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

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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 play in the process of propagation of invasion. Simulations by inferring the pest's natural ability to fly long distance revealed that *T. absoluta* could reach 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.

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, 1917) (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 conditions. 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.,

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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 Africa, the pest is swiftly moving southwards to invade several eastern and western sub-Saharan 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 greenhouses 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 and 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 inform 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, 2015; Desneux et al., 2010; Ouardi et al., 2012; Tonnang et al., 2015; APHIS-USDA, 2011). They are georefence points 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 was obtained from the U.S. Geological Survey (USGS) website (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 (the year 2014) is produced at 16 days intervals. NDVI values for Africa (the 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 fall between -1 and 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. The values of relative humidity obtained were organized in text files with the geographical coordinates of the Earth surface spaced by 1×1 degree. The Inverse Distance Weighting method (IDW) (Roshan and Kang, 2011) was used to interpolate the relative humidity values to generate 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 ton per hectare for the year 2013 (Factfish, 2013). Information for 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 10–30 tons per hectare, and the third class (low producers), which corresponds to countries with production less than 10 ton per hectare.