Modeling the risk of invasion and spread of *Tuta absoluta* in Africa

Ritter Y. A. Guimapi[1,2], Henri E. Z. Tonnang[3], George O. Okeyo[2], Frank T. Ndjomatchoua[1,4], Samira A. Mohamed[1], Sunday Ekesi[1].

[1]icipe - African Insect Science for Food and Health, P.O. Box 30772-00100, Nairobi, Kenya.

[2] Department of computing, School of Computing & Information Technology, Jomo Kenyatta University of Agriculture and Technology (JKUAT), P.O. Box 62000-00200, Nairobi. Kenya

[3]International Maize and Wheat Improvement Center (CIMMYT)
ICRAF House, United Nation, Avenue, Gigiri, P. O. Box 1041 Village Market, 00621, Nairobi, Kenya.

[4]Laboratoire de Mécanique, Département de Physique, Faculté des Sciences, Université de Yaoundé I, P.O. Box 812, Yaoundé, Cameroun.

Corresponding author: Ritter Y. A. Guimapi

Email: yguimapi@icipe.org

Abstract

Tuta absoluta is an invasive insect that originated from South America and has spread to Europe Africa and Asia. Since its detection in Spain in 2006, the pest is continuing to expand its geographical range, including the recent detection in several Sub-Saharan African countries. The present study proposed a model based on cellular automata to predict year-to-year the risk of the invasion and spread of *T. absoluta* across Africa. Using, land vegetation cover, temperature, relative humidity and yield of tomato production as key driving factors, we were able to mimic the spreading behavior of the pest, and to understand the role that each of these factors in the process of propagation of invasion. Simulations by inferring the pest natural ability to fly long distance revealed that *T. absoluta* could reach the South of Africa ten years after being detected in Spain (Europe). Findings also reveal that relative humidity and the presence of *T. absoluta* host plants are important factors for improving the accuracy of the prediction. The study aims to inform stakeholders in plant health, plant quarantine, and pest management on the risks that *T. absoluta* may cause at local, regional and event global scales. It is suggested that adequate measures should be put in place to stop, control and contain the process used by this pest to expand its range.

Keyword: *Tuta absoluta*, spatial spread, vegetation, climatic factor, Cellular automata, prediction.

1. Introduction

World-wide, among vegetables, tomato, *Solanum lycopersicum* L. (Solanaceae), ranks high as a food as well as a cash crop (USAID, 2005). However, tomato production is constrained by numerous factors. Some important factors are arthropod pests such as the red spider mite (*Tetranychus evansi* Baker & Pritchard), African bollworm *Helicoverpa armigera* (Huebner), leafminers (*Liriomyza* spp.) and thrips (*Frankliniella* spp.) (Varela *et al.*, 2003). The problem is further compounded by the recent invasion by a micro-Lepidoptera moth, the tomato leafminer, *Tuta absoluta* (Meyrick, 1997) (Lepidoptera: Gelechiidae), which is currently the dominant pest of the crop devastating production in all the invaded regions, especially in Africa. *T. absoluta* has high reproductive potential, capable of yielding up to 12 generations per year under optimal condition. The optimal temperature for its development ranges from 21 to 30°C. Low temperature is a limiting factor for its survival but high humidity is suitable for its development and life span (Cuthbertson et al., 2013; Erdogan, 2014; Khadidja and Salaheddine, 2014; Miranda et al., 1998; NAPPO, 2014). A mature female can lay up to 260 eggs. The live cycle of this pest is comprised of four developments stage (egg, larva, pupa, adult); which are all harmful and can attack different parts (leaves, stems and fruits) of the host plants (Cuthbertson et al., 2013; Erdogan, 2014; Khadidja and Salaheddine, 2014; Miranda et al., 1998; NAPPO, 2014).

Although tomato appears to be the primary host of the *T absoluta*, it has also been reported to attack other cultivated solanaceous crops such as potato, (*Solanum tuberosum* L.) and eggplant,(Solanum melongena L.) (Ferracini et al*.* 2012; Mohamed et al. 2015). Outside its native home range the pest was detected for the first time in Spain in 2006, from where it has spread to several European countries including Italy (2008), France (2008), Albania (2009), Bulgaria (2009), Portugal (2009), the Netherlands (2009), United Kingdom (2009) and Serbia

(2011) (Desneux et al. 2011). The pest has further spread and has currently invaded and become established in North Africa, the Middle East and several other Asian countries including India (Abbes et al. 2012).

In African, the pest is swiftly moving southwards to invade several eastern and western sub-countries (Pfeiffer et al. 2013; Brévault et al. 2014; Tonnang et al., 2015). In all the invaded regions, the pest is threatening tomato production causing massive and sometimes completes loss of tomato in both green houses and open fields (Abbes et al. 2012; Mohamed et al. 2015). The pest continues to spread at an alarming rate across the continent as well as expanding its host range by attacking other vegetables and staple crops (e.g. African night shade, potatoes) that are important sources of food and income for millions of people, particularly in poor communities of Africa.

The study of pest invasion and spread is governed by a sequence of complex interactions between the invader and the recipient agro-ecological regions (Richardson & Pyšek 2006). Physical and biological characteristics of landscapes contribute to the establishment of invaders (Davies et al. 2005). Tropical regions such as the majority of Africa are highly vulnerable to insect species invasions, nevertheless, only a few scientific investigations on the dynamics and spread of invasive capability of alien species have been undertaken (Dangles et al. 2008; Crespo-Pérez et al. 2011; Osawa et al. 2013). Considering the economic importance of *T. absoluta* , and the threat it poses to the production and trade of its host plants, developing models to predict the risk of invasion and spread to new localities is of paramount importance for early warning of invasions and management of such colonization (Crespo-Pérez et al. 2011).

Many approaches for modeling species invasions and spreads have been documented (Balzter et al., 1998; Colasanti et al., 2007; Farashi and Shariati Najafabadi, 2015; Morozov et al., 2008;

Simpson et al., 2013). Mechanistic models are often been applied and their developments are based on the understanding of the studied system (Bullock et al., 2006; Nathan et al., 2003). Such a modeling framework is very useful and plays an important role in providing solutions for modeling phenomena that are difficult to measure in the field (Bullock et al., 2006; Nathan et al., 2003). Cellular Automata (CA) are methods of developing mechanistic models using a discrete representation of space, time, variables and local interaction between its elements. CA have been successfully used for various applications such as vegetation dynamics (Balzter et al., 1998; Colasanti et al., 2007), disease epidemics (Beauchemin et al., 2005; Rhodes and Anderson, 1996), microorganism growth and dispersal (Ferreira et al., 2013; Walters et al., 2006), urban growth and dynamics (Al-Ahmadi et al., 2009; Syphard et al., 2005) and prey-predator systems (Ferreri and Venturino, 2013). Moreover, CA has been intensively used for modeling the spread of processes driven by climatic and environmental factors (Cabrera, 2014; Gage, 1999; Crespo-Pérez et al., 2011; Zhang et al., 2008; Clarke et al., 1994). The temperature was coupled with CA to study the dispersal of potato tuber moth (Crespo-Pérez et al., 2011). Relative humidity and temperature within a CA framework were applied to study population dynamic of *aculops lycopersici* (Zhang et al., 2008); and wildfire propagation (Clarke et al., 1994). Some studies also investigated vegetation cover through a CA approach (Cabrera, 2014; Gage, 1999). The present study combined normalized difference vegetation index (NDVI), temperature, relative humidity and yield of tomato production within a CA conceptual framework to yield an integrated spatial and temporal model for predicting *T. absoluta* invasion and spread in Africa taking as the origin of spread Spain in Europe. The use of such an approach provides an early warning mechanism to serve as a tool for phytosanitary officers and policy makers to make informed decisions in order to safeguard against potential invasions, spread and establishment of *T. absoluta* and to prioritize the management needs.

2. Material and methods

2.1. Area of study and datasets used

The area of interest for this study includes Spain, Portugal, and the entire African continent. The datasets used are the following: *T. absoluta* occurrence data, normalized difference vegetation index (NDVI), temperature, relative humidity and the yield of tomato production per country. T. absoluta occurrences data were obtained from literature searches (Abbes et al., 2012; Anon. 2012; Desneux et al. 2010; Ouardi et al., 2012; Tonnang et al., 2015; USDA APHIS 2011). They are georefencing point representing the record of *T. absoluta* in a location. The NDVI is obtained using the visible and near-infrared light reflected by vegetation. It is calculated using near-infrared radiation (NIR) minus visible radiation (VIS) divided by near-infrared radiation plus visible radiation (NDVI = (NIR - VIS)/(NIR + VIS)). Calculations of NDVI for a given pixel always result in a number that ranges from minus one (-1) to plus one (+1) (Herring and Weier, 2000). NDVI for Europe was downloaded from an open source website BOKU (University of Natural Resources and Life Sciences, Vienna) (Vuolo et al., 2012) while NDVI for Africa were obtained from the U.S. Geological Survey (USGS) web site (https://dds.cr.usgs.gov/emodis/Africa/historical/TERRA/). Temperature values were retrieved from the WorldClim database (http://www.worldclim.org/current) (Hijmans et al., 2005); relative humidity datasets were obtained from the Surface meteorology and Solar Energy (SSE) website (http://eosweb.larc.nasa.gov/sse/). Information on harvested production per unit of area for tomato in Africa was retrieved from the “factfish” web site (http://www.factfish.com/statistic/tomatoes%2C%20yield)

2.2. Datasets transformation

The NDVI datasets for Europe (year 2014) is produced at 16 days intervals. NDVI values for Africa (year 2013) corresponding to satellite data are produced at 5-day intervals and the image represents the mean value of every month. For standardization, the values of NDVI were divided by 10,000 so that they range from -1 to 1. Temperature data were organized in monthly mean values with a grid of 30 arc-seconds, corresponding to approximately 1 kilometer of resolution. Using Geographic Information System (GIS) software Quantum GIS (QGIS) we extracted the values of temperatures by overlaying the geographic coordinates of the area of study on temperature files. Relative humidity data acquired were in text files and contained the geographical coordinates of the Earth surface spaced by 1x1 degree. The Inverse Distance Weighting method (IDW) (Roshan and Kang, 2011) was used to interpolate the relative humidity values to obtain a map, which was then aligned to the geographical coordinates of the area of study. This process was repeated for twelve months of the year. Tomato yield production of the world per country ranged from 0.46 to 499.6 tons per hectare for the year 2013 (Factfish, 2013). Information of 168 countries is available on the Internet; however, we only selected countries that belong to Africa and subdivided them into three classes. The classification exercise is performed to differentiate location with high production to those with low production of tomato. Class 1 (very high producers), corresponds to countries with a production greater than 30 tons per hectare. The second class (high producers), corresponds to areas with a production of 10 to

30 tons per hectare, and the third class (low producers), which corresponds to countries with production less than 10 tons per hectare.

2.3. Cellular Automata (CA) model development and implementation

The developed CA model is a spatially and temporally discrete system characterized by local interactions and synchronous dynamical evolution. Overall, it consists of five main elements: (i) a grid of cells, (ii) cell states, (iii) neighborhood, (iv) transition rules that determine how a cell changes from one state to another, and (v) time step. The area of study was divided into square regular lattices of 25x25 km to characterize an individual cell of the CA. Each cell can be in one of the following three states: susceptible exposed and invaded. During the simulation, a susceptible cell can either become exposed or invaded. The exposed state represents cells, which *T. absoluta* may have crossed before reaching invaded cells. The invaded state corresponds to the status of locations where the pest has a high risk of permanent establishment. Initially, all point locations are susceptible to the invasion by *T. absoluta*. Only the point location in Spain, which is the starting point of the simulation is considers invaded. The diagram in Fig. 2 is a schematic representation, which outlines the model processes, algorithms, and state transitions.

2.3.1. Cellular automata thresholds

The rules of the CA model are defined with the aim to mimic the dispersion of *T. absoluta* in Africa since its introduction in Europe. The optimum temperature threshold for its development and dispersion range was used to define the rules. This information comes from laboratory and field experiments on *T. absoluta*. Using the classification of NDVI developed by Badamasi et al. (2012), we adopted two thresholds: The first value of NDVI threshold (threshold1 = 0.1) is considered as the lower boundary to characterize the exposed zone; while the second threshold (threshold2 = 0.3) is applied as the lower limit when the quantity of tomatoes production is added as a variable for the selection of areas with risk of invasion and spread of the pest. Temperature values for the development of immature life stages of *T. absoluta* range from 13°C to 30°C and the complete developmental time of the pest is around 74 days at lower temperature and shorter at higher temperature (Cuthbertson et al., 2013; Erdogan, 2014; Khadidja and Salaheddine, 2014; Miranda et al., 1998). Between 21°C to 25°C the developmental time of *T. absoluta* is approximately 30 days; therefore, it was found convenient to use a monthly time step in the simulations, with a temperature threshold set at 22°C. Relative humidity for the development of *T. absoluta* is suitable when it is greater than 50% (Brito et al., 2015; Cely et al., 2011); for adequacy, it was set at 55%. Based on the classification on tomato yield production presented above, we assigned zero (0) to locations with low production (class 3), one (1) to locations of high production (class 2) and two (2) to locations of very high production (class 1). In addition, because *T. absoluta* is reported to fly up to 100 Km (Government of Canada, 2012), we opted for the Moore neighborhood (Moore, 1962) that covers an area of radius 100 km. However, it was considered that the application of pheromone traps, insecticides, parasitoids or any control and quarantine measures can contribute to reducing the population density and dynamics of the pest. By doing so, *T. absoluta* ability to fly long distance may be affected and the pest fly radius reduced. Under these assumptions, two simulations were carried out with small values of the pest fly radius (75km and 50km). The choice of squared Moore neighborhood provides a better coverage of space compared to the hexagonal neighborhood as shown Fig. 1(Langlois, 2013).

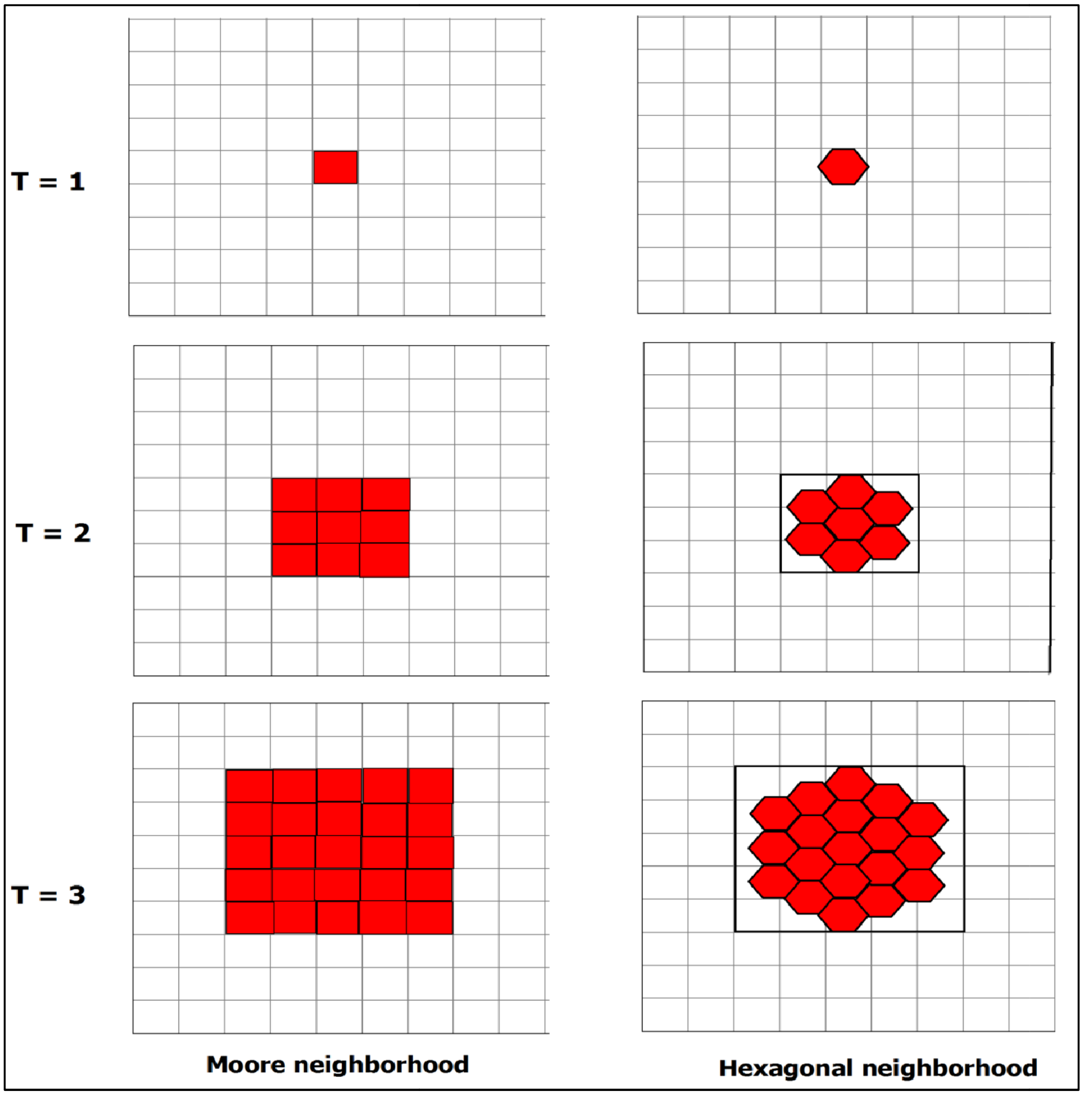

Fig. 1. Schematic representation of space coverage using squared Moore neighborhood and hexagonal neighborhood.

2.3.2. Rules of the CA

Cells in the neighborhood of infected area are updated deterministically according to the following rules:

Susceptible cell (S): A susceptible cell can become exposed (E), invaded (I) or still susceptible (S) depending on the state of the parameters. The following conditions allow a susceptible cell(S) to remain or change state. i) If the value of NDVI is lower than the NDVI threshold

(NDVI < threshold1), meaning that there is no reasonable environmental condition in the location to allow the change of state. The susceptible cell remains susceptible (S to S). ii) If the value of NDVI is greater than or equal to the NDVI threshold (NDVI ≥ threshold1); this means that the insect may be there but without clear damages to crops, probably because the climatic conditions are not favorable for its development and reproduction, the susceptible cell turns exposed (S to E). iii) A susceptible cell change state and becomes infected (S to I) when either one of the following conditions is satisfied: 1) If the value of NDVI, temperature, and relative humidity are greater than the value of their corresponding threshold (NDVI ≥ threshold1, temperature ≥ temperature threshold and relative humidity ≥ relative humidity threshold); or 2) if regardless of the value of relative humidity and temperature, the NDVI is greater than the NDVI threshold (threshold2) and the location belongs to an area of the first and second classes using the classification based on the quantity of tomatoes production (NDVI ≥ threshold_2 and tomato production=1or2).

An exposed location can become invaded (E to I) if environmental conditions change and become suitable for the establishment of *T. absoluta*, meaning that one of the rules for the infestation described above is satisfied otherwise, it does not change its state. An invaded location cannot change its state during the simulations if no quarantine and control measures against *T. absoluta* are applied.

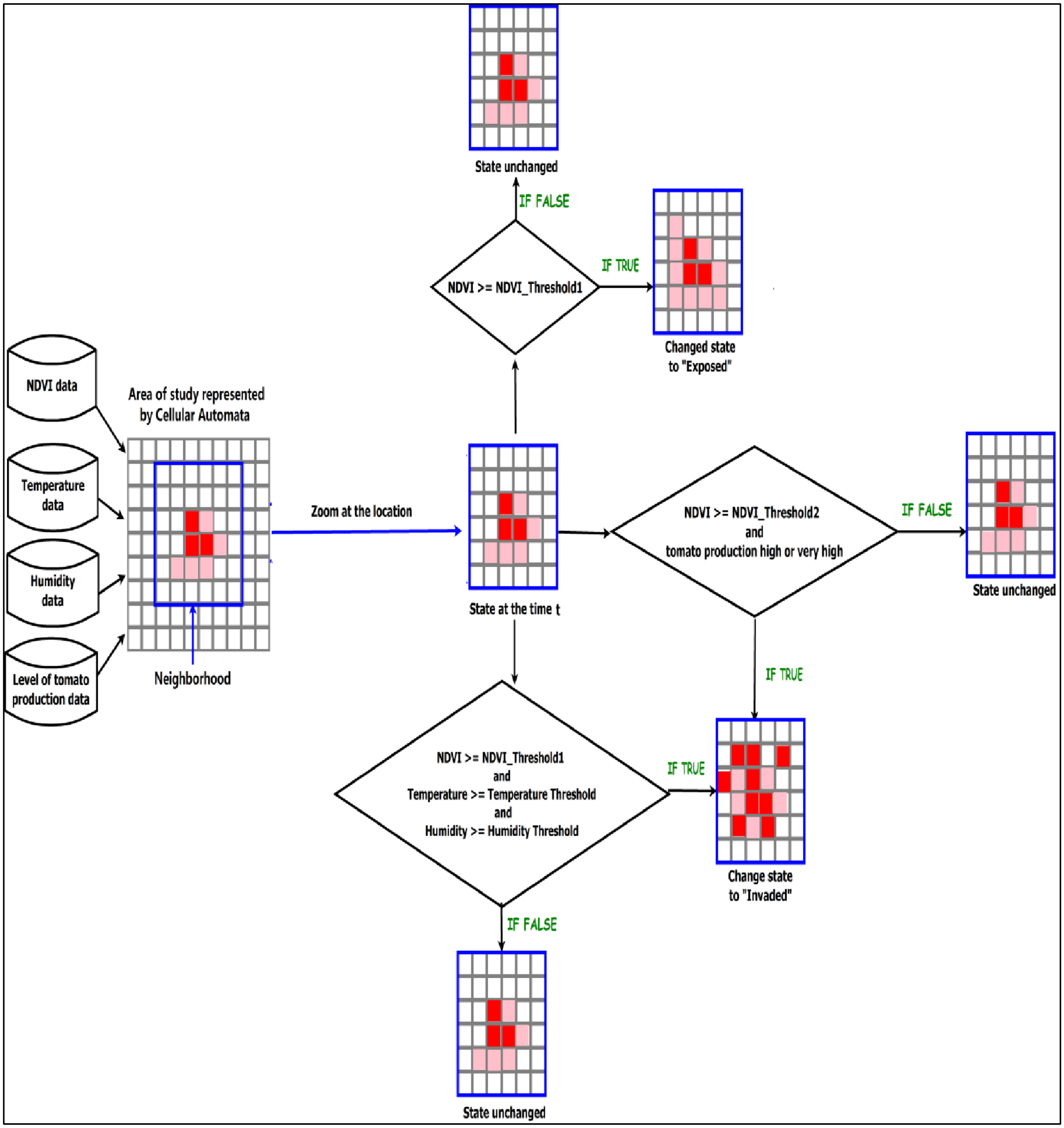

Fig. 2. Schematic representation of the modeling approach for the invasion and spread of *T. absoluta.* The approach is based on cellular automata and the grid represents the cells of our area of study. The rules of the cellular automata are defined using NDVI, temperature, relative humidity and yield of tomato production.

2.4. Model implementation and simulation processes

The model was implemented in MATLAB (R2010a, The MathWorks). Starting from the knowing infected locations in Spain, the temporal and spatial spreading of the insect-pest was observed considering different scenarios. It permits to evaluate the sensitivity of the model parameters (temperature, vegetation index and others) and to enhance the understanding of the invasion process of T. absoluta. We begin the simulations by taking in consideration only vegetation (NDVI) data as an input parameter; thereafter we progressively introduced temperature, relative humidity and the yield of tomatoes per region. Fig. 3 displays the overall studied areas and the initial geographical location of the simulations.

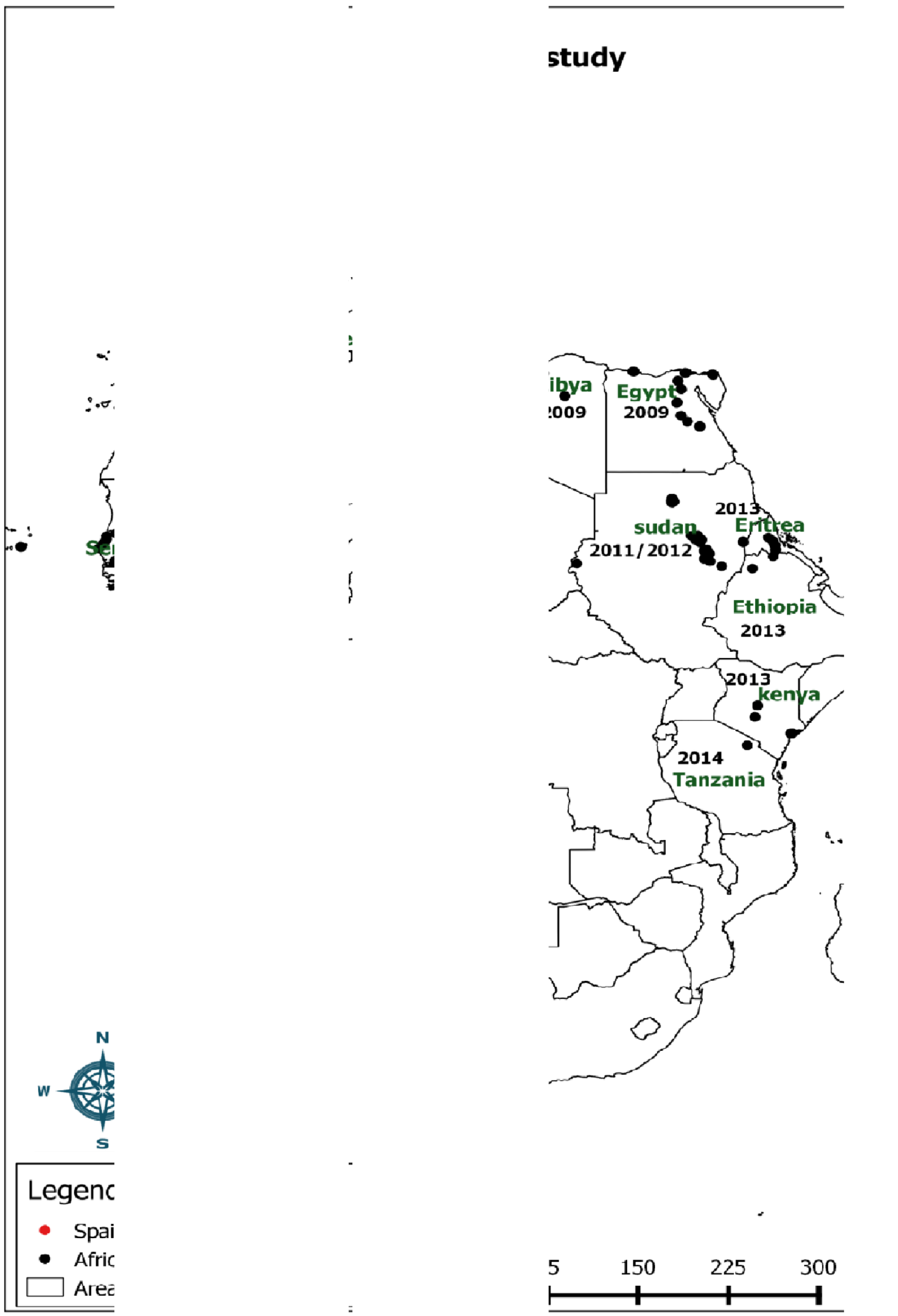

Fig. 3. Studied area where the spread of *T. absoluta* occurs. The geo-referenced points in black represent known locations of occurrence of *T. absoluta* and the red spot in Spain is considered as the initial point of invasion from where *T. absoluta* has spread in Africa.

2.5. Model validation

The validation of the model is done using pattern-oriented modeling strategy (Grimm, 2005; Grimm et al., 1996). With this approach, we have to assess the model ability to reproduce the time period that past events have occurred and to predict the timing of future advents. The Validation required that after 7 years *T. absoluta* should have reached Kenya. Further verification of the accuracy rests on the fact that, by reaching Kenya, the pest might have progressively infested other areas in the northern, western and eastern parts of the African continent. So far *T. absoluta* has been confirmed in the following countries: Morocco in 2007/2008; Algeria and North of Sahel in 2008; Tunisia in 2008/2009; Egypt and Libya in 2009; Ethiopia, Niger, Senegal, Sudan in 2011/ 2012; and Kenya in 2013 (Abbes et al., 2012; Desneux et al., 2010; Anon. 2012; Mohamed et al., 2012; Ouardi et al., 2012; Pfeiffer et al., 2013; USDA APHIS 2011). After several calibrations, once the developed model reasonably satisfied the evaluation criteria by correctly reproducing the timing known events described above, it was then used to predict the time *T. absoluta* is likely to take in order to reach the South of Africa.

2.6. Keys assumptions of the model

The model we designed and implemented is based on following assumptions: (i)The type of vegetation is not taking into consideration, meaning that in any location where there is vegetation, it was assumed that the area is suitable for the growth of any host plant of *T. absoluta*. (ii)Altitude is neglected because the current distribution of *T. absoluta* suggests that it can survive at both low and high altitude(BIOCOMES, 2015; Hardy and International Potato Center, 1996; Povolny, 1975). (iii) The values of NDVI are considered to be identical for the whole simulation period. No distinction was made on the fact that NDVI of Europe was produced in 16 days interval (Vuolo et al., 2012) whereas in Africa it was produced at 5 days interval (https://dds.cr.usgs.gov/emodis/Africa/historical/TERRA/). (iv)For every cellular automata (CA) cell, a barycenter was estimated and the closest georeference point location to this barycenter was considered as the center of the cell.

3. Results

The predictions of the risk of invasion and spread of *T. absoluta* in Africa considering Spain as the initial posit of the pest dispersal are presented in different maps. Fig. 4 displays the results of the simulation when only the vegetation parameter is taken into account. A similar trend is observed with the combined effects of both vegetation and temperature (Fig. 5). When the vegetation and relative humidity are both considered (Fig .6), it is observed that although *T. absoluta* has the ability to fly for long distances, its spread across the Sahara desert and its invasion into the sub-Sahara region could not have been via natural means, but rather through human-mediated activities such as trade. Taking into account relative humidity and temperature (Fig. 7) we obtained maps almost identical to the scenario, which only account for vegetation and relative humidity. The combined effects of vegetation, relative humidity and temperature (Fig. 8) did not show major changes from previous scenarios that include relative humidity. Fig. 9 shows 10 years of simulation of *T. absoluta* spread with the collective effects of vegetation, relative humidity, temperature and yield of tomato production per area. The introduction of the yield of tomato production allows the detection of some areas, which were not well captured in previous cases when only climatic factors were considered as main variables in the simulations. As shown in Fig. 6 and 7, relative humidity seems to be an important parameter for predicting the risk of invasion and spread of *T. absoluta.* In all simulations when this parameter is included, the pest invasion and spread evolution is the closest to the boundaries of natural observations.

Changes in the values of the relative humidity threshold from 50% to 60% gave good results; below 50% the spread and invasion observed is similar to Figures 5 and 6; while above 65% we observed a lot of discontinuity in the spread, which did not reflect the observed occurrence of the pest.

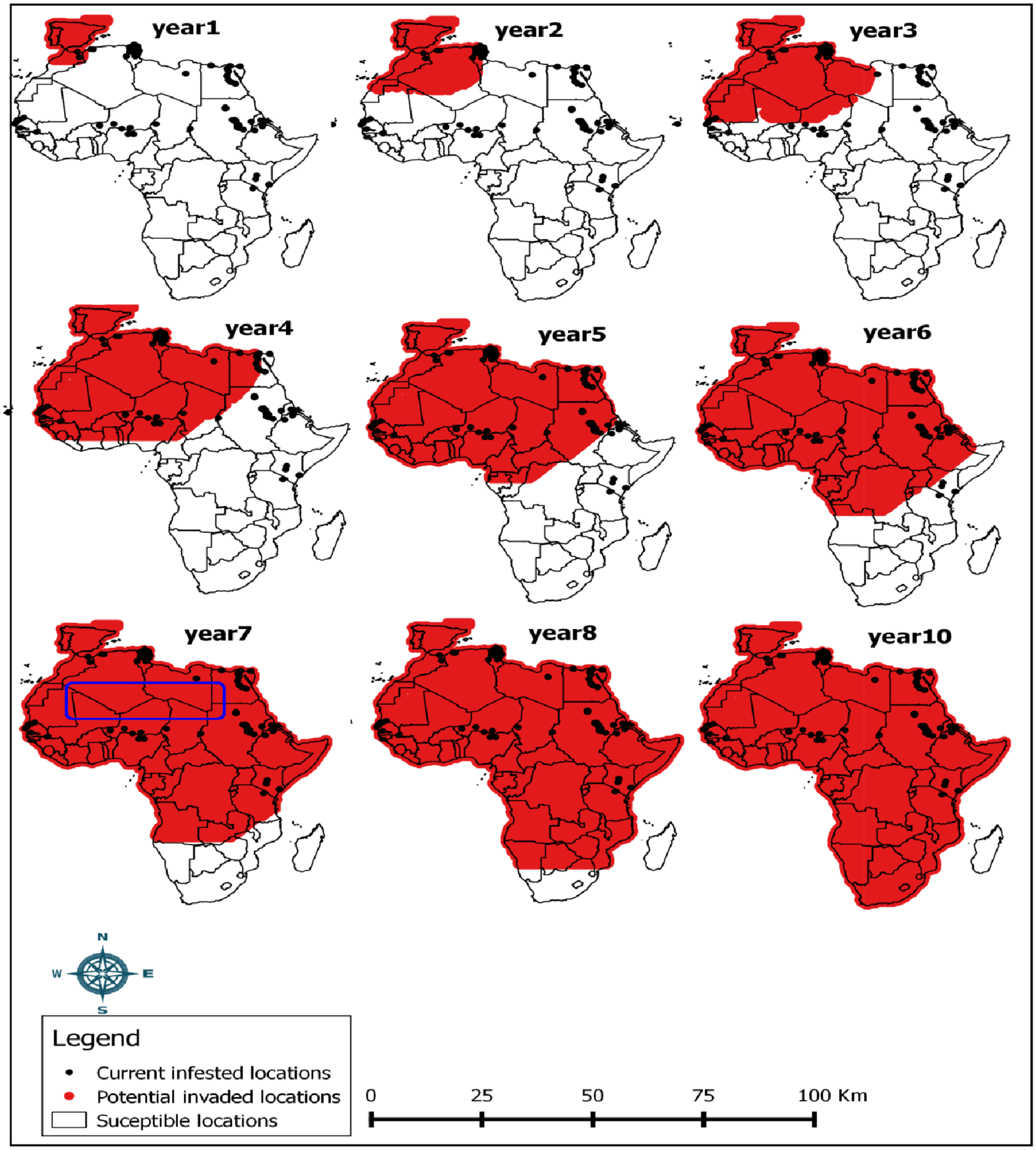

Fig. 4. The spread of *T. absoluta* in Africa obtained through a 10 years simulation taking into account only vegetation as a parameter for the pest propagation. The geo-referenced points in black represent locations of occurrence of *T. absoluta* and the areas in white are susceptible locations. Zones in red represent zones at high risk of invasion and spread of the pest. The simulations are carried out within the 10-year period from 2008 to 2018. Areas in blue color in year 7, represents zone of mismatch requesting an improvement of the model.

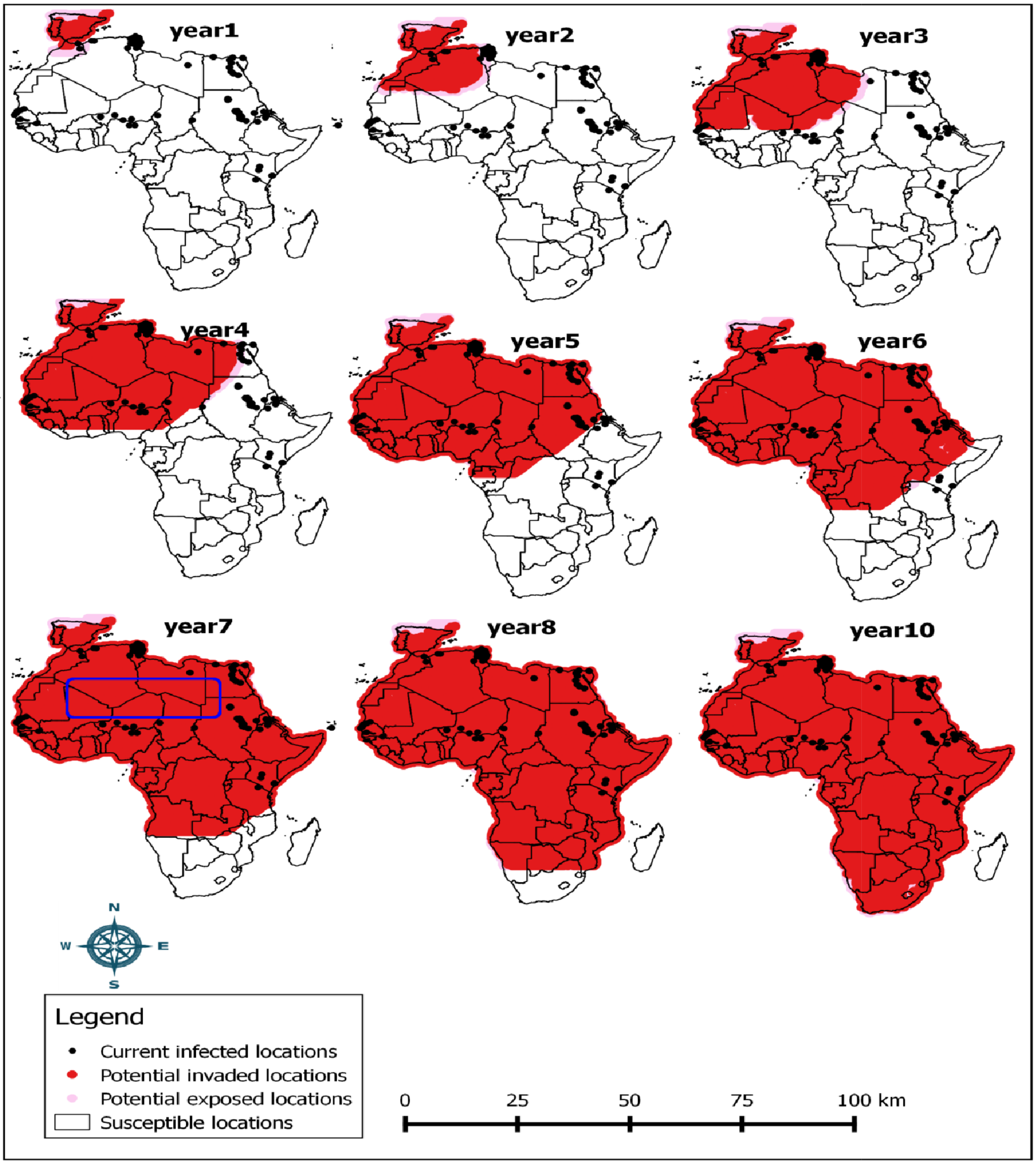

Fig. 5. The spread of *T. absoluta* in Africa obtained through a 10 years simulation taking into account vegetation and temperature as parameters for the pest propagation. The geo-referenced points in black represent locations of occurrence of *T. absoluta* and the areas in white are susceptible locations. Zones in pink are zone at low risk of invasion and spread of the pest. Zones in red represent zones at high risk of invasion and spread of the pest. The simulations are carried out within the 10-year period from 2008 to 2018. Areas in blue color in year 7, represents the zone of mismatch requesting an improvement of the model.

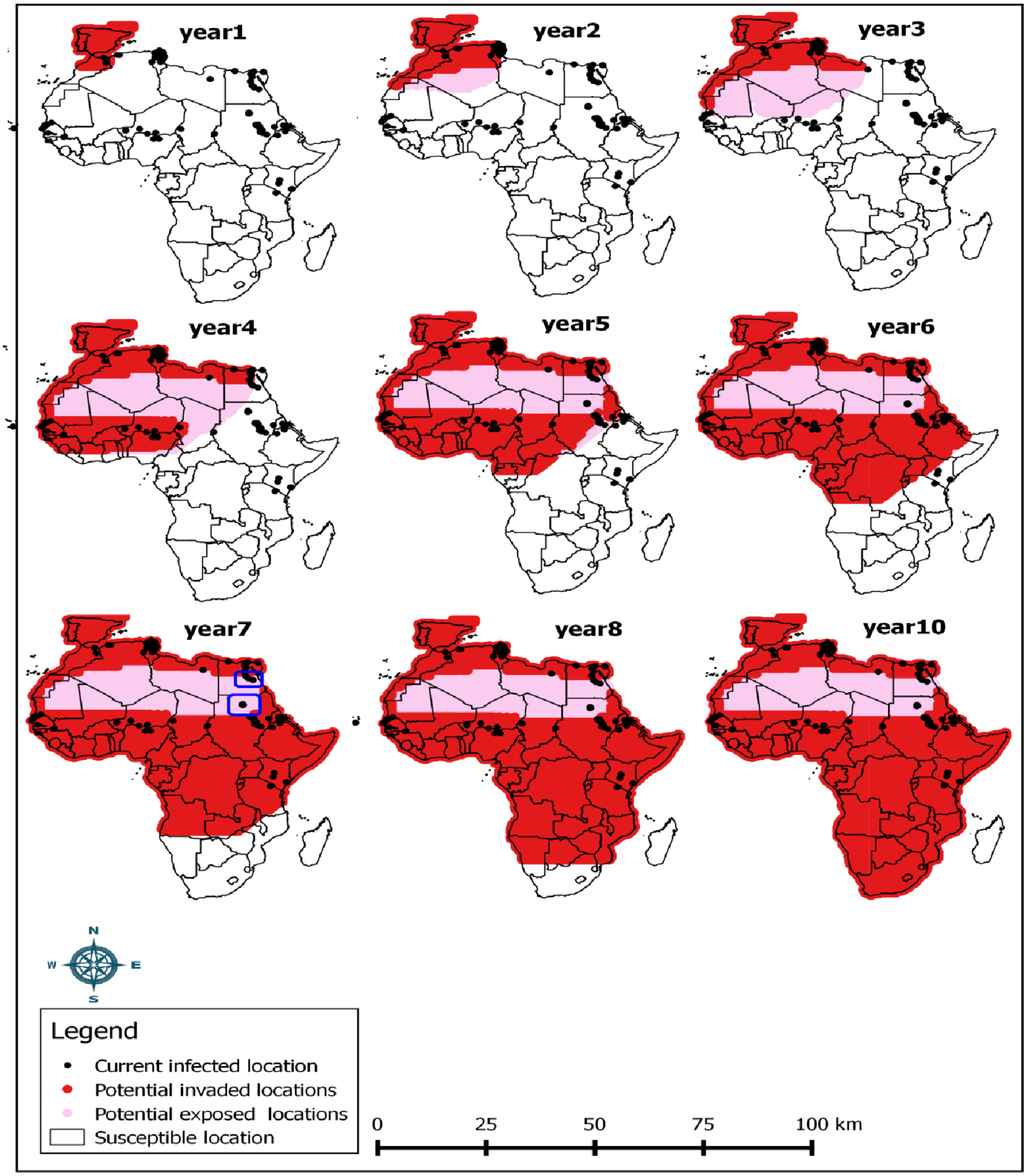

Fig. 6. The spread of *T. absoluta* in Africa obtained through a 10 years simulation taking into account vegetation and humidity as parameters for the pest propagation. The geo-referenced points in black represent locations of occurrence of *T. absoluta* and the areas in white are susceptible locations. Zones in pink are zone at low risk of invasion and spread of the pest. Zones in red represent zones at high risk of invasion and spread of the pest. The simulations are carried out within the 10-year period from 2008 to 2018. Areas in blue color in year 7, represents zones of mismatch requesting an improvement of the model.

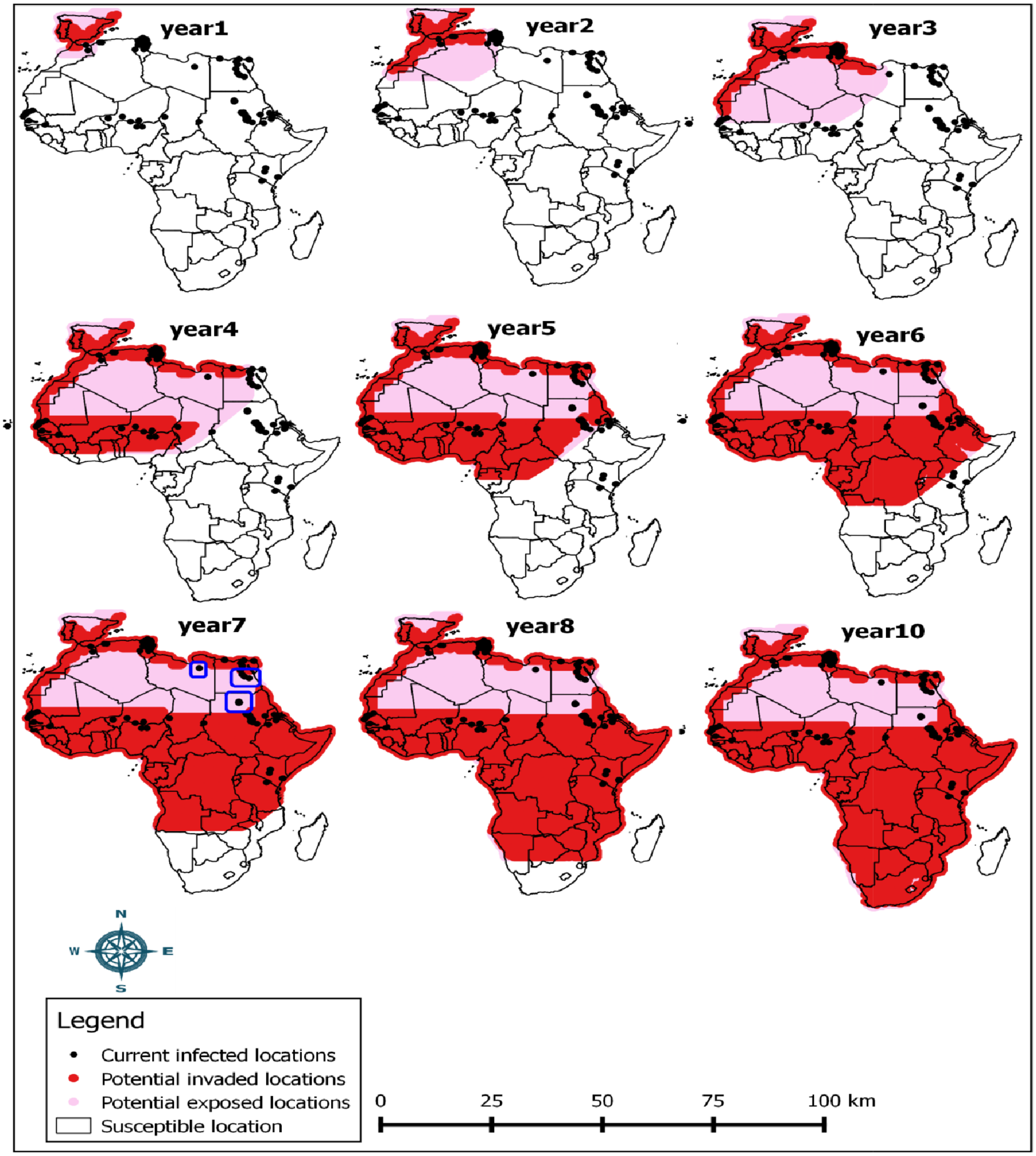

Fig. 7. The spread of *T. absoluta* in Africa obtained through a 10 years simulation taking into account humidity and temperature as parameters for the pest propagation. The geo-referenced points in black represent locations of occurrence of *T. absoluta* and the areas in white are susceptible locations. Zones in pink are zone at low risk of invasion and spread of the pest. Zones in red represent zones at high risk of invasion and spread of the pest. The simulations are carried out within the 10-year period from 2008 to 2018. Areas in blue color in year 7, represents zones of mismatch requesting an improvement of the model.

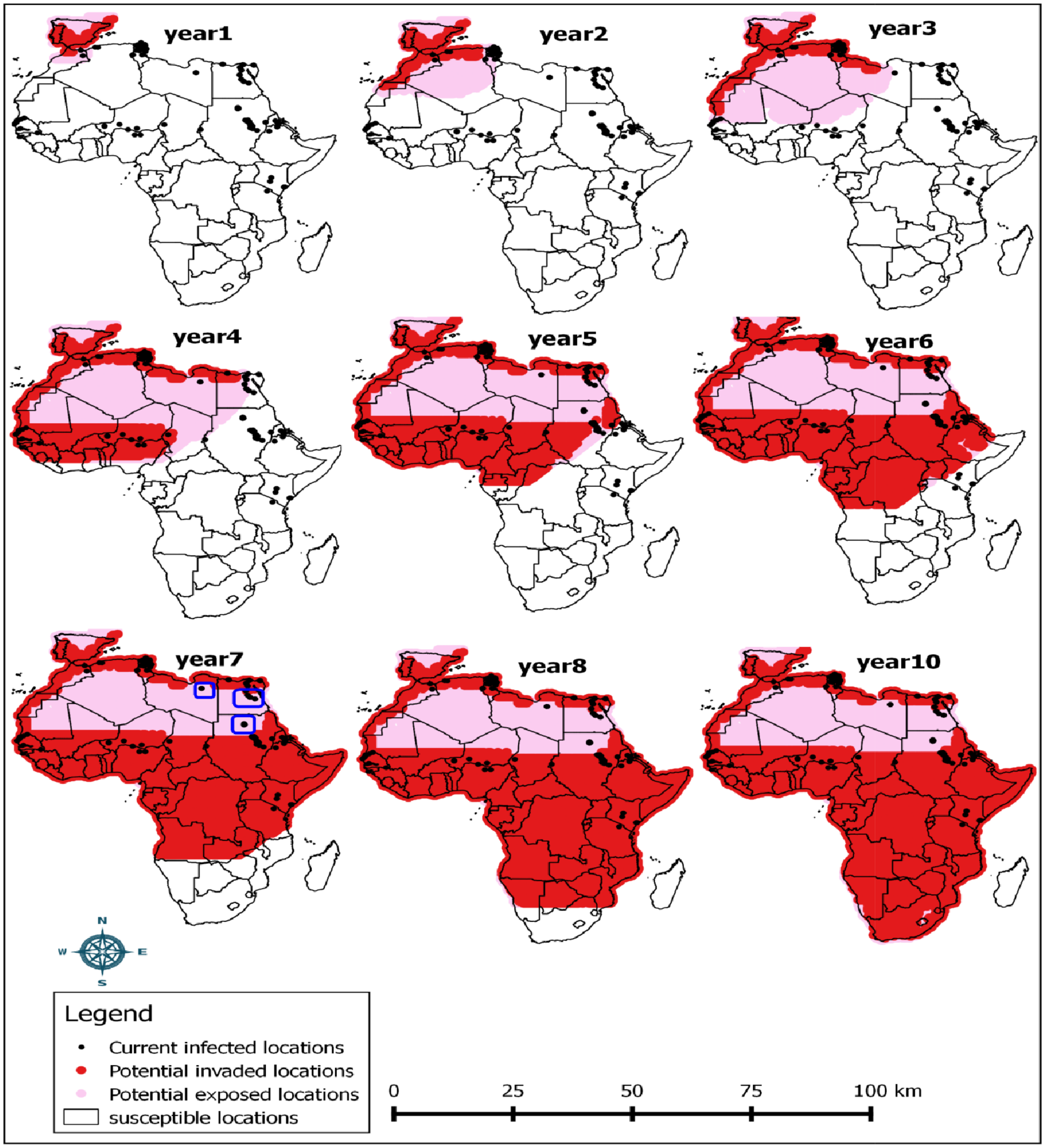

Fig. 8. The spread of *T. absoluta* in Africa obtained through a 10 years simulation taking into account vegetation, humidity, and temperature as parameters for the pest propagation. The geo-referenced points in black represent locations of occurrence of *T. absoluta* and the areas in white are susceptible locations. Zones in pink are zone at low risk of invasion and spread of the pest. Zones in red represent zones at high risk of invasion and spread of the pest. The simulations are carried out within the 10 year period from 2008 to 2018. Areas in blue color in year 7, represents zones of mismatch requesting an improvement of the model.

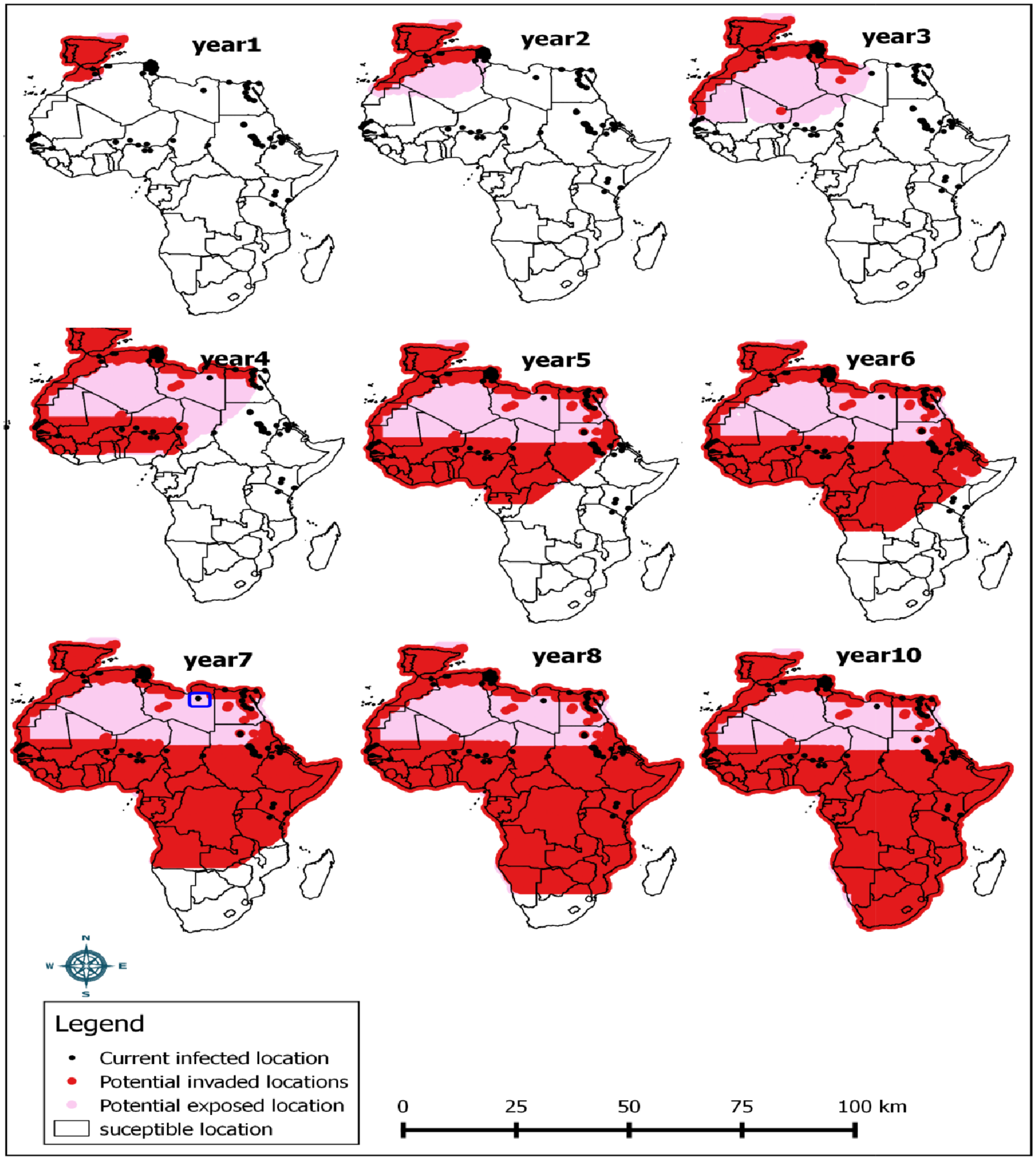

Fig. 9. The spread of *T. absoluta* in Africa obtained through a 10 years simulation taking into account vegetation, humidity, temperature and yield of tomatoes production as parameters for the pest propagation. The geo-referenced points in black represent locations of occurrence of *T. absoluta* and the areas in white are susceptible locations. Zones in pink are zone at low risk of invasion and spread of the pest. Zones in red represent zones at high risk of invasion and spread of the pest. The simulations are carried out within the 10-year period from 2008 to 2018. Areas in blue color in year 7, represents zones of mismatch requesting an improvement of the model.

The following table summarizes and compares simulation according to different parameters used and provides justification on why additional inputs were included to improve the model outputs.

Table 1: summary effects of inputs parameters on simulations results

	Parameter used				**Observation**
	NDVI	**Temperature**	**Relative humidity**	**Tomato Production**	
Fig. 4	✓				The model invaded Kenya after seven years but included the Sahara desert (graphical zone depiction in blue) as potentially invaded location, which in reality may not the case
Fig. 5	✓	✓			No improvement in the model output as the Sahara desert is still included as potentially invaded location by the pest.
Fig. 6	✓		✓		An improvement in the model output was observed because the Sahara desert is no more captured as potentially invaded locations. Nevertheless, some known invaded locations in Egypt and Sudan (graphical depiction in blue) are not captured
Fig. 7		✓	✓		Locations in Egypt, Sudan, and Libya (see the graphical areas depiction in blue) are not captured; as potentially invaded zone
Fig. 8	✓	✓	✓		No improvement as locations in Egypt, Sudan and Libya are still not identified as invaded
Fig. 9	✓	✓	✓	✓	The adding of tomato production improved the model output and more areas of Egypt and Sudan are captured.

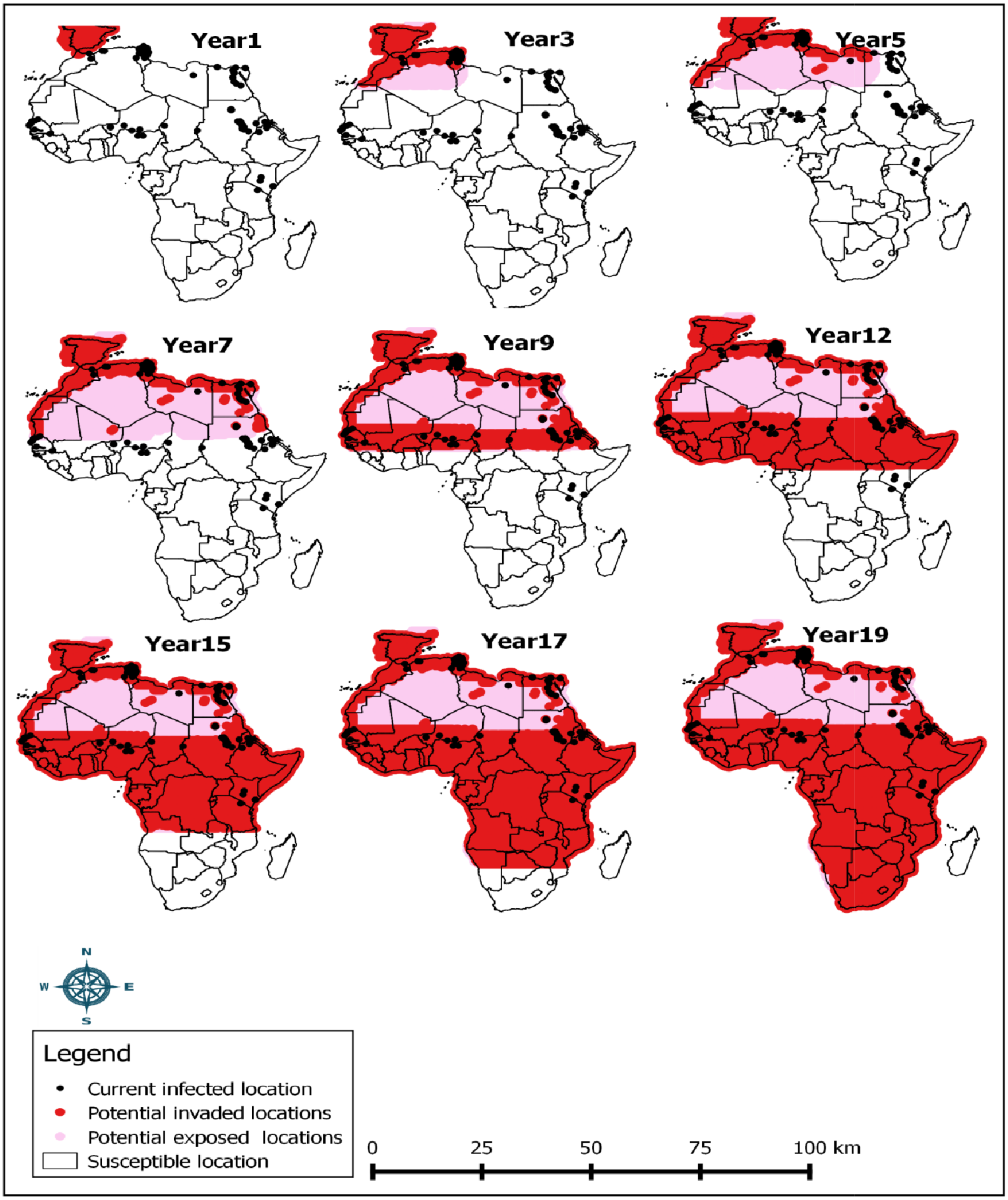

Fig. 10. The spread of *T. absoluta* in Africa at a flying radius of 75km. The result is obtained after 19 years of simulation (from 2008 to 2027) taking into account vegetation, humidity, temperature and yield of tomatoes production as parameters for the pest propagation. The geo-referenced points in black represent locations of occurrence of *T. absoluta* and the areas in white are susceptible locations. Zones in pink are zone at low risk of invasion and spread of the pest. Zones in red represent zones at high risk of invasion and spread of the pest.

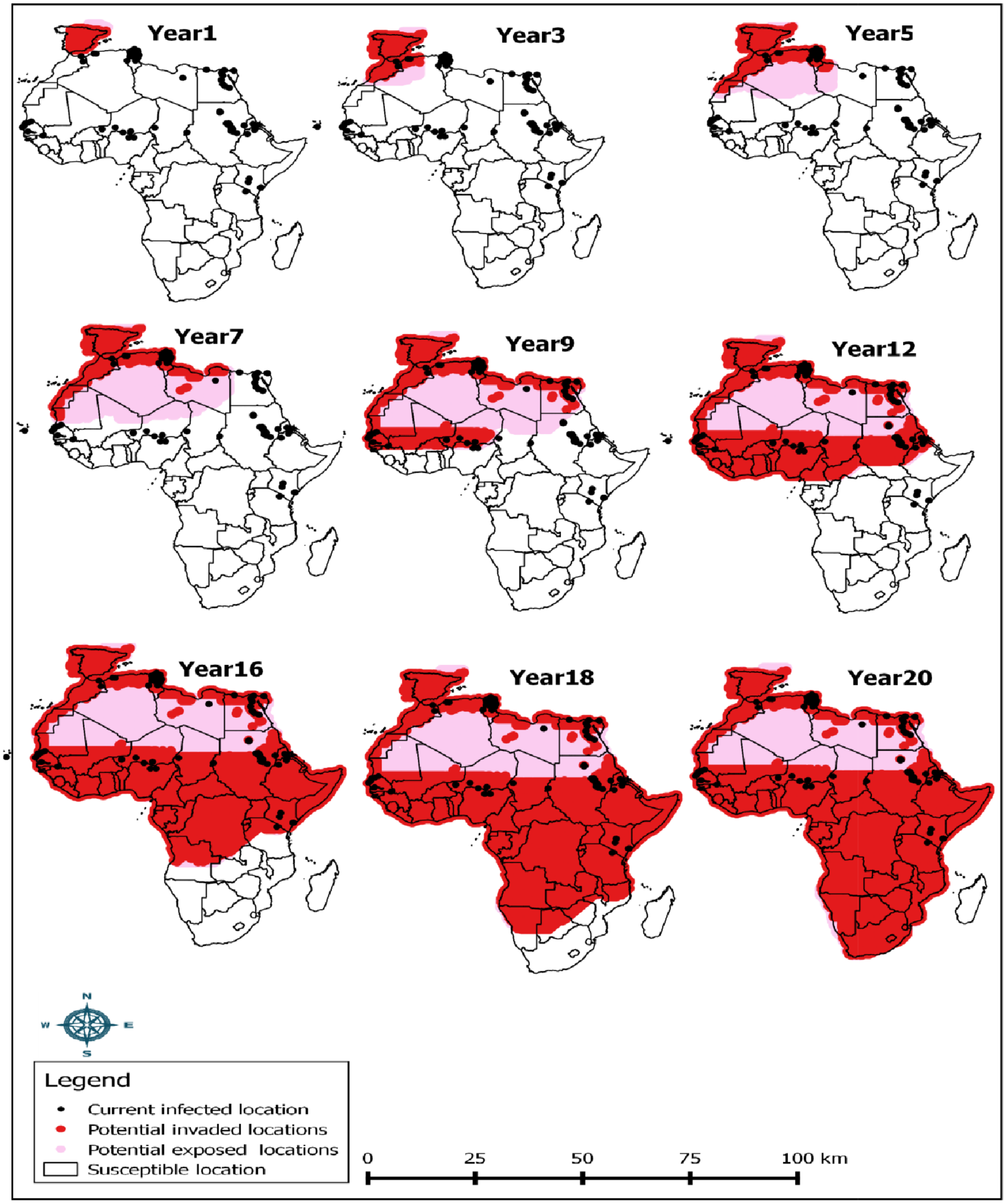

Fig. 11. The spread of *T. absoluta* in Africa at a flying radius of 50 km. The result is obtained after 20 years of simulation (from 2008 to 2028) taking into account vegetation, humidity, temperature and yield of tomatoes production as parameters for the pest propagation. The geo-referenced points in black represent locations of occurrence of *T. absoluta* and the areas in white are susceptible locations. Zones in pink are zone at low risk of invasion and spread of the pest. Zones in red represent zones at high risk of invasion and spread of the pest.

Overall, the simulations demonstrate that the entire continent is at high risk of invasion and spread of *T. absoluta*. The pest reaches Morocco after 1 year, Algeria and North of Sahel after 2 years, Tunisia after 3 years, Senegal in West Africa after 4 years, Sudan and Ethiopia after five years and Kenya after 7 years. These sequences of events confirm the reported dates of detection of the pest in these countries. Given the model adequacy in reproducing past and current events of *T. absoluta* invasion and spread, we found it adequate to use for predicting the time period when *T. absoluta* will reach the southern part of Africa if nothing is done to contain the pest and curb its southward movements. Based on our model predictions *T. absoluta* will reach South Africa 10 years after its presence was declared in Spain. Another important result showed by the simulations suggested that relative humidity is the environmental factor, which has the greatest influence on the suitability of the location for the establishment of *T. absoluta.* Moreover for locations where environmental factors are not suitable the presence of *T. absoluta* host plants such as tomato highly increases the pest risk of invasion and spread.

Results accounting on the application of some control measures that impact *T. absoluta* population density and dynamics are shown in Fig 10 - 11. These Figures display the outputs of the model simulations with the pest-flying radius of 75km (Fig. 10) and 50km (Fig. 11) respectively. With *T. absoluta* flying radius of 75km it takes 19years for the pest to reach the South of Africa and only Morocco, Algeria and Tunisia were invaded at the recorded time period of three years. When 50 km was considered as the flying radius, it takes 20 years for the pest to reach the South of Africa and none of the known areas of occurrence of *T. absoluta* within Africa were captured at the exact time period. Under these scenarios of varying the pest population density and dynamics by changing the values of the flying radius, we observed that *T. absoluta* would have taken at least 12 to reach Kenya. This outcome suggests that if adequate quarantine and control measures were introduced since the pest occurrence in Spain it should have taken several years (> 20) for the pest to be found under natural invasion and spread mechanism in South Africa.

4. Discussion

Developing dynamic models for invasive species such as *T. absoluta* spread in mixed environments is a challenging task that necessitates a robust conceptual framework, capable of exploring population dynamics both temporally and spatially as well as capturing the biology, life history, host plants and other biotic and abiotic factors (Sebert-Cuvillier *et al.,* 2008). Herein, we proposed a model based on cellular automata to predict the potential invasion of *T. absoluta.* The pest spread was sensitive to changes made on the thresholds values of some keys parameters that are related to the species life history and bioecology. Although this modeling framework uses simulations, it provides prediction of the timing and record dates that are compared to known time periods of the occurrence of *T. absoluta* in the regions of interest (Russell IPM, 2015).

NDVI dynamics have been reported as a good predictor for animal presence/absence (Pettorelli, 2013). The NDVI was used to study the change in the geographic distribution of black cutworm, *Agrotis ipsilon* (Hufnagel) (Insecta: Lepidoptera: Noctuidae) in the United States (Showers, 1997). However, it is important to note that there are two contradictory schools of thought that relate to the influence of NDVI for predicting species spread and distribution. The first highlights the influence of land cover on species distribution (Blake et al., 2013; Cornélis et al., 2011; Ito et al., 2006), especially when the study is conducted on a small scale, whereas the second school of thought supports the idea that there is no influence of land cover on the spread of species (Thuiller et al., 2004; Wilson et al., 2013). Indeed, our results, which are in agreement with previous studies on species invasion and spread conducted at large scales (Thuiller et al., 2004; Wilson et al., 2013), revealed that the spread of *T. absoluta* is not significantly influenced by NDVI.

Evidence of the direct and indirect effect of climatic factors on the spread of organisms has been broadly illustrated (Travis et al., 2013). Temperature is reported as one of the most important factors influencing the development and behavior of insects (Chapman et al., 2013). The use of temperature in a CA modeling framework for the spread of potato tuber moth was presented by Crespo-Pérez et al. (2011). The authors captured the variable temperature of a cell with a linear function. In the present study, although we selected temperature within the optimum threshold for *T. absoluta* development (Cuthbertson et al., 2013; Erdogan, 2014; Khadidja and Salaheddine, 2014; Miranda et al., 1998; NAPPO, 2014), it was found that temperature was not a key parameter in predicting the risk of invasion and spread of the pest.

High humidity is crucial for the growth of the solanaceae host (Bakker, 1991; Schwarz et al., 2014). It is also reported that high humidity is suitable for the development of *T. absoluta* (Cuthbertson et al., 2013; Erdogan, 2014; Khadidja and Salaheddine, 2014; Miranda et al., 1998). A review of the literature (Brito et al., 2015; Cely et al., 2011; Cuthbertson et al., 2013; Erdogan, 2014), permits the precise choice of the threshold of relative humidity. These values provide a good trend for the invasion and spread of *T. absoluta*. The inclusion of relative humidity as a variable in our simulation allows better predictions leading to the hypothesis that this variable might be an important climatic factor determining the choice of a location during the invasion and spread of *T. absoluta.*

One of the most important ecological causes of pest problems is the practice of monoculture (Pimentel, 2009, 1997). Current agricultural systems are characterized by the growing of one species of plant in large areas (Matson et al., 1997); such practice highly increases the probability of invasion and establishment of insect pests because it offers in permanence food (host plants). These findings are further confirmed by our results. Firstly, by comparing a recent map of the distribution of *T. absoluta* (Russell IPM, 2015) with the map of climatic suitability of Tonnang et al (2015), we observe that many of the current known occurrence locations belong to areas identified as not suitable or with moderate level of suitability for the establishment of *T. absoluta*. When the yields of tomatoes production per area were inputted into the simulations, we found a considerable improvement in the results by capturing more invaded locations in the Eastern part of Africa, which were not reflected when using only climatic factors. These results support the assertion that intensification of agriculture production widely increases the risk of invasion and spread as well as the density of pest damage in crops (Bianchi et al., 2006; Matson et al., 1997; Segoli and Rosenheim, 2012).

The model predicts that the invasion by *T. absoluta* could reach South Africa 10 (ten years) after its detection in Spain. An interesting feature is that the progress of the pest through simulation year-to- year is quite similar to the observed dates of progression of *T. absoluta* in Africa (Abbes et al., 2012; Anon. 2012; Desneux et al. 2010; Ouardi et al., 2012; Tonnang et al., 2015; USDA APHIS 2011). Madagascar, though it enjoys climatic conditions, which are conducive for establishment of *T. absoluta,* might not be invaded due to its geographical location as an isolated island except by accidental introduction. In this context, our results suggest that adequate measures should be put in place to stop, control and contain the process this pest is using to expand its range from the geographical areas it currently occupies into new zones. The effectiveness of such approach has been proved to be successful to slow down the spread and the crop production loss due to the pest (Adams and Lee, 2011). In regions already invaded by the pest, efficient control approaches within Integrated Pest Management (IPM) strategies should be introduced. This especially true knows that resistance of *T. absoluta* to insecticide has been reported (Gontijo et al., 2013; Silva et al., 2011). All locations predicted to be at risk of invasion belong to areas identified as potentially suitable for a long-term establishment of the *T. absoluta* (Tonnang et al., 2015). Moreover, the designing of this model is not based on presence/absence data such as that used for CLIMEX modeling approach by Tonnang et al. (2015), rather; time period of record data was used only for the model validation. Another peculiarity of the modeling approach used in this study is that the prediction is made on the annual basis, which allows predicting when *T. absoluta* might spread in time and space and invade new areas.

The studies of insects physiology and behaviors (Chapman et al., 2013; Wigglesworth, 2012) reported that, after reaching mature stages, these animals initiate the process of flight migration (Wigglesworth, 2012), looking for suitable environment to feed, mate and reproduce (Alyokhin and Ferro, 1999; Prasad, 1985). It is during these processes that agricultural crops are damaged by insects' herbivores. The goal of control measures is to maintain pest damage at economically acceptable levels (University of Minnesota, 2012) and direct impact of a good application of a control measure is to slow down the level of damage caused by pest. Current, strategies used to control *T. absoluta* are garden sanitation, destruction of alternative host and the use of mass trapping with sex pheromone. The majority of these methods aim to reduce the pest population density and dynamics. In this study, an attempt of introducing control measures was applied by varying *T. absoluta flying* radius ability. The findings suggest that efficient control measures would considerably slow down the progression of spread *T. absoluta* and if such measures were introduced since the pest detection in Spain in 2006 it should have taken more than 7 years to reach Kenya.

The spatial heterogeneity of the environment of study is one the key factor which greatly influences the invasion process; given that unsuitable locations will have the effect of slowing down the spread (Hastings et al., 2005). Indeed, CA by its definition offers the possibility to take into account this heterogeneity by applying rules on each cell of the area of study with a fixed time step for the pest progression. Reaction-diffusion, gravity, and individual-based models are also proposed as approaches which could handle spatial heterogeneity for modeling the complex process of insect invasion and spread (Hastings et al., 2005). However, some form of diffusion model based on partial differential equations sometimes ignores the underlying variation of the environment and assumes that movement is essentially the result of a very large number of steps of arbitrarily small size (Hastings et al., 2005). In the gravity model, the heterogeneity of the surrounding environment is used to estimate and determine the attractiveness of the given destination (Bossenbroek et al., 2001; Hastings et al., 2005). Individual-based models represent the best approach to incorporate all detailed information like fecundity, phenology and landscape structure in the process of invasion (Hastings et al., 2005). Another alternative to CA could have been the use of reaction-diffusion model, which is also suitable to study and understand the generality driving the process of invasion (Hastings et al., 2005). Moreover, it has been shown that CA can be used as an alternative to differential equations that are forms of reaction-diffusion model (Toffoli, 1984).

Although the time periods predict by our model to invade a location are not fully in-line with those obtained from the dates of occurrence, they give general insights on how and when *T. absoluta* could spread within Africa. Reasons for the discrepancies can be explained by the following arguments. 1) Data on NDVI, temperature and relative humidity used for every simulation are not those of the actually observed information corresponding to each specific year. The values of one year were assumed to represent all the years of the simulations. It is expected that the model predictions should have improved if during the simulation we used datasets corresponding to each year. 2) Insects behavior in nature is complex and random, thus, we cannot really predict with high accuracy their exact attitude but only identify areas with high suitability for its establishment. 3) Human-assisted invasion and spreading pathways were not included into the model (Crespo-perez et al., 2011; Gagnon et al., 2015; Koch et al., 2014). 4) There are also many other elements such as the phenology of *T. absoluta,* the speed and direction of the wind, the flux on exchange of host plants among different countries and regions that may greatly influence the spread of this pest. Nevertheless, the ability of the model to predict with certainty the exact year that *T. absoluta* was reported in Kenya and other countries provides some level of assurance to trust that the pest could reach South Africa if no control measures are applied ten years after been reported in Spain. Indeed, the present model can serve as an early warning tool for phytosanitary officers and policy makers to take appropriate decisions in order to safeguard against further invasion and establishments of *T. absoluta.* This calls to put in place adequate quarantine measures to counteract the pest invasion and spread.

5. Conclusion

The proposed model for the spread pattern of *T. absoluta* aimed to predict its timing of invasion across Africa. We were able to annually mimic and predict the spreading behavior and pattern of *T. absoluta* that lead us to estimate the time this pest will take to invade the whole Africa. We were able to understand among factors such vegetation, temperature, relative humidity, and tomato production per area, which one has a major influence in facilitating the spread of the pest.

When only considering the climatic factor, relative humidity seems to have the strongest influence in enhancing the spread of *T. absoluta*. In addition, taking into account areas with a high production of the pest host plant improved the model predictions. Including the life histories, biology, and ecology of *T. absoluta* could help extend this study. Simulations could also target the whole terrestrial planet.

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