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RAPID COMMUNICATION

From the Western Palaearctic region to beyond: *Tuta absoluta* 10 years after invading Europe

Mateus R. Campos[1,2] · **Antonio Biondi**[3] · **Abhijin Adiga**[4] · **Raul N. C. Guedes**[2] · **Nicolas Desneux**[1]

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Abstract The South American tomato pinworm, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae), is a devastating pest currently threatening the global tomato industry worldwide. In the last 10 years, it has spread and expanded to most of Europe, Africa and Asia, causing extensive damage to the crop itself and to the international tomato trade. With the aim of providing an overview of the current knowledge on this pest, we have briefly reviewed the available literature relying on its spread, quarantine, modeling and management. Finally, we have underlined the gaps in knowledge and provided several recommendations on how to achieve sustainable control as well as how to prevent further spread into unaffected areas.

Keywords South American tomato pinworm · Invasive pest · Biological control · Integrated pest management · Quarantine

Key message

- We have summarized the available information on *Tuta absoluta* 10 years after it was documented outside of its native range
- *Tuta absoluta* has increased its range radius by 800 km per year, infesting almost 60% of the tomato cultivated land worldwide, causing extensive direct and indirect damage
- Various phytosanitary measures, quarantine restrictions and early warning actions are being implemented in unaffected areas
- In the invaded regions, various non-chemical control packages have been set up and need to be prioritized over reiterative applications of broad-spectrum insecticides

Introduction

Trade and introduction of alien species have been intertwined since the dawn of the Industrial Revolution (Kolar and Lodge 2001; Schmitz and Simberloff 1997). However, with the advent of globalization, the current levels of international trade and human travel have not only brought the risk of introduction of invasive species to unprecedented levels (Essl et al. 2011) but also act as conduits for their rapid spread across the landscape (Hulme 2009; Lowry et al. 2013; Meyerson and Mooney 2007). While such typical anthropogenic activities favor biological

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✉ Antonio Biondi
antonio.biondi@unict.it

✉ Nicolas Desneux
nicolas.desneux@sophia.inra.fr

1 INRA (French National Institute for Agricultural Research), Université Côte d'Azur, CNRS, UMR 1355-7254, Institut Sophia Agrobiotech, 06903 Sophia Antipolis, France

2 Departamento de Entomologia, Universidade Federal de Viçosa, Viçosa, MG 36570-900, Brazil

3 Department of Agriculture, Food and Environment, University of Catania, via Santa Sofia 100, 95123 Catania, Italy

4 Biocomplexity Institute, Virginia Tech, Blacksburg, VA 24061, USA

invasion, this phenomenon is further aggravated by current global climate changes. These factors often determine successful invasions while affecting the patterns of species distribution and resource dynamics in the environment (Battisti and Larsson 2015; Dukes and Mooney 1999; Hellmann et al. 2008). As a consequence, the concern about invasive species, i.e., particularly invasive arthropod pests, has increased in recent years (Biondi et al. 2016a; Haye et al. 2015; Ragsdale et al. 2011; Keller et al. 2011). Among the invasive arthropod pest species drawing attention, the South American tomato pinworm *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) is one of the most harmful pests of solanaceous crops and represents a major threat to tomato production worldwide (Desneux et al. 2010, 2011; Guedes and Picanço 2012).

The tomato pinworm was observed for the first time outside South America, in eastern Spain, a little over 10 years ago. Currently, it can be found throughout Europe, Africa, the Middle East and parts of Asia with risks of outbreaks in bordering countries (Fig. 1). The economic and ecological problems caused by the tomato pinworm, its rapid dispersion and the difficulty in controlling it, especially in these past 10 years, has raised the level of concern of the principal producing countries, exporters and importers of tomatoes even further afield (Desneux et al. 2010, 2011). Some of these countries are still free from the tomato pinworm, thus requiring quarantine initiatives and further phytosanitary measures to minimize the risk of introduction. The need to determine the genotype of the spreading of *T. absoluta* is also relevant for gaining knowledge on the genetic basis of traits that enables successful invasion (Cifuentes et al. 2011). Detailed records on the spread of invasive pests and pathways of introduction are essential in order to understand the potential range and economic importance of invasive species (Guillemaud et al. 2015), as well as to be able to predict future trends and to identify management options (Asplen et al. 2015; Haye et al. 2016; Tonnang et al. 2015). In this paper, we have summarized and updated the information available about the tomato pinworm, including its economic impact, the recently invaded regions, current management efforts and the need for further future research.

Spread dynamics in invaded areas

Knowledge of the movement pathways of specific pest species is fundamental in reducing the likelihood of their introduction into new environments, forecasting trends and in identifying the most suitable and sustainable management options (Cesari et al. 2015; Roques et al. 2016). Recently, molecular evidence about the Old-World invasion by the tomato pinworm has been gained, suggesting that central Chile is the sole and very likely origin of the introduction of this species into Europe (Guillemaud et al. 2015). Spreading from its native range in the Peruvian

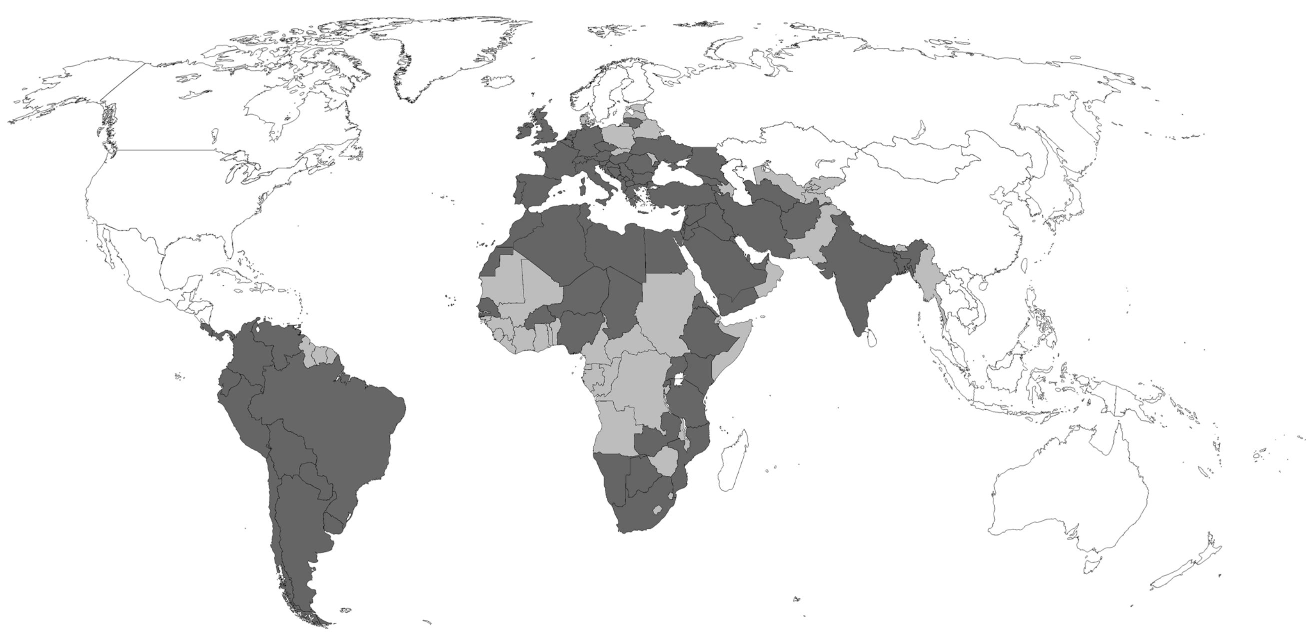

Fig. 1 Current worldwide *Tuta absoluta* distribution map (as of April 2017). Countries are indicated as follows: (1) *T. absoluta* presence has been confirmed (*dark gray*), and (2) *T. absoluta* could be considered present because of geographical and ecological proximity, or because the presence has not yet been confirmed after an initial record (*light gray*). The information provided is based on a compilation of reports from plant protection services and extension specialists (e.g., US Federal Order July 2014, EPPO reporting services), on published scientific articles and on personal communications (see also Table 1S for more details)

central highlands, the tomato pinworm expanded into other regions and countries of Latin America countries between the 1960s and 1980s, including Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Panama, Paraguay, Peru, Uruguay and Venezuela (USDA–APHIS 2014).

Invasive species usually spread very fast on most continents generally around 5 and 10 years after having been recorded in the invaded area. A recent evaluation on the spread of the tomato pinworm in Europe has shown that *T. absoluta* after first being recorded in the invaded area increased its radius by around 600 km per year over a period of 9 years (Roques et al. 2016). The rapid dispersion and the ecological and economic impacts on the countries after infestation by the species has increased the level of concern in tomato-producing countries free from this species (Fig. 1). This pest was first recorded outside Neotropical America in Spain in 2006, and within a few years it spread into most countries of the Mediterranean basin, besides North and Central Europe (Desneux et al. 2011) (Table S1). More recently, *T. absoluta* has invaded several Middle East countries, e.g., Afghanistan, and some sub-Saharan areas, from Gambia to South Africa, threatening tomato crop sustainability in these regions (Brévault et al. 2014; Pfeiffer et al. 2013; Tonnang et al. 2015).

Upon reaching the northern coast of Africa and the Sub-Saharan region, the pest started moving swiftly southwards, thanks to the spatial continuity of vegetable cultivation across political borders, the absence of effective surveillance mechanisms, the lack of specific phytosanitary expertise to intercept infested vegetables, ever-growing tourism and increasing intra-continental trade (Tonnang et al. 2015). The most recent African records are from southern countries, such as Zambia, Mozambique, Botswana and South Africa (Table S1). Nevertheless, records from several other African countries still need to be checked (Fig. 1; Table 1S). By 2017, it has been estimated the whole African continent will be totally invaded (Guimapi et al. 2016). By early 2014, *T. absoluta* was reported in southern India (Kalleshwaraswamy et al. 2015; Sridhar et al. 2014). In early 2016, the moth was found infesting tomato farms in the Kathmandu valley of Nepal (NARC 2016). In addition, reports have confirmed the pest north of Bangladesh (Hossain et al. 2016), thus showing how far east the tomato pinworm has so far spread.

Damage and economic impact

The economic impact of invasive pest species is directly reflected in the rising costs of crop production, namely additional costs for pest management, in the decrease of marketable products, and in the potential loss of trading partners through restrictions on export to non-infested countries. Moreover, as observed in many countries, it is very difficult to control and limit the spread of the invasive pest (Garnas et al. 2016; Keller et al. 2011). The tomato pinworm is a multivoltine species, showing high reproductive potential because of its adaptability which allows the pest population to increase very quickly (Tropea Garzia et al. 2012). The high reduction of tomato production is mainly due to the severe degree of tomato pinworm attacks, which mine the leaves, affecting the tomato plant photosynthetic capacity. Indeed, wandering larvae can bore through the stems, thus killing young plants which in turn compromise yield, or occasionally feed on fruits, increasing the costs for post-harvest selection (Galdino et al. 2015). Indirect damage can also be caused by secondary infections, with pathogens developing on the infested plant and fruit tissues (Tropea Garzia et al. 2012). The economic impact based on crop losses has been estimated at between €5 and 25 million per year in the Netherlands (Potting et al. 2013).

Control measures against the tomato pinworm are thus often used and chemical control is the most common tool used to suppress populations that suddenly grow in the open-field tomato crops (Guedes and Picanço 2012). In a worst-case scenario, an estimated average increase of 13–15 extra insecticide applications are necessary to fully control *T. absoluta* in the Netherlands, with an estimated increase in pest control-related costs of €4 million per year (Potting et al. 2013). In Spain and Tunisia, 15 and 18 active insecticide molecules, respectively, were specifically introduced to target *T. absoluta* between 2009 and 2011 (Abbes et al. 2012; Desneux et al. 2011). In South America, the introduction of *T. absoluta* in countries bordering the origin country has led to sudden increases in insecticide use in tomato fields from 12 to over 30 applications per cultivation period (Guedes and Picanço 2012; Gontijo et al. 2013). Such a huge insecticide selection pressure is obviously not compatible with most of the integrated pest management (IPM) programs implemented in the tomato systems. The increasing number of insecticide applications is mainly due to the problems linked to insecticide resistance in *T. absoluta* populations (Campos et al. 2014; Roditakis et al. 2015). It is also the consequence of potential disturbances of ecological services provided by pollinators and natural enemies exposed to the sublethal exposure of pesticides (Abbes et al. 2015; Barbosa et al. 2015; Biondi et al. 2012a, 2013a; Tomé et al. 2012, 2015). What is more, secondary pest chronic exposure to sublethal concentrations of pesticides can trigger unforeseeable consequences, such as pest outbreaks (Desneux et al. 2007; Guedes et al. 2016).

Current threat to global tomato industry

After 10 years outside Neotropical America, the tomato pinworm has already infested 2.8 million ha of tomato crop, i.e., more than half the land devoted to cultivating tomatoes (FAOSTAT 2012). Among the ten largest world tomato producers, six countries, namely India, Turkey, Egypt, Iran, Italy and Spain, have already been infested by this pest, and around 50% of the world tomato production is marketed among infested countries (FAOSTAT 2012). Three countries, China, India and Turkey, account for almost half of the land area covered worldwide with tomato crops i.e., 31, 11 and 7%, respectively. India is the second largest tomato producer in the world, 17.5 M tons, and exhibiting a tomato cultivated area of 870 M ha (FAOSTAT 2012). Despite efforts to prevent the *T. absoluta* invasion in China, the risk of introduction into this country within the next few years has increased considerably, as previously reported (Desneux et al. 2011). In addition to China's neighboring countries, Afghanistan and India, newly infested countries bordering China, such as Tajikistan and Kyrgyzstan, are currently under high risk of tomato pinworm outbreaks (Fig. 1).

The tomato acreage in Europe is half a million hectares, 11% of the global tomato area cultivated (FAOSTAT 2012). Most of Europe has recorded the presence of *T. absoluta*, except Moldova and central and eastern Russia, which currently remain free. Russia has the largest tomato cultivated area in Europe (117 M ha) (FAOSTAT 2012), but the presence of tomato pinworm has been restricted to western Russia since 2010 (Izhevskya et al. 2011). Although the tomato pinworm does not survive low temperatures, it can successfully overwinter in warmer environments, such as protected crops and indoor warehouses (Tonnang et al. 2015; USDA–APHIS 2011).

The African continent produces 18 M tons of tomatoes, which corresponds to 12% of the world production as of 2012. The biggest tomato producers in Africa are Nigeria, Egypt, Morocco and Tunisia; these four countries alone produced more than 70% of African tomato in 2012 (FAOSTAT 2012). Recently, the governments of northern Nigerian states declared an emergency after the tomato pinworm destroyed more than 80% of the tomato fields in the region, causing a 20-fold increase in the tomato price (FAO 2015). Due to the pattern of climate similarity with South America and the rapid spread of the tomato pinworm in recent years, all countries in the African continent are expected to record the presence of this pest species within 2018 (Tonnang et al. 2015).

Central America produces 4 M tons of tomatoes accounting for more than 16% of the total production in the Americas covering an area of 113 M ha. The spread of the tomato pinworm is still taking place in the continent, and its presence in Costa Rica was reported in 2014 (EPPO 2014), increasing the quarantine concern in Central and North America (USA and Canada). North and Central America, mainly Mexico, are seeking data about the dispersion dynamics and sustainable management options for the tomato pinworm (NAPPO 2013). The invasions of this pest in new regions appears linked to the import of tomato fruits, as in confirmed cases in Eurasia after 2010, e.g., the Netherlands and Russia (Desneux et al. 2011; Karadjova et al. 2013). The United States accounts for 25% of the world tomato imports of the tomato, and in 2015 such imports were received from different countries reaching a total of 1.5 M tons (Trade Map 2016). A fact worth mentioning is that in 2014 few of the US tomato imports came from tomato pinworm-infested countries, i.e., 0.01% or 245 tons, including tomatoes from the Netherlands, Spain, Ecuador, Italy and Colombia (Trade Map 2016).

In 2005 and 2006, Spain imported 23 and 29 tons of fresh tomatoes, respectively, from Chile, whose problems with tomato pinworm infestation date back from the 1960s. This, together with recent molecular evidence (Guillemaud et al. 2015), suggest that exported Chilean tomatoes are the most likely source responsible for the European invasion. Chile was also the source of the earliest report on insecticide resistance in this species, followed by Brazil and Argentina (Guedes and Siqueira 2012). Thus, the introduction of insecticide-resistant genotypes of the tomato pinworm into Europe probably occurred at the outset. By contrast, tomato trading could not be the sole cause for the Indian invasion, which took place in late 2014, because this country stopped importing tomatoes by late 2013 (Trade Map 2016). Therefore, the tomato pinworm presence may have remained undetected in India for a few years. The pest could have entered the country through (1) the importation of other commercial goods, including alternative host plant species or used packing materials, or (2) due to workers commuting between Middle Eastern countries and the Indian subcontinent.

Management efforts

Substantial economic and ecological damage was created by international trade and global environmental change which are significant components of the invasion of ecological systems by exotic species (Garnas et al. 2016). Policies against invasive species often involve unilateral defensive actions as opposed to coordinated international initiatives. However, an important step towards preventing threats from such infestation is the coordination and global cooperation in the management of phytosanitary risks

(Perrings et al. 2010). Trade patterns relative to pest species distribution and commodity production locations should be the main drivers of phytosanitary actions. However, pests vary among countries in their perceived risk to the agricultural industries and to the environment.

The International Plant Protection Convention of the United Nations Food and Agriculture Organization (UN/FAO) provides guiding principles applicable to phytosanitary importation and exportation activities (FAO 2006). Countries associated with the North America Plant Protection Organization (NAPPO) also selected appropriate phytosanitary measures that are important to minimize further spread and establishment of the tomato pinworm (USDA–APHIS 2014). The established measures were based on considerations followed by the International Standards for Phytosanitary Measures (ISPM) which guides the import and export of goods (NAPPO 2013). ISPM requirements are adapted to prevent spread of the organism via import and internal movement of plants and fruits of Solanaceae, especially tomato. In case of fruits originating from infested areas, procedures are required to sanitize them, thus preventing adult moths from escaping during the fruit transportation or at the time of its unloading; hermetic packaging conditions, refrigeration or netting are procedures used for the purpose (FAO 2006). The tomato pinworm is a major concern for the United States Department of Agriculture, Animal and Plant Health Inspection Service, Plant Protection and Quarantine (USDA–APHIS–PPQ), which has imposed quarantine restrictions for tomato import into the country. In response to this pest outbreaks in the EU, the US and Canadian authorities imposed strict import conditions for tomatoes from several EU countries and is also highly likely to impose quarantine restrictions on export of tomatoes from West and Central African countries (ECOWAS) (Pfeiffer et al. 2013; USDA–APHIS 2014; van der Straten et al. 2011).

Tomato fruit, either green, red or pink, produced in Chile and which are imported to US must be subjected to methyl bromide fumigation. However, this treatment can only be applied in a preclearance program. This implies conjunction of international services, preclearance inspections, treatments and/or other mitigation measures procedures which are designed to identify and/or mitigate the risk of invasive pest introductions through action taken in foreign countries under the supervision of APHIS personnel. Among the countries known to be infested with the tomato pinworm, only Chile has implemented a preclearance program (USDA–APHIS 2013). Nonetheless, fumigant applications and particularly methyl bromide use are currently facing phasing out due to its ozone-depletion characteristic. An alternative method in use which is internationally accepted for different fruits and vegetables is irradiation treatment protocols (Hallman et al. 2013). Ionizing radiation use as a phytosanitary treatment has increased against invasive pest species of fruits and vegetables in various countries, including Australia, New Zealand, and Malaysia (Hallman et al. 2013).

The use of pheromone traps is considered the major tool for early detection of this pest in newly invaded areas. Between 2010 and 2012, the US State of Florida implemented a *T. absoluta* detection network in 29 cities using traps baited with the sexual pheromone (NAPPO 2013). In Bosnia and Herzegovina and Montenegro, a molecular protocol to detect *T. absoluta* DNA from trapped individuals and from infested fruits was successfully tested (Đurić et al. 2014). Besides the high cost to implement the use of pheromone traps, decision-making studies focusing on the control of *T. absoluta* in infested crops are still linked to plant sampling (Cocco et al. 2015). Therefore, more studies are still needed to enable proper sampling when pheromone traps are used next to the plants in order to take the necessary decisions. Nevertheless, the use of synthetic pheromones for male mass-trapping or for mating disruption gave unsatisfactory results. As a result of such shortcomings, the detection of parthenogenesis among specimens of the tomato pinworm has given rise to further concerns (Caparros Megido et al. 2012, 2013; Cocco et al. 2013).

The first years following detection of the tomato pinworm and the awareness of its impact on tomato crops in Europe and North Africa have led to the extensive use of insecticides by growers in these regions (Desneux et al. 2011). This is similar to what was previously observed in South America (Guedes and Picanço 2012; Guedes and Siqueira 2012). However, insecticide applications are not always as efficient as expected to control this species. Insecticide efficacy is usually compromised due to the cryptic nature of the larvae, the high reproduction potential and the long tomato reproductive stage where the fruits remain exposed to direct injury (Guedes and Picanço 2012). In addition, several cases of insecticide resistance have been reported, including resistance to organophosphates, pyrethroids, abamectin, cartap, anthranilic diamides and spinosad (Campos et al. 2014, 2015; Haddi et al. 2012; Roditakis et al. 2015, 2017; Silva et al. 2016; Siqueira et al. 2000).

The susceptibility of the tomato pinworm to insecticides has been monitored over the past few years in Europe (Roditakis et al. 2013), following previous South American studies (as reviewed by Guedes and Picanço 2012), and subsequent intensification of tomato pinworm resistance to different active ingredients (Campos et al. 2014, 2015; Silva et al. 2016). In Italy, after <5 years of the *T. absoluta* arrival, the pest population was more than 1000-fold resistant to chlorantraniliprole and flubendiamide, as well as showing cross-resistance to both compounds (Roditakis et al. 2015, 2017). Besides the resistance of this species to pesticides, there are potential side effects on natural enemies that can induce multiple sublethal effects in individuals that survive pesticide exposure (Biondi et al. 2012b, 2013a; Desneux et al. 2007). Pollinators are also the unintentional targets of pesticide use in tomatoes, where pollination enhances fruit production and pesticide use can compromise such economic and environmental service (Barbosa et al. 2015; Biondi et al. 2012a; Lima et al. 2016; Tomé et al. 2012, 2015). As a consequence, non-chemical tools have to be prioritized.

IPM programs for the tomato pinworm management under development and/or implementation in several countries include tools for the pest prevention, monitoring and sustainable control. After the initial detection of the tomato pinworm, the elimination of symptomatic leaves and destruction of infested tomato plants are highly recommended against this pest, as well as environmental management practices such as tilling, manuring, irrigation, crop rotation and solarization (Terzidis et al. 2014). In greenhouses, one of the management practices used to reduce initial tomato pinworm infestations is to keep infested greenhouses closed after the harvest to prevent the migration of adults to open-field crops or to an alternative host (Derbalah et al. 2012; Desneux et al. 2011). Alternating host crops, mainly tomato and potato, with non-host cultures can ensure long-term reduction of pest pressure (Terzidis et al. 2014; Tropea Garzia et al. 2012). Nonetheless, area-wide tomato cultivation throughout the year compromises the potential effectiveness of this recommendation, which is also limited by the year-round existence of alternative hosts (Guedes and Picanço 2012).

Among the agronomic techniques experimented to control *T. absoluta*, several tomato accessions and cultivars (Oliveira et al. 2009; Sohrabi et al. 2016), as well as the nitrogen and water management (Han et al. 2014, 2016a), have been shown to impact the pinworm population dynamics. However, caution should be exercised in using IPM programs against *T. absoluta* when irrigation in tomato crops is performed with saline water (Han et al. 2016b). This knowledge has not been incorporated into *T. absoluta* IPM packages. By contrast, biological control against this pest has been widely implemented using indigenous natural enemies (Zappalà et al. 2013). Various predators and parasitoids have been reported naturally attacking the tomato pinworm in tomato crops in Europe and North Africa and more recently in India and South America (Biondi et al. 2013b; Calvo et al. 2016; Perdikis and Arvaniti 2016; Salehi et al. 2016). Some efforts have targeted the activity of the *T. absoluta* egg (Cabello et al. 2012; Chailleux et al. 2012; El-Arnaouty et al. 2014) and larval parasitoids (Biondi et al. 2013c; Chailleux et al. 2014). However, the most cost-effective and successful biological control programs are those based on the augmentation and/or conservation of mirid bugs, such as the omnivorous *Macrolophus pygmaeus* and *Nesidiocoris tenuis*, employed alone or in combination with parasitoids (Chailleux et al. 2013a, b; De Backer et al. 2015; Mollá et al. 2014; Naselli et al. 2017) or with selective pesticides (Zappalà et al. 2012).

Among the bioinsecticides used on tomato crops, commercial formulations based on *Bacillus thuringiensis* (*Bt*) and *Beauveria bassiana* are considered the most efficient and selective options, as they are highly compatible with the tomato pinworm natural enemies (Biondi et al. 2012b, 2013a; Klieber and Reineke 2016). Further studies should investigate possibilities for improving natural enemy ecosystem services via conservation and augmentation strategies, which would help their early establishment and persistence during the cropping season by providing additional food sources, and/or alternative plants and/or non-pest host sources (Biondi et al. 2016b; Urbaneja-Bernat et al. 2015). Nevertheless, in the pest native range, high natural enemy biodiversity has been recorded feeding and developing on this prey/host (Desneux et al. 2010; Salas Gervassio et al. 2016), but effective, coevolved and specialized natural enemy species have not yet been identified. Therefore, despite classical biological control programmes are being pursued for controlling several invasive insect pests in other agroecosytems (Daane et al. 2015, 2016; Desneux et al. 2012), this strategy is not currently considered as a priority for *T. absoluta* in Africa and Eurasia.

Modeling efforts

From the perspective of ecological models, there have been two CLIMEX-based approaches to determine regions of suitability for *T. absoluta* induced by current and future climatic conditions, one focusing on the Mediterranean basin (Desneux et al. 2010), and the other on the global distribution (Tonnang et al. 2015). The latter combines molecular characterization and geo-reference of incidence records in conjunction with ecological parameters to estimate potential spread of *T. absoluta*, mainly in sub-Saharan Africa. More recently, Guimapi et al. (2016) have developed a cellular automata model to study the dynamics of the pest in Africa. They have taken several factors into account such as: vegetation, temperature, humidity, production data, and have been able to estimate the invasion time and pattern for the whole of Africa. Integrated surveys are also the Physiologically Based Demographic Models (PBDM) as proposed by Ponti et al. (2015) to study the spread of *T. absoluta* in the Mediterranean area. Though literature contains mechanistic models for tomato growth, knowledge gaps in *T. absoluta* biology that need to be filled have been identified, in order to develop an effective PBDM. In the case of *T. absoluta,* however, any approach that only takes into account the ecological factors is inadequate. While these models provide accurate predictions on the potential risk of invasion and establishment, they do not throw light on possible pathways of introduction. Particularly in the case of *T. absoluta*, anthropogenic factors such as trade, travel and the global proliferation of greenhouses (main overwintering sites in cooler areas) are the leading causes for the rapid spread and survival of the pest (Desneux et al. 2011). Researchers are increasingly acknowledging the need for more holistic approaches towards modeling invasive species dynamics (Venette 2015). However, unlike ecological models, research on integrated models, especially those representing human-mediated factors, are in process of being developed, although well-defined methods for data acquisition and model design are lacking.

Conclusion and future outlook

A decade or so ago, *T. absoluta* arrived in Europe from South America, and within this period it has spread to almost the whole of Africa and Eurasia. It remains a significant threat to tomato production because it has reached the borders of the main tomato producing, exporting and importing countries, thus increasing the odds of the approaching introduction and subsequent outbreaks, particularly in China, Mexico and the US. Given the aggressive nature of the pest and the ever-increasing commercial travel, the introduction of the tomato pinworm into unaffected countries is an enormous and constant threat. Nevertheless, quarantine and phytosanitary measures, e.g., ionizing radiation could serve as important deterrents, and should be adopted according to international trade recommendations.

The tomato pinworm might be controlled effectively by devising an integrated approach which keeps in mind the host and climatic conditions of the geographical area. The integrated approach for pest prevention, monitoring and sustainable control include: (1) inspection and careful installation of pheromone traps in countries bordering areas exhibiting high risk of introduction; (2) highly recommended methods are the elimination of symptomatic leaves and destruction of infested tomato plants; (3) the development of resistant tomato varieties to minimize tomato pinworm infestations and losses, and (4) biological control implementation through the scouting of effective and specialized natural enemies in the native range and by the conservation and augmentation of locally available biocontrol agents in combination with selective insecticides. The knowledge and control methods studied are of great relevance not only to infested countries but also to the uninfested ones threatened by the imminent invasion of the tomato pinworm. The outcome would be enhanced human and environmental safety maintaining the affordability of tomatoes, the main horticultural product worldwide.

Author contribution statement

AB and ND conceived and designed the manuscript. MRC, AB and ND organized the manuscript based on written contributions from all authors. All authors wrote, read and approved the manuscript.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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