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CLIMATE CHANGE AND AGRICULTURE RESEARCH PAPER

Assessing the impact of global warming on worldwide open field tomato cultivation through CSIRO-Mk3·0 global climate model

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SUMMARY

Tomato (*Solanum lycopersicum* L.) is one of the most important vegetable crops globally and an important agricultural sector for generating employment. Open field cultivation of tomatoes exposes the crop to climatic conditions, whereas greenhouse production is protected. Hence, global warming will have a greater impact on open field cultivation of tomatoes rather than the controlled greenhouse environment. Although the scale of potential impacts is uncertain, there are techniques that can be implemented to predict these impacts. Global climate models (GCMs) are useful tools for the analysis of possible impacts on a species. The current study aims to determine the impacts of climate change and the major factors of abiotic stress that limit the open field cultivation of tomatoes in both the present and future, based on predicted global climate change using CLIMatic indEX and the A2 emissions scenario, together with the GCM Commonwealth Scientific and Industrial Research Organisation (CSIRO)-Mk3·0 (CS), for the years 2050 and 2100. The results indicate that large areas that currently have an optimum climate will become climatically marginal or unsuitable for open field cultivation of tomatoes due to progressively increasing heat and dry stress in the future. Conversely, large areas now marginal and unsuitable for open field cultivation of tomatoes will become suitable or optimal due to a decrease in cold stress. The current model may be useful for plant geneticists and horticulturalists who could develop new regional stress-resilient tomato cultivars based on needs related to these modelling projections.

INTRODUCTION

Tomato (*Solanum lycopersicum* L.) is one of the most economically important crop species globally and features as a model organism in many research studies (Jones 2007; Kimura & Sinha 2008; Caicedo & Peralta 2013; Chen *et al.* 2015). Tomatoes are universally one of the most widely used culinary ingredients and many of the inherent compounds have received much interest in recent years for their potential health benefits (Bhowmik *et al.* 2012; Combet *et al.* 2014). The global production of the crop has increased by about 300% over the last four decades (FAOSTAT 2015). Further, tomato production as an agricultural business is a major source of livelihood in many regions of the world, offering great potential for generating employment (Singh 2004; Robinson *et al.* 2013; Padilla-Bernal *et al.* 2015).

The cultivation of tomatoes is divided into two major production methods: the capital intensive system using modern technology in greenhouse structures, as opposed to the traditional farming of tomatoes in the open field (Lang 2004; Heuvelink 2005), which is far more influenced by climatic factors. Due to unfavourable environmental conditions caused by abiotic factors that include high or low temperatures and excessive water or drought, tomato production is sub-optimal over large parts of the tomato crop-growing areas of the world. Other factors that influence tomato production, such as irrigation and fertilization, apply equally to greenhouse and field production. Cultivation requires proper water

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management to obtain high yields and good quality fruit, thus irrigation is necessary where natural rainfall is lacking (Heuvelink 2005; Jones 2007).

The effects of global warming, also referred to as climate change, have been shown in several biological study areas (Parmesan 2006; Shabani *et al*. 2013; Wheeler & von Braun 2013) and for the first time an international climate agreement has established a goal to maintain warming below 2 °C (COP 2015). The scale of the potential impact of global warming is uncertain. Changes may be direct in bringing about sweeping changes in food production conditions and increasing the number of deaths from floods, storms, heatwaves and droughts, or may have indirect effects such as unemployment in rural areas that need specific climate conditions for the growth of agricultural crops, such as the open field cultivation of tomatoes (Carvajal 2007). While such impacts may be uncertain, there are many techniques that can be implemented for predicting potential impacts on agriculture through the use of modelling software.

Models are useful and important tools for the analysis of possible impacts on particular species on a local or global scale since they provide important information enabling the establishment of guidelines and principles for the implementation of remedial measures (Jarnevich *et al*. 2015; Miller *et al*. 2015). Some commonly used Species Distribution Models (SDMs), in terms of distribution of agricultural crops, are CLIMatic indEX (CLIMEX), Maximum Entropy (MaxENT) modeling and BIOCLIMatic variables (BIOCLIM) (Jarvis *et al*. 2008; Eitzinger & Läderach 2011; Shabani *et al*. 2012, 2014, 2015; Parthasarathy *et al*. 2013; Ramirez-Cabral *et al*. 2016).

The bioclimatic models most frequently used are correlative, such as MaxEnt, linking environmental spatial data and records of a species' distribution and employing either statistical or machine learning methods (Elith & Leathwick 2009). Mechanistic bioclimatic models, such as CLIMEX, are more intensive in terms of time and data, linking a species' ecophysiological responses to environmental covariates (Kriticos & Randall 2001; Kearney & Porter 2009; Webber *et al*. 2011). In this context, it is claimed that outputs of correlative models give closer alignment with realized distributions of species, while mechanistic models give a closer match to the fundamental climate niche (Soberón 2010; Rodda *et al*. 2011). In differentiating between the fundamental and realized niche, it should be clarified that this refers to climate factors, which constitute a component of a species' niche. Further defining the differentiation, fundamental climatic space outlines potential climatic conditions that would support a species if these were the only limitation factors, while realized climate space denotes the range of climate conditions actually occupied (Rodda *et al*. 2011). Of these, CLIMEX has been rated one of the most reliable and comprehensive inferential modelling programs (Kriticos & Randall 2001) and produces a niche model that may be described as process-oriented and ecophysiological. It is capable of combining inferential and deductive models to describe responses of a species to climatic factor variability in order to project potential geographical distribution (Webber *et al*. 2011).

There have been devastating forecasts of the potentially disastrous effects of climate change on food crop production. Moderate average temperature increases alone affect the quantities and quality of tomato production yields (Gould 1992; Heuvelink 2005; Jones 2007). An understanding of changing climatic factors linked to crop cultivation, in both the present and the future, is thus essential for effective optimal management of open field tomato cultivation. Using CLIMEX and the A2 emissions scenario (IPCC 2000), coupled with the Commonwealth Scientific and Industrial Research Organisation's (CSIRO) global climate model (GCM) CSIRO-Mk3·0 (CS), the current study sets out to establish the global impacts of climate change on the open field cultivation of tomatoes and the major stress factors that limit growth in the present and future, based on expected global climate changes for the years 2050 and 2100.

MATERIALS AND METHODS

CLIMatic indEX

CLIMEX is highly regarded as a suitable bioclimatic niche model for estimating a plant species' potential distribution (Kriticos & Randall 2001; Sutherst *et al*. 2007). It allows the prediction and mapping of potential distribution using specific climatic parameters representing the species' climatic responses (Sutherst *et al*. 2007). Favourable season growth is maximized and unfavourable season growth is minimized (Sutherst & Maywald 1985; Sutherst *et al*. 2007), as Fig. 1 illustrates. Based on the phenological or geographic range records of the species, parameters that illustrate response to climate may be inferred in CLIMEX to decide parameters that illustrate the species' response to climate (Sutherst *et al*. 2007).

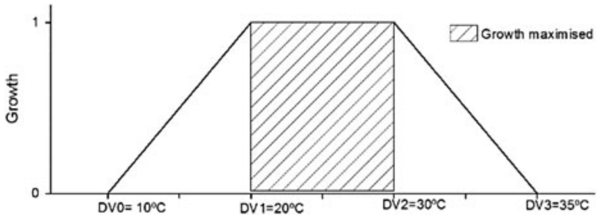

Fig. 1. Temperature as a function of population growth. DV0, DV1, DV2 and DV3 are parameters used to define the range of temperatures suitable for population growth where: DV0, the lower temperature threshold; DV1, the lower optimum temperature; DV2, the upper optimum temperature and DV3, the upper temperature threshold.

CLIMatic indEX enables the users to combine the growth and stress indices into an Ecoclimatic Index (EI). The EI is a general annual index of climatic suitability, which describes the climatic suitability of a location for a species, scaled from 0 to 100. In favourable climate conditions the annual growth index (GI_A) describes the potential for population growth. To determine the value of GI_A, temperature (TI) and moisture (MI) indices are used, which represent the requirements for species growth. Users may additionally include stress indices representing temperature and moisture extremes beyond which survival is unlikely. Thus, by considering factors denoting adverse seasonal conditions, a species' distribution may be determined (Sutherst *et al.* 2007).

Distribution of open field cultivation of tomatoes

Data representing open field cultivation of tomatoes (*S. lycopersicum*) was collected from scientific research publications, reports and an internet search of the Global Biodiversity Information Facility (GBIF http://www.gbif.org/, accessed 09 November 2015). The GBIF data from countries where greenhouse tomatoes are widely cultivated was used with caution. It should be noted that all SDMs are affected to some degree by data quality, completeness and potential biases (Stohlgren 2007). Thus, GBIF data from cultivation of tomatoes in greenhouses was discarded. However, open field cultivation data was collected from scientific publications and reports to represent those regions in which GBIF data was discarded (Sorribas & Verdejo-Lucas 1994; Heuvelink 2005; Hickey *et al.* 2006; Nordenström *et al.* 2010; Martínez-Blanco *et al.* 2011; Patanè *et al.* 2011; O'Connell *et al.* 2012; Gerard *et al.* 2013). A total of 6481 records representing the open field cultivation of *S. lycopersicum* are shown in Fig. 2(*a*).

Climatic data, models and scenarios

For the CLIMEX model, CliMond 10′ gridded climate data was employed (Kriticos *et al.* 2012). Average climate for the historical period 1950–2000 was denoted by the average maximum monthly temperature (T_{max}), average minimum monthly temperature (T_{min}), average monthly precipitation (P_{total}) and relative humidity recorded at 09.00 h (RH09 : 00) and 15.00 h (RH15 : 00). The same variables were used for the modelled future climate. Global distribution of *S. lycopersicum* for 2050 and 2100 was modelled under the A2 emissions scenario using GCM, CSIRO-Mk3·0 (CS) of the Center for Climate Research, Australia (Gordon *et al.* 2002). The CS climate system model contains a comprehensive representation of the four major components of the climate system (atmosphere, land surface, oceans and sea-ice), and in its current form is as comprehensive as any of the global coupled models available worldwide (Gordon *et al.* 2002).

The selection of CS from 23 other GCMs was based on its fulfilment of three basic requirements. Firstly, it supplied all the required CLIMEX variables: temperature, precipitation and humidity. Secondly, an output with relatively small horizontal grid spacing was required. Thirdly it was found that on a regional scale, this GCM performed well compared with others (Hennessy & Colman 2007; Kriticos *et al.* 2012). Predictions from CS incorporate an increase of 2·11 °C in temperature and a reduction of 14% in rainfall by 2100 (Suppiah *et al.* 2007; Chiew *et al.* 2009).

The choice of the A2 emissions scenario was based on the consistency of its assumptions and its inclusion of demographic, technological and financial factors relating to atmospheric greenhouse gases (GHG), established on data researched from independent and self-reliant nations. The A2 scenario assumes a relatively moderate increase in global GHG emissions, neither very high nor low compared with other scenarios such as A1F1, A1B, B2, A1 T and B1 (Bernstein *et al.* 2007).

Adjustment of CLIMatic indEX parameters

CLIMatic indEX parameter adjustments were made according to the open field distribution data of *S. lycopersicum*. The use of known distribution data is recommended because it produces a model suitable for creating a potential future distribution model (Kriticos & Leriche 2010). Thus, the experiment began with the objective of constructing a CLIMEX model determining the climate favourable for

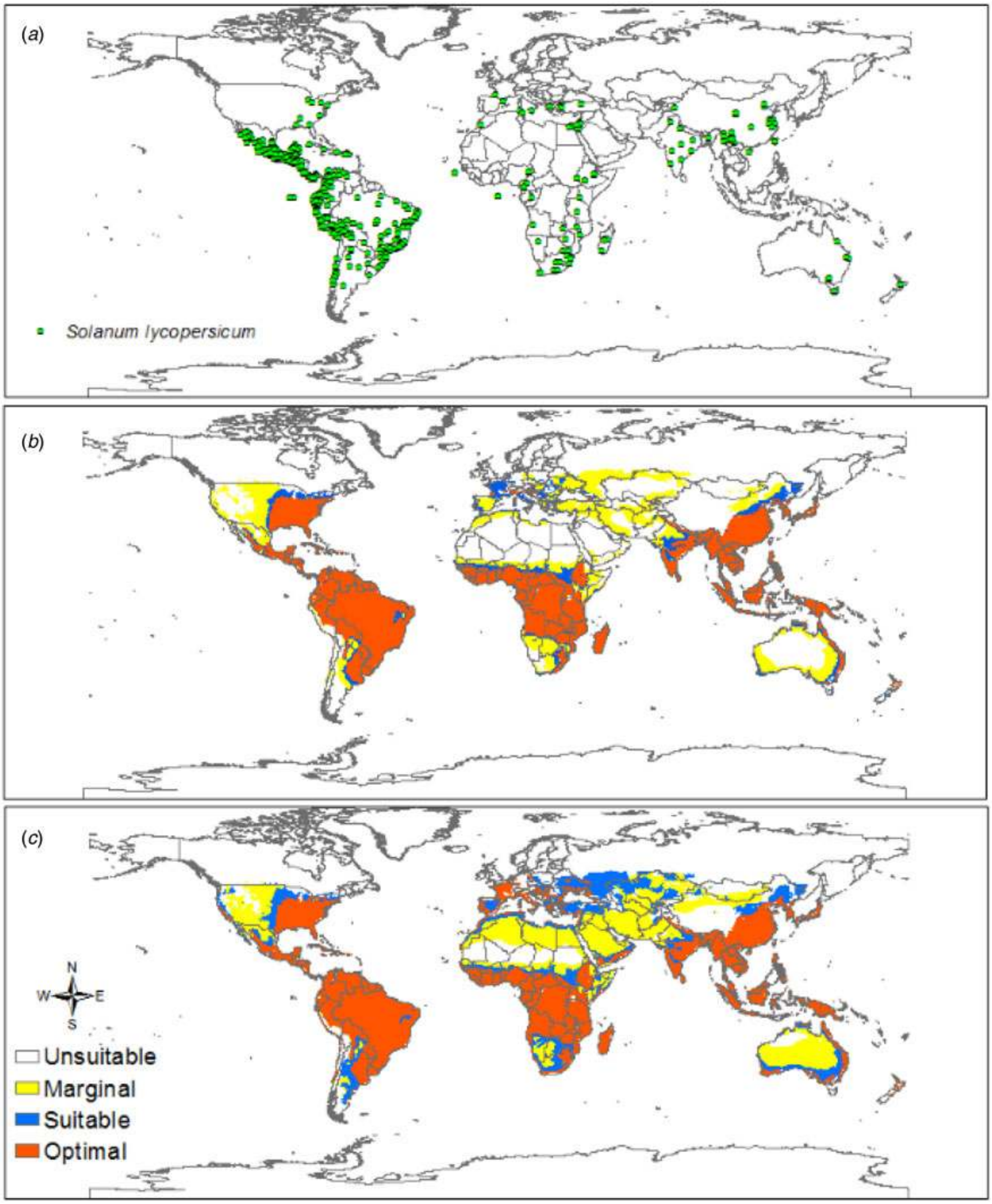

Fig. 2. The global known distribution of *S. lycopersicum* cultivated in open fields (*a*), and the Ecoclimatic Index (EI) for *S. lycopersicum*, modelled using CLIMatic indEX (CLIMEX) for current climate without (*b*) and with (*c*) irrigation scenarios. Colour online.

S. lycopersicum, based on some of the known distribution (Fig. 2(*a*)) and physiological data for *S. lycopersicum*. Small changes in each parameter value can result in large changes in model prediction or each classified EI group. Values in the current study were chosen according to physiological data of tomato to produce a realistic model.

Distribution data from Central America and the Andean region including parts of Peru, Chile, Ecuador, Colombia and Bolivia were excluded from parameter adjustment and reserved exclusively for model validation. CLIMEX stress parameter values were selected based on satisfactory agreement of predictions observed between known and potential

Table 1. *CLIMatic indEX (CLIMEX) parameter values used for* S. lycopersicum *modelling*

Index	Parameter	Values
Temperature	DV0 = lower threshold	10 °C
	DV1 = lower optimum temperature	20 °C
	DV2 = upper optimum temperature	30 °C
	DV3 = upper threshold	35 °C
Moisture	SM0 = lower soil moisture threshold	0·1
	SM1 = lower optimum soil moisture	0·8
	SM2 = upper optimum soil moisture	1·5
	SM3 = upper soil moisture threshold	2·5
Cold stress	TTCS = temperature threshold	9·5 °C
	THCS = stress accumulation rate	−0·00003/week
Heat stress	TTHS = temperature threshold	30 °C
	THHS = stress accumulation rate	0·00001/week
Dry stress	SMDS = soil moisture threshold	0·1
	HDS = stress accumulation rate	−0·005/week
Wet Stress	SMWS = soil moisture threshold	2·5
	HWS = stress accumulation rate	0·001/week
Degree Days	PDD = degree days threshold	940

distribution. Table 1 illustrates all CLIMEX parameter values used.

Temperature index

The tomato plant prefers warmer weather with the optimum range of air temperature for normal growth and fruit set between 20 and 30 °C (Heuvelink 2005; Jones 2007); however, the tomato plant can survive in a range between 10 and 35 °C (Heuvelink 2005; El-Amin & Ali 2012; Attoh *et al.* 2014). Temperatures below 10 °C cause inhibition of vegetative development and a reduction of fruit set and ripening, while air temperatures above 35 °C cause a reduction of fruit set and the inhibition of normal fruit colour development (Heuvelink 2005; Jones 2007). In lieu of these factors, the limiting low temperature (DV0) was set at 10 °C, the lower optimal (DV1) at 20 °C, upper optimal (DV2) at 30 °C and limiting high temperature (DV3) at 35 °C (Fig. 1).

Moisture index

Tomatoes may be cultivated on an extensive range of soil types (Heuvelink 2005; Jones 2007) and adjustment was made to the soil moisture index for the most favourable climate fit in open field tomato cultivation areas. The CLIMEX soil moisture index comprises the lowest threshold (SM0), the lower optimum (SM1), upper optimum (SM2) and the upper moisture threshold (SM3). The SM0 value was set at 0·1, representing the permanent wilting point (Sutherst *et al.* 2007) and fitting open field cultivation in the Mediterranean region, with lower (SM1) and upper (SM2) optimum moisture limits of 0·8 and 1·5, respectively. The upper threshold (SM3) was set at 2·5 to suit wet tropical region open field cultivation.

Cold stress

The temperature threshold of cold stress (TTCS) and the weekly rate of cold stress derived from it (THCS) are the CLIMEX parameters denoting cold stress. Cold stress has a strong negative impact on plant growth and development in cooler climates (Heuvelink 2005). For this reason, TTCS and derived THCS were set at 9·5 °C and −0·00003/week, based on a best fit for the observed distribution in the high-altitude Andes regions of South America (Dolstra *et al.* 2002).

Heat stress

CLIMatic indEX incorporates the heat stress parameter (TTHS) and heat stress accumulation rate (THHS). High temperature has a serious negative impact in open field cultivation of tomatoes (Heuvelink 2005; Jones 2007) and in most parts of the world high summer temperatures affect production negatively. Fruit set is one of the most sensitive stages and temperatures over 30 °C inhibit ripening (Heuvelink

2005; Jones 2007). Taking this into account, TTHS was set at 30 °C and THHS at 0·00001/week.

Dry stress

Low relative humidity may result in water stress and stomatal closure, and has an association with pest problems in open field cultivation of tomatoes (Heuvelink 2005; Jones 2007). The threshold soil moisture level for dry stress (SMDS) was set at 0·1, with the stress accumulation rate (HDS) set at −0·005/week, derived from known distributions in East Africa and Brazil.

Wet stress

Wet stress in tomato cultivation may decrease aeration, which will increase the likelihood of root disease, resulting in softer vegetative growth and poorer rooting (Heuvelink 2005; Jones 2007). The threshold value for wet stress (SMWS) was set at 2·5, with the derived accumulation rate (HWS) of 0·001/week, based on values proven satisfactory in known distributions.

Irrigation scenario

Irrigation was used in the final CLIMEX model for both present and future climate projections to top up natural rainfall to a level of 3 mm/day in summer and 1 mm/day in winter (rainfall + irrigation). Large quantities of high quality water are necessary for tomato plant transpiration, serving both to cool the leaves and to trigger transportation of nutrients from roots to leaves and fruits (Heuvelink 2005; Jones 2007). The total amount of water required for the irrigation of tomato plants is dependent on climatic conditions, and thus irrigation demands are higher during the summer than winter (Heuvelink 2005). These values were based on open field irrigation regimes in practice.

Model verification and validation

In the verification step, the initial model was based on the distribution of open field cultivation of tomatoes in Brazil, Mediterranean regions, Africa, Middle East, India, China, Australia and New Zealand. After minor adjustments to CLIMEX parameters, most of these distributions were modelled as having optimal conditions for open field cultivation of tomatoes. Thereafter the model was validated by comparing output to known open field distributions of *S. lycopersicum* in Central America and the Andean region that includes parts of Chile, Colombia, Ecuador, Bolivia and Peru. These model verification and validation results demonstrate realistic estimations and reliability in the final model.

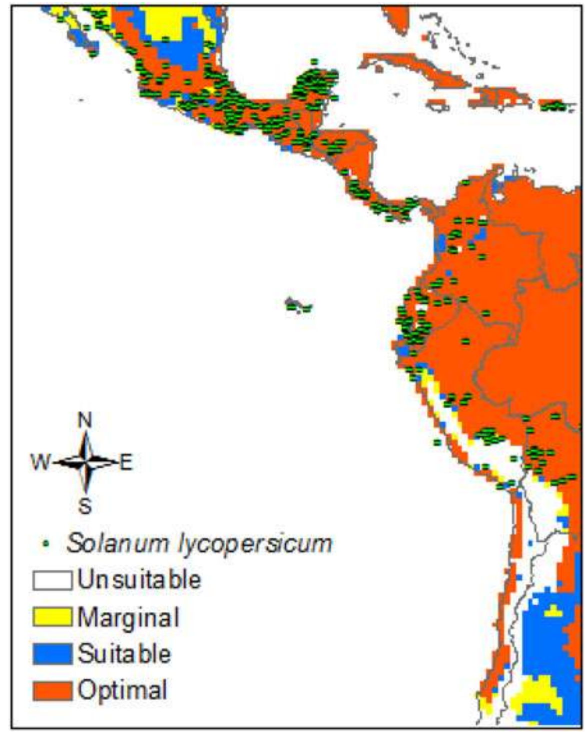

Fig. 3. Current and potential distribution of *S. lycopersicum* in validation regions based on Ecoclimatic Index (EI). The areas unsuitable in white (EI = 0), marginal in yellow (0 < EI < 10), suitable in blue (10 < EI < 20) and optimal in orange (20 < EI < 100). Colour online.

RESULTS

The records of *S. lycopersicum* in open field cultivation are represented in Fig. 2(*a*). In the model for current climate, a good match was achieved between the EI from the CLIMEX model and the global known distribution of *S. lycopersicum*, even without the irrigation scenario (Figs 2(*a*) and (*b*)). The major difference between these models is a prediction of greater optimal areas in Europe and more suitable and marginal areas with the irrigation scenario than without, especially in arid areas, such as Saudi Arabia and Australia (Figs 2(*b*) and (*c*)).

The validation of the model is shown in Fig. 3. Based on the EI values, a 99% match was found between the model predictions and the known distribution of *S. lycopersicum* in Central America and the Andean region that includes parts of Chile, Colombia, Ecuador, Bolivia and Peru. These are

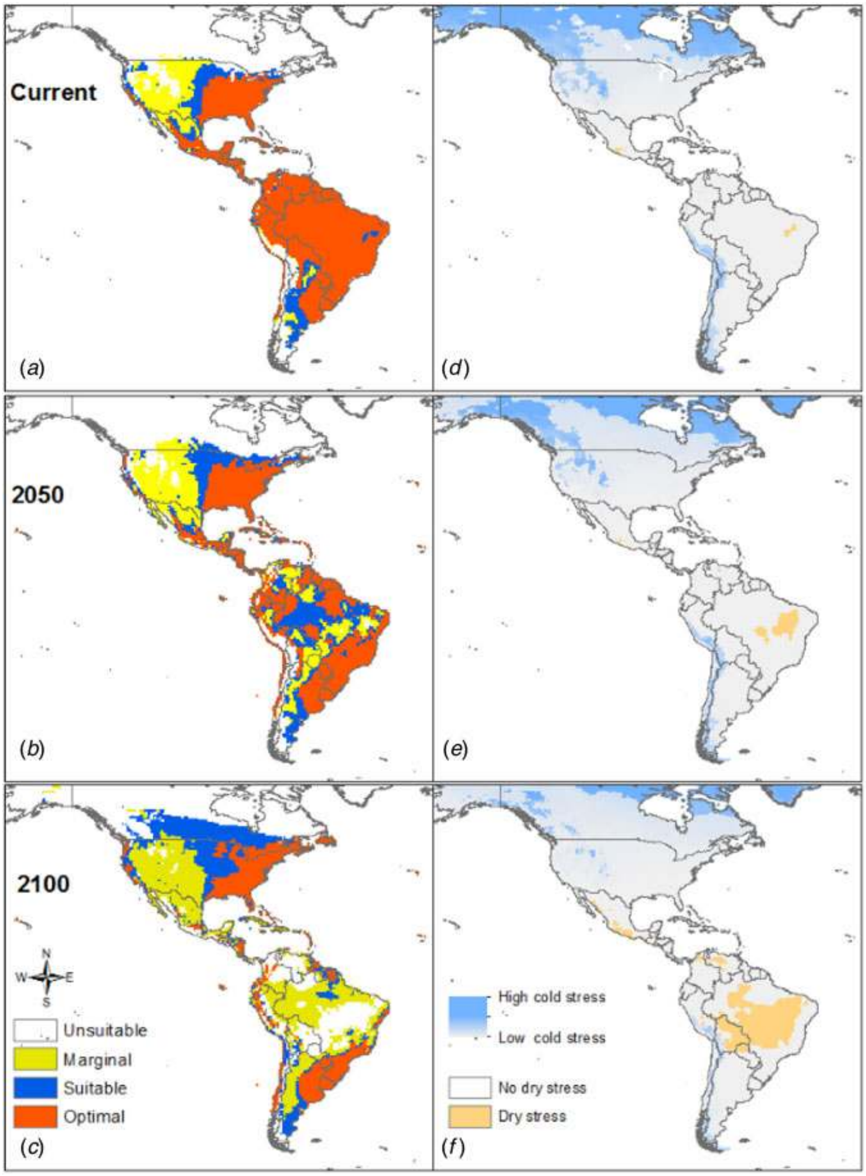

Fig. 4. The climate (Ecoclimatic Index (EI)) (*a–c*) and main stresses (*d–f*) for *S. lycopersicum* in current time and projected using CLIMatic indEX (CLIMEX) under the Commonwealth Scientific and Industrial Research Organisation (CSIRO)-Mk3·0 global climate model (GCM) running the A2 emissions scenario for 2050 and 2100 under irrigation scenario for the North, Central and South America. Colour online.

historically the regions of origin of the tomato species (Heuvelink 2005), confirming that the values selected for the various parameters in CLIMEX are valid.

The results of current climate and the GCM CS with the A2 emissions scenario for the potential and major stresses for open field cultivation for 2050 and 2100 are shown for North and South America, Europe, Africa and the Middle East, Asian countries, Australia and New Zealand (Figs 4–7).

From the prediction of CS GCM for 2050 and 2100 in relation to current climate, many regions in Central and South America are projected to suffer a reduction in the areas optimal for open field cultivation of tomatoes (Figs 4(*a*)–(*c*)). These reductions are associated with a projected increase of dry stress, which will become the main limitation for open field cultivation (Figs 4(*d*)–(*f*)). Conversely, large areas in North America currently unsuitable or marginal are projected to become suitable, mainly in Canada and the western USA (Figs 4(*a*)–(*c*)). This increase of suitable areas is explained by a projected progressive reduction of cold stress in these areas (Figs 4(*d*)–(*f*)).

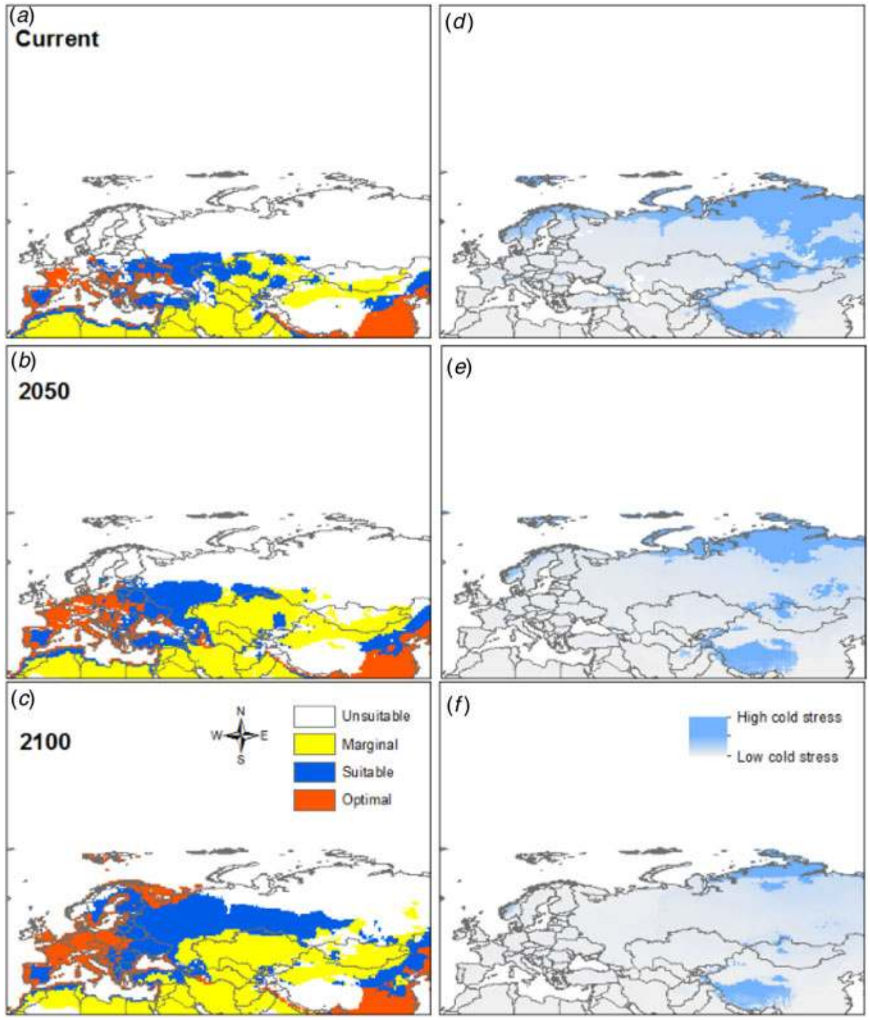

Fig. 5. The climate (ecoclimatic index (EI)) (*a*–*c*) and main stresses (*d*–*f*) for *S. lycopersicum* at the current time and projected using CLIMatic indEX (CLIMEX) under the Commonwealth Scientific and Industrial Research Organisation (CSIRO)-Mk3·0 global climate model (GCM) running the A2 emissions scenario for 2050 and 2100 under irrigation scenario for Europe and Russia. Colour online.

Under the current climate, there are large optimal areas for open field cultivation of tomatoes in Europe, mainly in Mediterranean regions (Fig. 5(*a*)). Additionally, the unsuitable areas in northern Europe and large parts of Russia are due to cold stress (Fig. 5(*d*)). In Europe, the CS GCM, projects that optimal and suitable areas will increase significantly between 2050 and 2100 (Figs 5(*b*) and (*c*)). In addition, CS GCM predicts that western Russia will become suitable for cultivation in the future (Figs 5 (*b*) and (*c*)). In these areas, a considerable reduction in cold stress is projected (Figs 5(*d*)–(*f*)). Thus, northern Europe is projected to become climatically suitable and western Russia will increase in areas with a suitable climate in a direction from west to east between 2050 and 2100 (Figs 5(*b*) and (*c*).

The areas in North Africa and the Middle East under the current climate have mainly marginal suitability (Fig. 6(*a*)) due to heat stress in these areas (Fig. 6(*d*)). In contrast, Central and South Africa have large areas with optimal index for cultivation (Fig. 6(*a*)) due to an absence of heat stress and dry stress (Fig. 6 (*d*)). The results of the CS GCM indicate a reduction of optimal areas for cultivation in Africa and the Middle East, most drastically in parts of Central Africa, Yemen and Oman, as well as India, between 2050 and 2100 (Figs 6(*b*) and (*c*)). The results of this drastic reduction are caused by a significant increase of dry and heat stress (Figs 6(*e*) and (*f*)).

Under the current climate, the model calculates that large areas in eastern China, Japan, Indonesia, the coast of Australia and New Zealand have an optimal

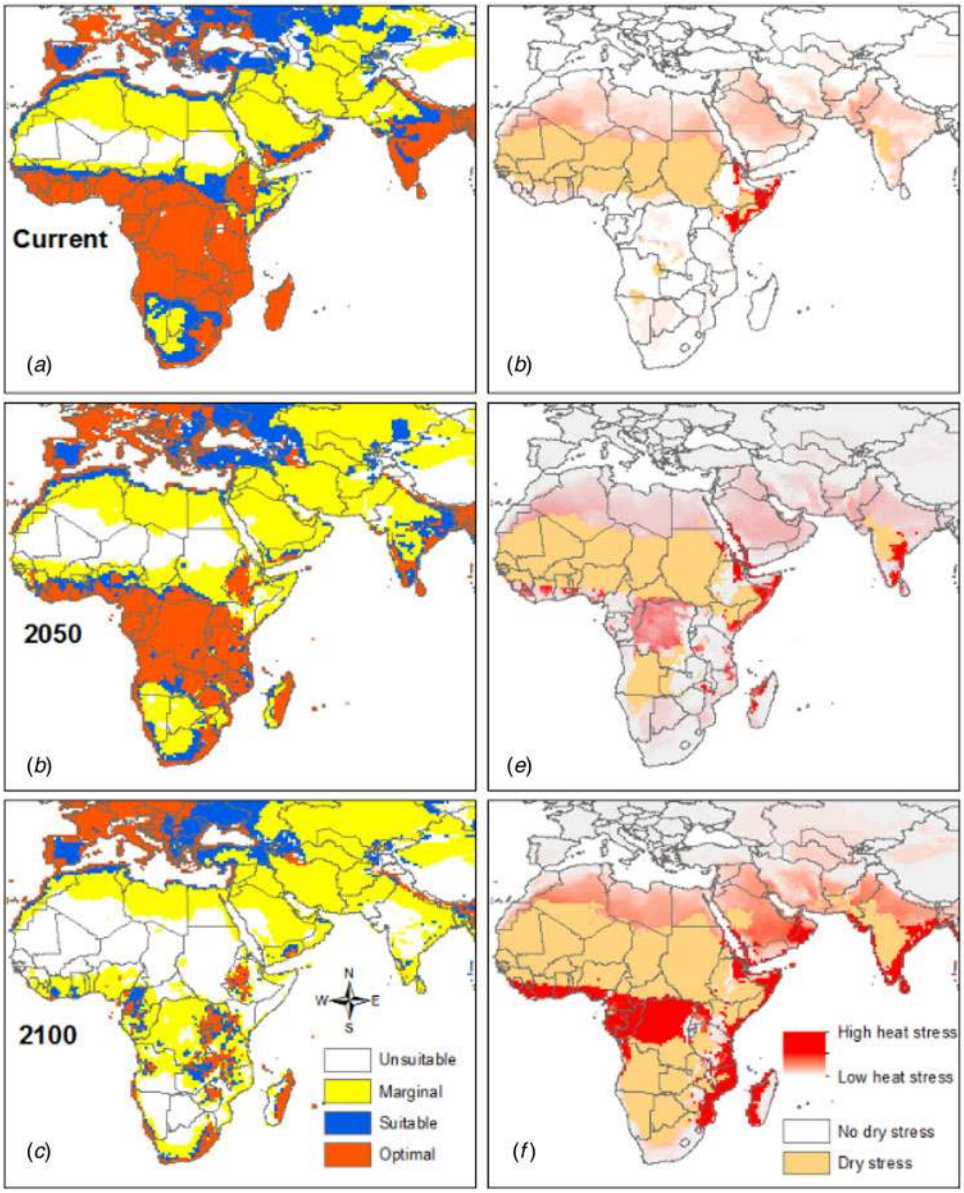

Fig. 6. The climate (ecoclimatic index (EI)) (*a–c*) and main stresses (*d–f*) for *S. lycopersicum* at the current time and projected using CLIMatic indEX (CLIMEX) under the Commonwealth Scientific and Industrial Research Organisation (CSIRO)-Mk3·0 global climate model (GCM) running the A2 emissions scenario for 2050 and 2100 under irrigation scenario for the north and south of Africa and the Middle East. Colour online.

climate (Fig. 7(*a*)). Additionally, Australia has large areas with marginal climate for cultivation due to a gradual increase of heat stress from south to north (Fig. 7(*d*)). Conversely, the CS GCM predicts a reduction of marginal areas in Australia in the future (Figs 7 (*b*) and (*c*)) due to an increase of dry stress from north to south and significant reduction of optimal climate areas for cultivation in Indonesia due to an increase of heat stress by 2050 and 2100 (Figs 7(*e*) and (*f*)). Eastern China will maintain large areas with optimal climate for cultivation (Fig. 7(*c*). In addition, Japan and New Zealand show increased areas with optimal climate for cultivation in 2100 (Fig. 7(*c*)) due to an absence of heat and dry stresses (Fig. 7(*f*)).

DISCUSSION

Current climate

Most regions in the world that are optimal for open field cultivation of tomatoes under the current climate have climatic zones where air temperatures

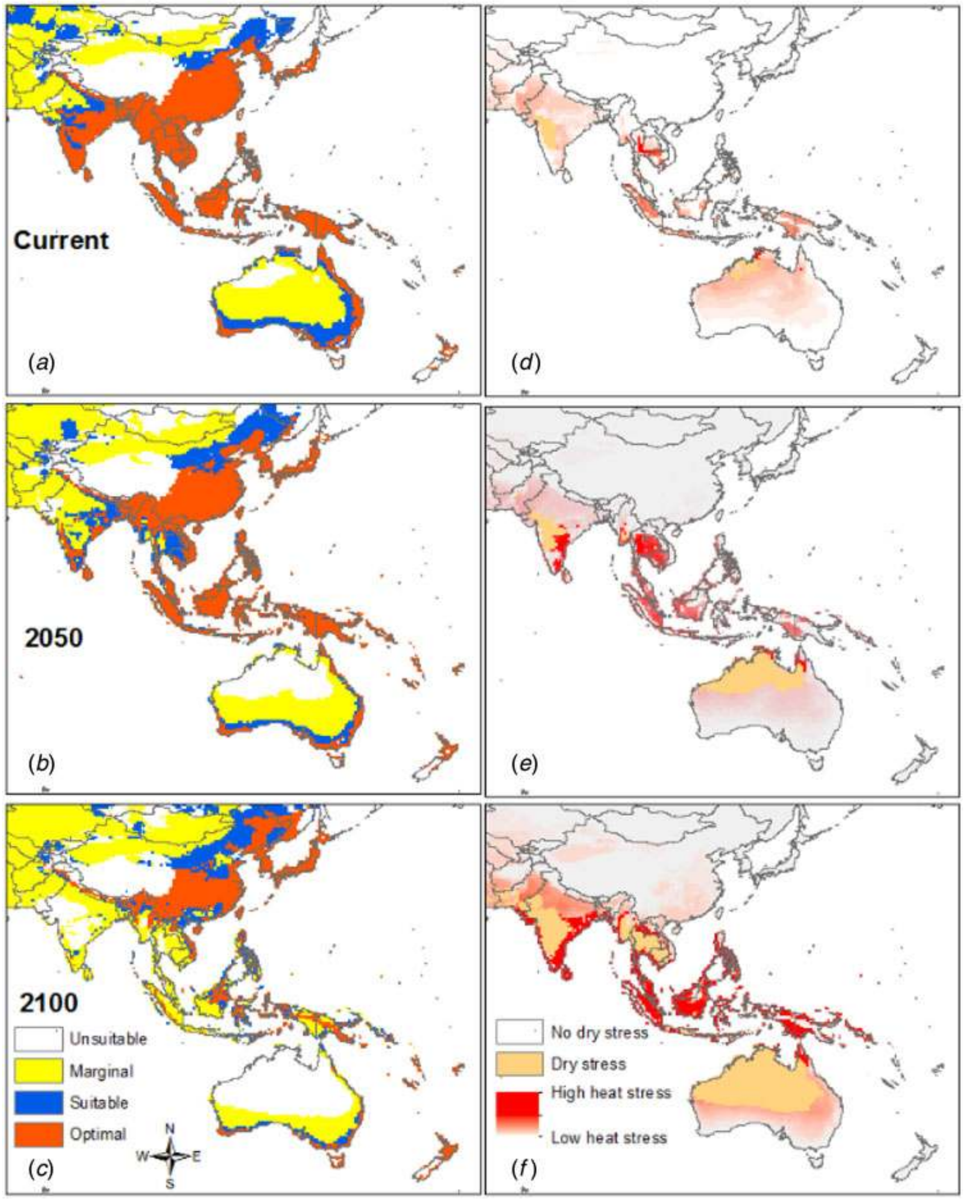

Fig. 7. The climate (Ecoclimatic Index (EI)) (*a–c*) and main stresses (*d–f*) for *S. lycopersicum* at the current time and projected using CLIMatic indEX (CLIMEX) under the Commonwealth Scientific and Industrial Research Organisation (CSIRO)-Mk3·0 global climate model (GCM) running the A2 emissions scenario for 2050 and 2100 under irrigation scenario for China, Japan, Indonesia, Australia and New Zealand. Colour online.

range between 20 and 30 °C, with long summers and mainly winter precipitation (Adams *et al.* 2001; Heuvelink 2005; Jones 2007). In most of these regions, tomatoes are already under open field production. However, tomato plants can survive a more extensive range of temperature, although plant tissues suffer damage below 10 °C and above 35 °C (Heuvelink 2005; Jones 2007; Golam *et al.* 2012). Thus, there are regions with mean annual air temperatures ranging between 10 and 35 °C where open field cultivation of tomatoes may also be found, such as some countries in Africa (e.g. Nigeria and Ethiopia) (Olaniyi *et al.* 2010; Gemechis *et al.* 2012). Below 10 °C plant growth will be reduced significantly and higher air temperatures, above 30 °C, can reduce fruit production (Jones 2007). Thus, the growth of tomato as a function of temperature was taken into consideration in CLIMEX, as is well illustrated in Fig. 1.

Since the tomato is sub-tropical in origin, tomato production is sub-optimal over large parts of the global crop-growing areas due to relatively unfavourable environmental conditions caused by abiotic factors that include heat, cold and dry stresses (Heuvelink 2005). In the current paper, the model provides an insight into favourable and unfavourable areas of open field cultivation, showing the major stresses responsible for limiting tomato production worldwide under the current climate.

Future projections

The projections illustrated for the USA in Fig. 4 show two main stresses, cold and dry, that will have opposite effects on cultivation. While cold stress is predicted to reduce, dry stress is shown to increase. The reduction of cold stress projected in areas of the western USA and Canada in 2050 and 2100 is the reason for the increase of marginal and suitable areas on these continents. Cold stress has a strong adverse effect on growth and development of the tomato (Heuvelink 2005; Jones 2007). Thus, these regions can have possibilities for future open field cultivation. Conversely, in Central and South America, particularly in Brazil, dry stress is projected to become an obstacle for cultivation. Where dry stress conditions surround the tomato plant's roots, there will be fewer flowers and fruit. Hence, it will not be possible to maintain cultivation of tomato due to drought conditions (Heuvelink 2005; Hanson *et al*. 2006; Jones 2007). Thus, countries in Central America and Brazil will have a large reduction in areas of ideal climate for cultivation.

The predictions show that a reduction in cold stress between current and future climate will also occur in Europe. This reduction will see a substantial increase of areas optimal for open field cultivation of tomatoes in Europe, from the Mediterranean to Northern Europe. Northern European tomato cultivation is capital-intensive, using modern technology such as greenhouse structures and climate control (Lang 2004; Heuvelink 2005). Therefore, because it is relatively expensive, future costs of tomato production in these regions could be decreased through open field cultivation, with a saving of the costly energy used to maintain optimal temperature greenhouses.

In sub-Saharan Africa (excluding South Africa) and the Middle East, average tomato yields are well below yields in temperate regions (FAOSTAT 2015). In the current model heat and dry stress have been highlighted as the two main stresses imposed by current climate, limiting yields in these regions. Even with the inclusion of the irrigation scenario in the current model, large areas were observed as unsuitable in North Africa (excluding the Mediterranean) due to heat and dry stress. In summer, due to high temperatures, a shortage of tomatoes is common in many parts of the African continent (El-Amin & Ali 2012). The CS GCM predicts that dry and heat stress will increase drastically in 2050 and 2100 in Africa and India. Thus, large areas in sub-Saharan Africa and India will no longer have an optimal climate for cultivation of tomatoes. Vegetables are generally sensitive to environmental extremes and thus high temperatures and limited soil moisture are the major causes of low yields in the tropics and will be magnified by climate change (Mattos *et al*. 2014). Thus, in the future the shortage of open field tomatoes could become greater, if research and development of hybridizing and cultivation strategies for tomato production under heat or dry stress is not undertaken.

Similar effects caused by heat and dry stress in Africa and the Middle East were also observed in Australia and Indonesia. In Indonesia, optimal areas will be reduced, while in Australia large marginal areas under current climate will disappear under the projected future climate. However, in Australia, this effect will not have too much negative impact on open field tomato production, of which the major part is along the coast, which will still maintain its optimal rating by 2100.

Worldwide, China is the largest producer of tomatoes (FAOSTAT 2015), a major factor being the optimal climate for open field cultivation of tomatoes in eastern China. The results clearly show a large area in East China with optimal climate and no stresses. In the projected future, large areas will maintain an optimal nature, while in northern China optimal areas will change to suitable or marginal due to the onset of heat stress from 2050. Additionally, Japan and New Zealand show an increase in optimal areas due to favourable climatic conditions, generally without stress.

Stresses caused by climate severely restrict plant growth and productivity and are classified as one of the major abiotic adversities of many crops (Shabani *et al*. 2012; Mattos *et al*. 2014; Ramirez-Cabral *et al*. 2016; Shabani & Kotey 2016). Tomato plants are subjected to different types of stresses, such as drought, wet, heat and cold, which result in disturbances in physiological and biochemical processes of development and plant growth (Heuvelink 2005; Jones 2007). These alterations may reduce growth capacity of tomato crops and therefore lower commercial yield. In the current work, the model results show that stresses can significantly affect suitability of regions because of an increase in stress levels, leading to an increase of harmful metabolic alterations.

The central CLIMEX assumption is that the primary determinant of growth of a species is climate (Sutherst *et al.* 2007). However, numerous genetic and cultural factors affect cultivation of the tomato, such as soil, water and fertilizer (Heuvelink 2005; Jones 2007). Thus, it is possible to refine the modelling results of CLIMEX in sequential studies, incorporating these factors after initial climate modelling. The modelling results are based only on climate and do not include non-climatic factors, such as occurrence of pests, diseases, weeds, soil types and biotic interactions. Further, refined results are also subject to the uncertainties surrounding future GHG emission levels.

Based on the projections from the present study, attention should be given to developing tomato varieties adapted to climate change, specially adapted for resilience to heat and dry stresses. This is important to reduce problems that will emerge from a reduction in open field cultivation of tomatoes. Conversely, cold stress reduction in Europe and North America will enhance opportunities for open field cultivation.

The results presented in the current study show the future negative impacts on open field cultivation of tomatoes, particularly in Brazil, Sub-Saharan Africa, India and Indonesia. Additionally, the results show that heat and dry stress are the major stress factors, limiting the growth of tomatoes and that decreased cold stress will become advantageous for open field cultivation in Europe and North America under future climates. Thus, this model may serve as a tool for plant geneticists and horticulturalists who could develop new regional stress-resilient tomato cultivars based on needs related to the current modelling projections. Hence, new varieties of tomatoes with tolerance to stress may reduce the risk of unemployment and enhance or maintain economic activity through open field tomato cultivation.

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