1559 doi:10.1093/jee/tov115

Nieves EL, Pereyra PC, Luna MG, Medone P, Sánchez NE (2015b) Laboratory Population Parameters and Field Impact of the Larval Endoparasitoid *Pseudapanteles dignus* (Hymenoptera: Braconidae) on its Host *Tuta absoluta* (Lepidoptera: Gelechiidae) in Tomato Crops in Argentina J Econ Entomol 108:1553-1559 doi:doi.org/10.1093/jee/tov115

NPPO (2009) *Tuta absoluta* Povolny (Gelechiidae) – tomato leaf miner - in tomato packaging facility in The Netherlands. National Plant Protection Organization of the Netherlands. https://english.nvwa.nl/documents/chek/chek/chek/documents/pest-report-tuta-absoluta-in-the-netherlands-at-tomato-packaging-facility. Accessed August, 15th 2017

OIRED OoIREaD- (2014) *Tuta absoluta*: the tomato leafminer. http://www.oired.vt.edu/ipmil/wp-content/uploads/2014/06/13-Muniappan-Tuta-absoluta-15May2014.pdf. Accessed August, 15th 2017

Ostrauskas H, Ivinskis P (2010) Records of the Tomato Pinworm (Tuta absoluta (Meyrick, 1917)) – Lepidoptera: Gelechiidae – in Lithuania Acta Zoologica Lituanica 20:151-155 doi:10.2478/v10043-010-0016-5

Ouardi K, Chouibani M, Rahel MA, El Akel M (2012) Stratégie Nationale de lutte contre la mineuse de la tomate Tuta absoluta Meyrick EPPO Bulletin 42:281-290 doi:10.1111/epp.2568

Owens HL et al. (2013) Constraints on interpretation of ecological niche models by limited environmental ranges on calibration areas Ecol Model 263:10-18 doi:https://doi.org/10.1016/j.ecolmodel.2013.04.011

Paini DR, Sheppard AW, Cook DC, De Barro PJ, Worner SP, Thomas MB (2016) Global threat to agriculture from invasive species Proceedings of the National Academy of Sciences 113:7575-7579 doi:10.1073/pnas.1602205113

Pereira EJG, Picanço MC, Bacci L, Crespo ALB, Guedes RNC (2007) Seasonal mortality factors of the coffee leafminer, *Leucoptera coffeella* Bull Entomol Res 97:421-432 doi:10.1017/S0007485307005202

Peterson AT, Papeş M, Soberón J (2008) Rethinking receiver operating characteristic analysis applications in ecological niche modeling Ecol Model 213:63-72 doi:https://doi.org/10.1016/j.ecolmodel.2007.11.008

Pfeiffer DG, Muniappan R, Sall D, Diatta P, Diongue A, Dieng EO (2013) First Record of Tuta absoluta (Lepidoptera: Gelechiidae) in Senegal Fla Entomol 96:661-662 doi:10.1653/024.096.0241

Phillips SJ, Anderson RP, Schapire RE (2006) Maximum entropy modeling of species geographic distributions Ecol Model 190:231-259 doi:https://doi.org/10.1016/j.ecolmodel.2005.03.026

Povolný D (1984) Four new Neotropical Gnorimoschemini from Venezuela (Lepidoptera, Gelechiidae) Dtsch Entomol Z 31:299-311

PURE-IPM (2017) Integrated management of the invasive tomato leafminer Tuta absoluta in Flanders (Belgium). http://www.pure-ipm.eu/sites/default/files/content/files/van%20Damme%20Veerle_0.pdf. Accessed August, 15th 2017

R Development Team (2015) R: A Language and Environment for Statistical Computing, 3.2.2 edn. The R Foundation for Statistical Computing, Vienna, Austria. doi:http://www.R-project.org/

Randin CF, Dirnböck T, Dullinger S, Zimmermann NE, Zappa M, Guisan A (2006) Are niche-based species distribution models transferable in space? J Biogeogr 33:1689-1703 doi:doi:10.1111/j.1365-2699.2006.01466.x

Rassoul MSA, Saffar HHA (2014) Parasitoid of the genus Liriomyza Mik. In Iraq Int J Curr Microbiol App Sci 3:678-624

Razuri V, Vargas E (1975) Biology and behaviour of *Scrobipalpula absoluta* Meyrick (Lepidoptera: Gelechiidae) on tomatoes Revista Peruana de Entomologia 18:84-89

Roda AL, Brambila J, Barria J, Euceda X, Korytkowski C (2015) Efficiency of Trapping Systems for Detecting Tuta absoluta (Lepidoptera: Gelechiidae) J Econ Entomol 108:2648-2654 doi:10.1093/jee/tov248

Roditakis E, Papachristos D, Roditakis NE (2010) Current status of the tomato leafminer Tuta absoluta in Greece EPPO Bulletin 40:163-166 doi:10.1111/j.1365-2338.2009.02367.x

Russell-IPM TaIN (2009a) Tuta absoluta in Albania. http://www.tutaabsoluta.com/news/55/tuta-absoluta-in-albania. Accessed August, 15th 2017

Russell-IPM *Ta*IN (2009b) *Tuta absolut*a in Libya. http://www.tutaabsoluta.com/news?news=17&lang=en. Accessed August, 15th 2017

Russell-IPM TaIN (2010a) Initial reports of Tuta absoluta in Syria. http://www.tutaabsoluta.com/news?news=143. Accessed August, 15th 2017

Russell-IPM TaIN (2010b) *Tuta absoluta* reaches Saudi Arabia. http://www.tutaabsoluta.com/news/227/ptuta-absoluta-reaches-saudi-arabiap. Accessed August, 15th 2017

Russell-IPM TaIN (2011) Tuta absoluta in KUWAIT. http://www.tutaabsoluta.com/reports/163/tuta-absoluta-in-kuwait. Accessed August, 15th 2017

Russell-IPM TaIN (2015) Nigerian Press Conference on Tuta absoluta http://www.russellipm.com/uncategorized/nigerian-press-conference-on-tuta-absoluta/. Accessed August, 15th 2017

Sanchez JA, Spina ML, Perera OP (2012) Analysis of the population structure of Macrolophus pygmaeus (Rambur) (Hemiptera: Miridae) in the Palaearctic region using microsatellite markers Ecology and Evolution 2:3145-3159 doi:10.1002/ece3.420

Sankarganesh E, Firake DM, Sharma B, Verma VK, Behere GT (2017) Invasion of the South American Tomato Pinworm, *Tuta absoluta,* in northeastern India: a new challenge and biosecurity concerns Entomol Gen 36:335-345 doi:10.1127/entomologia/2017/0489

Santana PA, Jr., Kumar L, Silva RSD, Picanço MC (2018) Routes of dispersion of *Tuta absoluta* in the world from the past until present and future projection based on climate change J Pest Sci doi:(In progress)

Schotman CYL (1989) Plant pests of quarantine importance to the Caribbean RLAC-PROVEG:21-80

Seplyarsky V, Weiss M, Haberman A (2010) Tuta absoluta Povolny (Lepidoptera: Gelechiidae), a new invasive species in Israel Phytoparasitica 38:445-446 doi:10.1007/s12600-010-0115-7

Shabani F, Kumar L (2013) Risk levels of invasive *Fusarium oxysporum* f. sp. in areas suitable for date palm (*Phoenix dactylifera*) cultivation under various climate change projections PLoS ONE 8:e83404 doi:10.1371/journal.pone.0083404

Sierra-Peña A, Machado I, redon K, Pozo-Velazquez E (2012) First record of *Apanteles dignus* on Keyferia lycopersicella in tomato of greenhouse Centro Agrícola 39

Silva GA, Picanço MC, Bacci L, Crespo ALB, Rosado JF, Guedes RNC (2011) Control failure likelihood and spatial dependence of insecticide resistance in the tomato pinworm, *Tuta absoluta* Pest Manage Sci 67:913-920 doi:10.1002/ps.2131

Silva RS, Kumar L, Shabani F, Picanço MC (2016) Assessing the impact of global warming on worldwide open field tomato cultivation through CSIRO-Mk3·0 global climate model The Journal of Agricultural Science 155:407-420 doi:10.1017/S0021859616000654

Silva RS, Kumar L, Shabani F, Picanço MC (2017) Potential risk levels of invasive *Neoleucinodes elegantalis* (small tomato borer) in areas optimal for open-field *Solanum lycopersicum* (tomato) cultivation in the present and under predicted climate change Pest Manage Sci 73:616-627 doi:10.1002/ps.4344

Silvestri F (1914) Viaggio in Eritrea per cercare parassiti della mosca delle olive Bolletino del Laboratorio di Zoologia 9

Soberón J (2005) Interpretation of models of fundamental ecological niches and species' distributional areas. Biodiversity Informatics 2:1-10

Son D et al. (2017) First Record of Tuta absoluta (Meyrick, 1917) (Lepidoptera: Gelechiidae) in Burkina Faso Afr Entomol 25:259-263 doi:10.4001/003.025.0259

Speranza S, Sannino L (2012) The current status of Tuta absoluta in Italy EPPO Bulletin 42:328-332 doi:10.1111/epp.2579

Sunari AAAAS, Supartha IW, Wijaya IN, Laba IW (2016) The Abundance Parasitoid Populations of *Neochrysocharis formosa* and *Neochrysocharis okazakii* (Hymenoptera: Eulophidae) on *Liriomyza* spp. (Diptera: Agromyzidae) Associated with Vegetable Crop in Bali Journal of Biology, Agriculture and Healthcare 6

Sutherst RW, Maywald GF (1985) A computerised system for matching climates in ecology Agric, Ecosyst Environ 13:281-299 doi:http://dx.doi.org/10.1016/0167-8809(85)90016-7

Sutherst RW, Maywald GF, Kriticos DJ (2007) CLIMEX Version 3: User's Guide Melbourne: Hearne Scientific Software Pty Ltd

Taylor KE, Stouffer RJ, Meehl GA (2012) An Overview of CMIP5 and the Experiment Design Bulletin of the American Meteorological Society 93:485-498 doi:10.1175/bams-d-11-00094.1

Taylor S, Kumar L (2012) Sensitivity analysis of CLIMEX parameters in modelling potential distribution of *Lantana camara* L PLoS ONE 7:e40969 doi:10.1371/journal.pone.0040969

Thailand Ppi (2017) Aproaerema modicella (Deventer) Accessed November, 16 2017

Thomson LJ, Macfadyen S, Hoffmann AA (2010) Predicting the effects of climate change on natural enemies of agricultural pests Biol Control 52:296-306 doi:https://doi.org/10.1016/j.biocontrol.2009.01.022

Tonnang HEZ, Mohamed SF, Khamis F, Ekesi S (2015) Identification and risk assessment for worldwide invasion and spread of *Tuta absoluta* with a focus on Sub-Saharan Africa: Implications for phytosanitary measures and management PLoS ONE 10:e0135283 doi:10.1371/journal.pone.0135283

Toševski I, Jović J, Mitrović M, Cvrković T (2011) *Tuta absoluta* (Meyrick, 1917) (Lepidoptera, Gelechiidae): a new pest of tomato in Serbia Pestic Phytomed 26:197–204 doi:10.2298/PIF1103197T

Townsend Peterson A, Papeş M, Eaton M (2007) Transferability and model evaluation in ecological niche modeling: a comparison of GARP and Maxent Ecography 30:550-560 doi:10.1111/j.0906-7590.2007.05102.x

Tran DH (2009) AGROMYZID LEAFMINERS AND THEIR PARASITOIDS ON VEGETABLES IN CENTRAL VIETNAM J ISSAAS 15:21-23

Trdan S, Kavallieratos NG, Stathakis T, Kreiter S, Stojanović A, Tomanović Ž, Bohinc T (2013) First records of three natural enemies in Slovenia: predatory mite Neoseiulus californicus (Arachnida, Acari, Phytoseiidae) and parasitoid wasps Neochrysocharis formosus (Insecta, Hymenoptera, Eulophidae) and Dibrachys microgastri (Insecta, Hymenoptera, Pteromalidae) [Conference poster]. Ljubljana,

Trottin-Caudal Y, Baffert V, Leyre JM, Hulas N (2012) Experimental studies on Tuta absoluta (Meyrick) in protected tomato crops in France: biological control and integrated crop protection EPPO Bulletin 42:234-240 doi:10.1111/epp.2560

Tsagkarakis AE, Kalaitzaki AP, Lykouressis DP (2013a) Phyllocnistis citrella and its parasitoids in three citrus species in Greece Phytoparasitica 41:23-29 doi:10.1007/s12600-012-0258-9

Tsagkarakis AE, Perdikis DC, Lykouressis DP (2013b) Introduced and native parasitoids of Phyllocnistis citrella Stainton in Greece: short term post-release evaluation Phytoparasitica 41:417-428 doi:10.1007/s12600-013-0303-3

Tumuhaise V, Khamis FM, Agona A, Sseruwu G, Mohamed SA (2016) First record of Tuta absoluta (Lepidoptera: Gelechiidae) in Uganda Int J Trop Insect Sci 36:135-139 doi:10.1017/S1742758416000035

Ubaidillah R (2007) DIVERSITY OF THE PARASITOID WASPS OF THE EULOPHTD SUBFAMILY EULOPHINAE (INSECTA: HYMENOPTERA, EULOPHIDAE) OF JAVA, INDONESIA AND THEIR DISTRIBUTION Berita Biologi 8

UNWTO UNWTO (2017) International tourist arrivals. Our World In Data. https://ourworldindata.org/grapher/international-tourist-arrivals-by-world-region. Accessed April 28th 2018

Urbaneja A, González-Cabrera J, Arnó J, Gabarra R (2012) Prospects for the biological control of *Tuta absoluta* in tomatoes of the Mediterranean basin Pest Manage Sci 68:1215-1222 doi:10.1002/ps.3344

Urbaneja A, Vercher R, Navarro V, F GM, J.L. P (2007) La polilla del tomate, Tuta absoluta Phytoma Espana 194:16-23

USAID UIAP- (2012) Iraqi Farmers Collaborate in Control of *Tuta absoluta*. http://www.inma-iraq.com/newsroom/iraqi-farmers-collaborate-control-tuta-absoluta. Accessed August, 15th 2017

USDA USDoA- (2011) New Pest Response Guidelines Tomato Leafminer (*Tuta absoluta*). https://www.aphis.usda.gov/import_export/plants/manuals/emergency/downloads/Tuta-absoluta.pdf. Accessed August, 15th 2017

van Vuuren DP, Carter TR (2014) Climate and socio-economic scenarios for climate change research and assessment: reconciling the new with the old Clim Change 122:415-429 doi:10.1007/s10584-013-0974-2

Vangansbeke D, Nguyen DT, Audenaert J, Verhoeven R, Gobin B, Tirry L, De Clercq P (2015) Prey consumption by phytoseiid spider mite predators as affected by diurnal temperature variations BioControl 60:595-603 doi:10.1007/s10526-015-9677-0

Vargas HC (1970) Observaciones sobre la biologfa y enemigos naturales de la polilla del tomate, Gnorimoschema absoluta (Meyrick) (Lepidoptera: Gelechiidae) Idesia (Chile)

Veloz SD (2009) Spatially autocorrelated sampling falsely inflates measures of accuracy for presence-only niche models J Biogeogr 36:2290-2299 doi:10.1111/j.1365-2699.2009.02174.x

Visser D, Uys VM, Nieuwenhuis RJ, Pieterse W (2017) First records of the tomato leaf miner *Tuta absoluta* (Meyrick, 1917) (Lepidoptera: Gelechiidae) in South Africa BioInvasions Records 6:1-5

Wang W, Lu S-L, Liu W-X, Cheng L-S, Zhang Y-B, Wan F-H (2014) Effects of Five Naturally Occurring Sugars on the Longevity, Oogenesis, and Nutrient Accumulation Pattern in Adult Females of the Synovigenic Parasitoid Neochrysocharis formosa (Hymenoptera: Eulophidae) Neotrop Entomol 43:564-573 doi:10.1007/s13744-014-0247-4

West AM, Kumar S, Wakie T, Brown CS, Stohlgren TJ, Laituri M, Bromberg J (2015) Using High-Resolution Future Climate Scenarios to Forecast Bromus tectorum Invasion in Rocky Mountain National Park PLOS ONE 10:e0117893 doi:10.1371/journal.pone.0117893

Xian X, Han P, Wang S, Zhang G, Liu W, Desneux N, Wan F (2017) The potential invasion risk and preventive measures against the tomato leafminer *Tuta absoluta* in China Entomol Gen 36:319-333 doi:10.1127/entomologia/2017/0504

Yefremova ZA (2007) The subfamilies Eulophinae, Euderinae and Entedoninae (Hymenoptera: Eulophidae) in Yemen FAUNA OF ARABIA 23:335–368

Yefremova ZA, Yegorenkova EN, Mishchenko AV (2013) Eulophid Wasps (Hymenoptera, Eulophidae), Parasitoids of Leaf-Mining Moths (Lepidoptera: Gracillariidae, Nepticulidae, Tischeriidae) on the English Oak in the Middle Volga Area Entomol Rev 93:309–315

Žežlina I, Benko Beloglavec A, Pajk O (2011) Tomato leaf miner (*Tuta absoluta* Povolny) - results of its special surveillance in slovenia in year 2010 Plant Protection Society of Slovenia

Zhu C-D, Huang D-W (2002) A Taxonomic Study on Eulophidae from Guanxi, China[1] Acta Zootaxonomica Sinica 27:583-607

Zweig MH, Campbell G (1993) Receiver-operating characteristic (ROC) plots: a fundamental evaluation tool in clinical medicine Clin Chem 39:561-577

蔡 篤, 西東 力 (2011) Current status of Liriomyza leafminers and their associated parasitoids in Shizuoka Prefecture Ann Rept Kansai Pl Prot 53:47-49 doi:10.4165/kapps.53.47

CONCLUSÃO GERAL

Os modelos apresentados neste estudo possibilitaram atualizar as informações sobre as áreas adequadas para *T. absoluta* e quatro importantes inimigos naturais deste inseto. Esta informação é fundamental para a implementação de sólidos programas de manejo e controle biológico para essa praga. Os modelos apresentados se mostram muito consistentes com a atual distribuição da praga e seus inimigos naturais. Portanto, permitem fazer inferências batante precisas sobre as rotas de dispersão da Traça do tomateiro e identificar os efeitos das mudanças climáticas previstas sobre a distribuição da praga e seus inimigos naturais. Além disso, é possível destacar as áreas em maior risco devido à alta adequabilidade para a praga e baixa adequabilidade a seus inimigos naturais.

Países como Alemanha, China, Holanda, México, Reino Unido e EUA possuem grandes áreas adequadas à praga e, portanto, devem se preocupar com uma possível invasão dessa praga no futuro.

As mudanças climáticas previstas irão afetar negativamente a distribuição de *T. absoluta* em regiões próximas ao equador e positivamente no hemisfério norte. Na América do Sul, as mudanças climáticas previstas levarão a uma diminuição de adequabilidade climática para *T. absoluta* e para *M. pygmaeus, N. formosa e P. dignus*. Somente para o parasitoide *S. japonicus* haverá um aumento de adequabilidade climática nessa região.

O aumento de adequabilidade climática para a *T. absoluta* em alguns países do hemisfério norte não será acompanhada por alguns de seus inimigos naturais. Devido à baixa adequabilidade climática aos parasitoides *N. formosa*, *S. japonicus* e *P. dignus* em países como a Alemanha, Holanda e Reino Unido esses inimigos naturais serão importantes agentes de controle biológico somente em ambiente protegido. Já devido a alta adequabilidade climática na maioria do países da Europa, o predador *M. pygmaeus* possivelmente será um importante agente de controle natural dessa praga. Portanto, praticas de preservação deste predador no campo devem ser priorizadas.

Portanto, as informações geradas neste trabalhos serão muito uteis aos países destacados, uma vez que os permitirá direcionar esforços para contenção da expansão da praga, aumentar barreiras quarentenárias e direcionar práticas de preservação desses inimigos naturais.