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Impacts of climate change on tomato, a notorious pest and its natural enemy: small scale agriculture at higher risk

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Abstract

Climate change (CC) clearly impacts food production, but risks on the climatic suitability of agricultural areas for vegetable crops, their pests and associated natural enemies are largely unexplored. Tomato, one of the most important vegetables in the world, is grown mostly outdoors, and may be severely impacted by CC. Farmers cultivating tomatoes need to adapt to an increase in the potential for outbreaks of pests favoured by CC and disruption of biological control, yet, no attempt has been made to simultaneously evaluate CC effects on a crop-pest-natural enemy system for tomato or any other crop. Here, we modelled the suitability of areas equipped with irrigation facilities (AEI) in 2050 for tomato, the two-spotted spider mite, *Tetranychus urticae*, a mite pest of tomato among more than 200 crops, and its key predator *Phytoseiulus persimilis*. We evaluated the suitability of AEI for tomato production under a 1.6 °C warming by 2050, within the targets of the Paris agreement. Projections show that climatic conditions become unsuitable for tomato production on 30%–100% of AEI for seven out of the 29 top tomato producing countries of the world. Model predictions suggest that two-spotted spider mite potential for outbreaks would increase substantially in nine countries in Europe, Africa and Asia, while biological control failures would occur globally. Model results have a significant relationship with growth rates for the three species measured in outdoor experiments, and farmer/expert perceptions on two-spotted spider mite outbreak severity captured via interviews. The expansion of AEI in other agricultural areas in the sub-Saharan Africa may offset losses of suitable land. However, several nations in the Middle East and South Asia with prevalent small scale agriculture would experience devastating impacts because of the unsuitability of conditions for tomato production and the potential increase in two-spotted spider mite outbreaks.

Introduction

Climate change (CC) impacts global agricultural production (e.g. Rosenzweig *et al* 2014, Fleisher *et al* 2017, Moat *et al* 2019, Yoon *et al* 2019). Considerable effort focuses on exploring CC risks on production of stable crops, with studies on vegetables, pests and natural enemies underrepresented in the literature (Porter *et al* 2017). While some studies have included both crops and pests (e.g. Berzitis *et al* 2014, Ponti *et al* 2014, Ramirez-Cabral *et al* 2018, Ramos *et al* 2018, Santana *et al* 2018), none has looked at a crop-pest-natural enemy system. We provide for the first time an assessment of CC impacts on the climatic suitability of agricultural areas for a vegetable-pest-natural enemy combination of global importance: Tomato (*Solanum lycopersicum* L.), the two-spotted spider mite (*Tetranychus urticae* (Koch)) and its key natural enemy, the predatory mite *Phytoseiulus persimilis* Athias-Henriot.

Tomato is one of the most popular vegetables in the world, with an annual value exceeding 90 billion USD (FAOSTAT 2019). Tomato acreage increased by almost threefold in the last 50 years to around five million ha in 2015. In the EU, one of the most important tomato producers, more than 85% of tomatoes are produced outdoors, mainly in Mediterranean Member States (Eurostat 2019). Modelling of worst-case CC scenaria revealed substantial restrictions of suitable areas for cultivation of the crop (da Silva *et al* 2017b, Ramos *et al* 2018). The Paris agreement created substantial interest in assessing the impacts of a 1.5 °C warming in different productive sectors (Hoegh-Guldberg *et al* in press), but currently no information exists for tomato. Furthermore, prior assessments for the crop were not restricted to agriculturally suitable land, as they included all terrestrial areas of the planet.

A suite of pests attack tomato, including the two-spotted spider mite (Meck *et al* 2013, Gigon *et al* 2016), one of the world's most notorious pests (Vacante 2015), with a host range of more than 200 cultivated crops (Migeon and Dorkeld 2006–2017). Control costs exceed $400 million annually in pesticide sales alone (van Leeuwen *et al* 2015). The pest has developed resistance to close to 100 chemical active ingredients, more than any other plant-feeding arthropod (Michigan State University 2019). The sequencing of its genome illuminated a vast array of unique detoxification genes that contribute to its impressive ability to develop resistance (van Leeuwen *et al* 2010, Grbić *et al* 2011).

The unmatched ability of the two-spotted spider mite to evade control has catalysed early on the search for effective natural enemies. The predatory mite, *P. persimilis,* has been one of the key successes of biological control worldwide (Knapp *et al* 2018). The predator is both mass produced by companies and occurs in natural populations around the globe (Demite *et al* 2014). The mite feeds almost exclusively on the two-spotted spider mite, and unlike its prey, it is limited by both high and low temperatures, and lacks the ability to diapause (Khodayari *et al* 2012, Coombs and Bale 2013). *Phytoseiulus persimilis* is known to develop strains adapted to the harsh environment of tomato leaves (Ditillo *et al* 2016), that are defended by glandular hairs oozing sticky exudates.

In the current work we used CLIMEX, a species distribution model, to assess the impacts of CC on tomato, the two-spotted spider mite and *P. persimilis.* CLIMEX is a semi-mechanistic model that has been used successfully to project climatically suitable areas under CC for many species including insects, plants and pathogens (Berzitis *et al* 2014, Burgess *et al* 2017, Ireland *et al* 2018). We restrict our analyses to agricultural areas equipped with AEI (Siebert *et al* 2013), and rely on outdoor experiments and a farmer survey to validate model findings.

The specific aims of the study were: (a) develop a global niche model for tomato, the two-spotted spider mite, and *P. persimilis*; (b) evaluate model results using global datasets, outdoor experiments and expert/farmer input and (c) assess the effects of CC by 2050 on the three species on areas equipped with irrigation facilities.

Materials and methods

CLIMEX models and spatial analysis

CLIMEX models

The software relies on data on the biology, seasonal phenology, and the geographic distribution of the organism to infer a set of parameters that summarise its response to the climate (Sutherst and Maywald 1985, Sutherst *et al* 2007). Once climatic parameters are inferred for the species using current climate data, CLIMEX can project the expected distribution based on different CC scenarios. The main CLIMEX output is the ecoclimatic index (EI), that ranges from 0 to 100 with low EI values indicating less suitable habitats that have a low probability for population persistence. Establishment is only possible when the value exceeds zero; areas with $EI \leqslant 10$ are generally considered as unsuitable for species persistence, and areas with an $EI > 30$ as very favourable (Sutherst *et al* 2007).

Phytoseiulus persimilis potential for effective biological control was evaluated with the biological control index (BCI): $BCI = EI_{predator} - EI_{pest}$. Where $EI_{predator}$ and $EI_{pest,}$ the EI for the predator and pest, respectively. Effective spider mite predators usually have an equal or greater intrinsic rate of population increase than the pest (Janssen and Sabelis 1992, Nomikou *et al* 2001), captured in a $BCI \geqslant 0$. BCI ranges from a potential maximum of 99 to a minimum of −99. BCI is a yearly summary statistic that does not capture the seasonal variation in EI for the two-spotted spider mite and *P. persimilis* nor the complex spatial component of prey–predator dynamics.

Distribution records

Presence data (see supplementary material available online at stacks.iop.org/ERL/14/084041/mmedia) for open field tomato distribution (1087) were retrieved from the Global Biodiversity Information Facility (figure S1(a)). Presence data for the two-spotted spider mite (931 single location records) were obtained from the literature in the Spider Mites Web database (Migeon and Dorkeld 2006–2017), and personal records (AM) (figure S2(a)), while for *P. persimilis,* the 143 single-location records (figure S3(a)) were retrieved from the literature and personal records (MST) (Migeon *et al* 2019).

Climate data

Global climate data were downloaded from the CliMond database (https://climond.org) at 10 arc minutes resolution (approximately 18.5 × 18.5 km at the equator) (Kriticos *et al* 2012). Historical climate data were centred on 1975H (1961–1990), and the CC

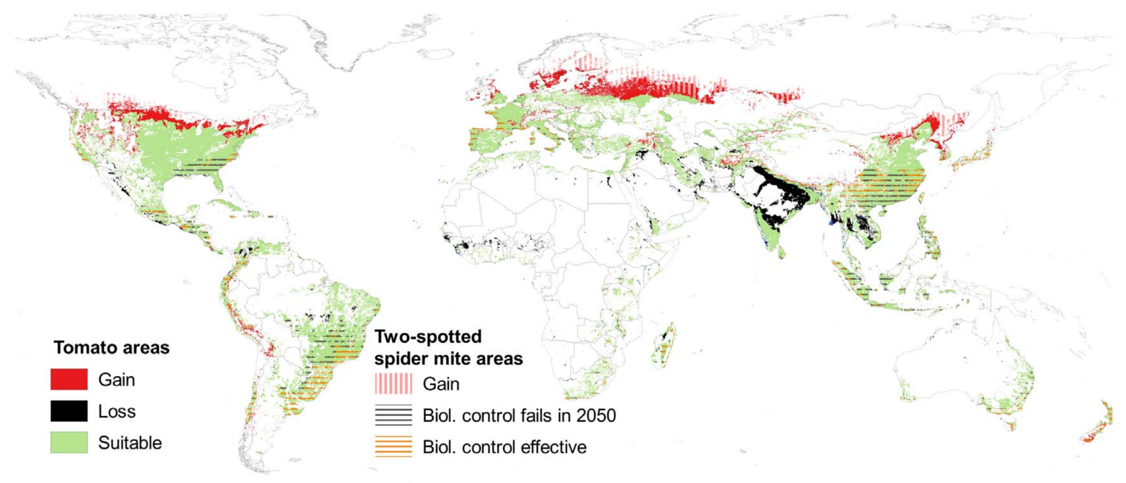

Figure 1. Changes in area suitability for tomato between 2050 (A1B—CSIRO MK.3) and 1975H. Area loss refers to area equipped with irrigation facilities (AEI) that was suitable for tomato cultivation under 1975H and becomes unsuitable-low suitability under 2050, while gain refers to the opposite case. The light green colour represents areas suitable for tomato cultivation under both 1975H and 2050 conditions. The two-spotted spider mite occupies virtually all areas suitable for tomato production in both 1975H and 2050, with the pink lines showing expansion areas under 2050. Black lines represent areas where biological control by *P. persimilis* was effective under 1975H and becomes ineffective under 2050 conditions. Orange lines represent areas where biological control is effective under 2050 conditions. Biological control is not effective in all areas outside orange lines. See text for more information on area classification.

scenario used was the IPCC SRES IV A1B for 2050 in the CSIRO-MK3.0 (CSIRO, Australia) global circulation model (GCM). The CSIRO-MK3.0 generates a 1.61 °C increase by 2050 relative to pre-industrial levels (or 1.18 °C relative to the 1961–1990 reference period), very close to the mean of models in the ensemble report of AR5, for RCP 2.6, the optimistic scenario for reaching the targets of the Paris agreement.

Model building and sensitivity analysis

Presence data for each species separately were used for the parameter fitting procedure with a special focus in Europe, Middle East and N. Africa. Starting parameter values for temperature and moisture limits, diapause (only for the two-spotted spider mite), as well as irrigation amounts were used from literature sources (Kroon *et al* 1998, Vangansbeke *et al* 2015, FAO 2017) and then adjusted iteratively until a close match was observed between the projected climate suitability patterns and the observed abundance patterns (Sutherst *et al* 2007). Sensitivity analysis was carried out to quantify the effect of parameters on model predictions for the three species (da Silva *et al* 2018). See supplementary material for a detailed description of the methodology.

Spatial analysis

CLIMEX model results at 10 arc minutes were projected on global areas equipped with AEI, retrieved from the Global Map of Irrigation Areas v. 5 at 5 arc minute resolution (Siebert *et al* 2013). The impact of CC on climatic suitability for tomato was evaluated at the country level for 29 countries with an average area of tomato cultivation exceeding 20 000 ha. The 29 countries represented more than 85% of the global tomato area (FAOSTAT 2019—see supplementary material for more details).

Model validation

Outdoor experiments

The experiments aimed at evaluating the relationship between EI values and growth for tomato, or population rate of increase for the two-spotted spider mite and *P. persimilis.* The experiments were conducted in eight locations in Cyprus in the summer of 2016, for tomato and the two-spotted spider mite, and repeated in six of these locations in 2017 with the addition of *P. persimilis* to the system (see supplementary material for detailed description). Each experiment lasted for a six-day period. The locations represented different climatic conditions, as they were placed in a temperature and altitude gradient from the coast to up to 1700 m.

Farmer/expert survey

A questionnaire survey was conducted on the island of Cyprus during the 2016 cultivation season to evaluate the relationship between CLIMEX EI values and farmer/expert perceptions on two-spotted spider mite infestation severity. A total of 80 persons were interviewed for the study—see supplementary material for a full description of the methodology.

Results

CLIMEX models and spatial analysis

Approximately 90%, 98% and 99% of the presence data for tomato, the two-spotted spider mite and *P. persimilis,* respectively, fell in areas with EI values greater than 10. Detailed results of the baseline model for each species are shown in the supplementary material and table S1.

Tomato

Approximately 20% of AEI was classified as unsuitable or low suitability (EI $\leqslant$ 30) for commercial tomato production in 1975H, while the rest 26%, 34% and 20% fell in the medium (EI from 31 to 40), high (EI from 41 to 50) and optimal categories (EI $\geqslant$ 50), respectively (figures 1, 2, S1(b), table S3). Categorisation of EI values in different classes was based on a spatial land use dataset depicting outdoor tomato crops (Monfreda *et al* 2008—see section on Categorisation of EI values suitable for commercial tomato production in supplementary material). The historic range for optimal suitability includes extensive areas throughout the world, and especially in the Americas.

In 2050 land available for tomato cultivation in the three upper classes is estimated at 69% of AEI (figures 1, 2 and S1(c)), because approximately 15% of AEI becomes unsuitable-low suitability, while 3% changes from unsuitable-low suitability to medium suitability or higher. Approximately 43% of AEI remains in the same category, while 13% of AEI becomes less and 9% more suitable. Most of the improvements in land suitability occur in North America, Europe and China. The model predicts that 12 nations in total (five EU members States) experience a positive impact of CC on conditions for tomato production (figure 3). Conditions become less suitable for commercial tomato cultivation on extensive areas in India and parts of South East Asia, as well as scattered areas in the Middle East and Africa (figures 2 and 3). Six out of the 10 worst affected by CC countries are in Africa, while the rest four nations are: Pakistan, Iran, India and Mexico (figure 3).

Two-spotted spider mite

Approximately 95% of AEI is classified as suitable for the two-spotted spider mite, with slightly less than 1/3 of AEI in the low suitability category, and 25%, 19% and 20% in the medium, high and optimal classes (figures 2 and S2(b), table S3). The historic range for the two-spotted spider mite includes the largest part of AEI in all continents, except for northern areas of Scandinavia, the Russian Federation and China. (figure 2).

Land suitable for the two-spotted spider mite drops slightly to 92% of AEI in 2050, with both expansion and contraction areas covering less than 5% of AEI (figures 2 and S2(c), table S3). Suitability remains the same on 57% of AEI, while 17% becomes less and 16% more suitable. The pest follows a northward expansion trend.

The two-spotted spider mite continues to persist in all areas suitable for commercial tomato production (suitability of land for tomato production medium or higher) in 2050. However, suitability of climate for the pest changes to a higher category on 15% or more of AEI suitable for commercial tomato production in nine countries: India and Pakistan in South East Asia, Nigeria and Cameroon in Africa, Italy, Bulgaria, Ukraine, Romania in Europe and China in Asia (figure S2(d)). The climate worsens for the pest in only two countries: Sudan and Uzbekistan.

Phytoseiulus persimilis

Only 56% of AEI is classified as suitable for *P. persimilis* (figures 2 and S3(c), table S3). Slightly less than 20% of AEI falls in the low suitability category, while 14%, 10% and 14% in the medium, high and optimal classes. AEI suitable for *P. persimilis* drops to 50% of AEI in 2050 (figures 2 and S3(c)), with expansion areas covering 5% and contraction areas 10% (table S3). Suitability remains the same on 25% of AEI, while 14% becomes less and 7% more suitable.

Under historical data, climatic conditions are not favourable for biological control (BCI $<$ 0) on 40% of AEI, while conditions favour pest suppression by the natural enemy (BCI $\geqslant$ 0) on 15% of AEI (figures 1 and S3(d) and table S4). The pest persists in the absence of the natural enemy on 39% of AEI. In 2050, the pest persists on 42% of AEI where the natural enemy is not present (figure S3(d) and table S4). The percentage of AEI where conditions favour biological control drops to 7%, while biological control is not favoured on 43% of AEI. Close to 8% of AEI switch from adequate to failing biological control, including an extensive area on the South east coast of the US, smaller areas mainly in West South America, and substantial areas in South Asia, and especially in South East China (figure S3(d).

In areas with conditions suitable for commercial tomato production (suitability of land medium or higher), biological control is effective on 15% of AEI in 1975H and drops to 7% in 2050 (table S4). Changes are not uniformly distributed among the top producing tomato nations (figure S3(e)). Brazil in South America, Algeria and Cameroon in Africa, and Indonesia and China in Asia experience a substantial reduction in the percentage of land under effective biological control.

Model validation

Outdoor experiments

There was a significant relationship between tomato RGR and EIw values from the baseline CLIMEX model ($P < 0.001$, figure S5, see supplementary material for full results). R^2 values ranged from 0.56 to 0.72 for the baseline CLIMEX model with 6 mm of irrigation and the model with irrigation adjusted to evapotranspiration, respectively. There was also a significant relationship between EIw and the rate of increase of the two mites ($P < 0.001$, figure S6). R^2 values for the CLIMEX model with 3 mm of irrigation were 0.26 and 0.32 for the two-spotted spider mite and *P. persimilis,* respectively, while for the model with irrigation adjusted to evapotranspiration R^2 values increased to 0.46 and 0.60 for the two-spotted spider mite and *P. persimilis,* respectively.

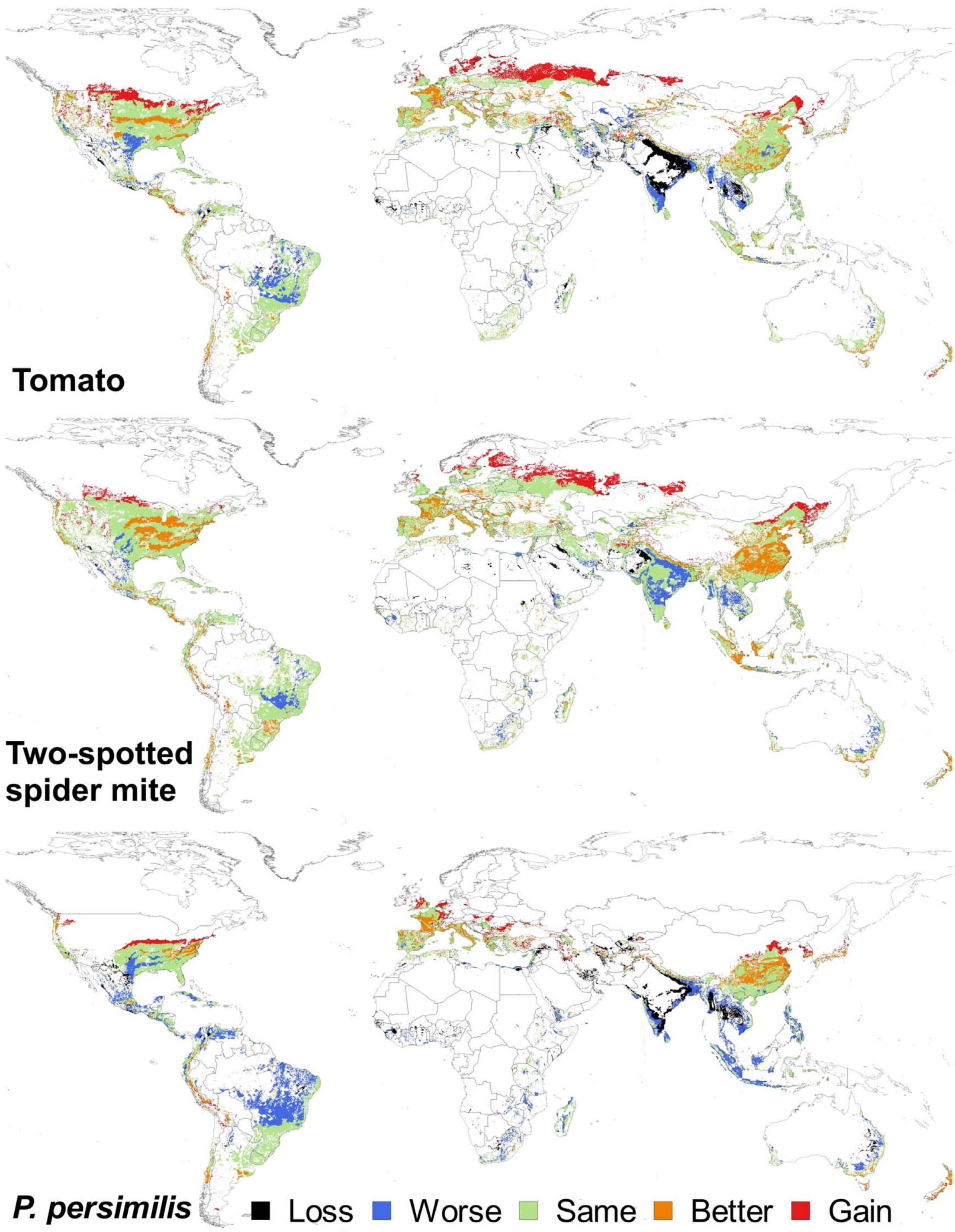

Figure 2. Changes in land suitability categories on area equipped with AEI between 2050 (A1B—CSIRO MK.3) and 1975H for: Tomato (top), the two-spotted spider mite (middle) and *P. persimilis* (bottom). For tomato, only areas considered suitable for large scale outdoor production (EI > 30—suitability category medium or higher) are included in the analysis, with area loss referring to areas with an EI > 30 under 1975H and an EI ⩽30 (categorised as unsuitable-low suitability) under 2050 (see Results). Worse refers to areas that changed to a lower suitability category and better to areas that changed to a higher category. Land loss for the two mites refers to area where suitability was low or higher (EI > 10) in 1975H and becomes unsuitable in 2050 (EI ⩽ 10), while area gain refers to the opposite case.

Farmer/expert survey

There was a statistically significant relationship between the rating of infestation severity by farmers/experts and annual EI values from the 1985-centred data ($F = 399.21$; $df = 1{,}78$; $P < 0.001$) (figure S7).

Discussion

The current study predicts a net loss in suitable AEI of 11.3% for tomato. Loss and gain of suitable AEI is not distributed uniformly across the globe, resulting in

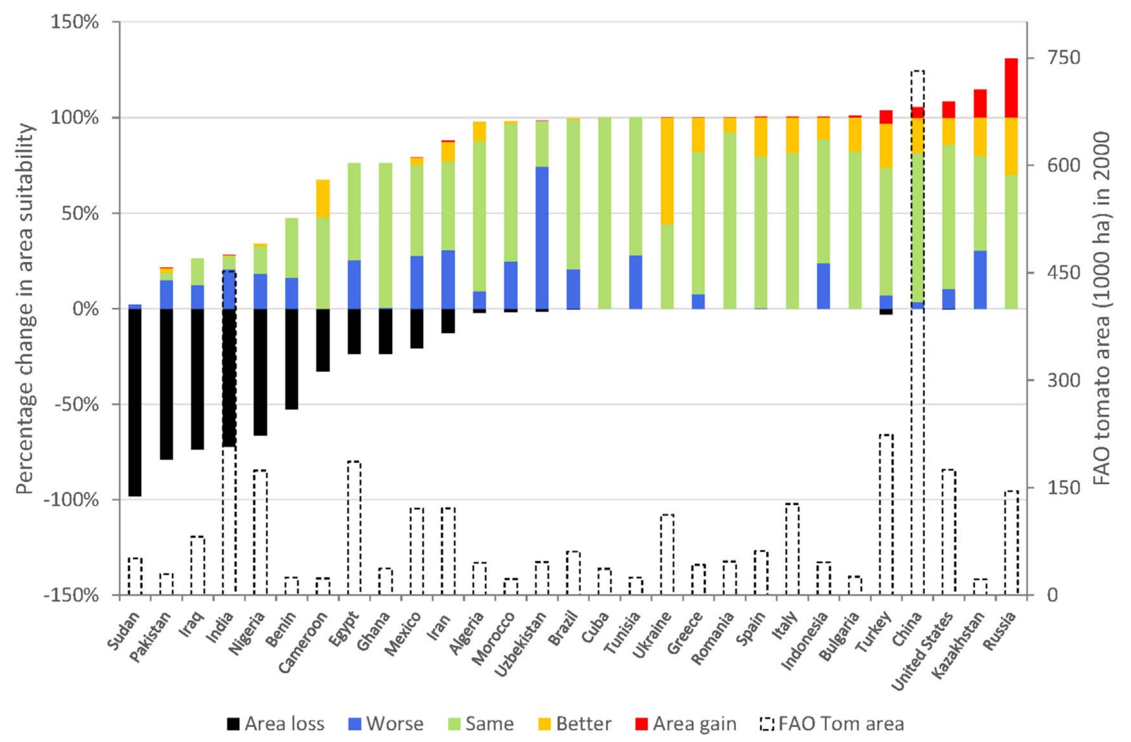

Figure 3. Change in area suitability for tomato cultivation between 1975H and 2050 (A1B—CSIRO MK.3). Data for areas equipped with AEI for 29 countries with more than 20000 ha of tomatoes in 2000 (FAOSTAT 2019), ranked from most to least affected. Area loss refers to areas suitable for tomato cultivation in 1975H (EI $>$ 30—suitability category medium or higher) and unsuitable-low suitability (EI $\leqslant$30) in 2050, while area gain refers to the opposite case. Worse/Better refers to a decrease/increase in area suitability, respectively. The black dashed line shows the average area of tomato cultivation (1998–2002) per country (FAOSTAT 2019).

dramatic impacts at the country level in some cases. Seven countries are projected to lose from 30% to almost all of their area suitable for tomato production (figures 2(a) and 3). Major losses of suitable AEI are expected to occur exclusively in parts of Africa (Sudan, Nigeria, Benin, Cameroon, Egypt, Ghana), South Asia (India and Pakistan) and Iraq and Mexico (figure 3). Most of the affected regions are characterised by small scale agriculture (Lesiv *et al* 2019), and are therefore more prone to CC risks.

The large variations in temperature on AEI is a major factor determining its suitability for tomato production, as was previously shown for wheat, rice, maize and soybean in a different modelling context (Zhao *et al* 2015). The CLIMEX model is very sensitive to minor changes in the value of irrigation (table S1), highlighting the importance of irrigation provision for tomato cultivation. The availability of irrigation water under CC seems to be a realistic scenario for most countries (Elliott *et al* 2014), and offers an adaptation strategy via the expansion of AEI into new suitable areas of agricultural land not equipped with irrigation facilities. For example, Sudan and countries in the sub-Saharan Africa are projected to have an abundance of water towards the end of the century even under RCP 8.5 (Elliott *et al* 2014), and can expand their AEI into agricultural land of high suitability (Portmann *et al* 2010). However, several countries are projected to have a deficiency of irrigation water—Morocco, West Egypt, Iraq, Uzbekistan, Pakistan, North West India, east China and Mexico (Elliott *et al* 2014)—and therefore our model may underestimate CC impacts as it assumes the provision of adequate volumes of irrigation water. Drought severity under CC is an ongoing area of research (Swann *et al* 2016). Engineering solutions, such as the cultivation of the crop under net-houses with cooling systems can enable its production in hot areas. Selection of heat/drought resistant varieties is another pathway towards CC adaptation. Development of models that incorporate the potential effects of new technologies/breeding efforts in the assessment of CC impacts (e.g. Asseng *et al* 2019) would enable the evaluation of the viability of different adaptation options.

Previous work on CC effects on tomato cultivation lacked a relevant spatial context as it included all terrestrial areas of the planet. Parameters of the baseline CLIMEX model (table S1) are generally similar/within reasonable range of that of da Silva *et al* (2017b). Variation in parameter values between the two studies probably reflects differences in the initial areas used for parameter estimation, and the literature sources for parameter identification. Saadi *et al* (2015) modelled CC impacts on tomato yield in the Mediterranean under the A1B scenario in 2050 and showed no major impacts, in accordance with the current work. Da Silva *et al* (2017b) and Ramos *et al* (2018) used projections for a warmer world than the GCM/SERS used in the current study and reported both restrictions and expansions in land suitable for tomato cultivation. The choice of the modelling platform, GCM and CC scenario/RCP can significantly influence predictions (Meynard *et al* 2013, Shabani *et al* 2016). An additional factor that needs to be incorporated in future modelling efforts is the potential positive effect of CO_2 fertilisation on tomato growth and yield. Wei *et al* (2018) have shown that elevated CO_2 mitigates the negative effects of drought and low nitrogen availability on the yield of tomato plants, and elevated CO_2 can also enhance tomato quality (Dong *et al* 2018).

Regional worsening of conditions for tomato cultivation is associated with an intensification of two-spotted spider mite infestations. Four countries with better conditions for the pest under CC (15% or more of area changing to a higher class) are in the top 10 countries worst affected by CC for tomato production: India and Pakistan in Asia, and Nigeria and Cameroon in Africa (figures 3 and S2(d)). The climate becomes less suitable for the pest in just two nations: Sudan and Uzbekistan. Drought can potentially intensify two-spotted spider mite pressure on tomato (Ximénez-Embún *et al* 2017), while a recent study on maize suggests that the increase in CO_2 can attenuate some of the positive effects of temperature increase on the species (Xie *et al* 2018).

Expected failures in biological control are highly concentrated in North and South America, China and South East Asia, as well as parts of the Mediterranean (figures 1 and S3(d)). Five countries (Brazil, Cameroon, Indonesia, China, and Algeria) experience a 20 to 40-unit reduction in area under effective biological control by 2050 (figures S3(d)–(e)). No meaningful increase in the area under effective biological control occurs for any country (figure S3(e)). Effects of CC on biological control as estimated in the current study represent the most optimistic scenario, as the underlying assumption is a temporal overlap between pest and natural enemy. Potential temporal differentiation in the periods of activity of pest and natural enemy will result in decreased effectiveness of biological control (da Silva *et al* 2017a). Both pests and natural enemies can adapt to CC through phenotypic plasticity and genetic adaptation, and future evaluations of CC impacts need to incorporate phenotypic and evolutionary processes (e.g. Bush *et al* 2016, Macfadyen *et al* 2018).

Model results showed good correspondence with the short-term outdoor experiments (figures S5 and 6), especially when irrigation in the model was adjusted to site-based evapotranspiration. Coefficient of determination values in regressions for the baseline model ranged from 26% for the two-spotted spider mite to 56% for tomato, and increased to 46% and 72%, respectively when irrigation was adjusted to field evapotranspiration (-see Results and figures S5–6). Future research based on long-term experiments would provide a more complete picture of the relationship between model predictions and field observations. EI values from the baseline CLIMEX model showed very good correspondence to farmer/expert opinion, highlighting the relevance of results to pest outbreaks in the field (figure S7). Further research needs to evaluate whether farmers are already experiencing a higher frequency of CC-related spider mite outbreaks as has been shown for other pests (e.g. Savary *et al* 2019). In North Carolina for example, Meck *et al* (2009) report an increase in spider mite outbreaks on tomatoes and other vegetables, with efforts focusing on improving biological control by *P. persimilis* (Meck *et al* 2013). While farmers in Cyprus generally agree that spider mite infestations are more problematic in recent years, it is very difficult to tease apart whether the increase is because of CC alone or because of the withdrawal of several pesticides from the EU market that were used against the multi-resistant pest.

Understanding and adapting to CC effects requires work on both detailed biophysical models (Antle *et al* 2017), as well as broader picture studies at different trophic levels, such as the current work. The present study predicts substantial impacts under a 1.5 °C warming, suggesting that impacts can be severe if the world overshoots this target. Future studies in the direction of developing detailed biophysical crop models for tomato and other vegetables, including CO_2 effects, as well as incorporating pest and natural enemy impacts under different CC futures (Donatelli *et al* 2017), including the difference between 1.5 °C and 2 °C of warming, will aid adaptation efforts.

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Data availability statement

Any data that support the findings of this study are included within the article.

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