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Exploring the Mechanisms of the Spatiotemporal Invasion of *Tuta absoluta* in Asia

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Abstract: International crop exchange always brings the risk of introducing pests to countries where they are not yet present. The invasive pest *Tuta absoluta* (Meyrick 1917), after taking just a decade (2008–2017) to invade the entire Africa continent, is now continuing its expansion in Asia. From its first detection in Turkey (2009), the pest has extended its range of invasion at a very high speed of progression to the southeast part of Asia. This study adopted the cellular automata modelling method used to successfully predict the spatiotemporal invasion of *T. absoluta* in Africa to find out if the invasive pest is propagating with a similar pattern of spread in Asia. Using land cover vegetation, temperature, relative humidity and the natural flight ability of *Tuta absoluta,* we simulated the spread pattern considering Turkey as the initial point in Asia. The model revealed that it would take about 20 years for the pest to reach the southeast part of Asia, unlike real life where it took just about 10 years (2009–2018). This can be explained by international crop trade, especially in tomatoes, and movement of people, suggesting that recommendations and advice from the previous invasion in Europe and Africa were not implemented or not seriously taken into account. Moreover, some countries like Taiwan and the Philippines with suitable environmental condition for the establishment of *T. absoluta* are not at risk of natural invasion by flight, but quarantine measure must be put in place to avoid invasion by crop transportation or people movement. The results can assist policy makers to better understand the different mechanisms of invasion of *T. absoluta* in Asia, and therefore adjust or adapt control measures that fit well with the dynamic of the invasive pest observed.

Keywords: cellular automata; *Tuta absoluta*; insect's pest invasion; dispersal pattern; international crop trade; integrated pest management

1. Introduction

Tuta absoluta (Meyrick 1917) (*Lepidoptera: Gelechiidae*), the South American tomato pinworm, is considered a serious lepidopteran pest that causes severe damage to tomatoes, leading to economic losses with a shortage of tomato supply in affected countries [1–4]. After its initial arrival from South America to Spain in 2006, other European countries including Italy (2008), France (2008), Albania (2009), Bulgaria (2009), Portugal (2009), the Netherlands (2009), United Kingdom (2009), and Serbia (2011) were also affected [5,6]. Later, *T. absoluta* also invaded Africa through Morocco (2007/2008), Algeria (2008), Tunisia, Libya, (2009), Senegal (2011), Sudan (2011), Ethiopia (2013), Kenya (2013), and

South Africa in 2017 [7–13], as well as Benin in 2018 [14]. Turkey was the first country in Asia to detect the presence of *T. absoluta* in 2009 [15], and from there it has spread and reached many countries in South and Central Asia including India (2015), the northwestern Himalayan region of India, Bangladesh (2016), Nepal (2016), Kyrgyzstan (2017), Tajikistan (2018) [16–22], and possibly in Myanmar (2018) in both greenhouse and open field conditions. However, despite the wide spread of *T. absoluta* in South Asia, the invasive pest has not yet been officially reported in many countries in Southeast or East Asia, including Laos, Thailand, Cambodia, Vietnam, Malaysia, Indonesia, Philippines, Taiwan, Koreas and Japan.

While spreading from one location to another, *T. absoluta* causes crops damage, with losses which can reach up to 100% in tomato production [10,23]. However, the complex physiology and ecology of *T. absoluta* may be in part responsible for the lack of successful management strategies [10], in spite of multiple activities and efforts undertaken both in laboratory and in the field during the last decade to control this invasive pest [24–35]. *Tuta absoluta* has a high reproduction rate, with about 12 generations per year in optimal conditions, which range between 21 to 30 °C, and higher than 50% relative humidity. In addition, a mature *T. absoluta* female can lay up to 260 eggs with very high flight ability, reaching up to 100 km during its lifetime [36–38].

According to [39], species with a high growth rate, maturation, and reproduction on a wide range of environmental conditions are those with a great probability of invasion [39]. These attributes perfectly fit with the physiological and ecological description of *T. absoluta*. A combination of these factors with the constant interaction of *T. absoluta* with human activities such as crop transportation favors the expansion of its range to new regions where the invasive pest was not present before. The consequence of theses interactions is that it becomes difficult and complex to implement efficient control measures against *T. absoluta* due to multiple paths of invasion. There are three main paths of insect invasion: it can occur naturally, by introduction, or accidentally, and is caused either by human activities or by natural dispersal [40]. Previous work has shown that from its first detection in Morocco in 2006, *T. absoluta* has invaded the entire African continent in ten years naturally, just by its flying ability [7]. However, there is not yet a report of any study exploring the mechanism of invasion of *T. absoluta* in Southeast Asia through modeling and simulation.

Many modelling concepts exist to simulate insect population dynamics and risk of invasion, including the use of the Species distribution modelling (SDM) approach, differential equations, individual-based models and cellular automata [41,42]. The success of one approach depends on selection of an appropriate complexity level for the modelling experiment objectives and the availability of data [42]. SDM is often used for predicting the suitable area for occurrence and the distribution of species without emphasis on the dispersal pattern across space and time. These modelling approaches cannot inform about the speed of spread and when the event will occur in a given location. Differential equations (DE) are frequently used to address the issues related to temporal predictions of insect population dynamics and abundance [43,44]. The inconvenience of using the DE approach is that they presume the space to be uniform and continuous, which is generally not the case in reality, especially for large scale areas of study like countries and continents. Indeed, models that attempt to integrate all existing knowledge about an insect species such as DE, and to serve all possible purposes, usually become obsolete before completion and have unexpectedly limited usage because of their lack of flexibility [45]. On the other hand, models with spatiotemporal approaches using cellular automata (CA) have been useful to understand the path of invasion and predict the timing of invasion of *T. absoluta* in Africa [7] and Asia [46]. The CA-based approach is spatially explicit and favors the consideration of the spatial heterogeneity of interactions in the dynamic process. The aim of this work is to use the model previously designed by [7] in order to predict the timing of invasion of *T. absoluta* in Southeast Asia, compare the path and mechanism of the invasion of the pest in Asia, and advise on suitable management strategies to be adopted.

2. Materials and Methods

2.1. Area of Study and Data Transformation

To process the simulations, temperature, relative humidity, and *T. absoluta* occurrence data from Asia were used (Figure 1). Previous works have highlighted the key role played by temperature and RH for the survival of *T. absoluta* both in the laboratory and in the field [37,47–49]. The vegetation variable, characterized by the normalized difference vegetation index (NDVI), was not taken into account in this study because it was demonstrated that NDVI did not really influence the choice of a location of *T. absoluta* during the process of invasion, unlike temperature and relative humidity [7]. Moreover, NDVI does not negatively affect the flying distance of *T. absoluta* during the invasion process. This is the same with the parameter quantity of tomato (main host plant) production per hectare, which mainly improves detection of potential invaded locations where environmental conditions are not suitable, without necessarily slowing down the flying distance [7]. Given that the main interest here was to explore if the path of invasion in Asia is the same as the one in Africa, only the climatic parameters were used. The temperature dataset was obtained from the WorldClim database (http://www.worldclim.org/current) (Hijmans et al., 2005); relative humidity data were downloaded on the Surface meteorology and Solar Energy (SSE) website (http://eosweb.larc.nasa.gov/sse/). However, *T. absoluta* occurrence data in Asia were collected from different scientific publications [16–21].

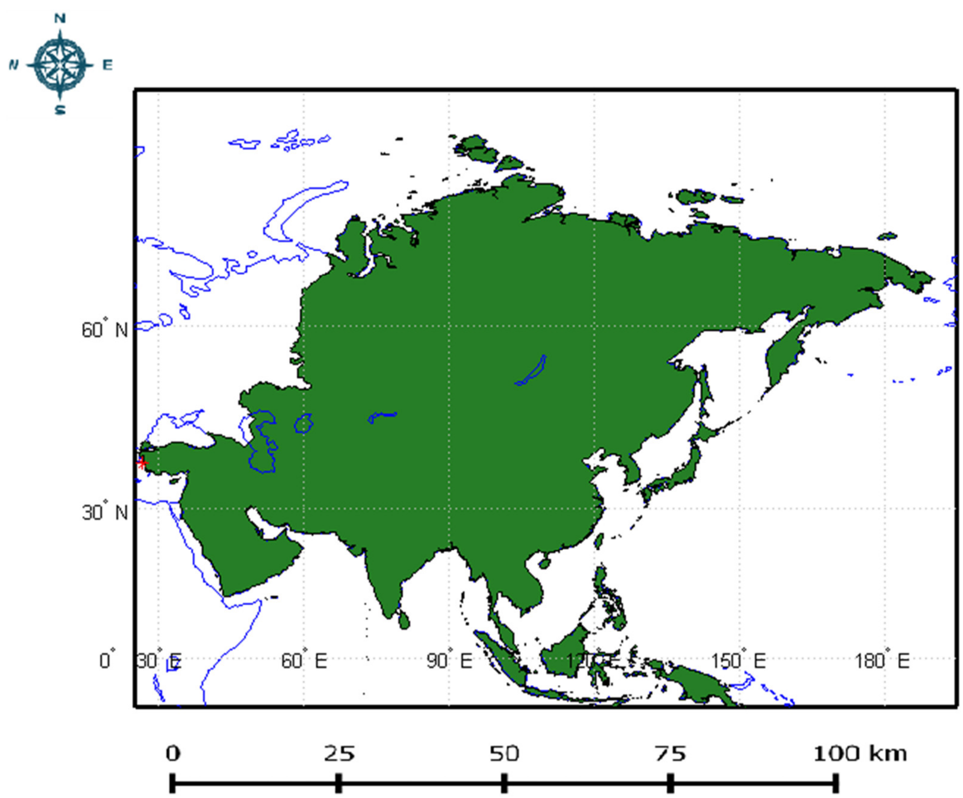


Figure 1. Area of study. The location in green represents the Asian continent; the red dot is the Asia location in Turkey where *T. absoluta* was discovered for the first time in 2009. This point is also the initial location for the model simulation.

The temperature datasets were organized into monthly mean values using a grid of 30 arc-seconds that correspond to about 1-km resolution. These processes were carried out using the functionalities offered by the R-packages sp (1.3.1) and raster (2.6.7). These allow reading, writing and manipulating of the gridded spatial data. We further applied the rgdal (1.3.4) functionalities for bindings. The Geospatial Data Abstraction Library (GDAL) was useful to handle and convert different geospatial data in different formats [50–52]; the function *extractValue()* was implemented using the R programming language to extract temperature values of all geographic coordinates overlapping the area of study for a temperature raster file. Relative humidity data were obtained and organized into text file format containing coordinates of the Earth's surface spaced by 1 × 1 degree. The inverse distance weighting method (IDW) [53] functionality built in the Geographic Information System (GIS) software Quantum GIS (QGIS) was used to interpolate value and produce a raster file of relative humidity data. Hence, the method *extractValue()* was used again following the same process as described for the extraction of the temperature value.

2.2. Cellular Automata (CA) Model Thresholds, Rules and Implementation

The model used in the current study is based on the CA model designed by [7] to predict the invasion of *T. absoluta* in Africa, due to the accuracy provided to spatially mimic the timing of invasion of *T. absoluta* in Africa. cellular automata have been very useful to explore the dynamics of many agricultural systems and processes such as the prediction of land use and land cover change, or the vegetation and landscape dynamics [54–56]. CA modeling is characterized by a set of states and a set of rules that describe the dynamics of the studied system after every time step. It can be represented by a square lattice where each cell represents a location. Therefore, the state of a cell at any given time t depends on its state at the time t-1 and the transition rule applied from t to t-1. In the context of this study, a location can be found in two possible states, which are susceptible (S) and invaded (I). All the locations of our area of study at the beginning of the simulation are in the state susceptible, except the location in Turkey from which the pest invaded Asia. Therefore, that particular location was used in the state invaded (I).

For the CA model, a monthly time step was used for simulations. A temperature threshold was defined at 22 °C, while RH threshold was at 55%. As the natural ability of flight of *T. absoluta* is taken into account, 100 km was used, considering the Moore neighborhood [57]. From the transition time t to t + 1, cells in the neighborhood of an invaded area are updated based on the following rules:

Susceptible cell (S): As previously explained, all the locations within the area of study and at the beginning of the simulation are Susceptible to be invaded, except the first invaded location in Asia (i.e., Turkey). The location will remain susceptible (S to S) if the combination of environmental condition does not favor the settlement of the invasive pest. However, a susceptible location turns into invaded (S to I) if both temperature and relative humidity value in the location are greater than their respective threshold. Once it becomes invaded, the state of the location cannot change anymore and will remain invaded (I to I) as no control measures are taken into account during the simulation.

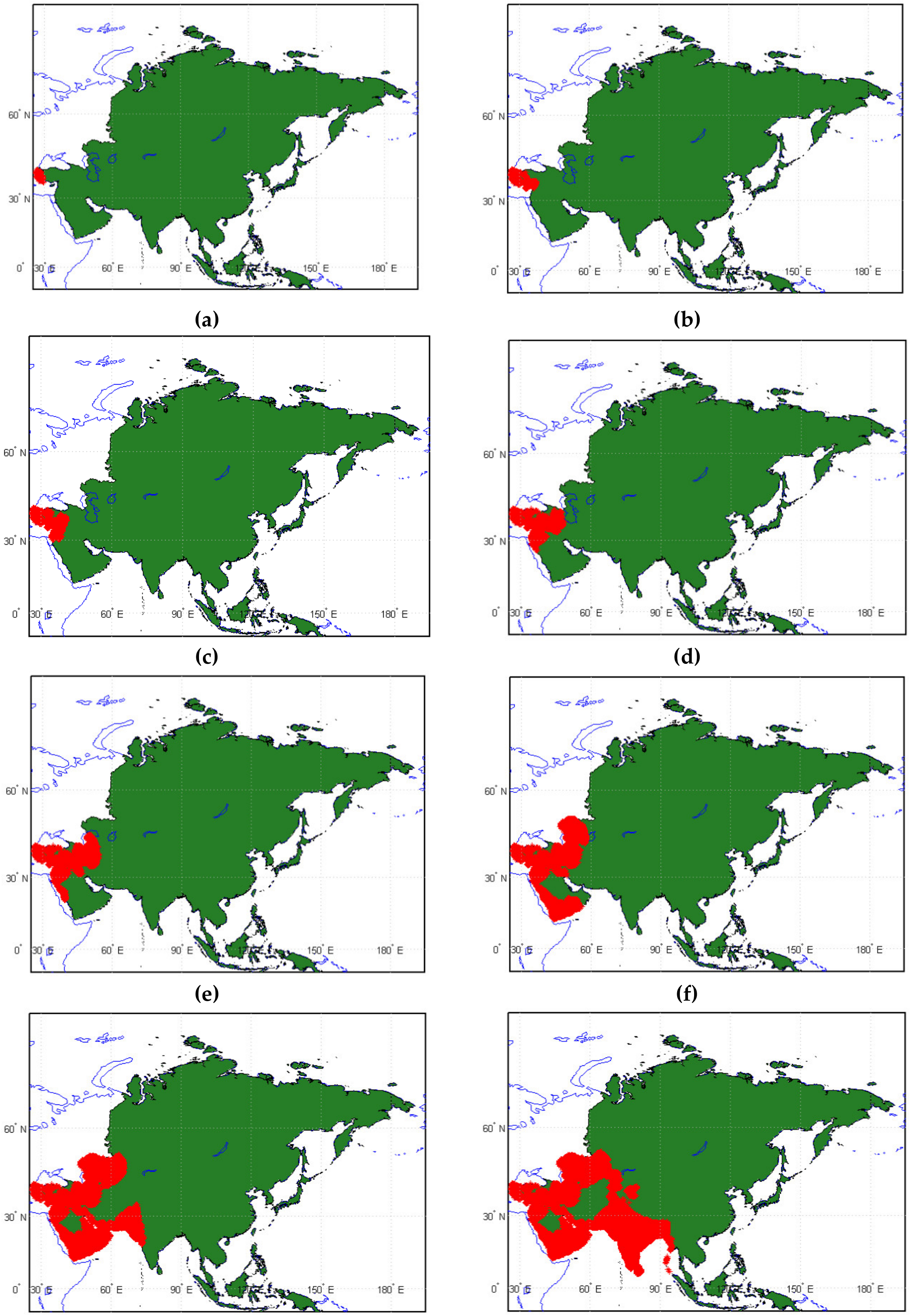
MATLAB (R2010a, The Math-Works) was used as a programming medium to implement the model. Therefore, simulations were made starting from Turkey, and were processed until the entire Asian continent was covered; from there, the number of years was recorded, and a comparison was made with the progression under real conditions.

2.3. Keys Assumptions

The developed model is based on the following assumptions: (1) the time scale of *T. absoluta* invasion process is driven by its natural flight ability like in Africa, without human assisted transportation; (2) for all locations where the environmental conditions are favorable for agricultural activities, there is sufficient host plant vegetation for sustaining the spread of this invasive pest. However, despite the presence of three main tomato producers of the world in Asia, there are many areas unsuitable for tomato cropping.

3. Results

The simulation of the invasion process of *T. absoluta* in Asia, considering Turkey (2009) as the entry location in Asia, is presented in the following maps (Figure 2), showing the progression of the invasion when temperature, relative humidity, and the natural flight ability of *T. absoluta* were taken into account. From the start of invasion, and based on the simulation model, *T. absoluta* would require 25 years for natural dispersal into Southeast Asia.



(a) **(b)** **(c)** **(d)** **(e)** **(f)** **(g)** **(h)**

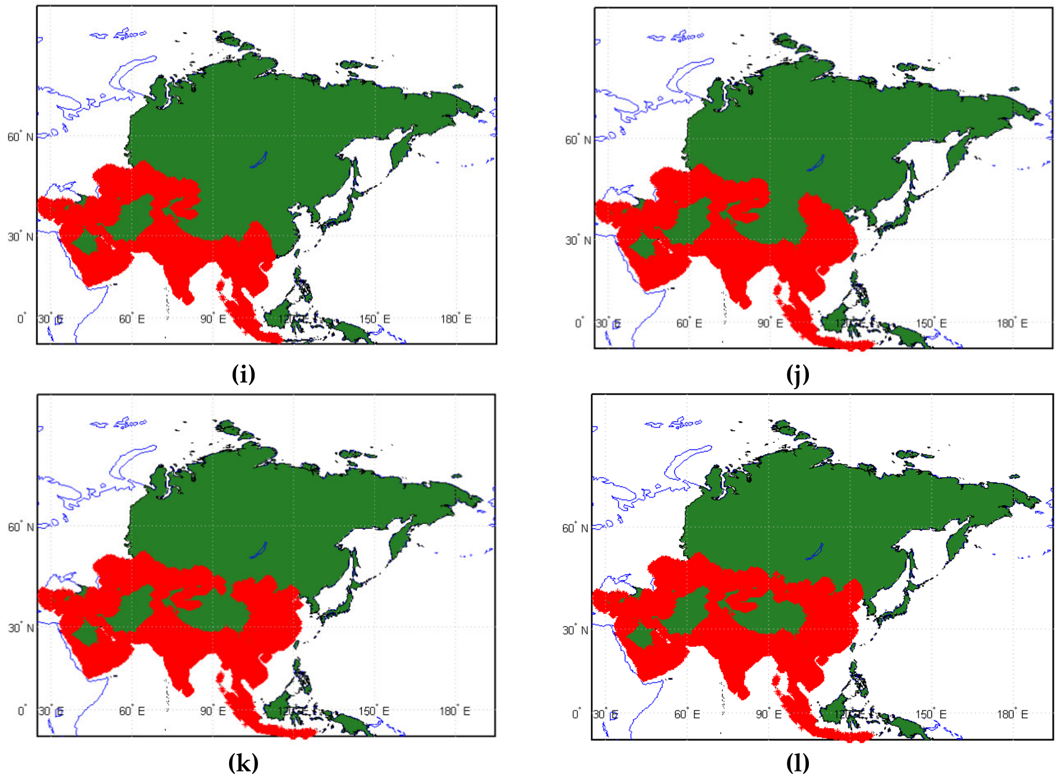


Figure 2. The invasion of *Tuta absoluta* in Asia. The simulation is made for 25 years considering the temperature and relative humidity as parameters. Locations in green are those susceptible to being invaded; locations in red are those invaded by the spread of *T. absoluta*. **(a)** 1 Year; **(b)** 4 Years; **(c)** 6 years; **(d)** 8 years; **(e)**10 years; **(f)** 12 years; **(g)** 15 years; **(h)** 17 years; **(i)** 19 years; **(j)** 21 years; **(k)** 23 years; **(l)** 25 years.

Comparison between the simulations and current progress showed a contrasting story, since the current invasive pest progress is much faster than the one predicted from the simulation model. More specifically, it took about ten years for *T. absoluta* to reach Myanmar (no official report yet, but the invasive pest presence has been suspected). These observations, therefore, reject the hypothesis that the invasion of *T. absoluta* in Asia is only due to its natural flight ability, as previously found under African conditions. Moreover, isolated regions or countries like the Philippines, Taiwan, parts of Indonesia and Malaysia seem to show a low risk of natural invasion, due to the large distance between continental Asia and these island regions, restricting natural flight arrival. In addition, and based on the simulation model, the northern part of Asia would be also out of risk of natural invasion mainly because of the environmental conditions, which seem to be unsuitable for the establishment and development of the invasive pest.

4. Discussion

The development and implementation of efficient control measures against insect invasive pests with complex biological and physiological characteristic such as *T. absoluta* require a good understanding of the mechanism used by the insect pest to disperse and establish. Here we used the CA model developed by [7], who successfully predicted the spatiotemporal invasion of *T. absoluta* in Africa to explore if the mechanism and path of dispersal being used by the invasive pest in Asia are the same. The details about the phenology of *T. absoluta* are not taken into account by the model. However, without minimizing the level of damage caused by the larvae of *T. absoluta* in crops [58], the simulations have provided a broad idea about when the invasive pest is supposed to reach certain location(s) in order to anticipate and adopt proper management strategies in place to slow down the arrival of the pest.

Regardless of the simulation model, an important observation is that *T. absoluta* has spread in Asia faster than initially supposed considering only its natural flight ability. Using the simulation model, *T. absoluta* was expected to invade Southeast Asia naturally in about 20 years after its first detection in Turkey. However, in the current real-time situation, the invasive pest reached this region less than 10 years from its first report in Turkey. International crop trade and movement of people have proven to be responsible for expediting the invasion of insect pests [40,59–61]. These factors can easily explain the high speed of invasion of *T. absoluta* in Asia, especially among the top five highest tomato producing regions in the world, including three Asian countries: China, India, and Turkey. Although it has not yet been reported from China, its presence in Myanmar, Laos or Vietnam can expedite the invasion into southern China. Likewise, it is worrying that a large quantity of tomato produced in these affected regions/countries is exported to other countries that have not yet reported the presence of the invasive pest. Therefore, it is expected and predictable that a rapid introduction and invasion of this pest to other neighboring countries in the short term is possible.

Many Asian countries are among the world top five producers of potatoes and eggplants, with about 40% of the world production for potatoes and more than 75% of world production for eggplants [62]. This includes China and India for potato production and China, India, Turkey, and Iran for eggplant [63]; moreover, these crops are also widely cultivated on the entire continent by other countries (FAO: http://www.fao.org/faostat/en/#data/QC/visualize). These factors make the Asian continent extremely vulnerable and more suitable for the invasion of *T. absoluta.* Considering that a huge number of these products are traded worldwide assisted by human transportation, this will speed up the spread of *T. absoluta* towards surrounding locations. Although damages due to *T. absoluta* on crops in Asia have been reported on all previous mentioned crops [64], recent studies reported that this invasive pest poses a major threat to tomatoes and less to potato, eggplant, and other solanaceous species [18,65]. With tomatoes as the main target and the preferred host plant of *T. absoluta,* it would be advisable to focus the development and implementation of control strategies on tomatoes, and also the improvement of regulation of human mediated international crop trade to slow down and limit the spread.

Apart from the contrast observed with the speed of invasion of *T. absoluta* in Asia, the simulations also showed that the northern part of Asia seems not to be at risk of natural invasion by *T. absoluta,* due to unfavorable climatic conditions for the establishment of this invasive pest. These results are in agreement with the previous suitability map produced for the same pest in Asia [18,66]. Moreover, most of the isolated countries in Southeast or East Asia such as Taiwan, the Philippines, Koreas or Japan are also out of risk from natural invasion by flight, despite suitable environmental conditions for the establishment of *T. absoluta* [18,66]. However, the invasive pest can be easily introduced if these countries import tomatoes from those countries which have already reported the presence of *T. absoluta.* Therefore, proper quarantine measures are highly recommended in these countries to curtail or slow down the invasion by crop transportation or human movement.

According to [18], many countries in Asia, including both invaded and non-invaded ones, do not seem to take the economic and ecological damage due to *T. absoluta* seriously, because the invasive pest has not been included in their quarantine list [18]. Unfortunately, local farmers tend to adopt the use of chemical pesticides once the pest is detected, but it has already been proven to be inefficient against *T. absoluta* [67–71]. It is quite usual that farmers change and adopt IPM strategies including pheromone trapping, the use of natural enemies and microbial insecticides only after realizing the control failures even after applying these chemical pesticides [72–75]. Phytosanitary officers can play a key role in preventing or slowing down the progress of *T. absoluta* in Asia, especially by (i) advising government(s) of *T. absoluta*-free countries but with suitable environmental conditions for the invasive pest to adopt quarantine measures, and avoid or limit crop importation from already invaded countries; (ii) educating and training farmers in *T. absoluta*-invaded regions in the successful existing IPM strategies to control or reduce damage from *T. absoluta* intrusion; (iii) creating a platform for technical information exchange, where farmers, researchers, phytosanitary officers and governmental staff from different countries will interact for timely and rapid communication of advances in *T. absoluta* management.

5. Conclusion

Herein we investigate the process of the spatiotemporal invasion of *T. absoluta* in Asia using a CA model to predict its natural spread pattern. We realized that the speed of spread of *T. absoluta* in Asia is accelerated by international crop exchange and human movement across the continent. Therefore, including information about the trade of the main host plant (tomatoes) could help extend this study and help policy makers to adapt control measures that fit well with the observed dynamic of the pest.

Author Contributions: R.A.G., R.S, S.A.M. conceived and designed research. R.A.G. implemented and did the simulations. R.A.G., H.E.T., P.S.-C., wrote the manuscript. All authors read, edited and approved the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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