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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

Ricardo Siqueira da Silva,[a,b*] Lalit Kumar,[b] Farzin Shabani[b] and Marcelo Coutinho Picanço[a,c]

Abstract

BACKGROUND: *Neoleucinodes elegantalis* is one of the major insect pests of *Solanum lycopersicum*. Currently, *N. elegantalis* is present only in America and the Caribbean, and is a threat in the world's largest *S. lycopersicum*-producing countries. In terms of potential impact on agriculture, the impact of climate change on insect invasions must be a concern. At present, no research exists regarding the effects of climatic change on the risk level of *N. elegantalis*. The purpose of this study was to develop a model for *S. lycopersicum* and *N. elegantalis*, utilizing CLIMEX to determine risk levels of *N. elegantalis* in open-field *S. lycopersicum* cultivation in the present and under projected climate change, using the global climate model CSIRO-Mk3.0.

RESULTS: Large areas are projected to be suitable for *N. elegantalis* and optimal for open-field *S. lycopersicum* cultivation at the present time. However, in the future these areas will become unsuitable for both species. Conversely, other regions in the future may become optimal for open-field *S. lycopersicum* cultivation, with a varying risk level for *N. elegantalis*.

CONCLUSION: The risk level results presented here provide a useful tool to design strategies to prevent the introduction and establishment of *N. elegantalis* in open-field *S. lycopersicum* cultivation.

Keywords: climate change; CLIMEX; modelling; tomato; invasive species

1 INTRODUCTION

Crop losses to weeds, animal pests and pathogens reduce the output levels of food and cash crop production worldwide.[1,2] Damage caused by insect pests is one of the primary factors leading to the reduced production of major crops. This loss potential due to pests varies enormously according to regions and crops.[2,3] Several estimates of worldwide losses caused by insects have been made since the mid-twentieth century. For example, an average annual loss of 7.7% in production in Brazil is caused by insect pests.[2−4] These losses correspond to approximately 25 million t of food, fibre and biofuels annually.[5] Total annual economic losses are estimated at more than $US 18.9 billion and $US 17.7 billion in China and Brazil respectively.[5,6] In coverage area terms, tomatoes suffer one of the greatest crop losses, valued at $US 3806 ha^{-1}.[5]

Insect invasions and climate change have received much attention in recent years, in terms of identifying underlying mechanisms and their impact and the large-scale related documentation.[7−10] The analysis of large datasets, by virtue of greater computing power and the emergence of modelling software, has greatly enhanced our knowledge of the role of climate in insect invasions.[10−12] A recent study has demonstrated that, since the mid-twentieth century, China's increasing rate of insect invasions has a positive correlation with increases in surface air temperatures.[10] In addition, studies have documented that economic damage associated with non-indigenous species invasions in the United States, the United Kingdom, Australia, India, South Africa and Brazil total more than $US 336 billion per year.[13] It is thus essential to consider climate change when designing strategies and policies to deal with insect invasions in agricultural systems.[14]

Climate change can affect the physiology, distribution and management of invasive species.[15] One technique that may be applied

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[*] *Correspondence to: RS da Silva, Ecosystem Management, School of Environmental and Rural Science, University of New England, Armidale, NSW 2351, Australia. E-mail: rsiqueri@une.edu.au*

[a] *Departamento de Fitotecnia, Universidade Federal de Viçosa, MG, Brazil*

[b] *Ecosystem Management, School of Environmental and Rural Science, University of New England, Armidale, NSW, Australia*

[c] *Departamento de Entomologia, Universidade Federal de Viçosa, MG, Brazil*

to investigate the impact of climate change on invasive species is mechanistic process-based modelling, using modelling software such as CLIMEX.[16–22] Other techniques can be implemented using other available programs such as EcoMod,[23] VisTrails SAHM,[24] Maxent,[25] BIOMOD,[26] R packages[27] and BIOCLIM.[28]

CLIMEX software is considered to be a comprehensive and reliable inferential modelling software.[29] The advantages of this program are that it can produce a niche model without requiring pseudo-absence data. The relationships between climate change and potential distribution of species can be projected on a global scale to investigate the potential of invasion, and may provide information to promote risk status and aid management decisions.[11,30] Thus, modelling the potential of major insect pests of agricultural crops can provide important information to cope with invasions and avoid economic losses in affected regions, as well as ward off invasions in regions without insect pests.

Neoleucinodes elegantalis (Guenée) (Lepidoptera: Crambidae), often referred to as the small tomato borer, is a most devastating invader of *Solanum lycopersicum*, tomato. Currently, *N. elegantalis* is present in some countries of South, Central and North America and the Caribbean.[31,32] The pest is absent in the largest tomato-producing countries in the world. However, there are 1175 records of interception from the United States,[33] and 31 recorded interceptions on fruit in baggage at airports by Netherlands' officials.[34] *N. elegantalis* was listed as an EPPO A1 pest in 2014.[32] The species is a serious threat to tomato farmers owing to the great economic losses caused by direct damage to produce by larvae. In some countries in South America, the crop losses caused by *N. elegantalis* are estimated at between 50 and 90% of total cultivation.[31,32,35,36]

Despite the recent attention devoted to insect invasions, there is still a lack of effective research that can impact at the practical level. For example, after the initial detection of the tomato leafminer *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in eastern Spain in 2006, in less than 10 years this pest has rapidly spread to various European countries such as Italy, France, Albania, Bulgaria, Portugal, the Netherlands, the United Kingdom and Serbia, as well as India, Israel, Iran and Turkey.[37,38] It was later reported in the Canary Islands and parts of North and Sub-Saharan Africa (Algeria, Morocco, Egypt, Libya, Tunisia, Ethiopia, Niger, Senegal, Sudan, Tanzania, Uganda and Kenya).[37,38] The introduction of *T. absoluta* saw a notable increase in yield losses in tomato crop production.[37–39] We highlight that *T. absoluta* is native to South America, similarly to *N. elegantalis*.[31,38] However, the control of *N. elegantalis* is considered to be one of the most difficult tasks in tomato cultivation.[40] Thus, studies of investigations of the potential risk of *N. elegantalis* are needed to prevent its introduction and the development of a future problem such as is the case with *T. absoluta*.

Despite the potential losses of an *N. elegantalis* invasion in many countries and the projections of general climate change impacts, there has been no research analysing the risk levels of *N. elegantalis* under climate change. A complete analysis of the potential impact of climate change linked to the cultivation of crops, under both present and projected climate scenarios of the future, is thus a prerequisite for the optimal production techniques and management of open-field *S. lycopersicum* cultivation. Thus, the aim of this study was to utilise CLIMEX to model the responses of both *N. elegantalis* and open-field *S. lycopersicum* cultivation under climate change. Thereafter, these projections were overlaid to determine the risk level of *N. elegantalis* for optimal areas for open-field *S. lycopersicum* using ArcGIS software.

2 METHODOLOGY

2.1 CLIMEX modelling

CLIMEX is a semi-mechanistic modelling software considered to be reliable and powerful in predicting the potential impact of invasive species under varied scenarios in ecological studies.[41,42] CLIMEX was used to estimate the climatic suitability for *N. elegantalis* and open-field *S. lycopersicum* cultivation worldwide. The model-fitting strategy used in CLIMEX to set the biological parameters, such as temperature threshold, moisture requirements, minimum growing degree-days, known as the growth index (GI), and stress parameters, such as cold, heat, wet and dry stress indices, was based on climatic requirements and distribution records for both species. The combination of GI and stress indices generates the ecoclimatic index (EI), which defines the climatic suitability of a species within a location. EI is an average yearly index of the level of climatic suitability, on a scale from 0 to 100, such that $EI > 0$ denotes a potential for establishment of the species. Thus, there are regions where the population grows and other regions where the population decreases, based on the EI value.[29]

2.2 Distribution of *N. elegantalis* and open-field *S. lycopersicum* cultivation

We found 103 registers of *N. elegantalis* in America (Fig. 1a) and 6481 records representing open-field *S. lycopersicum* cultivation (Fig. 2). These datasets were obtained from published literature and from the Global Biodiversity Information Facility.[31,43–62]

The registers of *N. elegantalis* in Central America and the Andean region, including parts of Chile, Colombia, Ecuador, Bolivia and Peru, and the registers of open-field *S. lycopersicum* cultivation in Central and South America were reserved and not used in adjusting the parameters in CLIMEX. These registers were set aside for model validation.

2.3 Climatic data, model and scenarios

We used the CliMond gridded 10′ spatial resolution historical dataset from the period 1950–2000.[63] This dataset has high quality and provides a good spatial resolution. It consists of long-term monthly average values for minimum temperature, maximum temperature, precipitation and relative humidity at 0900 and 1500 hours.

The potential distributions of both species were modelled under the A2 SRES scenario using the global climate model (GCM) CSIRO-Mk3.0 (CS) of the Centre for Climate Research, Australia.[64] CS assumes a temperature increase of 2.11 °C and a 14% rainfall reduction by 2100. Our decision to use A2 SRES was due to the proven consistency of its premises and incorporation of technological, demographic and economic variables relating to greenhouse gas (GHG) emissions, derived from data representative of the world's independent, self-reliant countries.[65,66] It should be mentioned that there are various GCMs, such as CCSM3, CSM1.0, ECHAM5/MPI-OM, ECHAM3, LSG, IPSL-CM4, IPSL-CM2 and MIROC-H, that could be applied; however, in the present study only the CS GCM was utilised through CLIMEX.

2.4 Parameters in CLIMEX

CLIMEX parameters were adjusted with reference to the distribution data of the species *N. elegantalis* and *S. lycopersicum* under open-field cultivation. It is recommended to use the data of known distribution because it produces a model well suited to potential distribution.[67] Thereafter, we adjusted parameters to population

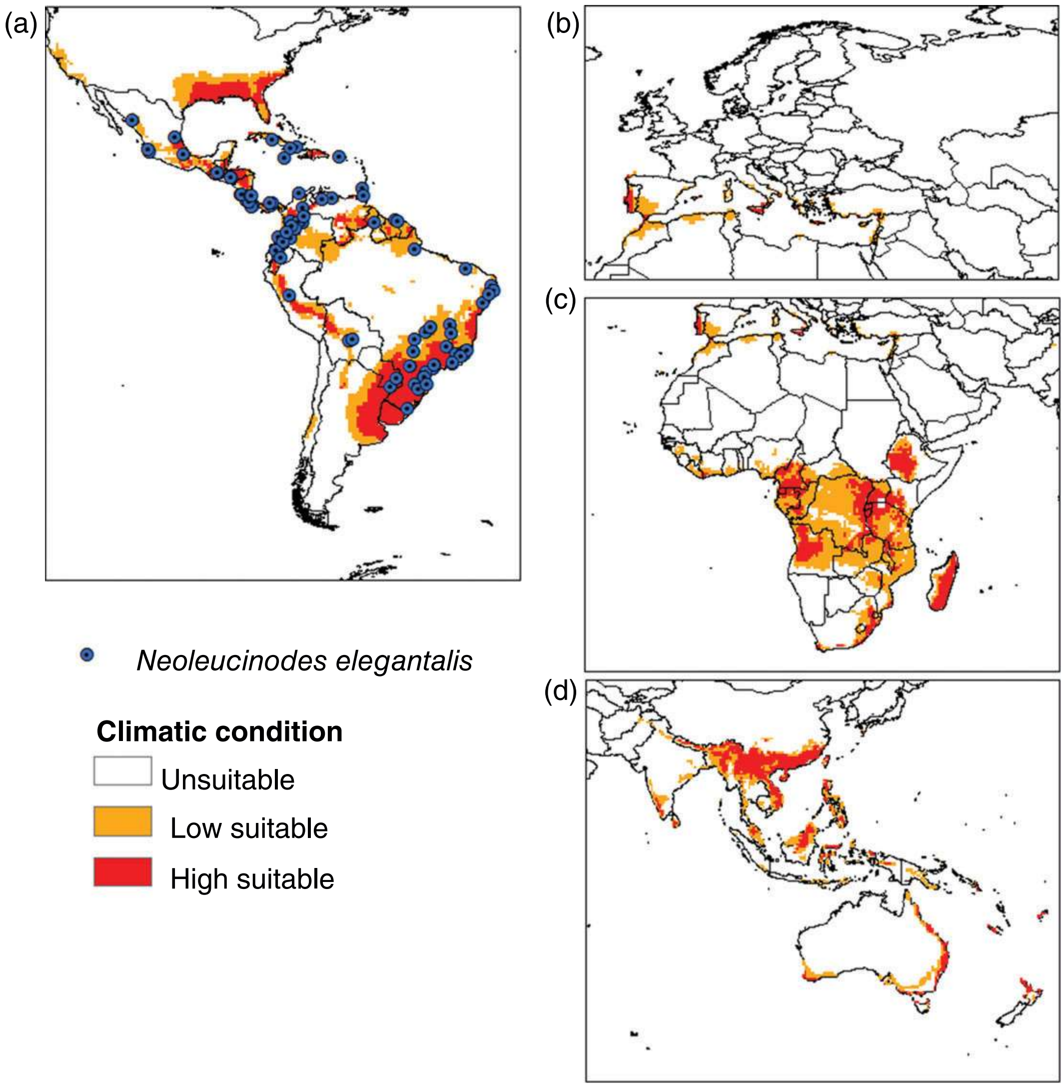

Figure 1. Ecoclimatic index (EI) for *N. elegantalis*, modelled using CLIMEX for current climate – unsuitable (EI = 0), low suitability (0 < EI ≤20), high suitability (EI > 20) – for North, Central and South America (a), Europe (b), Africa (c) and Asia, Australia and New Zealand (d). No suitable areas exist in other parts of the world.

growth and stress. Values set for these parameters were sourced from published data on *N. elegantalis* developmental characteristics and for climatic requirements for open-field *S. lycopersicum* cultivation. In addition, CLIMEX stress parameter values were set on the basis of satisfactory agreement of predictions observed between known and potential distribution of species in this study.

2.5 Growth parameters

Eight parameters were adjusted to set environmental conditions suitable for population growth of *N. elegantalis* and *S. lycopersicum* under open-field cultivation. These parameters are represented by the temperature and moisture indices. The temperature parameters are denoted by DV0 (limiting low temperature), DV1 (lower optimal temperature), DV2 (upper optimal temperature) and DV3 (limiting high temperature). The moisture parameters are denoted by SM0 (lowest threshold), SM1 (lower optimum moisture level), SM2 (upper optimum moisture level) and SM3 (upper moisture threshold).[29]

Studies of thermal requirements for *N. elegantalis* indicate suitable temperature parameters as DV0 = 8.8 °C and DV3 = 30 °C.[46] In addition, a temperature range of between 15 and 27 °C is regarded as being of high suitability for *N. elegantalis* population growth,[46] and thus DV1 and DV2 were set at 15 and 27 °C respectively. *N. elegantalis* has a higher incidence in wet tropical regions (Fig. 1), and thus we set SM0 = 0.35, SM1 = 0.7, SM2 = 1.5 and SM3 = 2.5, values representative of the distribution in wet tropical regions.[29,68]

Temperatures below 10 °C and above 35 °C can cause several physiological disorders in tomato plants, such as a reduction in vegetative development, inhibition of normal fruit colour and a reduction in fruit set and ripening.[55,69] The tomato plant survival range is from 10 to 35 °C;[55] however, the optimal temperature for high production and growth of tomato is between 20 and 30 °C.[55] Thus, DV0, DV1, DV2 and DV3 were set at 10, 20, 30 and 35 °C respectively. Tomatoes may be cultivated on different soil types.[55,69] Thus, our SM0 value was set at 0.1, to denote the permanent wilting point,[29] and SM1 and SM2 were set at 0.8 and 1.5 respectively. As in the case of *N. elegangalis*, SM3 was set at 2.5 to suit the wet tropical regions where open-field *S. lycopersicum* cultivation records are found.

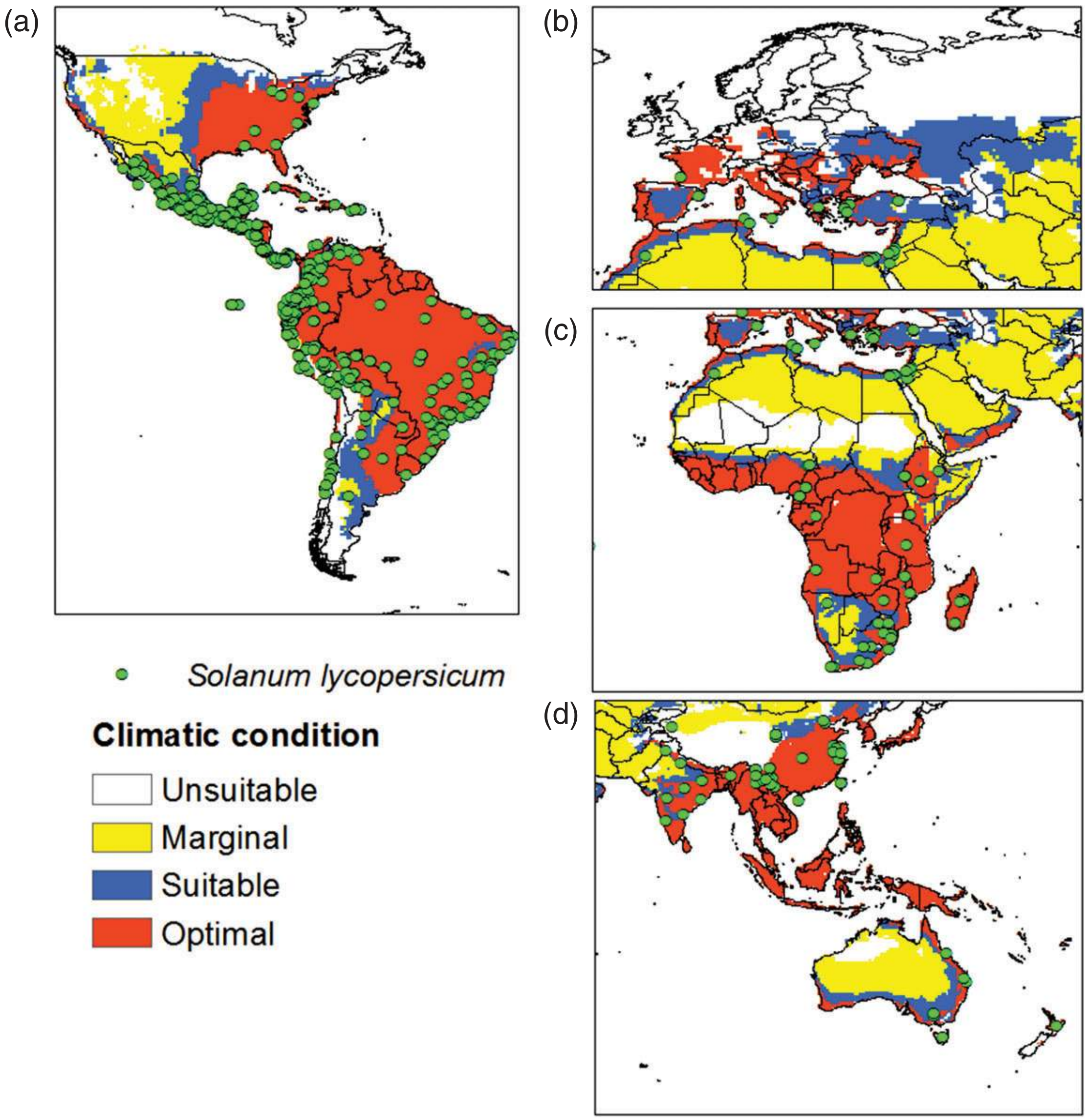

Figure 2. Ecoclimatic index (EI) for open-field *S. lycopersicum* cultivation, modelled using CLIMEX for current climate – unsuitable ($EI = 0$), marginal ($0 < EI \leq 10$), suitable ($10 < EI \leq 20$) and optimal ($EI > 20$) – for America (a), Europe (b), Africa (c) and Asia, Australia and New Zealand (d). No suitable areas exist in other parts of the world.

2.6 Cold stress

Cold stress may cause death of a species because the daily thermal accumulation is too low to maintain metabolism. This occurs when a threshold number of degree-days above the developmental temperature threshold (DVCS) is not reached. This threshold parameter is called the cold stress degree-day threshold (DTCS) and is expressed in units of degree-days. A species may also not survive if exposed to excessively low temperatures. In CLIMEX, the cold stress temperature threshold (TTCS) and cold stress temperature rate per week (THCS) represent the parameters of cold stress.[29] Thus, DTCS was set at 15 °C-days and DHCS at −0.001 week^{-1} for *N. elegantalis*. These values were chosen in terms of the prediction based on the known distribution of *N. elegantalis*. In cooler climates in particular, cold stress is a severely negative factor in the growth and development of the tomato plant.[55] For this reason, TTCS was set at 9.5 °C and THCS at −0.00003 week^{-1} for *S. lycopersicum*. These values provided a good fit for the distribution of *S. lycopersicum* cultivated in the open field.

2.7 Heat stress

Excessively high temperature exposure can have extremely negative impacts on species development. Insects may become infertile and crop production may be drastically reduced.[55,69] In CLIMEX, TTHS and THHS define the heat stress parameter and heat stress accumulation rate respectively. The embryonic development of *N. elegantalis* eggs does not occur above 30 °C.[46] Thus, TTHS was set at 30 °C and THHS was set at 0.0007 week^{-1} for *N. elegantalis*. High temperature is one of the most serious problems in open-field *S. lycopersicum* cultivation[55,69] owing to the physiological disorders that result in the plants. For example, temperatures over 30 °C inhibit fruit ripening. Thus, TTHS and THHS were set at 30 °C and 0.00001 week^{-1}, respectively, for *S. lycopersicum*.

2.8 Dry stress

The major known distributions of *N. elegantalis* are recorded in humid regions.[68] The dry stress threshold moisture level

Table 1. CLIMEX parameter values used for modelling

Index	Parameter	Values[a]	Values[b]
Temperature	DV0 = lower threshold	8.8 °C	10 °C
	DV1 = lower optimum temperature	15 °C	20 °C
	DV2 = upper optimum temperature	27 °C	30 °C
	DV3 = upper threshold	30 °C	35 °C
Moisture	SM0 = lower soil moisture threshold	0.35	0.1
	SM1 = lower optimum soil moisture	0.7	0.8
	SM2 = upper optimum soil moisture	1.5	1.5
	SM3 = upper soil moisture threshold	2.5	2.5
Cold stress	TTCS = temperature threshold	–	9.5 °C
	THCS = stress accumulation rate	–	-0.00003 week^{-1}
	DTCS = degree-day threshold	15 °C-days	–
	DHCS = stress accumulation rate	-0.001 week^{-1}	–
Heat stress	TTHS = temperature threshold	30 °C	30 °C
	THHS = stress accumulation rate	0.0007 week^{-1}	0.00001 week^{-1}
Dry stress	SMDS = soil moisture threshold	0.35	0.1
	HDS = stress accumulation rate	-0.001 week^{-1}	-0.005 week^{-1}
Wet stress	SMWS = soil moisture threshold	2.5	2.5
	HWS = stress accumulation rate	0.002 week^{-1}	0.001 week^{-1}
Degree-days	PDD = degree-days	588.2	940

[a] Values used for *N. elegantalis*.
[b] Values used for *S. lycopersicum*.

(SMDS) was thus set at a value of 0.25, and dry stress accumulation (HDS) at a rate of -0.001 week^{-1}. These values account for the absence of *N. elegantalis* in central-western Brazil. Where tomato plants are exposed to extreme low humidity, there is a reduction in growth owing to stomatal closure and therefore reduced photosynthesis.[55,69] SMDS was set at 0.1 with HDS at -0.005 week^{-1} for *S. lycopersicum*, values based on known distributions in Brazil and East Africa.

2.9 Wet stress

Wet stress may negatively affect both species under study. Insects can die owing to high precipitation, and in *S. lycopersicum* cultivation, diseases may increase.[55,70] Thus, the wet stress parameter (SMWS) was set at 2.5 for both species and the stress accumulation rate (HWS) at 0.002 week^{-1} for *N. elegantalis* and 0.001 week^{-1} for *S. lycopersicum* cultivation. The values listed showed a satisfactory match with known distributions for both species.

2.10 Irrigation scenario for *S. lycopersicum* cultivation

Both a lack of and excess irrigation in *S. lycopersicum* cultivation are factors that influence production. Cultivation requires proper water management to obtain high yields and good-quality fruit, and thus where natural rainfall is lacking, irrigation is necessary. Thus, we used the irrigation scenario in CLIMEX with projections to top up natural rainfall to a level of 3 mm per day in summer and 1 mm per day in winter, based on irrigation regimens used in open-field cultivation.[55,69] All CLIMEX parameter values are presented in Table 1.

2.11 Validation of models

The models were validated against independent observations from Central America and the Andean region (Chile, Colombia, Ecuador, Bolivia and Peru), and verified visually according to the known distributions. We calculated the percentage of the occurrence points of both species that fall within the model prediction to evaluate the reliability of our models.

2.12 Determining the risk levels

Agreement in projections of areas for *N. elegantalis* growth were overlaid with optimal areas for open-field *S. lycopersicum* cultivation ($EI > 20$) to identify current risk levels of *N. elegantalis* growth worldwide, and for the years 2030, 2050, 2070 and 2100. All locations that satisfied the condition $EI = 0$ for *N. elegantalis* and $EI > 20$ for open-field *S. lycopersicum* cultivation were considered to be at low risk of invasive *N. elegantalis*. The condition $0 < EI < 20$ for *N. elegantalis* and $EI > 20$ for open-field *S. lycopersicum* cultivation was used to identify areas optimal for open-field *S. lycopersicum* cultivation with a moderate risk level of *N. elegantalis*. Lastly, areas with $EI > 20$ for both species were defined as areas optimal for open-field *S. lycopersicum* cultivation with a high risk level of *N. elegantalis*.

3 RESULTS

The potential distribution of *N. elegantalis* and open-field *S. lycopersicum* cultivation matches well with the known distribution of these species (Figs 1a and 2). In Central America and the Andean region, the model sensitivity of *N. elegantalis* was high, with 95% agreeing with the known distribution of this species (Fig. 1). Analysing the distribution of *S. lycopersicum* in Central and South America, the global climate suitability model of open-field *S. lycopersicum* cultivation shows a 99% correlation with the modelled EI (Fig. 2). Thus, the high percentage of agreement with the validation areas has shown our models to be highly reliable. Our models show large areas in North America, Europe, Africa, Asia, Australia and New Zealand with high suitability for *N. elegantalis*, ignoring the distribution of species host, at the present time (Fig. 1). Considering the *S. lycopersicum* model, we observed that most of the known distribution for open-field *S. lycopersicum* cultivation

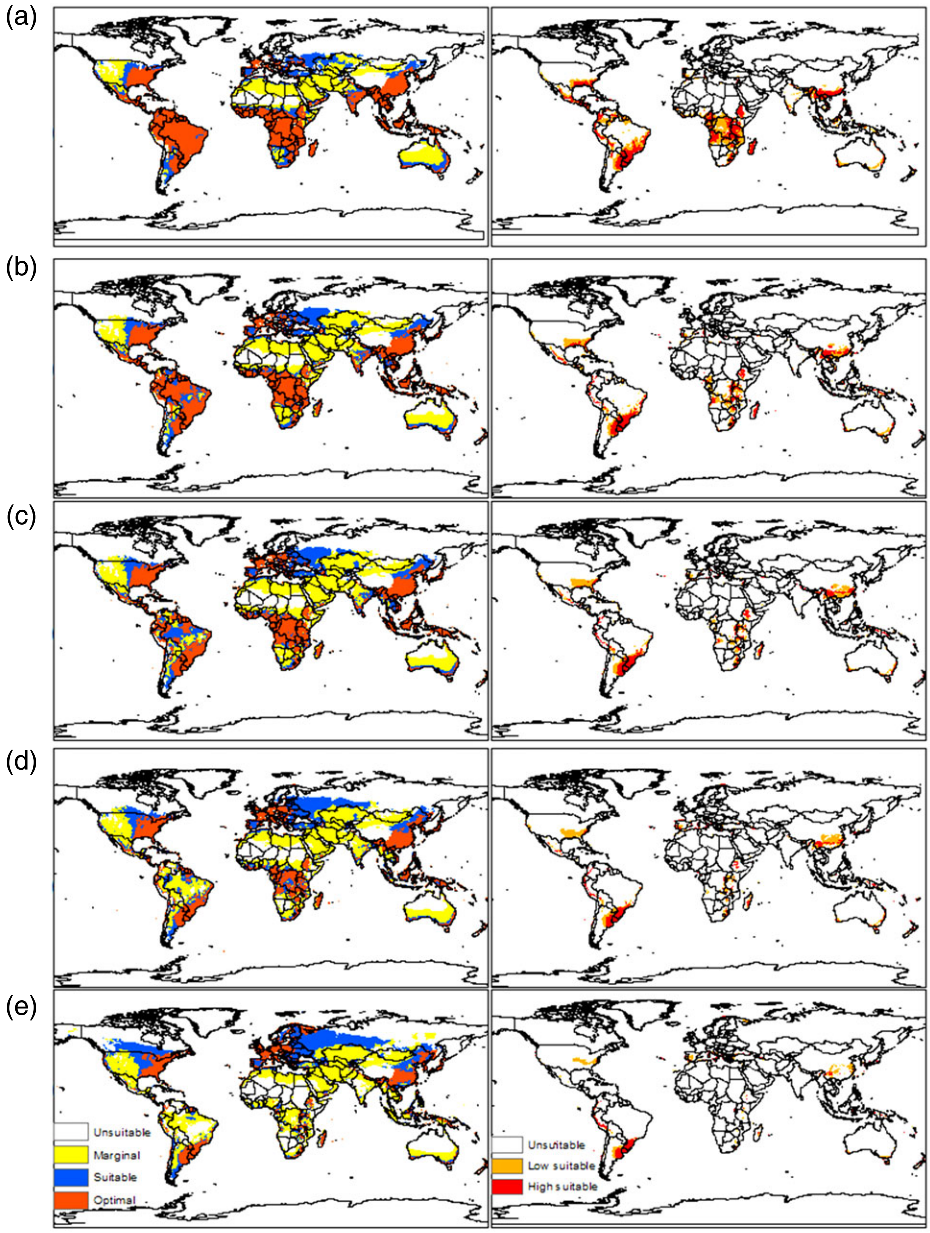

Figure 3. The climate EI for open-field *S. lycopersicum* cultivation (left) and *N. elegantalis* (right), projected using CLIMEX for the present time (a) and CSIRO-Mk3.0 GCM running the SRES A2 scenario for 2030 (b), 2050 (c), 2070 (d) and 2100 (e).

in North America, Europe, Africa, Asia, Australia and New Zealand matches the model prediction of optimal areas for *S. lycopersicum* growing (Fig. 2).

In relation to current climate, the CS GCM predictions for 2030, 2050, 2070 and 2100 project that many regions of Central and South America, Sub-Saharan Africa, India and Indonesia will undergo a reduction in areas optimal for open-field *S. lycopersicum* cultivation (Fig. 3). Conversely, however, large areas of North America and Europe that are currently unsuitable or marginal are likely to become suitable or optimal in the future (Fig. 3).

In the majority of the countries, the CS GCM indicates a progressive reduction in areas with highly suitable climatic conditions for *N. elegantalis* by 2030, 2050, 2070 and 2100 in relation to the present. Large areas in Central and South America, Sub-Saharan Africa, Asia and Australia may become unsuitable for *N. elegantalis* in the future. Conversely, Portugal and other European Mediterranean regions, including parts of Spain, France, Italy, Greece, Croatia, Albania and Turkey, are projected to maintain or become highly suitable for *N. elegantalis* according to the projected scenarios for the future (Fig. 3).

Figures 4 to 7 show the results of current climate and projections for the risk levels of invasive *N. elegantalis* for areas optimal for open-field *S. lycopersicum* cultivation for 2030, 2050, 2070 and 2100 for North, Central and South America, Europe, Africa, Asia, Australia and New Zealand respectively.

Much of the Americas have low, moderate or high risk levels for *N. elegantalis* in areas climatically optimal for open-field *S. lycopersicum* cultivation at the present time (Fig. 4). Almost all areas in Central and South America with a high risk level of *N. elegantalis* already have this species (Fig. 1). However, in most of the areas with low, moderate or high risk levels, as projected by CS GCM, a progressive decrease occurs over the years 2030,

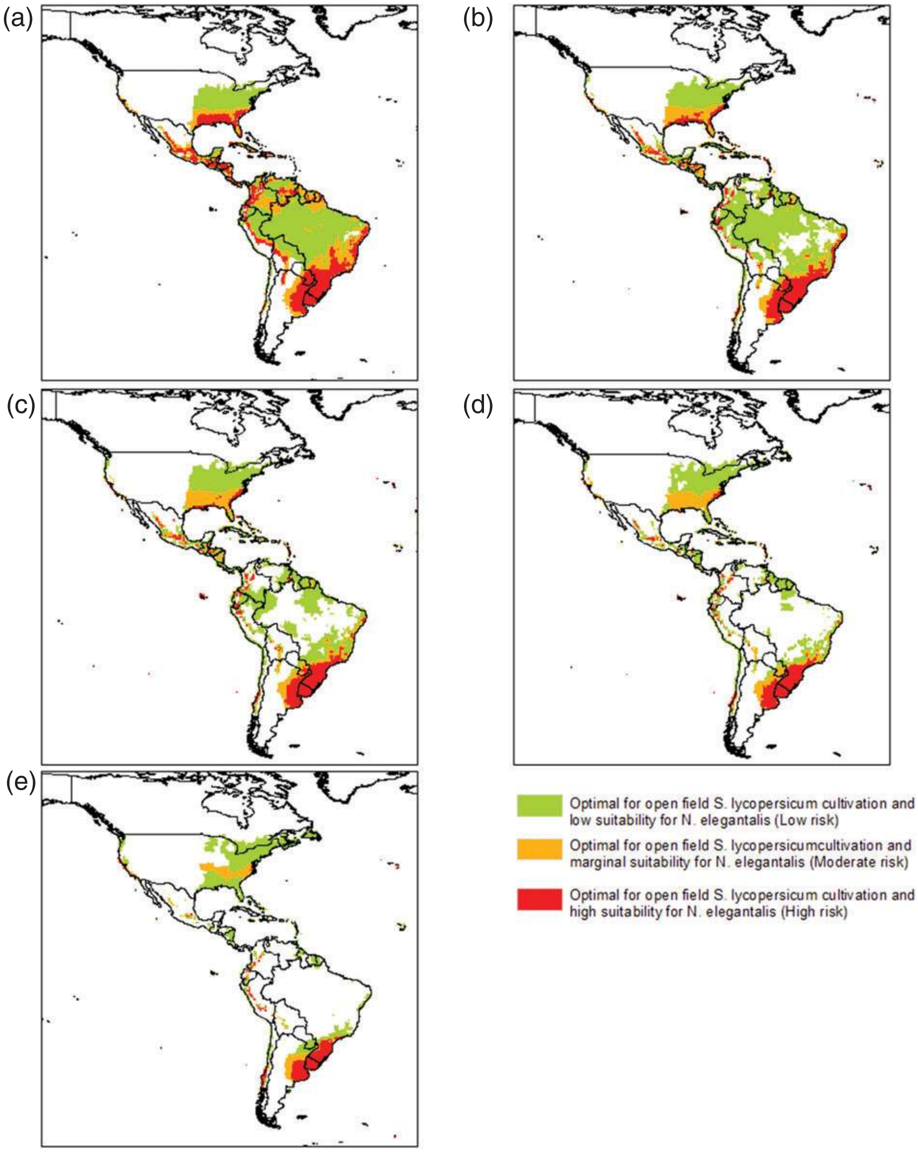

Figure 4. Agreement in the CLIMEX projection optimal areas for open-field *S. lycopersicum* cultivation growth with three risk levels of invasive *N. elegantalis* at the present time (a) and CSIRO-Mk3.0 GCM running the SRES A2 scenario for 2030 (b), 2050 (c), 2070 (d) and 2100 (e), based on EI for both species for North, Central and South America.

2050, 2070 and 2100 (Fig. 4). Conversely, areas in South Chile will become moderate risk levels from 2030 to 2070, and some areas will become high risk levels of *N. elegantalis* by 2100 (Fig. 4).

In the European Mediterranean region, the risk level of *N. elegantalis* is moderate or high in southern regions, while Northern Europe has large areas optimal for open-field *S. lycopersicum* cultivation but unsuitable for *N. elegantalis*, and thus at a low risk level at the present time (Fig. 5). According to projected scenarios for 2030, 2050, 2070 and 2100, the risk level from *N. elegantalis* in European Mediterranean regions will increase progressively (Fig. 5).

In large areas of Sub-Saharan Africa, the greater risk levels from *N. elegantalis* at the present time are moderate and high (Fig. 6), mainly in regions with optimal climatic conditions for open-field *S. lycopersicum* cultivation that already have tomato production (Fig. 2). The CS CGM results show a great reduction in risk level from *N. elegantalis* for the future (Fig. 6) owing to a progressive reduction in climatic conditions suitable for both species (Fig. 3). On the other hand, we observe an increase in the risk level in northern Iran, as well as in Algeria, Morocco, Western Sahara and Tunisia (Fig. 6).

At the present time, the results show great areas under high risk of *N. elegantalis* in southern China, Malaysia and in the coastal regions of Australia and some areas in northern New Zealand (Fig. 7). The prediction of the CS GSM for China, Malaysia and the coast of northern Australia shows a change in areas from high risk level to low and moderate risk levels of *N. elegantalis* from 2030 to 2100 (Fig. 7). However, a high risk of *N. elegantalis* remains along the coast of southern Australia, and a progressive increase in northern New Zealand is observed in the future (Fig. 7).

4 DISCUSSION

The models presented here show a high degree of reliability. The models show a 95 and 99% agreement between known distribution of *N. elegantalis* and *S. lycopersicum* cultivation, respectively, with the modelled global climate at the present

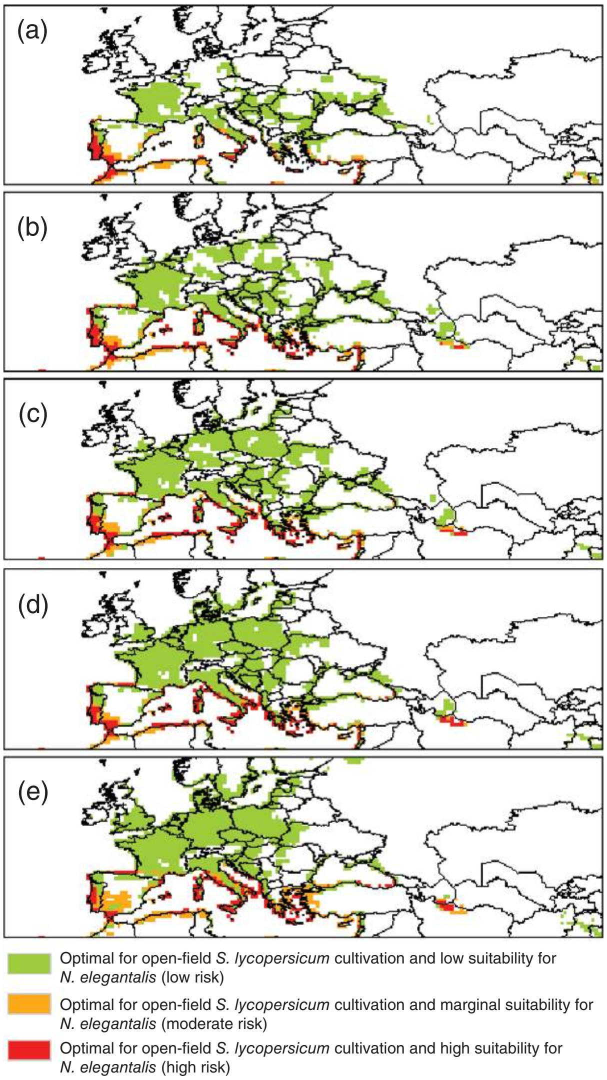

Figure 5. Agreement in the CLIMEX projection optimal areas for open-field *S. lycopersicum* cultivation growth with three risk levels of invasive *N. elegantalis* at the present time (a) and CSIRO-Mk3.0 GCM running the SRES A2 scenario for 2030 (b), 2050 (c), 2070 (d) and 2100 (e), based on EI for both species for Europe.

time. The high percentage of accordance with the distributions of both species highlights the suitability and consistency of these models.[71] Thus, the results of overlaying these models are very reliable for evaluating the risk levels of *N. elegantalis* worldwide.

The results of our research point to some potential future threats to open-field *S. lycopersicum* cultivation, particularly in South America, Indonesia, India and Sub-Saharan Africa. Further, the results indicate that, under projected future climates, North America and large parts of Europe will become suitable for open-field *S. lycopersicum* cultivation. The CS-predicted increases in temperature may either increase or reduce stresses that impose limitations on the growth of *S. lycopersicum*, which are generally sensitive to environmental extremes, and thus high or low temperatures can impact negatively.[55] In general, vegetables react adversely to environmental extremes. High temperatures are a major cause of reduction in yields in tropical regions, which will be magnified by climate change.[72]

While the majority of models investigating the behaviour of invasive insect pests under climate change predict an increase in invasions,[73–76] we found the converse for *N. elegantalis* in some regions of the world. In almost all countries in Central and South America, Sub-Saharan Africa, Asia and North Australia, the climatic conditions, currently favourable both for *N. elegantalis* and for open-field *S. lycopersicum* cultivation, will become less suitable or unfavourable for them, according to projected scenarios for 2030, 2050, 2070 and 2100. In contrast, areas in South Chile, European Mediterranean regions, the coast of North Africa, southern Australia and northern New Zealand are predicted to maintain or increase progressively optimal climate conditions for open-field *S. lycopersicum* cultivation, as well as becoming highly suitable for *N. elegantalis*. These predictions imply that greater areas of Central and South America may experience a reduction in impact. Conversely, in Europe, the coast of North Africa, southern Australia and northern New Zealand, the introduction of *N. elegantalis* may have a negative impact on cultivation.

Although many parts of the world have favourable conditions for *N. elegantalis*, it only occurs in Central and South America (Fig. 1). Some hypotheses explain this as a result of an efficient system of border protection or a lack of host species for *N. elegantalis*. There is no evidence showing that *N. elegantalis* has diapause, and thus to maintain survival over time there is a need for host plants.[31,46,47] In Central and South America, where its occurrence is high, there are 23 and 16 host species of *N. elegantalis* respectively.[77,78] Of these species, six are weed species, all with occurrence only in South America and four in Central America with high numbers of occurrences registered.[62] Weed species are important for the maintenance of insect pests.[79] However, the major host of *N. elegantalis* is tomato, *S. lycopersicum*.[31,36] This species is cultivated worldwide and has been spreading extremely rapidly, increasing by about 300% over the last four decades.[55] Thus, the predictions of risk levels of *N. elegantalis* for *S. lycopersicum* at the present time and the future predictions in this study are relevant.

The pathways of *N. elegantalis* introduction could be via international trade or through travellers with fruits infested. The survival of *N. elegantalis* is possible owing to the high registers of interception of *N. elegantalis* reported in the Netherlands and the United States.[33,34] The rates of invasive alien species have been increasing in Europe,[80] China[81] and North America[82] in recent decades. This is largely attributable to increased international trade.[83–85]

S. lycopersicum cultivation is expanding into previously uncultivated areas owing to increases in the transportation costs of this perishable vegetable, from the traditional production areas to consumption centres, as well as owing to a general increase in the consumption of vegetables.[86,87] Additionally, in 2015 there were over 1 billion travellers moving between different countries around the world, and this is forecast to reach 1.8 billion by 2030.[88] Thus, the introduction and establishment of *N. elegantalis* in new areas may well be only a matter of time, if no preventive measures are established in areas optimal for open-field *S. lycopersicum* cultivation with a high suitability for *N. elegantalis*. Thus, the modelling results of overlaying both species at the present time for North America, European Mediterranean regions, North and Sub-Saharan Africa, China, Indonesia, Australia and New Zealand provide useful information to governments for developing strategies of inspection and interception for *N. elegantalis*, particularly in zones with high risk levels.

Insects are poikilothermic organisms and as such are particularly sensitive to temperature changes, especially those species that have narrow thermal tolerances, such as *N. elegantalis*.[89] In most countries, vegetable production is always dependent on environmental conditions, which vary according to season and

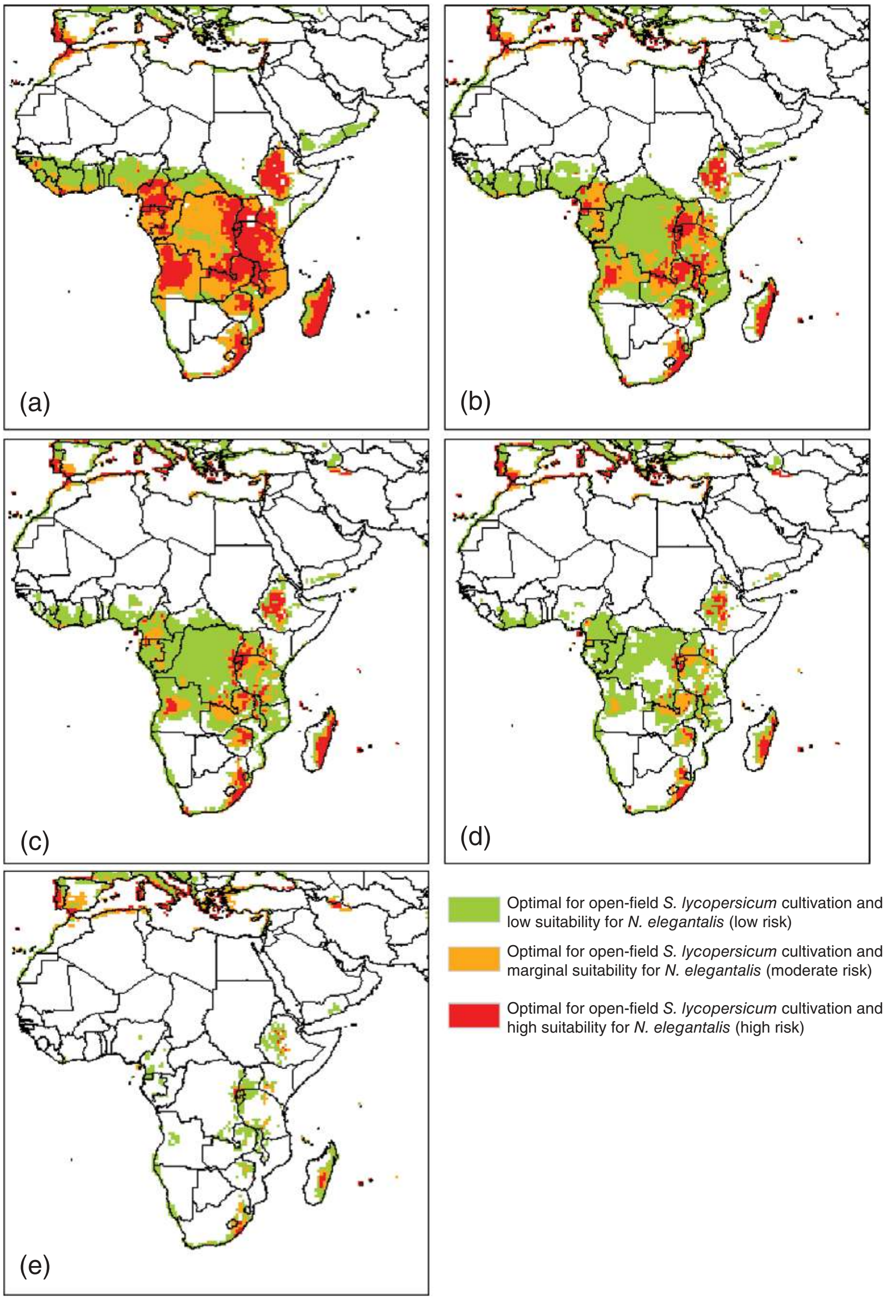

Figure 6. Agreement in the CLIMEX projection optimal areas for open-field *S. lycopersicum* cultivation growth with three risk levels of invasive *N. elegantalis* at the present time (a) and CSIRO-Mk3.0 GCM running the SRES A2 scenario for 2030 (b), 2050 (c), 2070 (d) and 2100 (e), based on EI for both species for Africa and the Middle East.

region.[72,90] Thus, the impact of climatic changes on vegetable crop production and the potential distributions of pests should be a major concern.

The predicted climate change will have positive or negative impacts in terms of climatic suitability for both species in this study (Fig. Y3), and regions predicted to become highly conducive for open-field *S. lycopersicum* cultivation may have different risk levels to that of *N. elegantalis* in the future. We find a reduction in risk levels of *N. elegantalis* agrees with our model predictions for countries in North, Central and South America (exception Chile), Sub-Saharan and North Africa, Asia and North Australia. Conversely, our results show Chile, European Mediterranean regions, northern Iran, Algeria, Morocco, Western Sahara and Tunisia, the coast of southern Australia including Tasmania and New Zealand having an increase in risk levels.

The overlay models created in this study, comparing current climatic conditions and future projections, can provide decision-makers with information about the risk levels of *N. elegantalis*. In interpreting these results, the following should be considered: (a) the modelling was performed based only on climate and does not take into consideration other factors such as land uses, soil types, biotic interactions, diseases and competition; (b) this research was based on currently available broad-scale climate data, and therefore it only shows broad-scale shifts; (c) it is indicative because a certain level of uncertainty is associated with future levels of GHG emissions; (e) in the present study, carbon

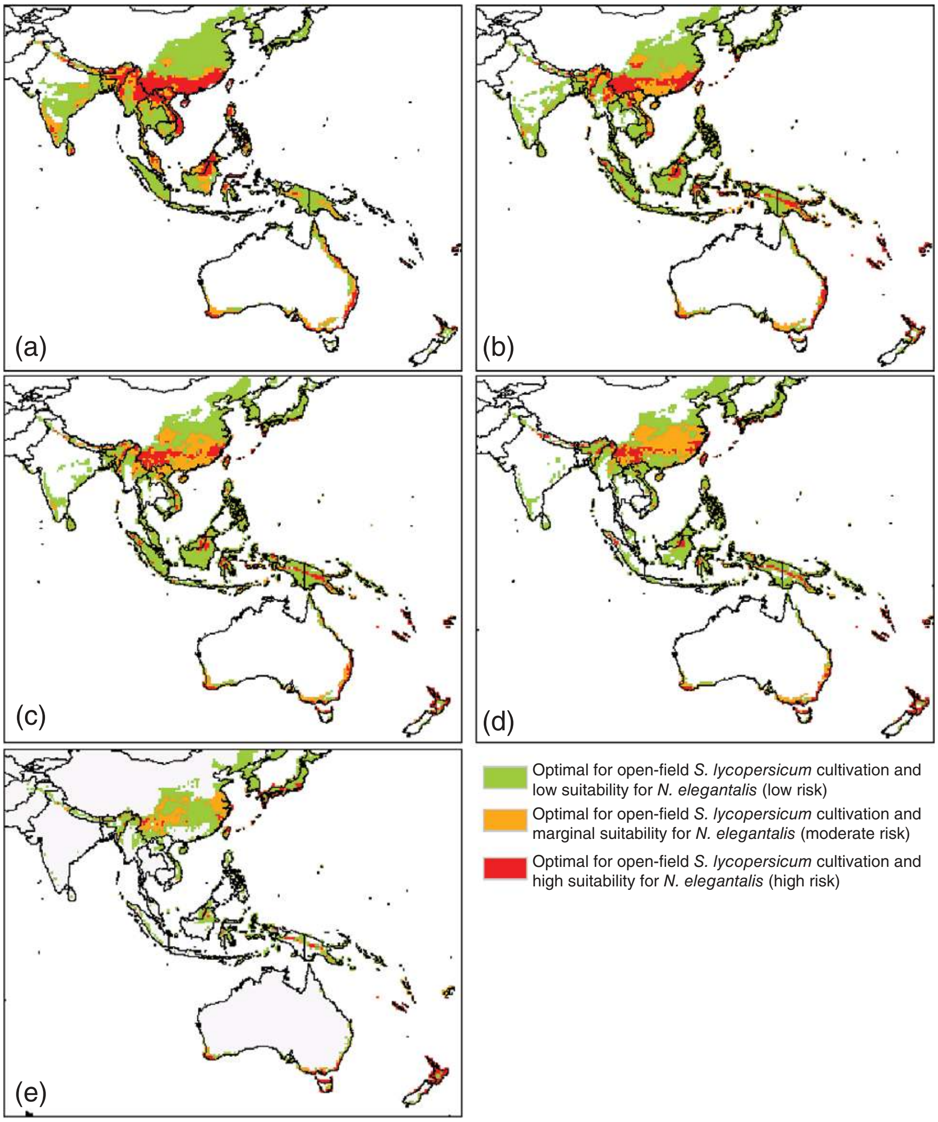

Figure 7. Agreement in the CLIMEX projection optimal areas for open-field *S. lycopersicum* cultivation growth with three risk levels of invasive *N. elegantalis* at the present time (a) and CSIRO-Mk3.0 GCM running the SRES A2 scenario for 2030 (b), 2050 (c), 2070 (d) and 2100 (e), based on EI for both species for Asia, Australia and New Zealand.

dioxide enrichment and the potential genetic progress were not taken into account.

5 CONCLUSION

The predicted climate alterations may have positive or negative impacts in terms of climatic suitability for different species. In this study, some regions are predicted to become highly conducive for open-field *S. lycopersicum* cultivation, with different risk levels of *N. elegantalis* in the future. The risk level results presented here provide an initial study, using CLIMEX modelling, of the risk assessment of *N. elegantalis* in potential areas with optimal climatic conditions for open-field *S. lycopersicum* cultivation. Our models have been proven to be robust and reliable and thus may be used in designing strategies to prevent the introduction and establishment of *N. elegantalis* in new areas, as well as for monitoring programmes in areas with a current occurrence of *N. elegantalis*. In addition, these results can be used in future research plans of *N. elegantalis* management, with the inclusion of non-climatic factors such as biotic interactions, establishment, dispersal and adaptations.

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